

Seismic and sequence stratigraphic study of the Neogene-Quaternary Taranaki Basin, New Zealand: implications for reservoir prediction

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M.Sc. in Petroleum Geoscience Project Assessment Questionnaire

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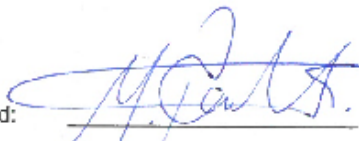
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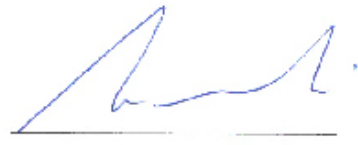
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(student)

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(supervisor / course director)
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Abstract

The Taranaki Basin has developed between the Pacific and Australian Plates on the West coast of New Zealand. Sequence stratigraphic and trajectory analysis of Neogene-Quaternary sediments was conducted to better understand the migration and depositional processes of the basin through time. The trends observed are low angle ascending regressive, stationary, high angle ascending regressive and descending regressive trends. In addition, it was observed that the region showed differences in the geometry of the Northern and southern parts after a certain period. The Northwards progradation of clinoforms is observed in the study area, developing during the Plio-Pleistocene period. Twelve different sub-sequences were defined including top-basement. Sub-sequences were defined by 4 different stages, which are related to sea level changes. During stage 2 and stage 4, relative sea level-fall indicates forced regression, and during these two stages, Falling Stage Systems Tract (FSST) is observed. As a result of the sequence stratigraphic study, three systems tracts: FSST, Highstand Systems Tract (HST) and early Transgressive Systems Tract (TST) were defined. Potential reservoirs locations and styles have been predicted based on the systems tract definition. Key probable reservoirs are located in shoreline and shoreface throughout the study area during the predominant period of HST. In the case of FSST, the possible reservoirs are related to deep water submarine fans. Probable reservoirs in the early TST phase are hypothesised to have developed in low density turbidity flows and debris flows, estuarine deltas and back stepping beaches. The predicted reservoirs may hold significant prospectivity for petroleum, a full analysis of migration pathways and maturity needs to also be conducted.

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1. Introduction

The majority of New Zealand is under water and only 5% of the island is above the sea level. This submergence occurred as a result of thinning of the continental crust to an average of 25km (Campbell et al. 2012). Extensional phase caused the separation of the Tasman Sea and Gondwana (Holt and Stern, 1994; King and Trasher, 1996). Campbell et al. (2012) determined the age of this separation as 83 Ma. Separation of Australian and Pacific plate during Miocene caused active margin tectonism. Wood and Stagpoole (2007) reported that New Zealand was uplifted and increased erosion allowed sediment entry to the basins in the region.

Petroleum potential of the region is quite high. The first oil in the region began to be produced in 1865, but the first important discoveries were found in 1950. The age of source rocks in the region as Cretaceous – Eocene. Reservoir, on the other hand, associated with fluvial and deep marine systems and gave their age as Pliocene. Oligocene and Early Miocene aged rocks are the seal rock (Campbell et al. 2012). The aim of the study is to understand the development of Cenozoic basin in the region and the presence and distribution of reservoirs.

1.1. Study Area

The study area is shown in Figure 1, the focus of the area is the Taranaki Basin (Shown in Red).

1.2. Objectives

The aim of this study is to obtain information about Neogene - Quaternary depositional evolution of the region by using the given well-data (Formation tops) and 2D seismic lines. In this study, one of the objectives of the study is to determine the unconformities, sequence boundaries and maximum flooding surface, maximum regressive surfaces by applying seismic stratigraphy, sequence stratigraphy, trajectory analysis. Sea level changes, tectonic processes and sediment influx, which are important parts of sequence stratigraphy will be discussed. The main objective of the study is identifying sequence stratigraphic systems tracts in order to describe potential oil and gas reservoirs.

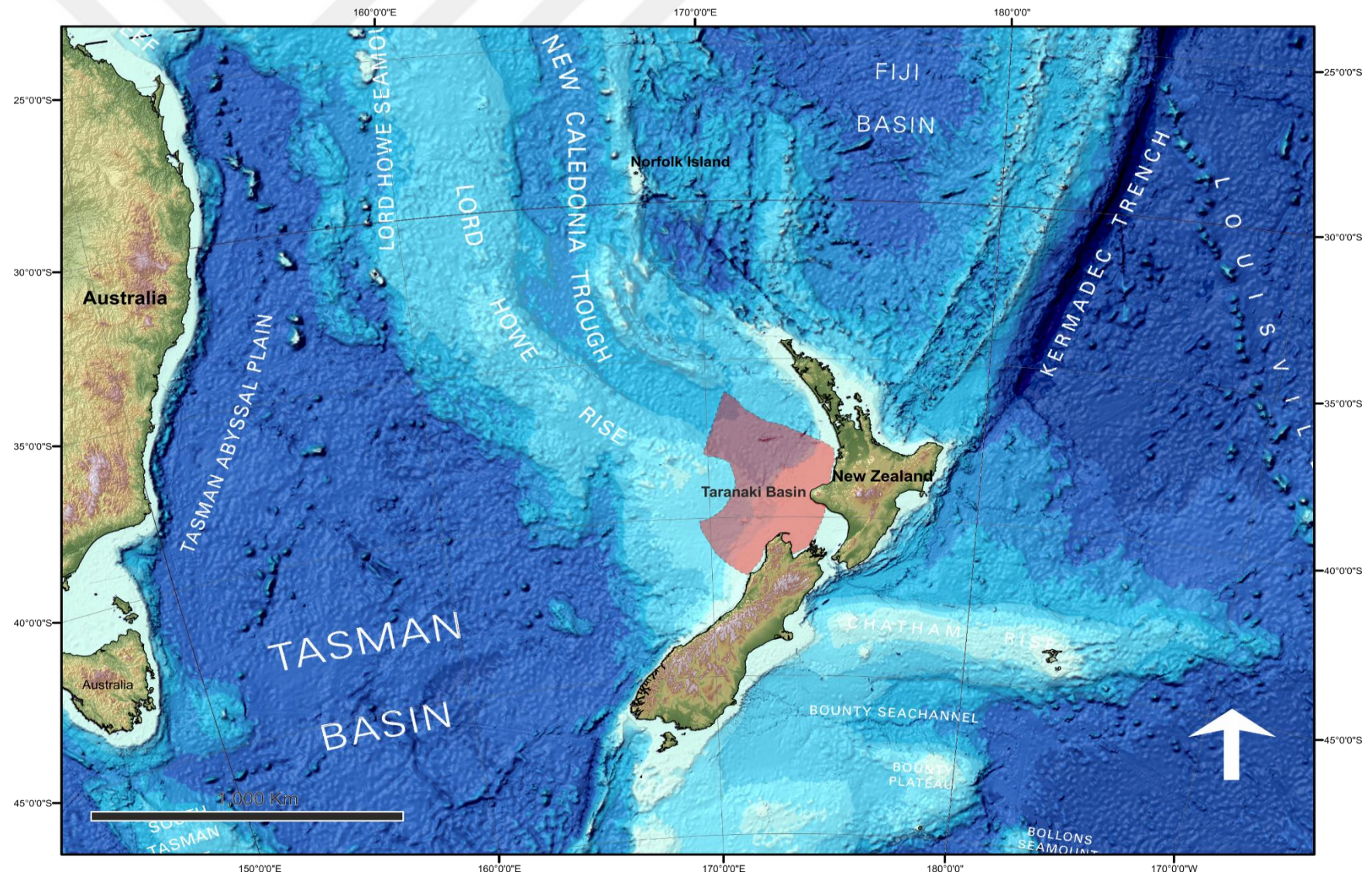


Figure 1: Showing Location of the Taranaki Basin and Study Area

1.3. Regional Overview

The study area is located on the west coast of the North Island of New Zealand. According to Storgen (2011), Taranaki Basin started to occur as rift basin during the Middle-Late Cretaceous to Paleocene. The Taranaki Basin is a continental passive margin during Eocene – Oligocene and a foreland basin during Miocene. It was defined as the back-arc basin during the Late Miocene period. Uplift and erosion events following Collision caused progradation in Early Miocene. The sediment influx observed in the rising areas showed a Northwards-oriented progradation in the Taranaki Basin. Bull et al. (2016) reported that after the Late Miocene inversion phase of the basin, Pliocene sediments started to precipitate on the previous layer and then continued with Plio-Pleistocene progradation (Figure 2).

2. Geological Settings

2.1. Introduction

New Zealand is located between the Pacific and Australian plates. The Northern Island of the New Zealand region, part of the Australian plate, and a large part of the Southern island are on the Pacific plate. The movement of the North Australian plate on the Pacific plate and the Australian plate movement makes these two plates move in the opposite direction. Movements are connected to the Pacific Plate on the Australian Plate, forming the Alpine Fault and Southern Alps (Norris et al. 1990). The shallow marine areas covering the vast area in the North-west, south and west of New Zealand are the regions under the plateau and rift systems, while the North and the Northeast are the deep-sea basins of the Pacific Ocean and the Tasman Sea. With the separation of the Gondwana occurring in the last 100 Ma in the Cretaceous, countless basins were formed in this region (Cook and Gregg, 1997) and this supports the views of Laird (2003) (Figure 3). Except from this period, Pliocene Harve Trough (Walcott, 1987) and Eocene Solander and Emerald Basins (Figure 3) occurred (Sutherland, 1995). Sedimentation has experienced many deformations in active tectonics from the Cretaceous to the Cenozoic (King, 2000). Sedimentary basins occurring during rifting in this region are terrestrial and transgressive marine sediments (Stagpoole et al. 2002). New Zealand sedimentary basins are shown in Figure 3. The paleogeographic and tectonics of New Zealand has been reconstructed by King et al. (1999) and King (2000) as

presented in Figure 4. According to Baur (2014), convergent margin phase started with mid to Late Eocene. The Neogene Alpine fault forms a link between the subduction in the North and the oblique extension in the southwest (King, 2000).

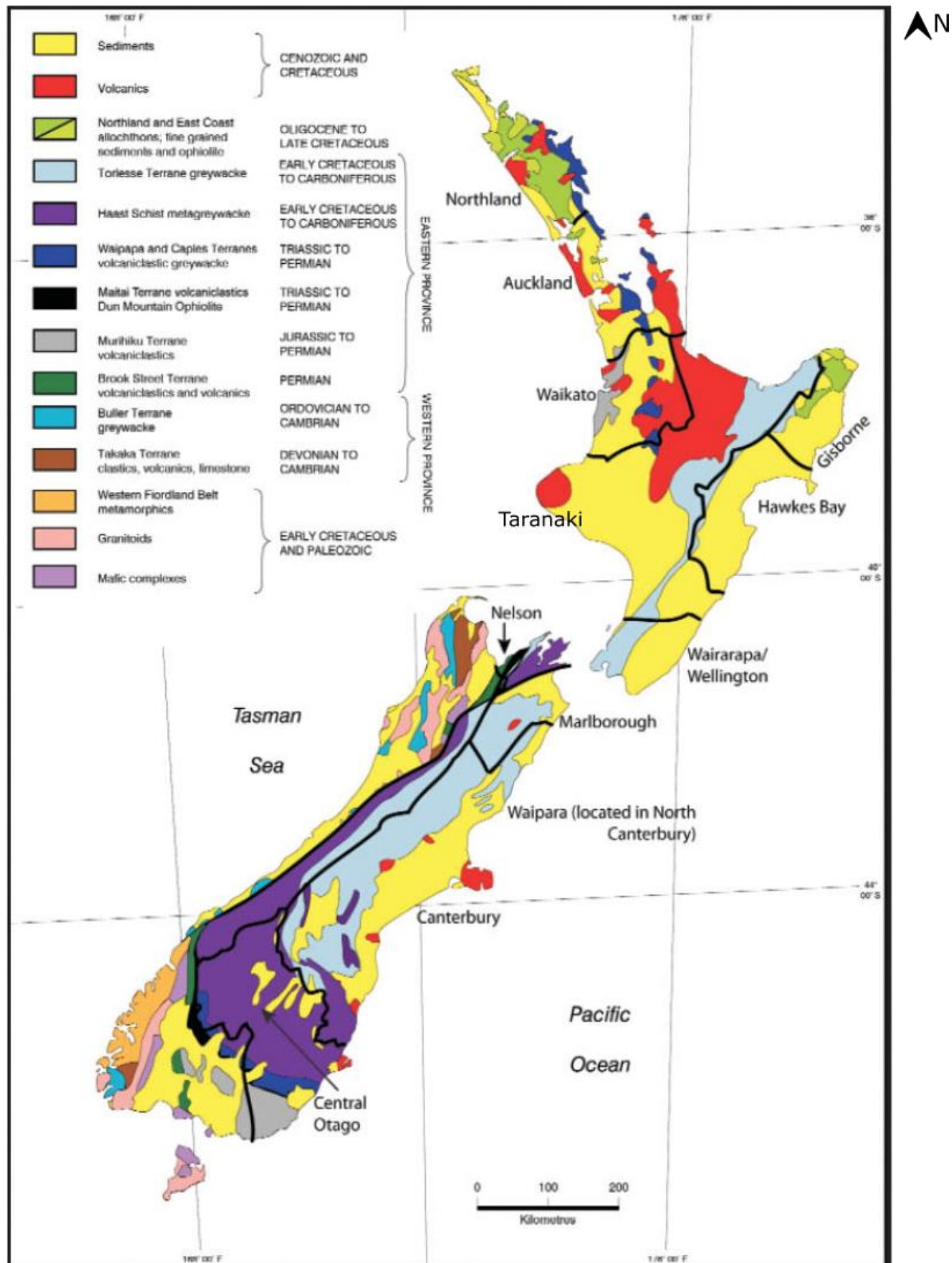


Figure 2: Regional Overview of New Zealand (from Graham, 2008)

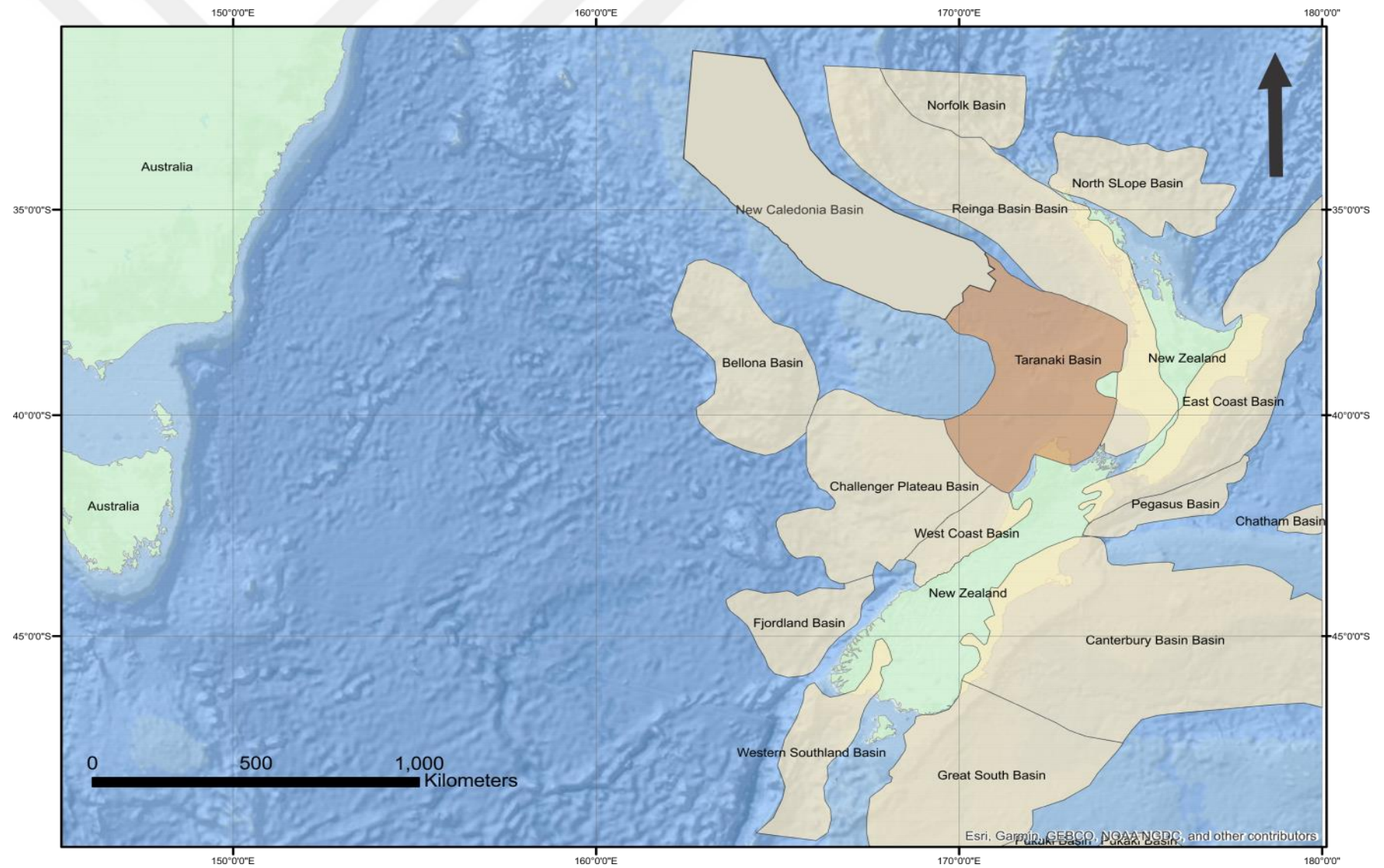


Figure 3: Adapted from Chenrai (2016) Map of New Zealand's sedimentary basins

This study focuses on the Taranaki Basin. It is located in the North of New Zealand (Figure 3). The early evolution of this basin system started with the separation of the Gondwana and the formation of the Tasmanian Sea during the Cretaceous and Paleocene periods (Burns and Andrews, 1973; Uruski and Wood, 1991; King and Trasher, 1996; Lafoy et al. 2005) and the evolution of the system continues today. (Knox, 1982). The Taranaki Basin is mainly offshore under the modern continental shelf and slope (Crowhurst et al. 2002). The Taranaki Basin is bounded by the Taranaki Boundary Fault, Cape Egmont Fault and Cook-Turi Lineament (Knox, 1982).

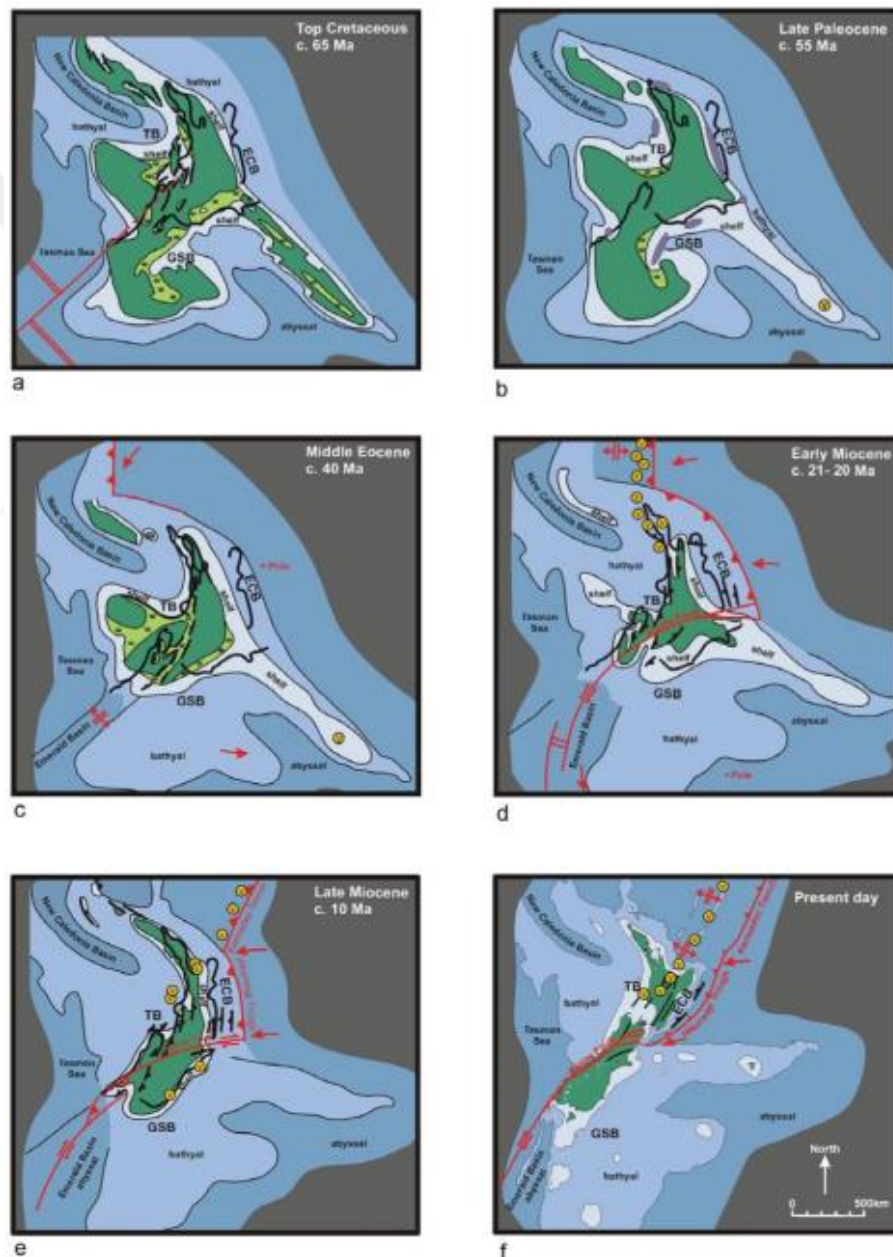


Figure 4: Adapted from Chenrai (2016) Paleogeographic and tectonic of New Zealand (GSB: Great South Basin, TB: Taranaki Basin)

2.2. Regional Geology

As discussed in section 2.1, the basin is under the influence of various tectonic regimes from the Cretaceous to the present (King and Trasher, 1996). The sediment in the basin is terrestrial, marginal marine and shallow marine, deposition of which occurred between the Cretaceous-Oligocene (Chenrai, 2006). The first stages of basin formation are influenced by rapid subsidence and extensional tectonic regimes which are controlled by the basin bounding faults.

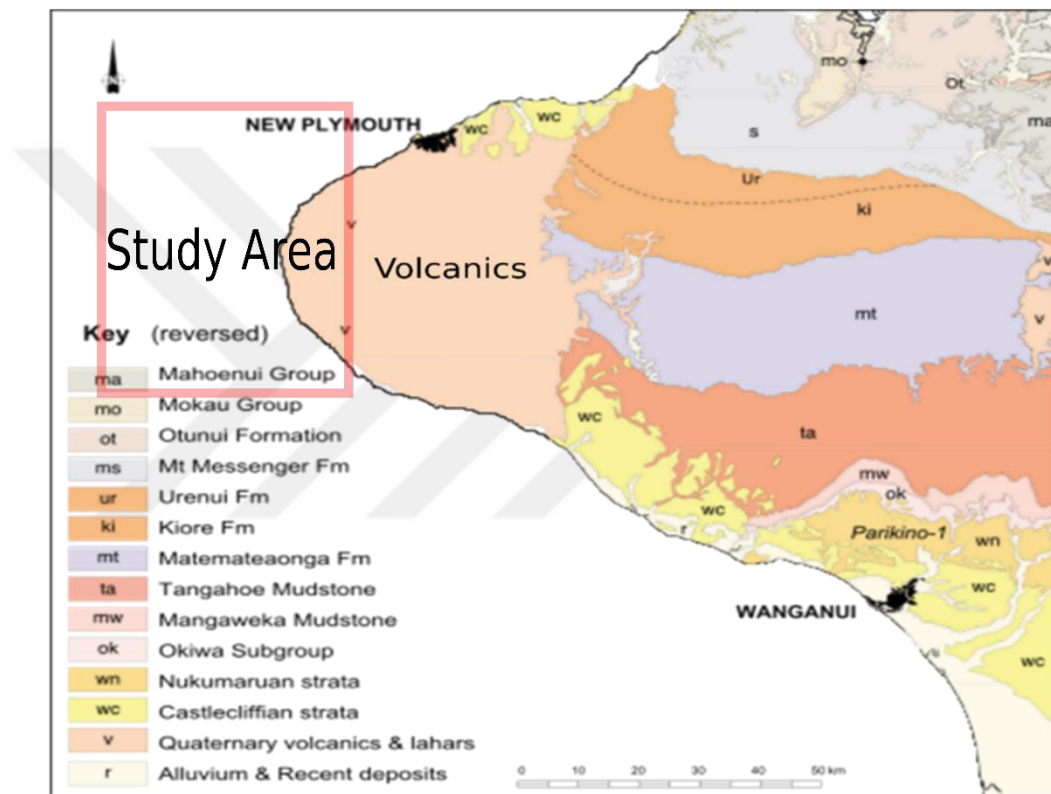


Figure 5: Geological map of Taranaki Basin, Onshore areas, Adapted From Kamp et al. (2002)

Regional subsidence during Eocene-Oligocene is related to thermal contraction. Pacific and Australian plates at the end of the Oligocene affect the formation of uplift, subsidence and deep-sea sediments in the region (Chenrai, 2006). The Eastern and Southern parts of the Neogene basin are located between the borders of Australia-Pacific. The Taranaki basin was formed between the Early and Late Miocene periods as complex fold-thrust belt and back-arc basin (King and Trasher, 1992). A large part of the basin was formed during this period.

The anticlines observed in the region were formed by the inversion of the grabens during the Late Cretaceous-Eocene period. While most of these structures plunge towards the North, they rise to the south. Maui, Kapuni and Kupe are examples of nearby fields with hydrocarbon potential. These inversions have shown angular unconformity (King and Trasher, 1996).

In the study conducted by Crowhurst (2002) and others on the Wakamarama fault, the Late Cretaceous Pakawau group was encountered in this region. The Eocene-Early Oligocene aged Kapuni group is present above this group. The inversion of the Wakamarama and Cook anticlines probably has same age (Miocene). Both anticlines are formed at the top of the syn-rift structures.

This region also contains a large amount of volcanic rocks (Figure 5). According to Muir (1995), the first volcanic activity in the region occurred at the time of early Cretaceous. Uruski and Wood (1991) say that this activity began when the Pacific plate in Miocene moved under the Australian plate (subduction). According to Campbell (2012), this led to the occurrence of iron rich sediments (Throughout the extent of the volcanics in Figure 5).

The region has been divided differently by various authors, Knox (1982) divided the region into three units, whilst King and Trasher (1996) have divided it into five. In this study the Knox division will be used, and this will subdivide the basin into the Western unit, Southern unit and Northern unit, these divisions were made according to the deformation style (shown in Figure 6).

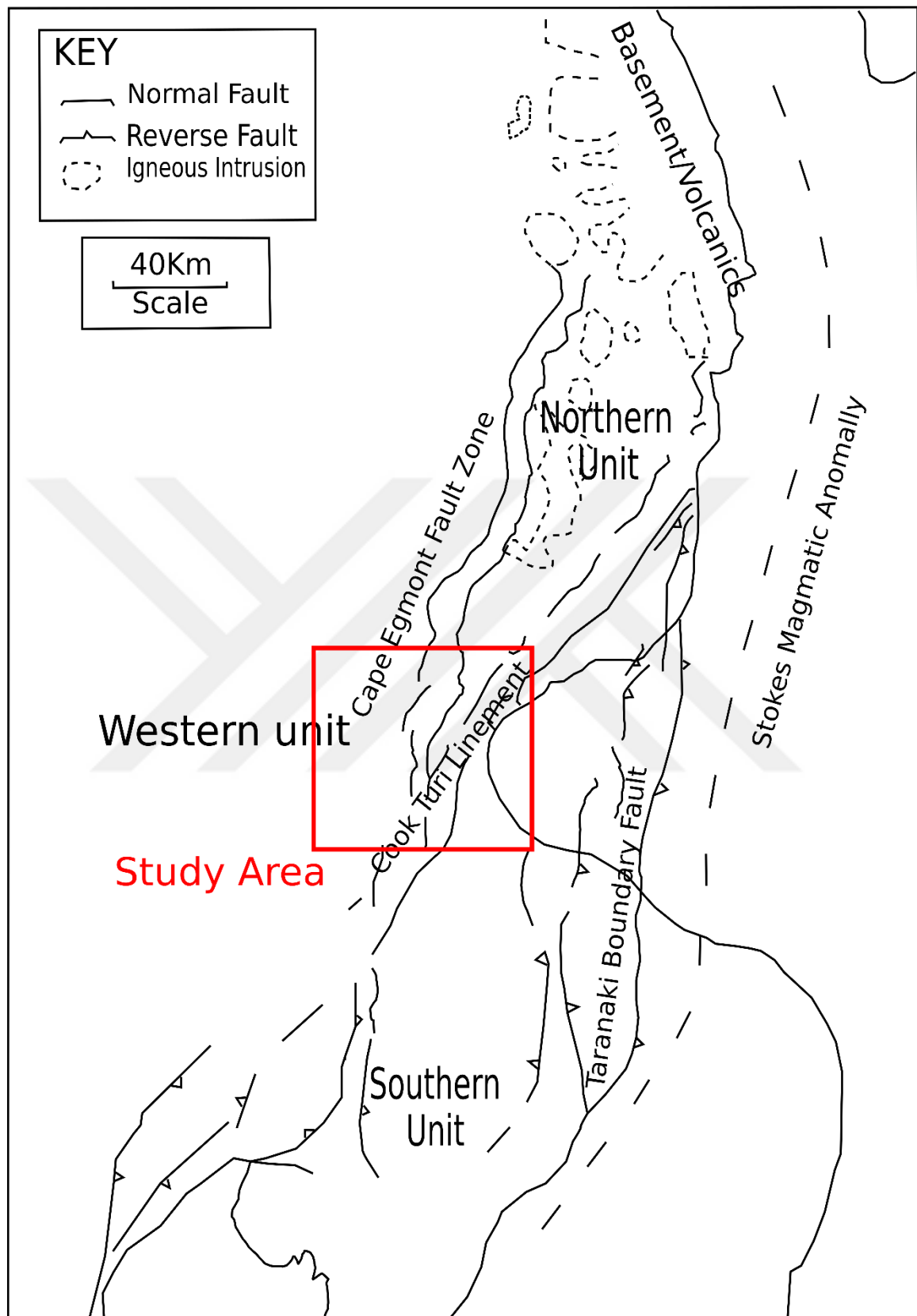


Figure 6: Adapted from Knox (1982) Structural units based on deformation style

2.3. Tectonic and Subsidence History

The tectonic history of the basin is given in Figure 4 and Figure 7 (with subsidence relation).

2.3.1. Mid to Late Cretaceous

According to Palmer and Andrews (1993), in New Zealand, at 80 Ma extension began at the Tasman Sea and it is triggered to form Taranaki Basin, extension continued during the Late Cretaceous and Palaeocene. King and Trasher (1996) said that the basin was formed by the transform rift system as a passive margin, however Laird (1993) said that the basin was simply related to faulting in a continental rift system. In the Late Cretaceous, two graben systems formed the Taranaki Basin, one is North-South trending normal faults, and the second is Northeast-Southwest trending dip-slip faulting (Trasher, 1990). According to King and Trasher (1996), as the Taranaki Basin was forming, the rapid spreading in the Tasman Sea and the slow opening of the New Caledonia Basin affected the West-Coast Taranaki rift system.

In the Jurassic-Early Cretaceous, the Western unit west of the Cape Egmont Fault belt was formed during the Rangitata Orogeny. This unit has been stable since the Eocene. The Cook-Turi Lineament is the boundary between Southern Unit and Western Unit. Again this unit is separated from the Northern Unit by the Taranaki boundary Fault (Cristie, 2007). The Northern Unit, formed by continuous subsidence, is dominated by normal faults. In addition, this section is often observed in intrusions and is usually Cenozoic. The grabens in these regions are generally bound to faults, but they show terrestrial conglomerate and coal layers (Palmer and Andrews, 1993). King and Trasher (1996) reported that these half-graben systems were asymmetric due to separate extension events.

2.3.2. Paleocene

Continuing subsidence in the North led to transgression in a South-Eastern direction, and the formation of an embayment open to the sea in the Northwest. The presence of glauconite in the otherwise terrestrial deposits at Kapuni Group suggest that the shoreline fluctuated laterally during the Palaeocene, eventually becoming established by Late Palaeocene and remaining until the Middle Eocene (Palmer and Andrews, 1993). Unlike the Pakawau Group, the faulting of the facies in the Middle Palaeocene ensured that the

Kapuni group was trapped in a wider region. Knox (1982), right at the end of the Palaeocene, with the activation of the faults, Eocene floor was cause erosion. This shows that towards the end of the Palaeocene the faulting has increased. Another proof of this is warping. According to Knox (1982), this warping event has two reasons. One of them, in the Tasman Sea, is likely to be associated with the dying phase and the spreading of the seabed, and the second one is the separation from Antarctica, which is from 55 Ma (Knox, 1982).

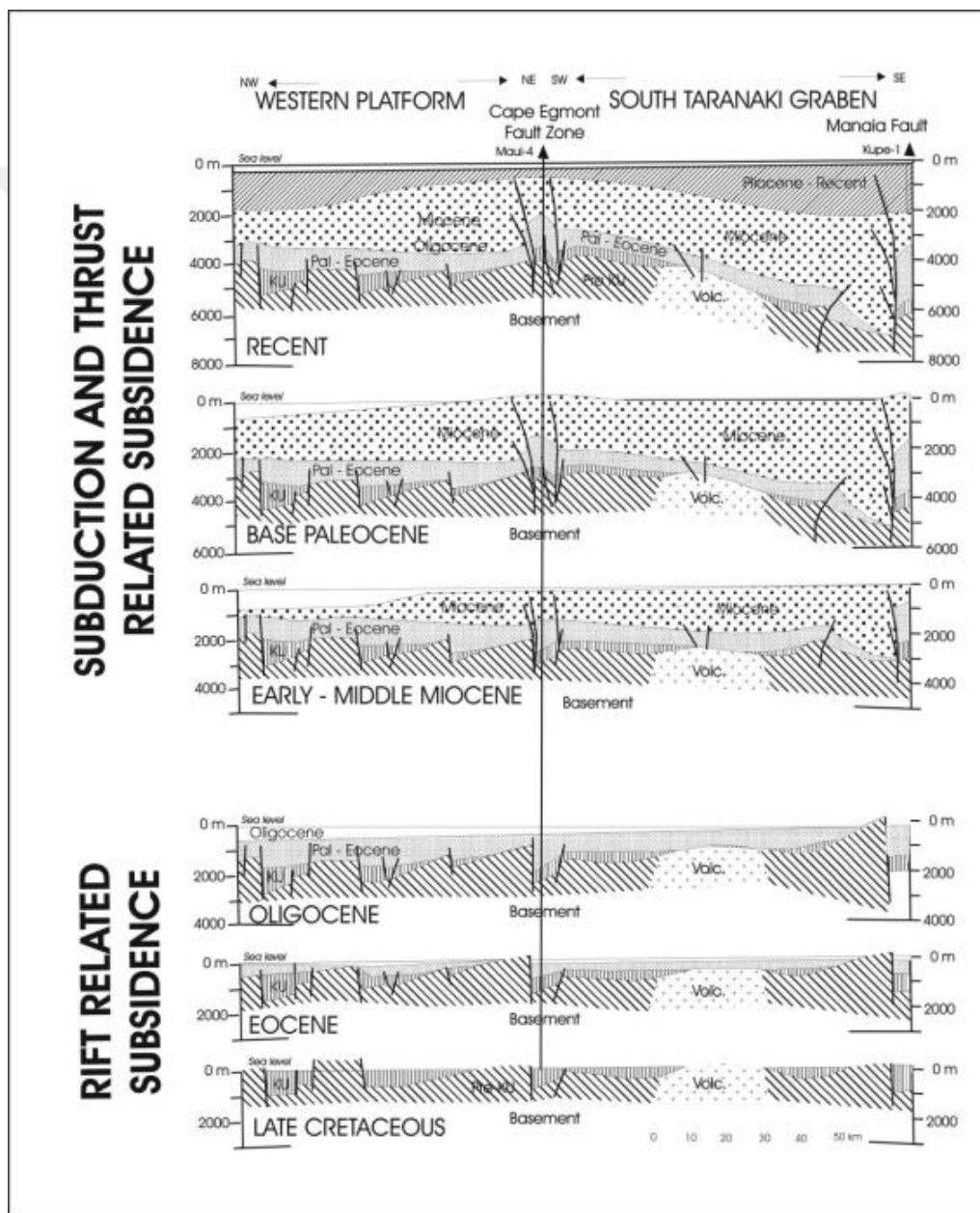


Figure 7: Adapted from Christie (2007) Reconstruction showing the magnitude and distribution of subsidence

2.3.3. Eocene

Although the fault activity is low in the Early and Middle Eocene periods, there is syn-sedimentary faulting along the Cape Egmont Fault Zone, and this is likely to be related to New Zealand Crustal events (Knox, 1982). During the Late Miocene, the extension phase in Taranaki Basin was finished and a phase of compression began. In the meantime, this movement of the Australian-Pacific Plate caused North-south trending anticlines. The basin full of bathyal mudstones in the North of the basin was cut by Mesozoic sandstone. The Taranaki Fault, which rises in the North, caused the deposition of Mesozoic sediments in the south (King and Trasher, 1996).

2.3.4. Oligocene

In the Early Oligocene the Taranaki Basin is submerged. In this period, sedimentation is generally dominated by calcareous sediments (Palmer and Andrews, 1993). During the Eocene- Oligocene time, the passive thermal-decay observed in the Cretaceous was finished and in this period subsidence can be related with the extensional tectonic regime. According to King and Trasher (1996), the change in tectonic regime is first seen in the North. Subsidence initiated in the North and takes effect in the south and east. Trasher (1996) suggests that subsidence was counteracted by minor uplift along the Manaia Fault.

There are various theories about subsidence that occurred in this period. King and Robinson (1988) attributed this to the extension related with grabens. Stern and Dawey suggested that it was associated with an isostatic loading. Another theory belongs to Stern and Holt (1994), is that the situation is due to the mantle processes occurring along the Australian-Pacific Plate boundary.

2.3.5. Miocene

The tectonic movements in the Miocene are highly variable. In the Early Miocene, the Taranaki Fault Zone is very active and during this period we can mention about the presence of the Northland Allocton (Isaac et al. 1994). The expanded load on the adjoining lithosphere lead to an increment in foreland subsidence and the North-Westward propagation of a sedimentary wedge, commonly seen in foreland basin zones (Holt and Stern, 1994). Whereas uplift on the Taranaki Fault was well underway by the Early

Miocene, an increment in sedimentation is not seen on the region until 17.5 -1.5 Ma. Regional subsidence is controlled by the rise of Taranaki and associated fault systems (Palmer and Andrews, 1993). Sutherland (1995) says that this rising in the region is related to clockwise rotation between the plates of the Australia-Pacific. A second theory of this uplift is that the erosion reduced the loading on the thrust zone (Holt and Stern, 1994). During the compression period, a regressive cycle begins (King and Robinson, 1988).

2.3.6. Pliocene to Recent

During this period, reverse faulting continued in Southern inversion zone and accordingly an extension is observed across the Taranaki Basin (Armstrong et al. 1998). Tilting and subsidence in the basin is related to flexural tilting or thermal uplift mechanisms. Results suggest that tilting and subsidence patterns can be explained by the slab-pull force of the subduction slab on the overriding plate (Stern et al., 1992).

2.4. Continental Margin Progradation

During the Early Miocene, the continental shelf-slope margin initiate in the Southern Taranaki Basin as a regressive phase (a first order megacycle) (King and Trasher 1992) but the massive part of the progradation pattern was formed during the Middle Miocene (Kamp et al. 2004). The Whangamomona Sequence is the first significant Northward progradation of the continental margin wedge. The age of this sequence is Middle Miocene to Early Pliocene and is restricted between the shelf slope systems of the Taranaki Basin (Kamp et al. 2004). The Giant Foresets Formation is located within the Rangitikei Sequence and indicates a Pliocene-Pleistocene progradational margin. It is located under the shelf and slope in Taranaki Basin (Hansen and Kamp, 2004).

The sediment layers in Taranaki Basin generally shows back-stripped and decompaction. Mount Messenger Formation is represent by basin floor deposits at the bottom. This formation is intercalated with Mohakatino formation. The Matemateaonga, Urenui and Kiore formations can be described as forsets and topsets of Whangamomona Sequence, respectively. During the Early Opotian, Whangamomona Sequence ceased its progradation. Taranaki basin prograded Northward into Northern as the Giant Foresets Formation established the slope and shelf during the Late Opotian. The deposition of Ariki

Formation began when the Taranaki Basin reached its maximum progradational extent. The uplifting lead the Ariki Formation to accumulate in the Waipipian (3.6-2.6 Ma). During the Middle Pliocene, The progradation of Giant Foreset Formation was much more extensive than the Ariki Formation in the Taranaki Basin (Hansen and Kamp, 2004).

2.5. Stratigraphy

The stratigraphic chart of the Taranaki Basin is shown in Figure 8.

2.5.1. The Pakawau Group

This group includes all sediments in the Cretaceous. This group is divided into two as the North Cape formation which contains coal facies and consists of Rakuvik Formation and shallow marine lithofacies (Palmer and Andrews, 1993).

Rakopi Formation: it is mainly composed of nonmarine coal sediments, and is it also contain marine coal sediments (Roncaglia et al. 2013).

North Cape Formation: According to Suggate (1956) it is composed of interbedded sandstone and silt stone facies.

2.5.2. The Kapuni Group

The Kapuni Group is a late-rift accumulation of Palaeocene to Eocene sediment (King and Thrasher, 1996). This group is divided into four as Farewell, Kaimiro, McKee and Mangaheva. In this group, transitions from terrestrial to marine environments are observed. According to Palmer and Andrews (1993), the basin shows the basin pattern observed in the Cretaceous in the South while it is under deep sea and shore migration in the North. The region in which the Kapuni group was showed Eocene decreasing transgression, which caused the Moa group to deposit in a larger area (Christie, 2007).

Farewell formation: It is lowermost formation of Kapuni group and it is composed of fluvial sandstones and were deposited as a transgressive sequence. Oil is accumulated at the top of this formation (Roncaglia et al. 2013).

Kaimiro formation: According to Palmer (1985) it is composed of coarse grain, poorly sorted sandstone and interbedded silty mudstone.

McKee formation: is the uppermost formation of Kapuni Group and it is composed of quartzose sandstone, mudstone (Roncaglia et al. 2013).

Mangaheva formation: It is composed of interbedded sandstone, carbonaceous mudstone and coal. It has an unconformable surface with Farewell Formation. The origin of sediment generally is terrestrial and marginal marine (Palmer, 1985).

2.5.3. The Moa Group

This group is Palaeocene-Eocene aged and indicates a post-rift transgressive sequence (King and Trasher, 1996). Marshall paraconformity¹ is observed in other parts of New Zealand and also on top of this group. Below this zone is the Tangaroa Formation and Turi Formation. Tangaroa Formation and Turi Formation are defined as fine-grained, calcareous siltstone and sandstone.

Turi formation: According to Palmer (1985) is composed of micaceous, carbonaceous marine mudstone. It is also known as Kaiata Formation.

Tangaroa Formation: It is composed of sandstone and it is represented by submarine fans (Roncaglia et al. 2013).

2.5.4. The Ngatoro Group

King and Trasher (1996) stated that this group was deposited in the Late Eocene-Oligocene in the West of the basin and in the Late Oligocene-Early Miocene time period in the basin. Otaraoa, Tikorangi and Taimana Formations belong to this group and they contain high calcium carbonate. The base of the group is evidence of marine inundation (King and Trasher, 1996). Holt and Stern (1994) point to rapid platform subsidence and deep water depth in the middle and Late Oligocene.

Otaraoa formation: It is composed of calcareous siltstone and mudstone. They are intercalated with sandstone (Palmer, 1985).

Tikorangi formation: It is composed of limestone and interbedded claystone (Palmer, 1985)

¹ The Marshall paraconformity is a regional Mid-Oligocene unconformity (Fulthorpe et al., 1996)

Taimana formation: It is composed of strongly calcareous claystone. This formation overlies Otaraoa Formation unconformably (King, 1988a,b)

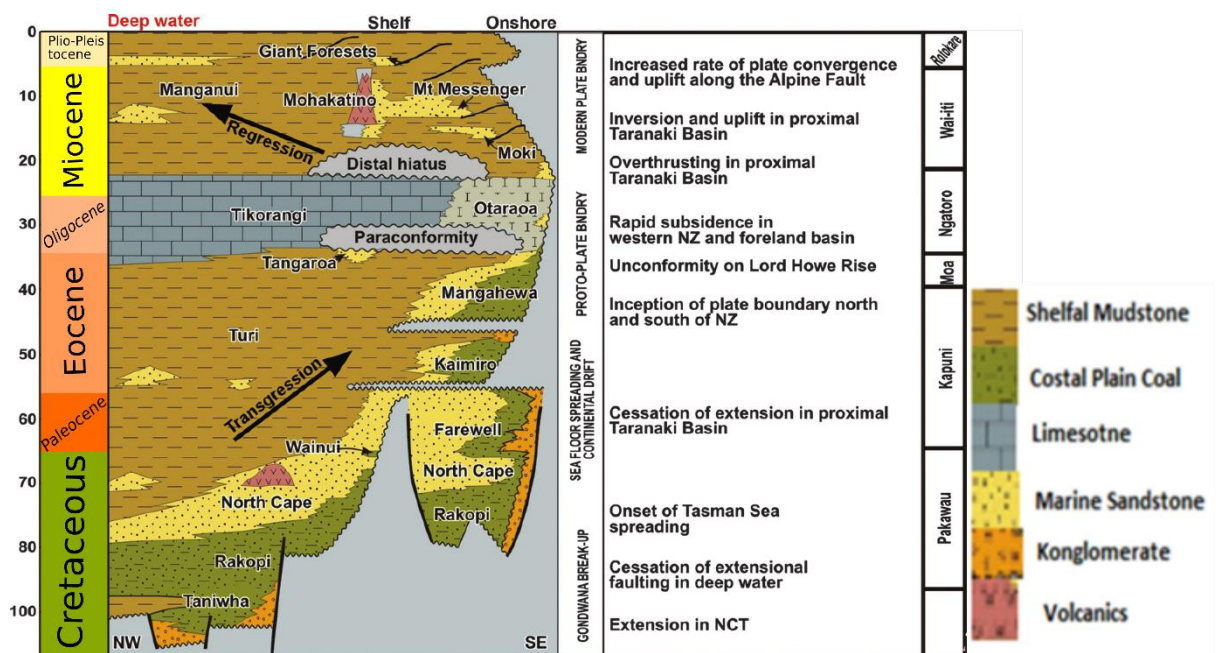


Figure 8: Chronostratigraphic chart outlining the stratigraphy and the key tectonic events that have influenced the basin from the Cretaceous to the present day (adapted from Baur et al. 2014)

2.5.5. The Wai-iti Group

This group is Miocene age. Formations of the group; Manganui, Moki, Mohakatino, Mount Messenger, Urenui and Ariki Formations. Regression is dominant (King, 1988a, 1988b). Due to the convergent plate boundary this group has high sedimentation (King and Trasher, 1996).

Manganui formation: It was accumulated as hemipelagic mudstone and siltstone in Taranaki Basin and also at interbedded with Mohakatino and Mount Messenger Formations (King, 1988a,b).

Moki Formation: It is mainly composed of sandstone interbedded with mudstone and limestone (Lock, 1985).

Mount Messenger Formation: It is represented by basin floor deposits and consist of sandstone. It is interfingers with Mohakatino Formation (Roncaglia et al. 2013)

Urenui Formation: It is base composed of marly sediments and it is grading upward into siltstone (Roncaglia et al. 2013).

Ariki Formation: It is widely deposited at the Western Stable Unit of the basin and mainly consist of marl which origin comes from planctic foraminifera

2.5.6. The Rotokare Group

This group shows regression. The reason for the regressive sequence is the intra-basinal and hinterland regions of uplift and erosion. This resulted in high sedimentation (Funnel et al. 1996). This group consists of Matemateaonga, Tangahoe, Mangaa and Giant Forset Formations.

As a result of the compression, it is the inversion of normal faults and the inversion that occurs at the early stages of the formation of the basin (Late Cretaceous). Continental shortening occurs in this zone known as the Southern inversion zone. The uplift in the North caused a repeat subsidence and extension (Cristie, 2007).

Matemateaonga Formation It is composed of and succession is related with interplay between climatically-driven 6th-order (41 k.y.) eustatic sea-level changes (Roncaglia et al. 2013).

Tangahoe Formation It is composed of mudstone and it shows proradational slopesets (Roncaglia et al. 2013).

Mangaa Formation It was affected by graben subidance and is composed of basin-floor deposits (Roncaglia et al. 2013).

Giant Foresets Formation It is mainly composed of siltstone and mudstone layers and it was formed by an extensional tectonic regime. Their depositional environment is slope to shelfal (Pilaar and Wakefield, 1978). It is thickest in the Northern Graben and representes both aggradation and progradation phases. This formation is upper part of the study area.

3. Methods

3.1. Introduction

The purpose of this section is to provide information about the methods to be applied during the project. The methods used are Seismic stratigraphy, Shoreline Trajectory, Sequence Stratigraphy. Kingdom was used during seismic interpretation. Corel Draw and Inkscape programs were used to digitize seismic sections and maps.

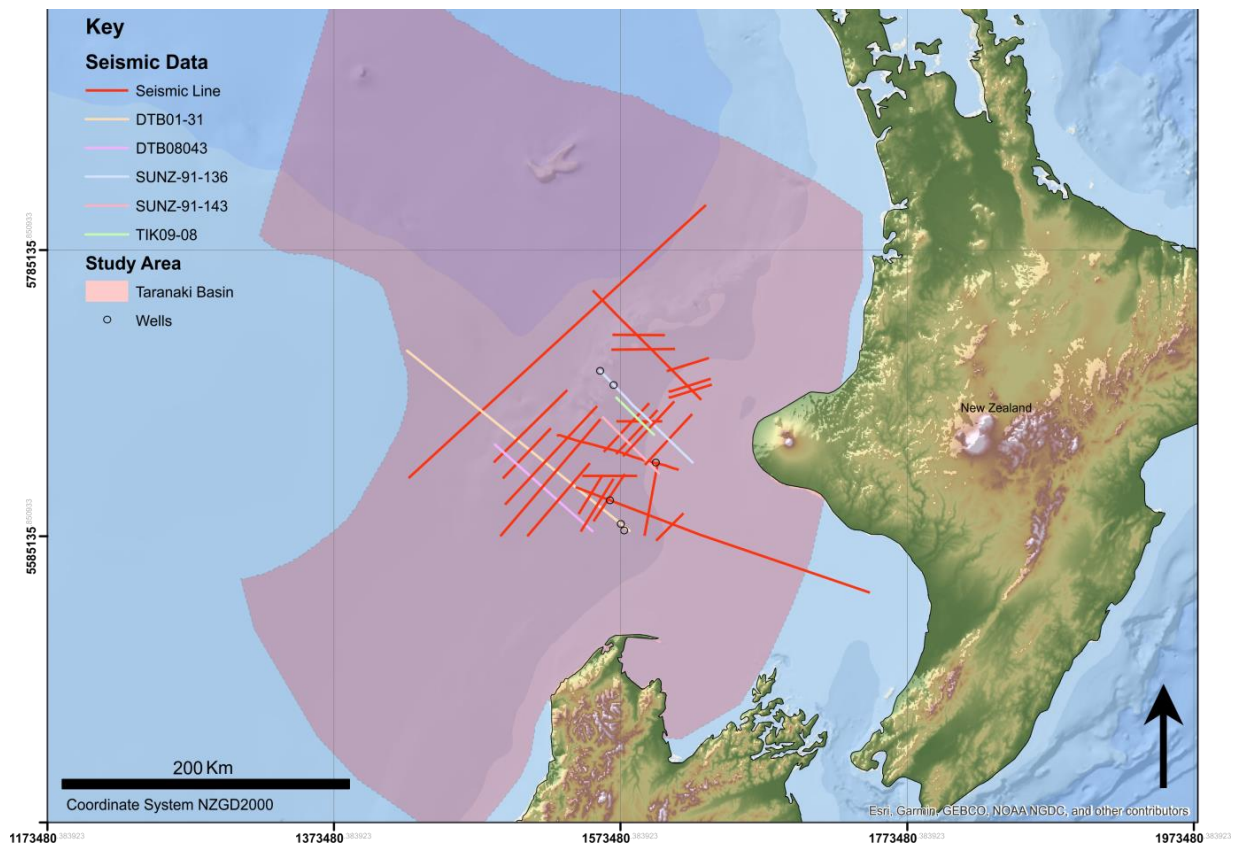


Figure 9: Seismic Lines in Area

3.2. Data Set

The data set map given below was made by using ARCGIS program. 2D seismic survey and wells were used during the study on the map. 6 well studies were included in the region. 5 regional lines were selected to illustrate in this studies and 21 perpendicular 2D seismic lines were interpreted to understand their lateral continuity.

3.3. Method

The workflow of the Project given in figure 10. During interpretation, seismic lines were separated sub-sequences with using stratal terminations. Sea level changes were observed using trajectory analysis and then systems tracts were determined. By using the well data in the region, the age of the formations in the studied interval was determined. Core-Log was not provided during the study.

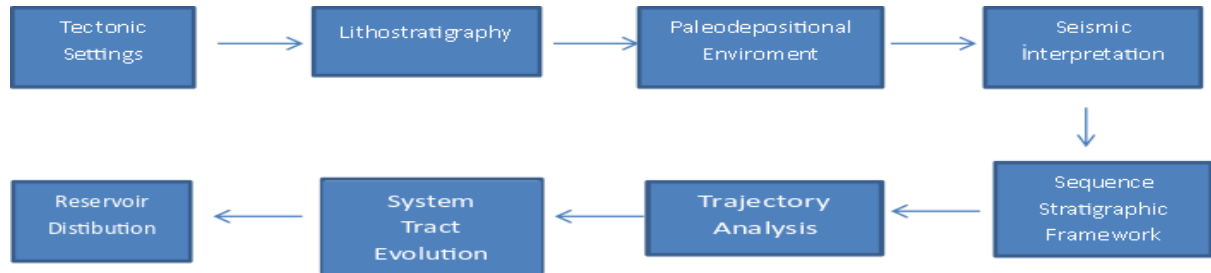


Figure 10: Workflow

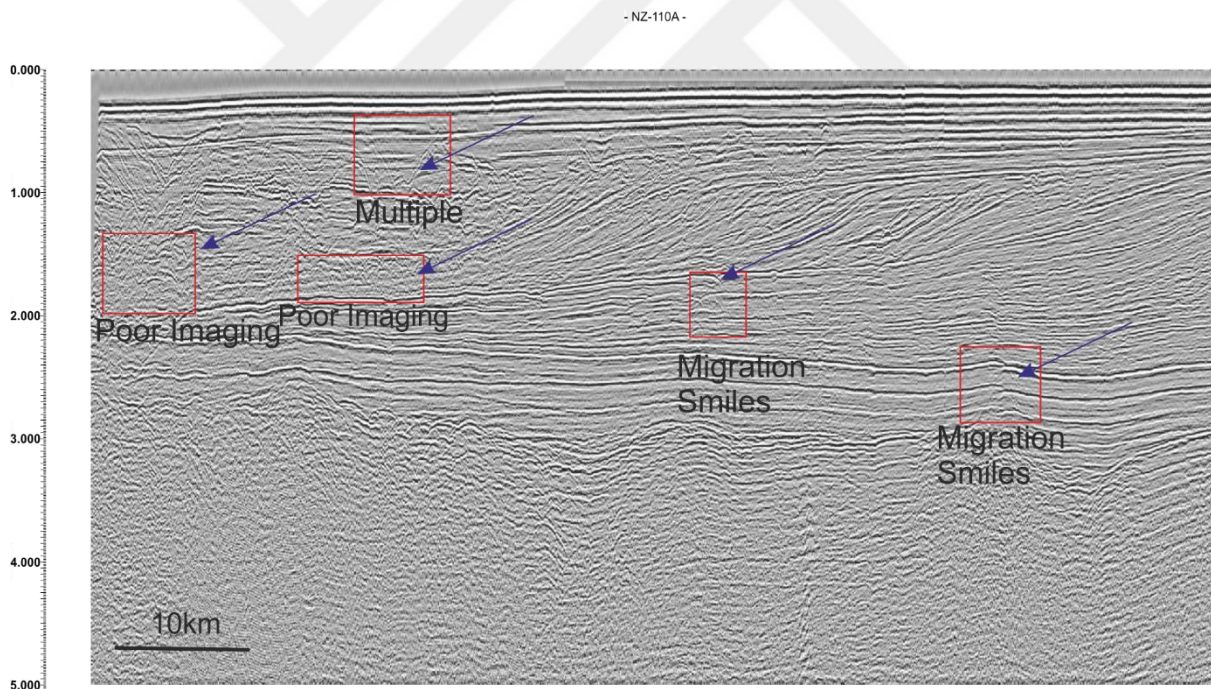


Figure 11: Artefacts in seismic line

In some seismic line, artefacts prevent the precise interpretation. During the interpretation, generally poor imaging and migration smiles create a difficulties. In addition multiples are seen which make some parts of the interpretation more difficult. On the whole the seismic data quality is good (Figure 11).

3.3.1. Seismic Stratigraphy Techniques

The primary objective of seismic stratigraphy is to identify units with their genetic similarity. These genetically similar units are called depositional sequences (Mitchum et al. 1977). These sequences are divided into system tracts (Van Wagoner et al. 1987). Conformities and unconformities are used when determining system tracts. The technique used to determine all these boundaries is called seismic stratigraphy. Stratal terminations has an important place in seismic stratigraphy applications (Figure 12) (Vail et al. 1977). In summary, seismic stratigraphy is a way to determine depositional sequences and system tracts, and seismic sequences are the first step in stratigraphy studies.

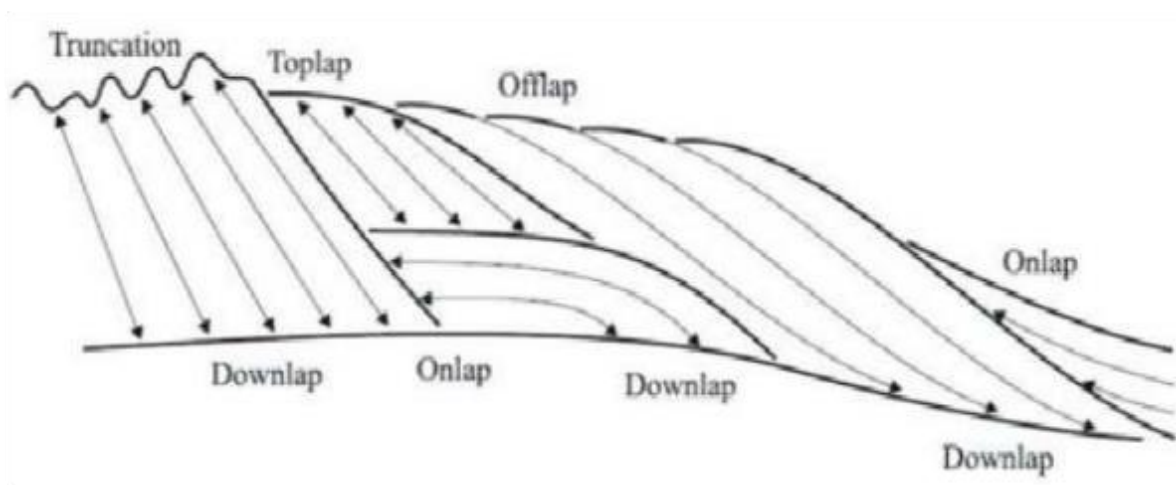


Figure 12: Stratal Terminations patterns (modified after, Van Wagoner et al. 1988)

The main types of stratal terminations, namely onlap, downlap, toplap, truncation and offlap, can be observed in 2D seismic lines and large scale outcrops. Stratal terminations are related to specific depositional trends and determine shoreline shifts and base level changes, generally, onlap point to transgression, offlap point to forced regression. Downlap show normal or forced regression (Catuneanu, 2006). These terminations are used to define the system tracts and sequence stratigraphic surfaces (eg, Posamentier et al. 1988; Van Wagoner et al. 1988; Christie-Blick, 1991).

According to Catuneanu (2006) the definition of stratal terminations are;

Truncation: Where the layers end up against erosion. It may end up with toplap, but truncation usually indicates an angular unconformity or erosional relief.

Toplap: It is an inclined strata (clinoform) that develops on the low-level layer at the bottom. They are usually formed as a result of sediment bypass. The strata developed towards the land extend gradually towards the sea while they are deposited behind the unit. Proximal deposition boundary is the surface of the tolap.

Onlap: It ends on low-angle stratigraphic surfaces. It shows the lateral development boundary of the sedimentary unit and is also known as lapout.

Downlap: It is known as the termination of curved layers on lower angle surfaces and indicates the deposition limit of the sedimentary unit. Generally, the base of the prograding clinoforms refers to shallow or deep sea sedimentation environments.

Offlap: This term indicates the fall of the base level and is important in determining forced regression.

After interpreting the seismic line, separating the packages, the reflection continuity, configuration, amplitudes and frequency control in the seismic line should be checked. The aim is to obtain information about the depositional process. The important evidence and precise description is given below.

It is important to understand seismic reflections. The character of seismic reflections helps understand the type of depositional energy and lithology. Generally, high amplitude and lateral continuity indicate low energy and inter-bedded marine limestone and shales deposition, but high amplitude and low lateral continuity indicate terrigenous deposition, while low amplitude and high lateral continuity may indicate deep sea shales (Mitchum et al. 1977).

The product of the frequency analysis is obtaining information about bed thickness and fluid contacts. However, seismic interpretations still need to be ground truthed by well log data confirm that a seismic character is indicative of specific lithology. Check-shots were used in order to calibrate the well-data to the seismic (Figure 13).

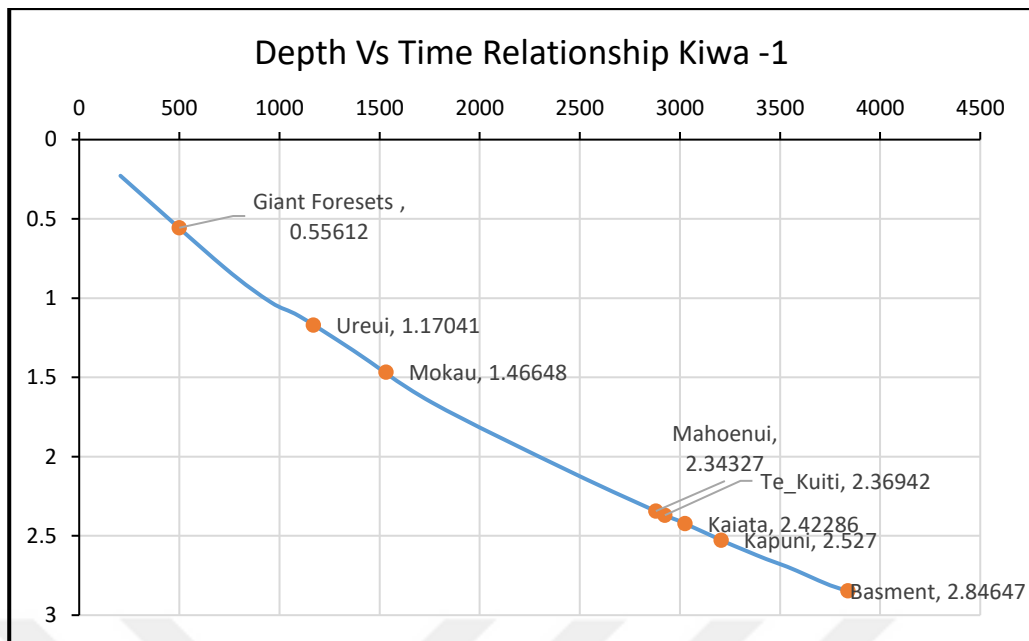


Figure 13: Depth and time relationship from Kiwa-1 well

In cases where internal reflection shows parallel or subparallel patterns, uniform strata are observed, indicating stable platform sedimentation or shelf sedimentation. In cases where internal reflections show divergent and wedge shape patterns, tilting during sedimentation can be mentioned. Prograding is observed in two important cases. First, sigmoidal, oblique shingled hummocy is observed in internal reflections. The second one is observed in the environments that show the transition from shallow sea to deep sea filled by channel structures. If internal reflections show a chaotic pattern, it may refer to pen contemporaneous soft-sediment deformation, fluidized bed flow during natural seismic event, over-pressured unconsolidated sediments. However, in cases where contored patterns are observed, soft sediment slumping and deformation may occur. Finally, in cases where internal reflections show a free pattern, homogeneous non-stratified rock units can be mentioned, in addition, such cases show pure domes and igneous strata (Mitchum et al. 1977).

Further details and schematic representation of the continuity, amplitude, frequency and configuration of the seismic package can be found in Figure 14.

3.3.2. Shoreline Trajectory

According to Helland-Hensen and Hampson (2009), the purpose of this method is to find lateral and vertical migration of sediments over time. Shoreline or Shelf margin Trajectory is a path. When the sedimentation of basin is completed, the shoreline and shallow margin shelf facies change their position. The change in the base level, the amount of sediment added to the sediment and the slope and shape of the depositional environment has an important role on Trajectories. The trajectory analysis conducted using the 2D seismic data.

The evolution in the geometry of clinoform is well known regardless of whether they are carbonate [e.g.: margin of the Permian basin of Texas and New Mexico (Kendall et al. 1989; Borer and Harris, 1995; Kerrans and Fitchen, 1995; Hunt et al. 2000)] or clastic [the Tertiary of Spitsbergen (Steel et al. 1985), the Lower Cretaceous of South Africa and the NPRA (Kendall et al. 2000), etc].

Developing geometries of clinoforms are important in explaining progradation of basin margin. Basically, trajectories are responsible for the development of the retrogradational, aggradational and progradational pattern identified from Van Wagoner et al. 1990.

Where water depth and sediment supply are sufficient, the progression of coastal prisms basinwards leads to clinoform formation (Pirmez et al. 1998; Steel and Olsen 2002) and assists in determining the successive positions of clinoforms during shoreline trajectory (Helland-Hansen and Gjelberg, 1994; Helland-Hansen and Martinsen, 1996). The trajectory analysis done uses these points, formed as a result of the migration of clinoforms, called offlap break (Figure 15) (Vail et al. 1991) and the position of these points is called shelf edge trajectory (Mellere et al. 2002) or clinoform trajectory (Steel and Olsen, 2002).

In order to determine the position of the points, the orientated profile must be parallel to the depositional dip direction of the clinoform (Bullimore et al. 2005). Sediment supply and 4th-5th order sea level changes are important in defining the shoreline trajectory (Helland-Hansen and Gjelberg, 1994; Helland-Hansen and Martinsen, 1996), but only the 3th order sea level changes and sediment information are obtained from the sediment supply (Steel et al. 2002). The scheme used to define shoreline trajectories is by Helland-Hansen and Hampson (2009), the ones relevant to the study location are shown in Figure 15.

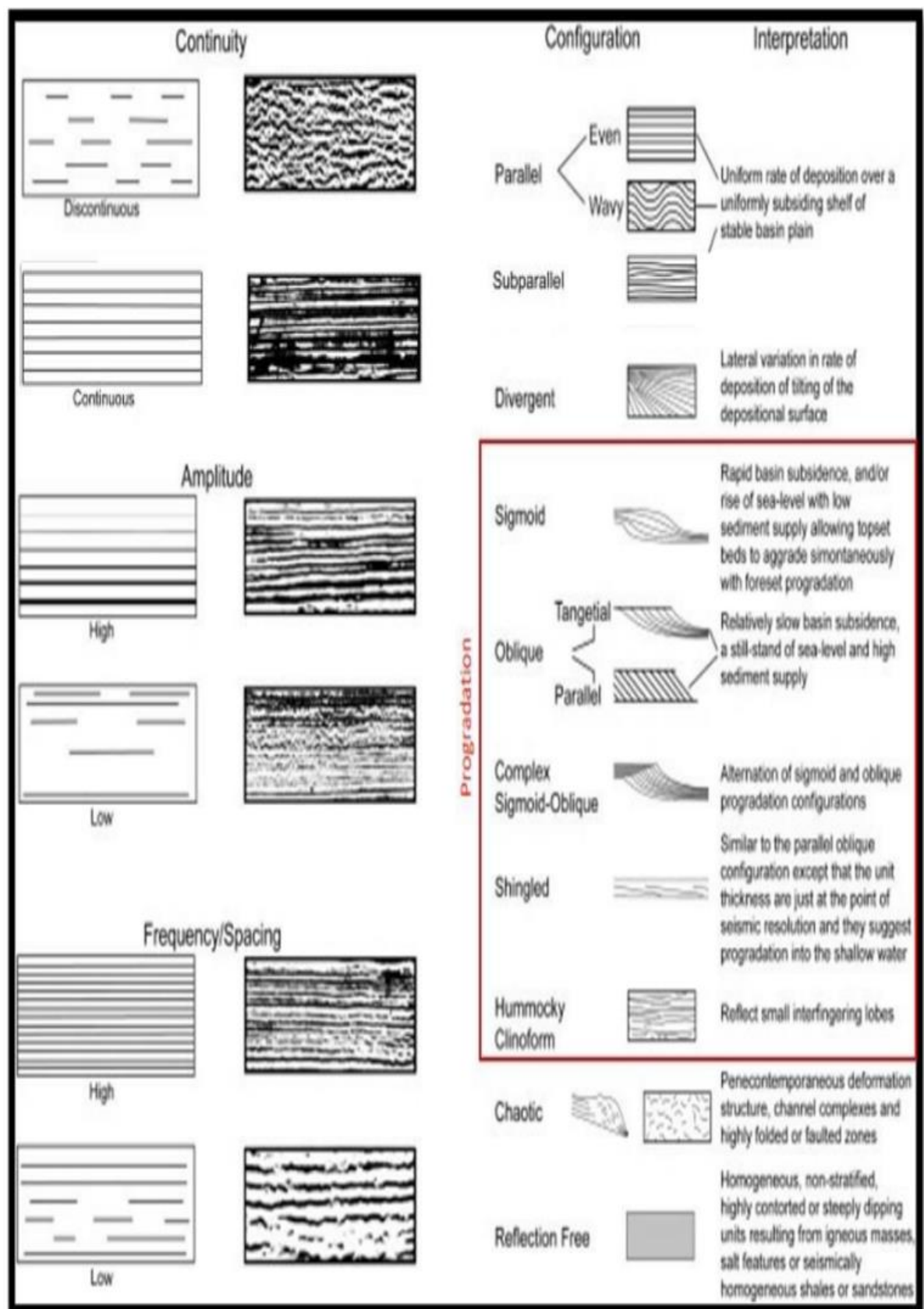


Figure 14: Classification of Seismic Facies and Related Depositional Environments. (Adapted from Badley, 1985; Vail, 1987 and Veenken, 2007)

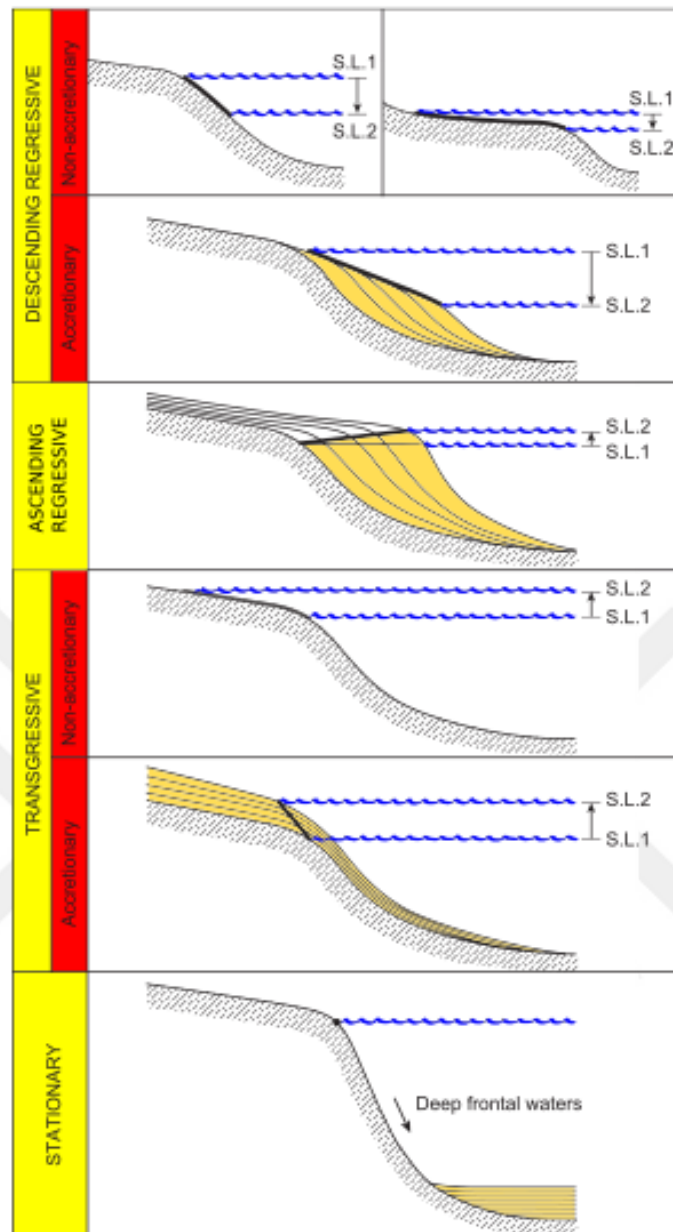


Figure 15: The classification of shoreline trajectory. Bold lines shows trajectory of shoreline. Modified from Helland-Hansen and Martinsen (1996).

3.3.3. Sequence Stratigraphic Concepts

Sloss (1950) was the first to define the sequence. During this definition, the sequence was defined as unconformity –bounded stratal unit. Sloss (1963) in the North American craton, aged from the Precambrian to Holocene defined 6 different sequences. Mitchum et al. (1977) stated sequences as 'a stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities and their correlative conformities'. Mitchum et al. (1977) and Sloss (1963) When the sequence definitions are compared, Sloss (1963)'s North American craton 6 sequences can

be expanded. Later, Sloss re-called these series "super-sequences". The concept of Eustasy is the sequence of stratigraphy to Vail et al. (1977a, b). According to Vail (1977a, b), eustasy is one of the important factors in sequence analysis.

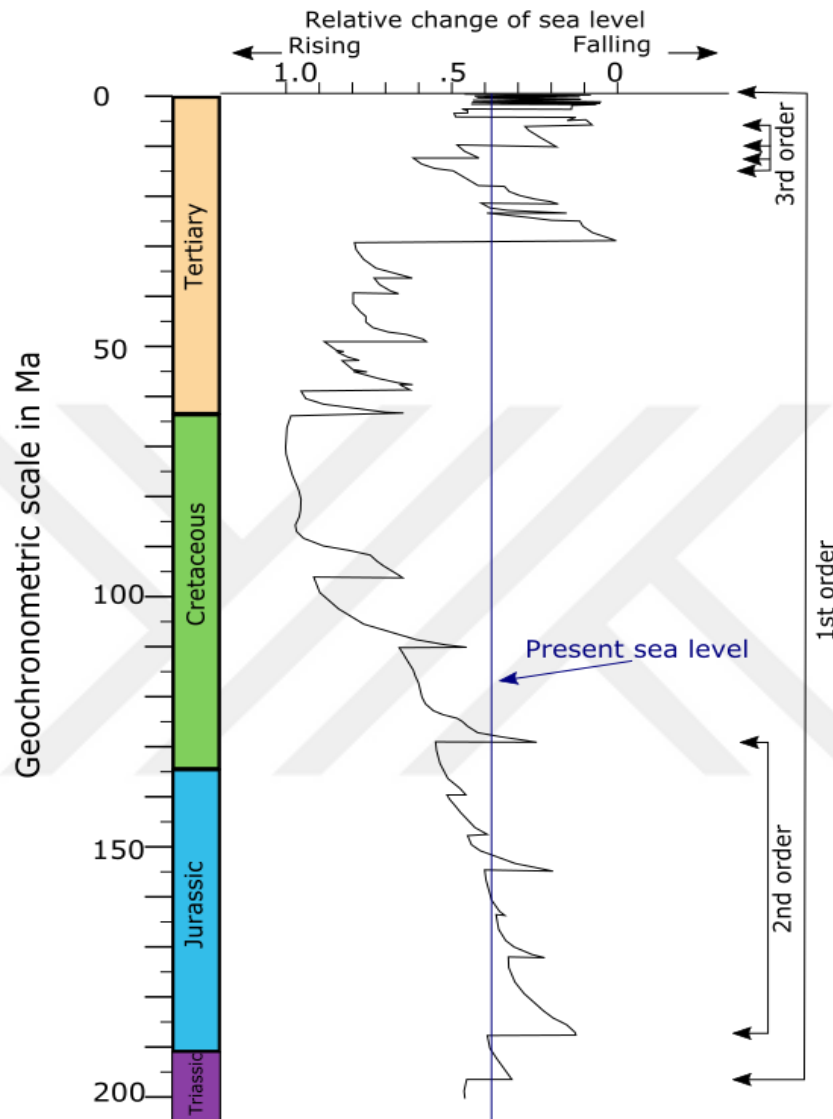


Figure 16: Jurassic-Tertiary global cycle chart indicating three orders of cyclicity, During this study, the Miocene / Plio-Pleistocene time interval was focused. (Modified from Williams, 1993 after Vail et al. 1977b)

Seismic sequence analysis by Payton (1977) was further developed by Jervey (1988) and Posamentier et al. (1988). During this analysis, chronostratigraphically significant erosion surfaces and non-depositional correlative surfaces of these surfaces is outlined. When determining the sequence boundary, erosional truncations, which are usually located above and below, are selected. Figure 16 shows studies that have demonstrated global sea

level changes throughout Phanerozoic from 1970 to 1980 (Vail et al. 1977b; Haq et al. 1987, 1988). Cloetingh (1986) tried to explain the stratigraphic changes in the passive margin and intracratonic basins with a few hundred bar temporary stress changes in the lithosphere. It is known that a stress change of one kilobar will change the sea level by 50 meters or more (Williams, 1993). Therefore, the changes observed at sea level in Figure 16 may be related to lithospheric stress (Bally, 1982).

Sequence stratigraphy aims to distinguish sedimentary basins into their depositional sequences by considering two basic parameters such as sediment supply and accommodation space. The main purpose of this method is to understand how sediments are developed in the basin and how stratigraphy occurs in accommodation space and time. It also examines the relationship between facies cyclic and their relation.

In the Sequence stratigraphic model, while the sediment supply is assumed to be constant, the accommodation space is assumed to be variable as a result of sea level changes. In addition, tectonics, subsidence and compaction play an important role in the application of seismic sequence stratigraphy (Figure 17). The effect of tectonism and eustasy on sequence boundary formation is highly controversial (eg. Bally, 1982; Thorne and Watts, 1984; Cloetingh, 1986; Hubbard, 1988; Sloss, 1988). Based on this, sedimentary sequences refer to a stratigraphy that occurs in relation to changes in the sea level. In general, such deposition sequences are termed system tracts.

Another important factor in seismic sequence stratigraphy is base level Changes; One of the most important analyzes of sequence stratigraphy studies is to reveal the relationship between sediment supply and accommodation space. Jervy (1998) defined accommodation as “the space available for potential sediment accumulation.” Base level fluctuations affect the volume of accommodation space. Jervy (1998) stated that one of the main factors controlling accommodation space would be relative sea level (eustasy). In addition, tectonic and climatic were also important, but the climatic effect was indirect (Catuneanu, 2002).

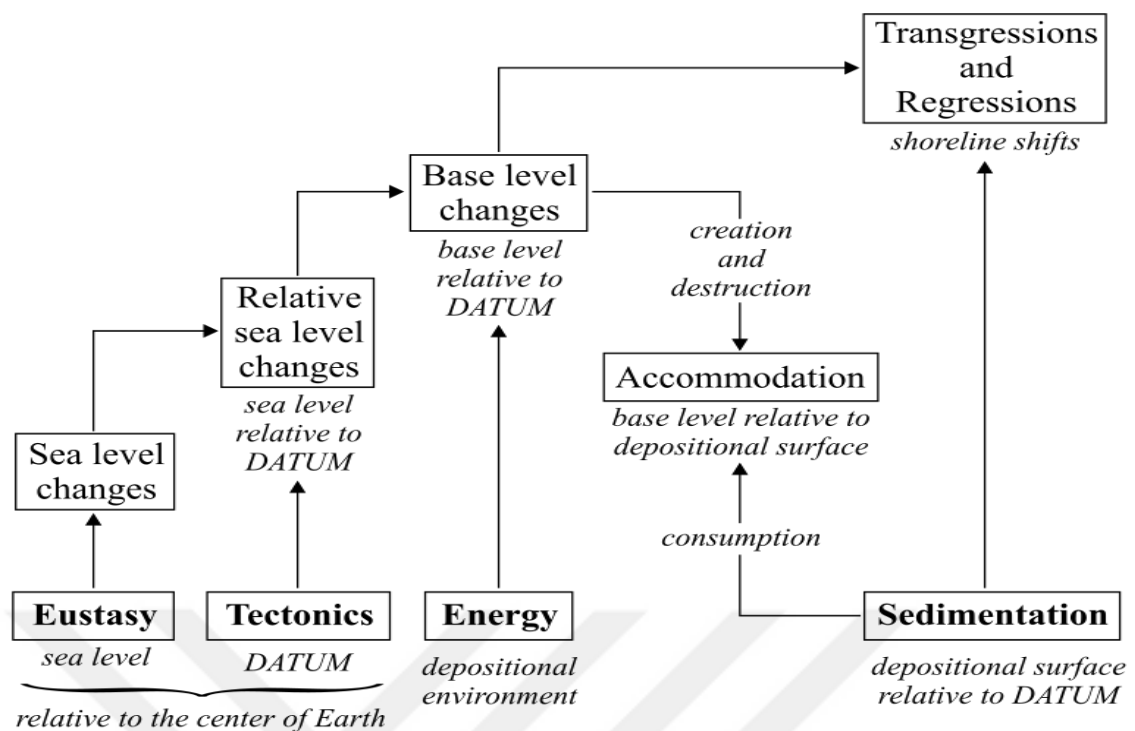


Figure 17: Factors involved in seismic sequence stratigraphy (Adapted from Catuneanu, 2002)

According to Catuneanu (2002), when measuring eustatic fluctuations, an imaginary reference point close to the sea floor is used (Figure 18). The important factor in the selection of this datum is to reveal the effects of tectonism, sedimentation and sediment compaction separately. When the datum rises above the ground, it points to the tectonic uplift. When the sea floor rises, it represents total subsidence / uplift and sediment influx are important concepts in sea level changes.

Various scenarios due to the sea level changes are given in the figure. First of all, we should know that the base level is an imaginary line. Sediment supply and energy are two important factors. Base level elevations often create accommodation space. Decreases in base level cause accommodation space to decrease. The point to note in these analyzes is that base level changes are independent of sedimentation, but water depth changes are related to sedimentation.

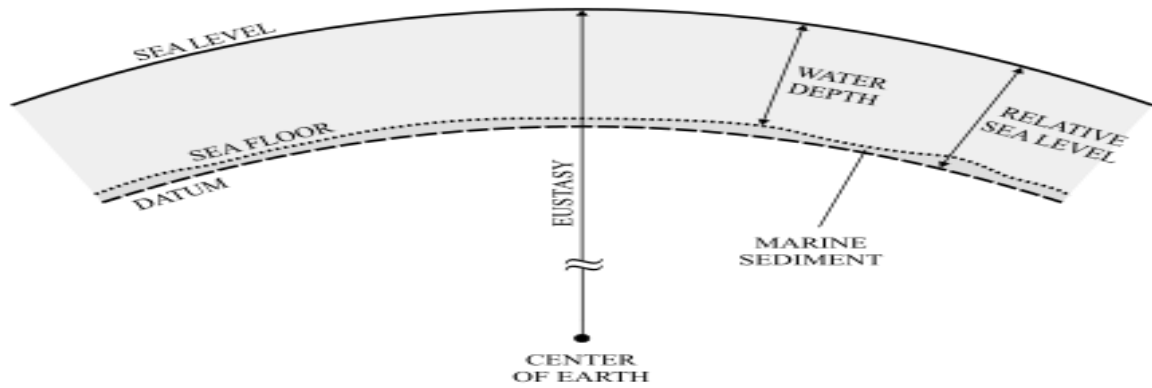


Figure 18: Imaginary datum, Eustasy, relative sea level, and water depth as a function of sea level, sea floor, and datum reference surfaces (modified from Posamentier et al. 1988)

When the relative sea level is increased and the sediment flux is zero or low, transgression occurs, and when the relative sea level increases, but the sediment flux is low, retrogradation occurs. In cases where the relative sea level is almost equal to the rise of sea level rise with agglutimentised flux, aggradation and coastal parasequences are observed. If the relative sea level and the sediment flux sea level rise are exceed other parameters, the progradation of sequence parasequence is observed (Figure 19).

Eustasy and subsidence on the total seabed, as well as changes in hydrodynamic conditions, affect the accommodating space.

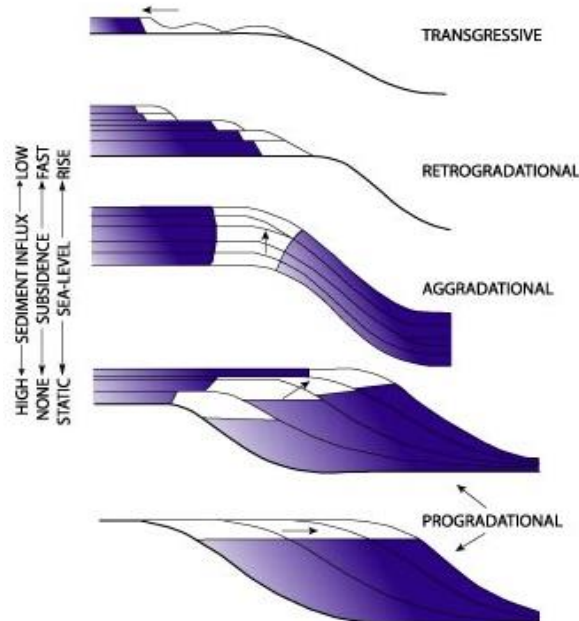


Figure 19: Depositional Architectures as a function of accommodation Volume and sedimentary supply (Adapted from Emery, 1999; after Galloway, 1989)

Sea level changes sediment supply and tectonic changes can be affected by basin stratigraphy. Both sea level changes and tectonic changes are directly affected by accommodation space.

Sea Level Changes; Eustatic sea level changes may affect the volume of seawater during glacial and deglacial periods. In addition, this volume may vary with tectonic effects or with the combined effect of both factors. Glacial and deglacial are represented by third order cycle or second order cycle according to Figure 16. Unlike Vail et al. (1977b), Pitman (1978) and Posamentier (1988) presented a different model, according to which the increase or decrease of the eustatic sea level is related to subsidence.

Subsidence/Uplift; The factors that trigger subsidence and uplift are primarily the increase or decrease in the thickness of the crust and lithosphere. The second is loading and unloading the lithosphere. The last reason is the thermal changes occurring in the lithosphere.

Following these tectonic events, we encounter three types of basin types. These; Thrust related, rift-related and wrench related. There is a stratigraphic evolution of each basin. In thrust-related basins, mountain front offlap, erosion and progressive unconformities are dominant, while foreland margined progressive onlap are observed (Figure 20) Ricci-Lucchi (1986) cited the Po basin in Italy as an example.

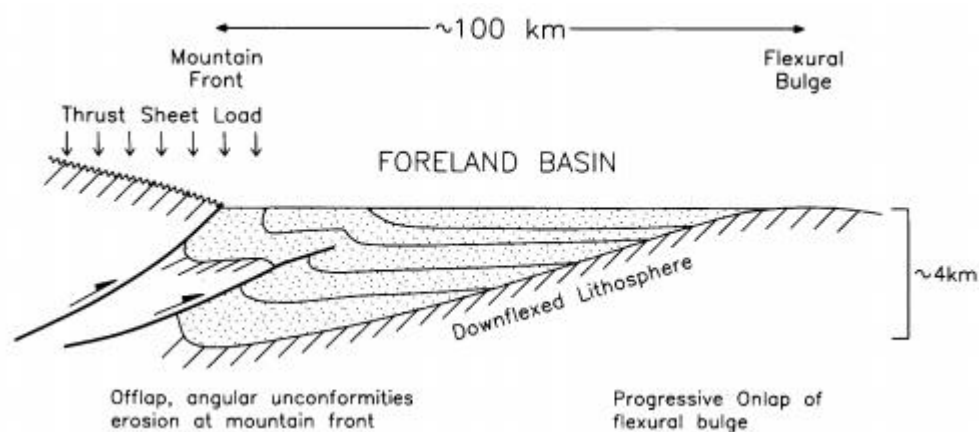


Figure 20: Schematic diagram to indicate gross stratigraphic patterns and main structural controls in a thrust-related Po basin from Williams, (1993)

Rift-related basins can be divided into pre-rift, syn-rift, post-rift mega sequences according to Hubbard (1988). Basinward progradation occurs, especially in the post-rift phase.

Sediment Supply; Accommodation space usually occurs under the influence of eustatic level increase and subsidence. The sediment supply (ratio) will determine the volume of accommodation space. The thickness of sediments deposited in the basin is not directly related to the subsidence and relative sea level changes of the basin. This is because basins may remain under filled for significant periods of time (Williams, 1993).

Another important concept of sequence stratigraphy is transgression and regression events. Transgression is defined as the movement of the shoreline towards landward (Figure 21 and Figure 22). This orientation triggers the facies to drift towards the shore and deepens the seawater around the shoreline. Transgression usually shows a retrogradational pattern in seismic lines and outcrops. In the non-marine part of the basin, fluvial succession, sigmoidal cross-bedding and tidal bedding are observed (Shanley et al. 1992; Miall, 1997). Retrogradation is a typical transgression pattern (Bates and Jackson, 1987). In summary, transgression is observed in the basin when the accommodation space created is more than the sediment supply (Catuneanu, 2002).

Regression is defined as progradation of the shoreline (Figure 21 and Figure 22). This immersion allows the sediments in the basin to develop towards the sea. As a result of the regression, the progradational pattern is observed and this represents the shifting of non-marine facies towards the sea (Catuneanu, 2002). Progradation shows that beach material is carried to the sea by waves (Bates and Jackson, 1987).

According to Catuneanu (2002) forced regression occurs at the stages where the base level falls and the sediment supply develops independently of the base level drop (Figure 22).

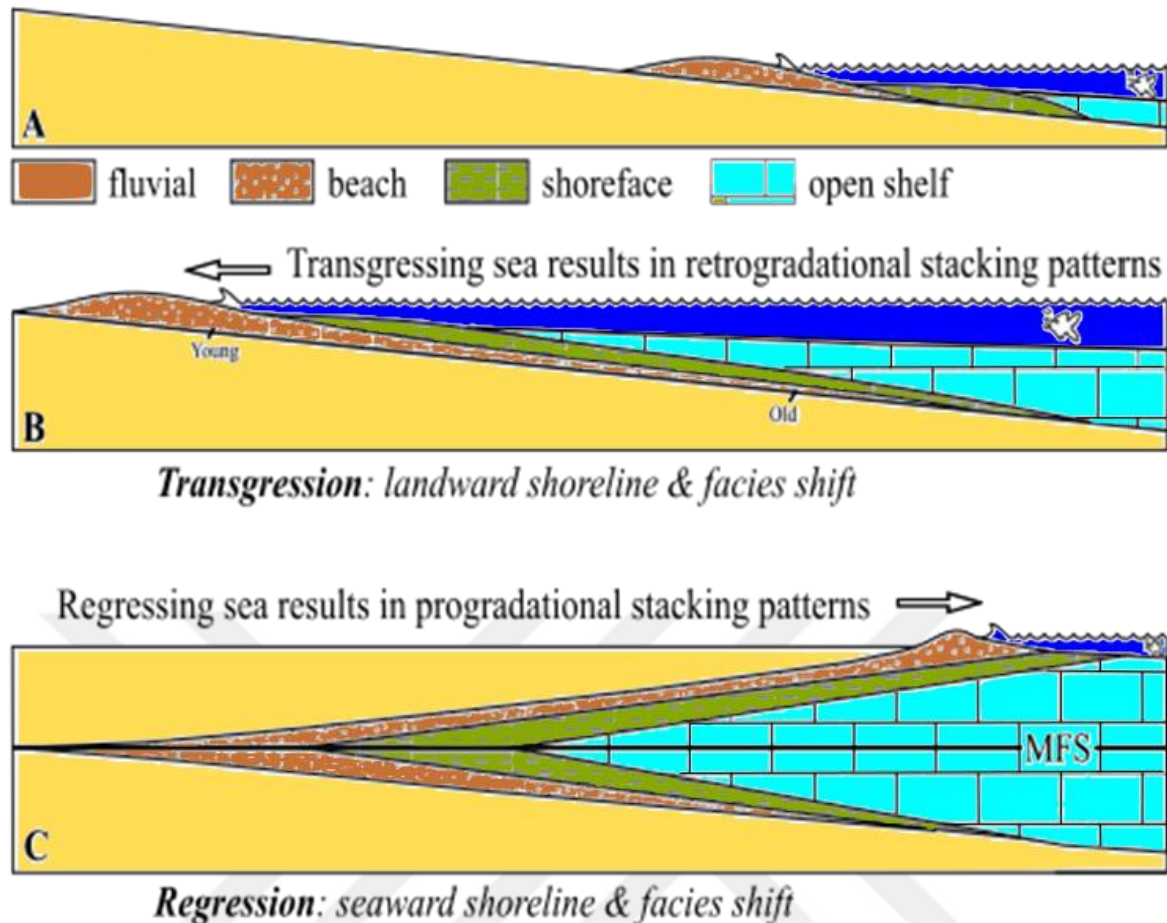


Figure 21: Transgression and regression. MFS is a surface which separates retrogradational from overlying progradational geometries (adapted from Catuneanu, 2002).

Normal Regression occurs in the early and late stages of the base level uplift, in the periods where the sedimentation is higher than the base level uplift in the shoreline. In normal regression, the available accommodation space is almost completely filled with sedimentation (Catuneanu, 2002).

The relationship between transgression and regression is related to deepening and refilling of sea water.

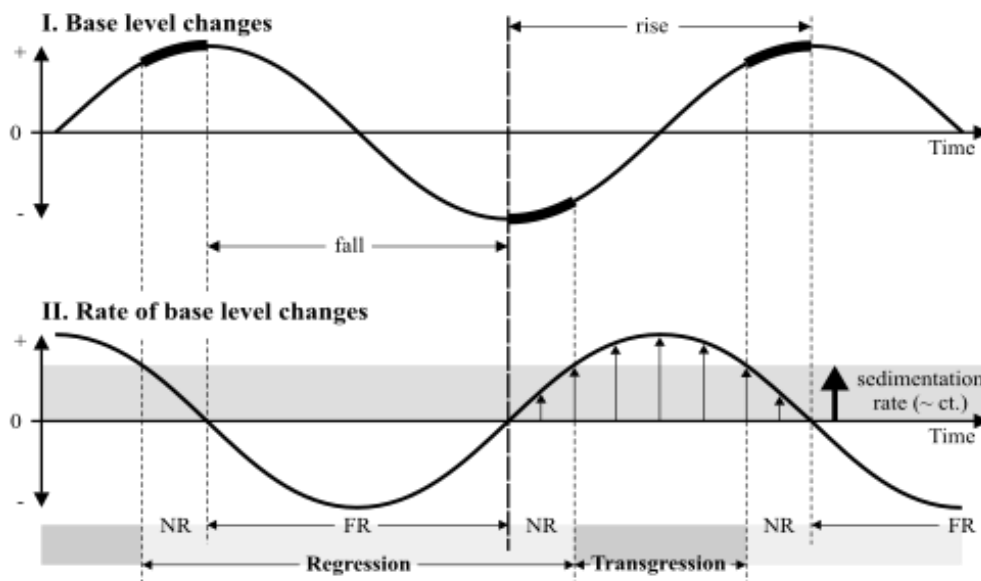


Figure 22: Concepts of transgression, normal regression, and forced regression, as defined by the interplay between base level changes and sedimentation (FR: Forced Regression; NR: Normal Regression) (Catuneanu, 2002)

Transgression and normal regression occur during base level elevations. In both cases there is a balance between accommodation space and sedimentation. Figure 22 shows that the transgressive phase lasts shorter than the normal and forced regressive phases. Surface aggradation and retrogradation shoreface deposits interrupted by waves during transgression. During forced regression, fluvial incision offlapping shoreface deposit is seen. In normal regression, the newly created accommodation space is consumed by sedimentation in the basin. In addition, sedimentary bypass and progradation of facies are seen (Catuneanu, 2006) (Figure 23).

3.3.3.1. System Tracts

Another factor related to seismic sequence stratigraphy is system tract. Brown and Fisher (1977) describe the concept of system track as sub-units of a sequence. During the determination of system tracts, stratal stacking patterns, position within the sequence, and types of bounding surfaces concepts are important (Catuneanu, 2002). System tracts are very important in determining reservoirs. Each system tract shows different reservoir quality, formation and location in itself.

Systems tract	Significance	Fluvial	Coastal	Shallow-water	Deep-water
Highstand Systems Tract	Sediment budget	Good: aggrading systems	Good: Deltas and Strandplains (coastal prisms)	Good: gradationally based shoreface and shelf facies	Poor
	Reservoir	Fair: channel fills,	Good: shoreline sands	Good: shoreline sands	Poor
	Source and Seal	Poor source, fail seal: overbank facies	Poor	Fair: shelf fines	Good: pelagic facies
Transgressive Systems Tract	Sediment budget	Good: rapidly aggrading systems,	Good: estuarine deltas, backstepping beaches,	Fair: onlapping shoreface and shelf facies	Fair: low-density turbidity flows and debris flows
	Reservoir	Fair: channel fills,	Good: estuarine, deltaic and beach sands	Fair: shelf-sand deposits, basal healing-phase wedges	Fair: turbidites
	Source and Seal	Poor source, fail seal: overbank facies	Poor source, fail seal: central estuary facies	Good: shelf fines	Good: pelagic facies
Lowstand Systems Tract	Sediment budget	Good: amalgamated channel fills, incised and unincised	Good: Shelf/shelf-edge deltas, strandplains	Good: gradationally based shoreface and shelf facies	Fair: low-density turbidity flows
	Reservoir	Good: channel fills	Good: shoreline sands	Good: shoreline sands	Good: turbidites (basin floor)
	Source and Seal	Poor	Poor	Fair: shelf fines	Fair: "overbank" pelagics
Falling-stage Systems Tract	Sediment budget	Poor	Fair: offlapping deltas, downstepping beaches	Fair: sharp-based shoreface, and shelf facies	Good: debris flows and high density turbidity flows
	Reservoir	Poor	Fair: detached shoreline sands	Fair: shoreline sands	Good: turbidites (slope and basin floor)
	Source and Seal	Poor	Poor	Fair: shelf fines	Fair: "overbank" pelagis

Table 1: Petroleum Play and Sediment budget of system tracts (Catuneanu, 2006)

3.3.3.1.1. Lowstand Systems Tract

During a lowstand system tract, subaerial unconformities and correlative conformities locate at the base, maximum regressive surface is locate at the top. LST is bounded by between those two surfaces. Low stand system tract shows coarsest sediment fractions in marine and non-marine basins. Marine succession also shows upward coarsening trend while non-marine basins Show fining upward trend (Catuneanu, 2002). The maximum regressive surface formed as a result of shifting towards Landward is positioned between lowstand fluvial and overlying estuarine facies (Figure 23). Subsequent facies show a gradational pattern between fluvial and estuarine facies. Amalgamated chanel fills are the best reservoirs in fluvial depostional systems. The most important reservoirs in lowstand system tracts occur in fluvial systems. The shelf-edge deltas and correlative strandplains show progradation towards the upper slope, which explains why fluvial reservoirs move towards the basinward. It cannot be said that lowstand system tract is sufficient in terms of source and seal quality.

3.3.3.1.2. Transgressive Systems Tract

The transgressive system tract is limited to the maximum regressive surface at the bottom and the maximum flooding surface at the top. Transgressive system tract occurs when the base level increases the sedimentation rate. This system tract shows a fining upward trend in non-marine and marine succession and is characterized by a retrogradational pattern. According to Galloway (1989) transgressive system tract shoreline develops in the shallow areas with correlative condensed section (Figure 23).

This system tract has two different phases. Early Transgression, petroleum plays in this stage develops in transgressive wedge, continental wedge and deep water wedge. The best reservoir within this system is developed with backstepping beach, estuary-mouth complexes or prograding deltas. The problem with the coastal part is that they cannot maintain the reservoir due to the high energy of the waves. Landward from the shoreline towards the petroleum exploration of the transgressive system tract is poor in terms of exploration (Catuneanu, 2006).

The petroleum plays of the late transgression are concentrated in the fluvial to shallow-marine depositional systems. Reservoirs during this period may show fluvial architectural elements. According to Posamentier (2002), the late transgression stage is characterized by shelf-sand deposits. This phase is generally important in oil exploration because seal tends to form as mudstone.

3.3.3.1.3. Highstand systems Tract

The highstand system tract is positioned between the maximum flooding surface at the bottom and the subaerial unconformity at the top (Figure 23). High stand system tract refers to the last stages of base level uplifting. Subsequent high stand system tract erosion or pedogenic exposure is likely (Wright and Mariot, 1993). Highstand system tract coarsening-upward shows trend and is related to basinward shift of these facies. The best reservoirs in the highstand system tract are reservoirs related to shoreline and shoreface depositional systems due to the high sand / mud ratio. The reservoir can show quite good lateral continuity. The deposits can be truncated by the subaerial unconformities. Reservoirs are usually represented by channel fills and finer-grained floodplain.

3.3.3.1.4. Falling Stage Systems Tract

The falling stage systems tract contains all stratas during the base level fall (Figure 23). Falling stage systems tract are deposits with shallow marine sediments, prograding and offlapping patterns, and age equal to deep sea submarine fans (ex. Hunt and Tucker, 1992; Plint and Nummedal, 2000).

The reservoir distributions of the facies differ in stratigraphically according to the lower or upper falling stage systems tract. Submarine fans, which are important reservoirs in early stage falling stage system tract, show lower reservoir quality due to low sand / mud ratio. The best reservoirs seen in late stage falling stage systems tract are sandy turbidites associated with late stage forced regression. The turbidity observed in this stage is related to deep-water submarine fans.

3.3.3.1.5. Regressive Systems Tract

Regressive system tract is located between the maximum flooding surface at the bottom and the maximum regressive surface at the top. According to Embry (1995), the regressive systems tract, non-marine strata with subaerial conformity, and marine succession is limited to the maximum regressive surface.

Regressive system tract is usually represented by a progradational pattern. Regressive package generally shows coarsening upward trend. This trend is seen as a progradational pattern and is certainly different from the shallowing-upward trend (Catuneanu et al. 1998). Regressive system tract contains the economic potential of all the phases mentioned above.

3.3.3.2. Sequence Stratigraphic Surfaces

3.3.3.2.1. Subaerial Unconformity

Subaerial unconformity erosion or non-depositional surface during base level fall. Forced regression develops basinward at the end.

3.3.3.2.2. Correlative Conformity

A correlative conformity occurs at the end of the base level in the marine environment. Correlative conformity is also called paleo-sea floor. It is also observed between highstand normal regression and forced regression, or between forced regression and lowstand normal regression (Hunt and Tucker 1992).

3.3.3.2.3. Basal Surface of Forced Regression

The basal surface of forced regression deposits during the forced regression (Hunt and Tucker 1992, Posamentier et al. 1988). In Shallow marine succession, this surface can be conformable. This surface is also known as regressive slope onlap surface (Embry, 2001a).

3.3.3.2.4. Regressive Surface Marine Erosion

During a forced regression, the surface of the marine surface is interrupted by shoreface waves, but the surface of the surface tries to maintain its concave-up profile (Bruun, 1962; Plint, 1988; Dominguez and Wanless, 1991; Plint and Nummedal, 2000). This surface distinguishes between basal surface of forced regression and forced regressive sediments (Catuneanu, 2002).

3.3.3.2.5. Maximum Regressive Surface

According to Helland-Hansen and Martinsen (1996), this surface is located between regression and sub-sequent transgression. This surface is conformable. It represents the transition from a progradational pattern to a retrogradational pattern (Catuneanu, 2002).

3.3.3.2.6. Maximum Flooding Surface

The maximum flooding surface is represented by the end of the shoreline transgression (Frazier, 1974; Posamentier et al. 1988; Van Wagoner et al. 1988; Galloway, 1989). This surface separates prograding above and retrograding strata below (Catuneanu, 2002).

3.3.3.2.7. Ravinement Surface

Ravinement surface is the erosional surfaced by upper shoreface waves during shoreline transgression (Bruun, 1962; Swift et al. 1972; Swift, 1975; Dominguez and Wanless, 1991).

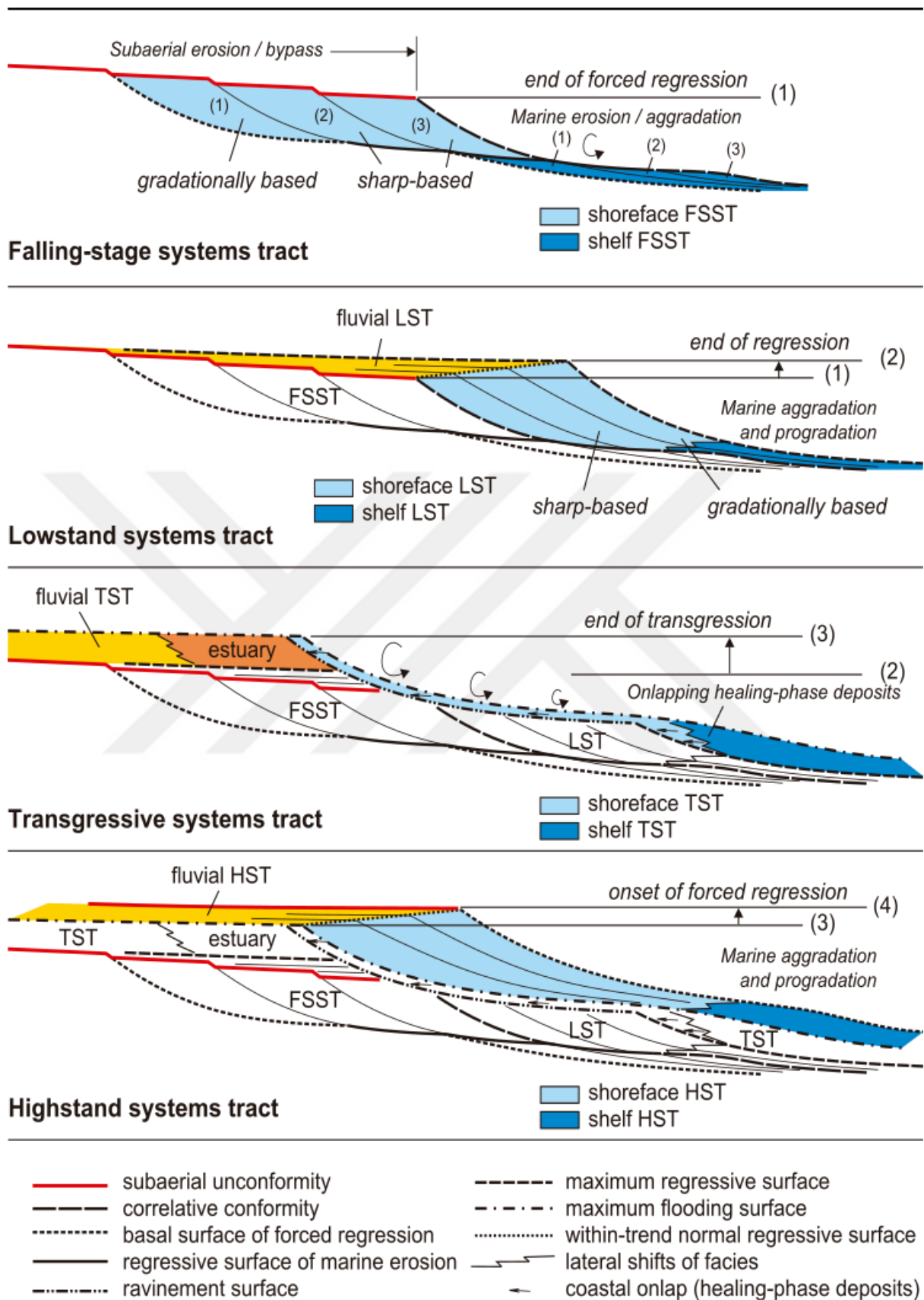


Figure 23: System Tracts (Modified from Catuneanu, 2006)

4. Results

4.1. Introduction

In this section, the results of seismic stratigraphy, sequence stratigraphy, trajectory analysis, and grid maps generated from horizons, obtained by applying seismic stratigraphy methods are given. This section will contain the results of the seismic interpretation, their seismic sequence analysis and finally the trajectory analysis and grid maps will be mentioned.

4.2. Seismic Interpretation

During the study, DTB08043, DTB01-31, RWT10-01, WM-14_0, NZ-110A, SUNZ-91-143, TIK09-08, Sunz-91-136 were the dip seismic lines and 21 perpendicular lines were used while making the grid map. Five regional lines were selected to illustrate seismic stratigraphic and sequence stratigraphic studies. These are DTB01-31, DTB08043, SUNZ-91-136, SUNZ-91-143 and TIK09-08. SUNZ-91-136 is located at the Northernmost and all seismic lines are parallel to the South. Downlap, onlap and toplap (Figure 25, 26, 27, 28, 29) surfaces were determined in the region with more detail, subsequences were also defined on these figures. In Table 2, the colour codes of the sub-sequences identified in the region are given.

Sub-sequence Colour Table

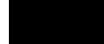
Oldest						
	S1	S2	S3	S4	S5	S6
						
	S7	S8	S9	S10	S11	S12
						Youngest

Table 2: Defined Sub-Sequences and their boundaries color codes

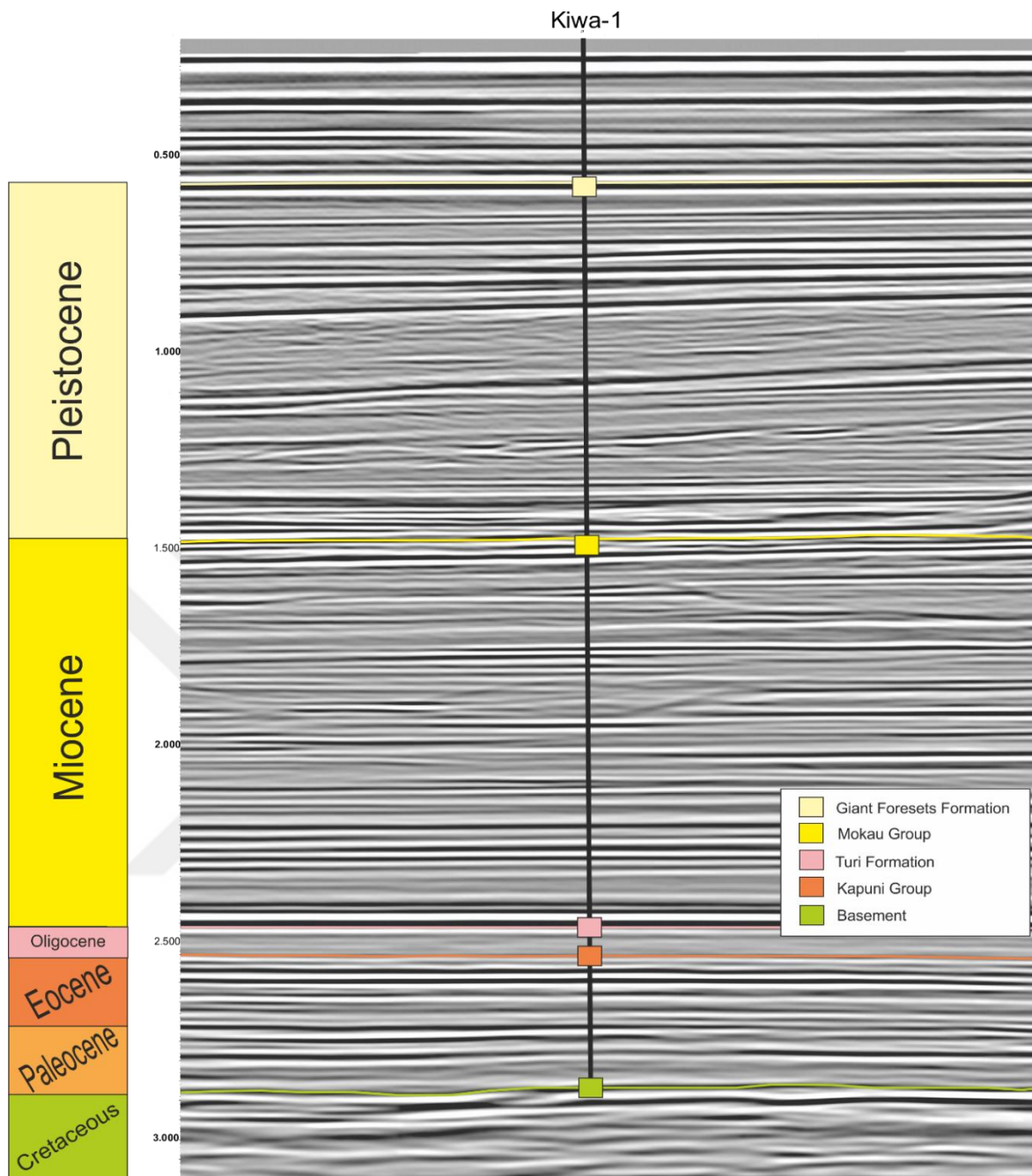


Figure 24: Main Stratigraphic Horizon (Cretaceous-Neogene)

4.3. Seismic Stratigraphy Results

This study is limited between Miocene and Plio-Pleistocene. In this age range, progradational clinoform systems are in the Taranaki Basin. Horizon 11 was seen only in DTB01-31 and DTB08043 seismic lines, but not in other seismic lines. Sub-sequence 1 and sub-sequence-2, which will be discussed below, have been studied to understand the basin development, but not between Miocene and Plio-Pleistocene sediments.

4.3.1. Sub-Sequence-1(S1)

This sub-sequence is generally continuous and shows parallel configuration. According to Veenken (2007), parallel configuration refers to subsiding shelf or stable basin plain (Figure 24). Although high amplitude is observed in this seismic package, low amplitude is observed in general. High frequency reflectors are observed at the top and bottom of this package. In the middle part of the package, high frequency reflectors are sometimes seen. This package shows the aggradation pattern.

4.3.2. Sub-Sequence-2(S2)

Sub-sequence 2 is deposited conformable on sub-sequence 1. This package shows continuous and parallel configuration. This seismic package shows high amplitude and frequency reflections in the upper and lower regions. Observed pattern type is aggradational as in sub-sequence 1.

4.3.3. Sub-Sequence-3(S3)

Although sub-sequence 3 is sometimes continuous in the middle and upper parts, the reflection is generally discontinuous. This sub-sequence shows the oblique tangential configuration. According to Veenken (2007), this configuration is associated with relatively slow basin subsidence. Even though this sub-sequence shows high amplitude and high frequency reflection in the middle and upper parts, in general, low amplitude and low frequency are observed in this package.

4.3.4. Sub-Sequence-4(S4)

The middle part of sub-sequence 4 is continuous. The upper parts of this package are discontinuous. This sub-sequence shows the complex sigmoid-oblique configuration. According to Veenken (2007), this configuration is related to sea level rise. These reflectors mainly downlap horizon 4 and toplap horizon 5.

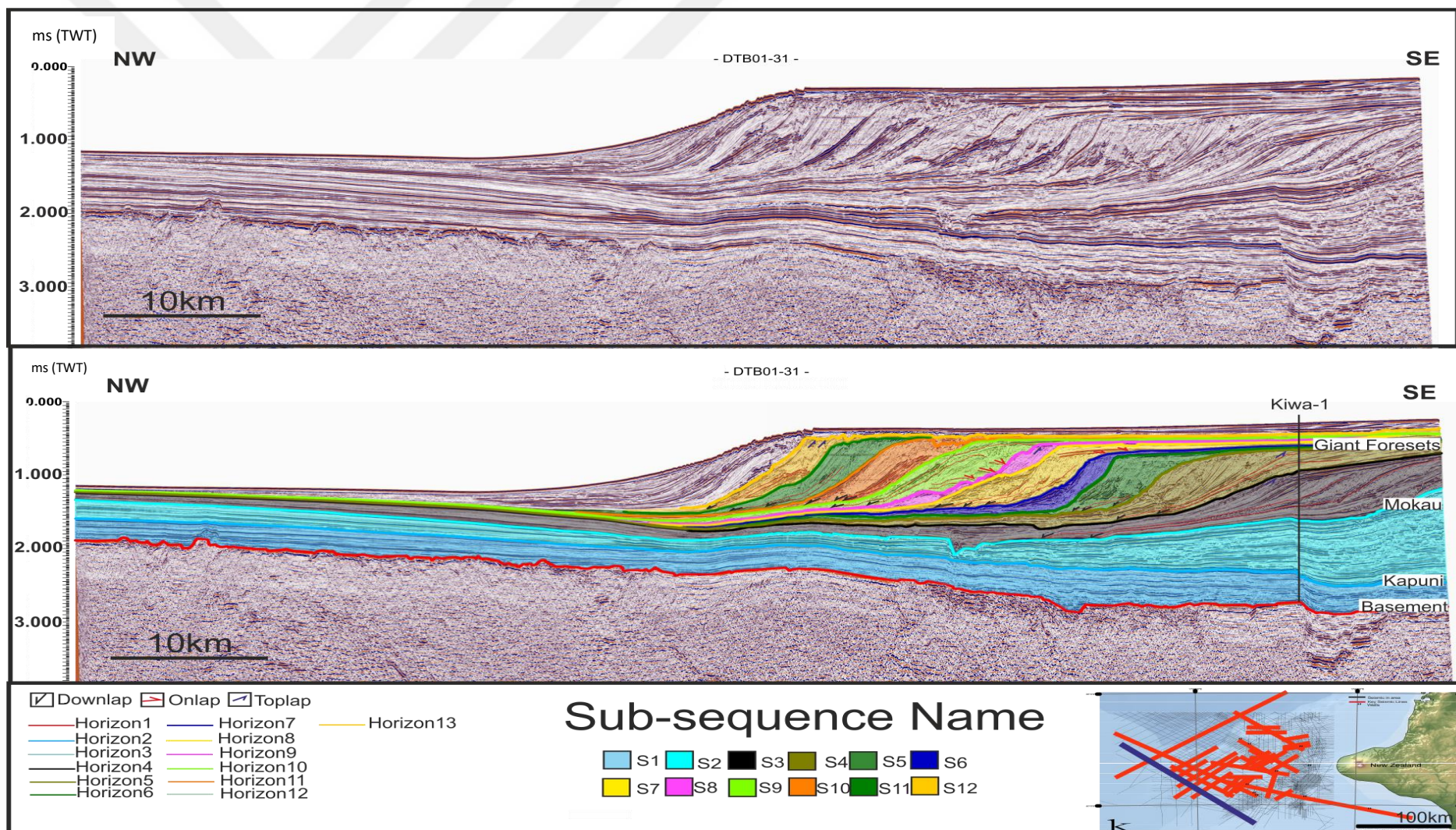


Figure 25: DTB01-31 Stratal Terminations and Sub-sequences (Age of; Giant Foreset Formation:Plio-Pleistocene, Mokau Group: Early Miocene, Kapuni Group: Paleocene-Eocene)

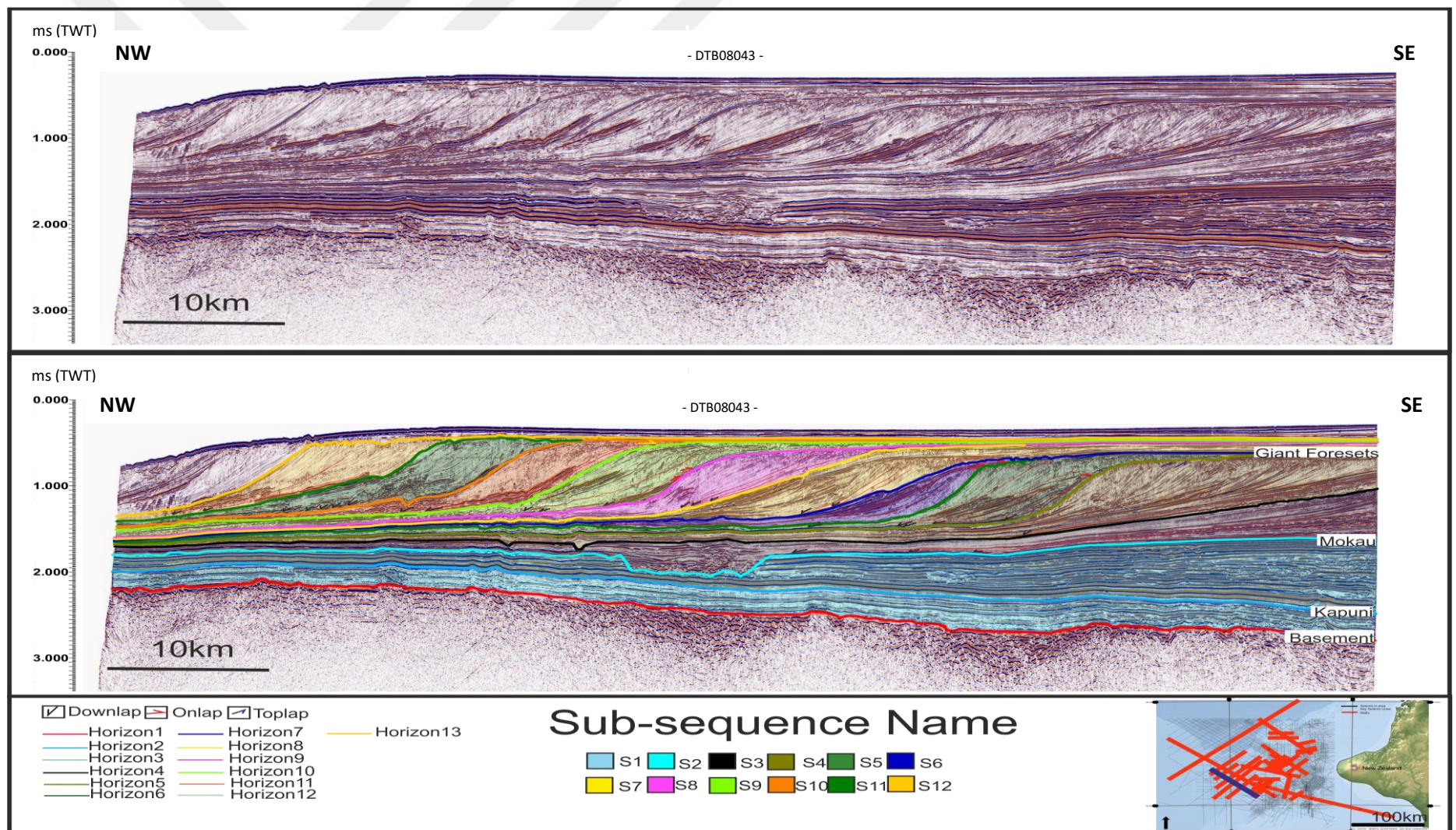


Figure 26: DTB08043 Stratal Terminations and Sub-sequences(Age of; Giant Foreset Formation:Plio-Pleistocene, Mokau Group: Early Miocene, Kapuni Group: Paleocene-Eocene)

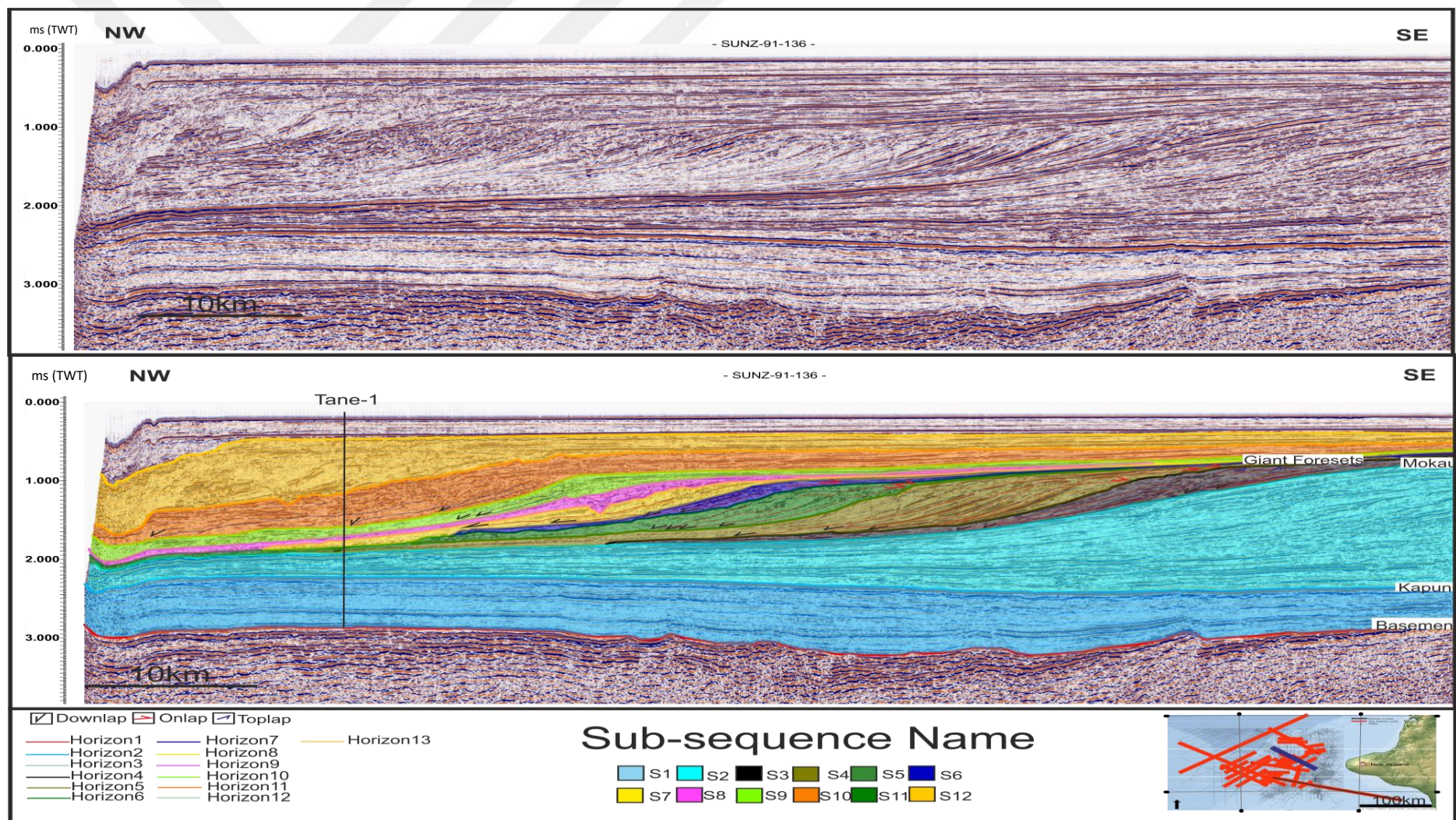


Figure 27: SUNZ-91-136 Stratal Terminations and Sub-sequences(Age of; Giant Foreset Formation:Plio-Pleistocene, Mokau Group: Early Miocene, Kapuni Group: Paleocene-Eocene)

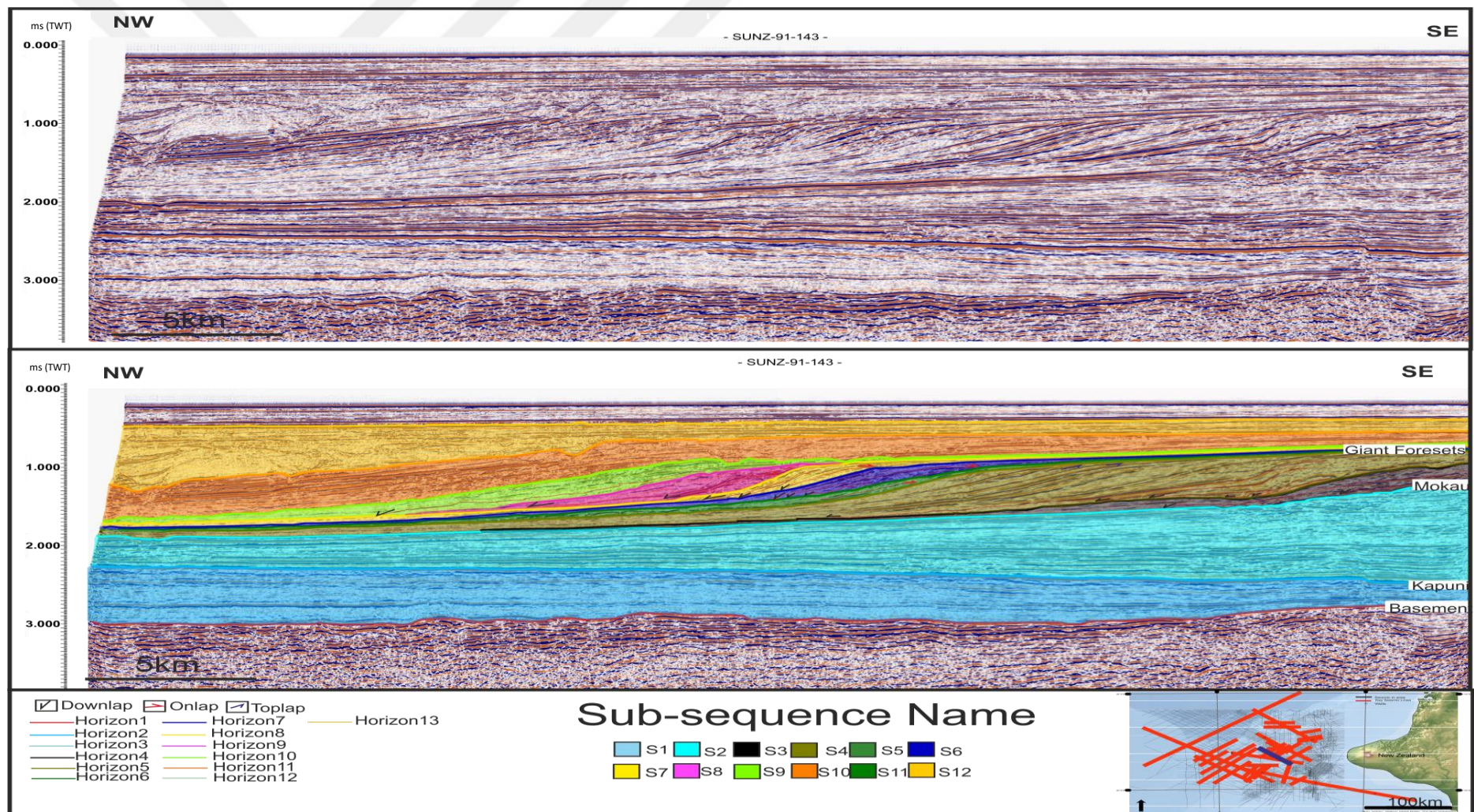


Figure 28: SUNZ-91-143 Stratal Terminations and Sub-sequences (Age of; Giant Foreset Formation: Plio-Pleistocene, Mokau Group: Early Miocene, Kapuni Group: Paleocene-Eocene)

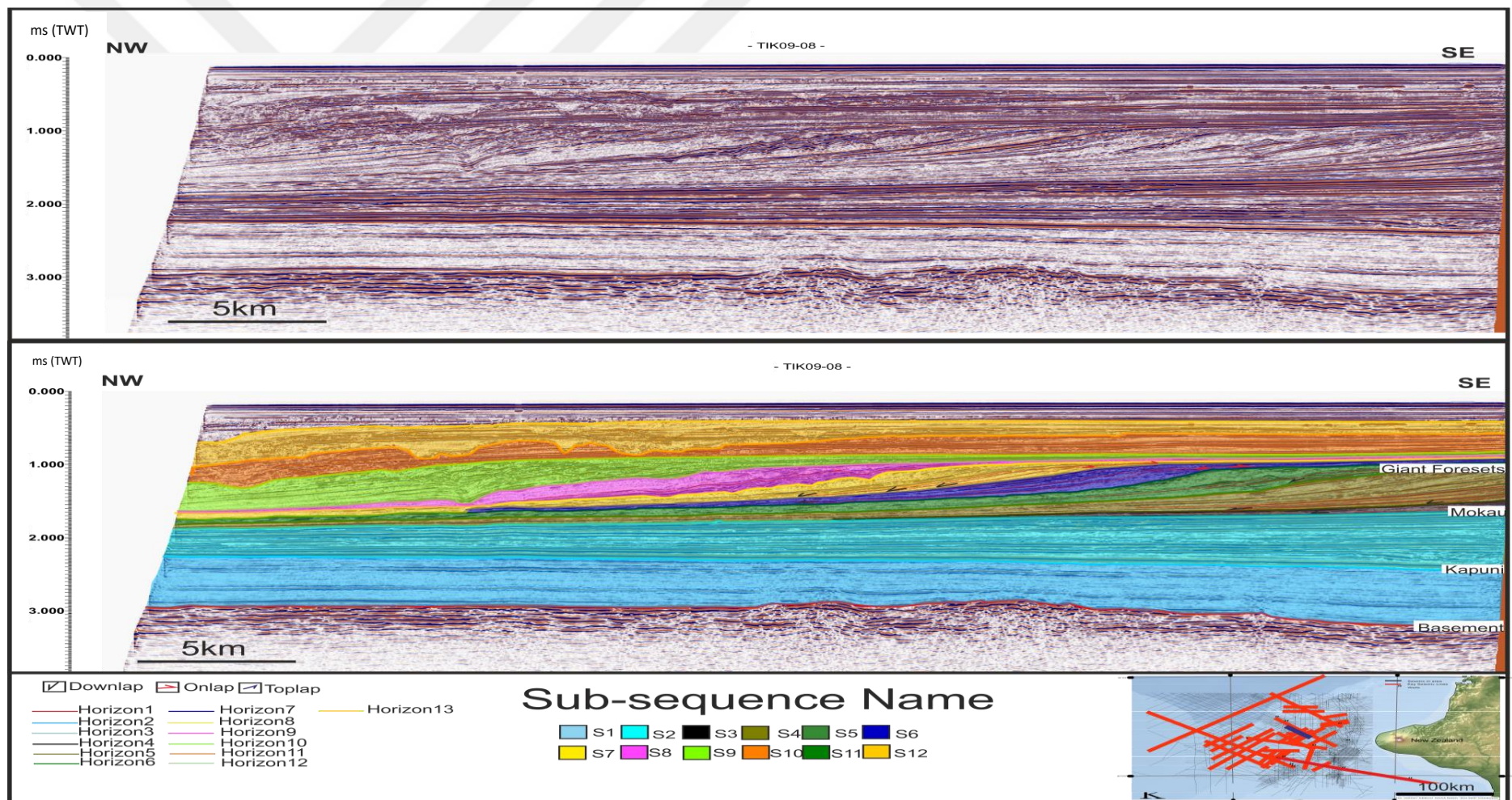


Figure 29: TIK09-08 Stratigraphic Terminations and Sub-sequence (Age of; Giant Foreset Formation: Plio-Pleistocene, Mokau Group: Early Miocene, Kapuni Group: Paleocene-Eocene)

4.3.5. Sub-Sequence-5(S5)

S5 is discontinuous. Some high frequency reflections have been observed, especially in the middle and lower parts. In addition, sub-sequence 5 shows low amplitude reflections (Figure 25). This sub-sequence shows complex sigmoid-oblique configuration, such as sub-sequence 4. These reflectors downlapping horizon 5.

4.3.6. Sub-Sequence-6(S6)

The upper and middle portions of this sub-sequence are continuous whereas the lower part is discontinuous. It was also observed that this sub-sequence shows high frequency reflection in the upper and middle parts. Amplitude can be defined as moderate. Sub-sequence 8 has a complex sigmoid-oblique configuration. These reflectors onlapping and downlapping horizon 6.

4.3.7. Sub-Sequence-7(S7)

Sub-sequence 7 shows sigmoid configuration. According to Veenken (2007), sigmoid configuration develops with the rapid subsidence of the basin and aggradation of topset beds and forset progradation. Reflections in the middle and upper parts show high frequency. Especially in the middle and upper sections, high amplitude is observed. The upper parts of this sub-sequence are continuous but the lower parts are discontinuous. These reflectors are onlapping and downlapping the horizon 7 surface.

4.3.8. Sub-Sequence-8(S8)

Sub-sequence 8 shows low amplitude and low frequency reflections, occasionally this sub-sequence shows high frequency reflections. Sub-sequence 8 shows an oblique configuration. In Figure 29 sub-sequence-8 shows, high amplitude and high frequency reflections at the bottom is observed. It is also continuous at the bottom of this seismic package. Reflectors are downlapping and toplapping the horizon 8 surface.

4.3.9. Sub-Sequence-9(S9)

Sub-sequence 9 is discontinuous. In general, low amplitude and low frequency reflections are observed, but especially high amplitude and high frequency reflections have been

found in the upper parts of sub-sequence 9. S9 shows a sigmoid configuration. These reflectors downlapping and onlapping horizon 9.

4.3.10. Sub-Sequence-10(S10)

In Figure 27, 28, 29, sub-sequence 10 is continuous. They also show high amplitude and high frequency reflections. In these seismic lines, the configuration is observed as shingled. Veenken (2007) shows that shingled configurations indicate shallow water conditions during progradation. This sub-sequence shows a sigmoid configuration in Figure 25 and 26. The reflectors are downlapping horizon 10.

4.3.11. Sub-Sequence-11(S11)

Sub-sequence 11 is only observed in Figure 25 and 26. In general, it is continuous but the amplitude and reflection frequency in the seismic DTB01-31 is lower than in DTB08043. It also shows an oblique configuration. These reflectors are mainly downlapping horizon 11.

4.3.12. Sub Sequence-12(S12)

Sub-sequence 12, as well as sub-sequence 10 observed in different seismic lines show different features. S12, in Figure 27, 28, 29 shows a shingled configuration, while in Figure 25 and 26 shows an oblique configuration. High amplitude and high frequency reflectors were also observed in the lower part of these lines. In Figure 27, 28, 29 the upper parts are more continuous. Amplitude and frequency can be defined as moderate. These reflectors are mainly downlapping horizon 12 at southern and downlapping Horizon 11 at Northern part of area. This is because horizon 12 does not exist in the Northern region as it is thinning.

4.4. Sequence Stratigraphic Analysis Results

Three different stratal relationships in all old and modern continental margins have been linked to the relationship between accommodation and sedimentation. These are downbuilding progradation, upbuilding progradation and retrogradation (Figure 30; ex, Hunt and Tucker, 1992; Posamentier and Morris, 2000; Catuneanu, 2006; Catuneanu et al. 2009; Helland-Hansen and Hampson, 2009; Franzel and Back, 2019). The sequences are defined as a 4th order sequences because the sequence is not complete.

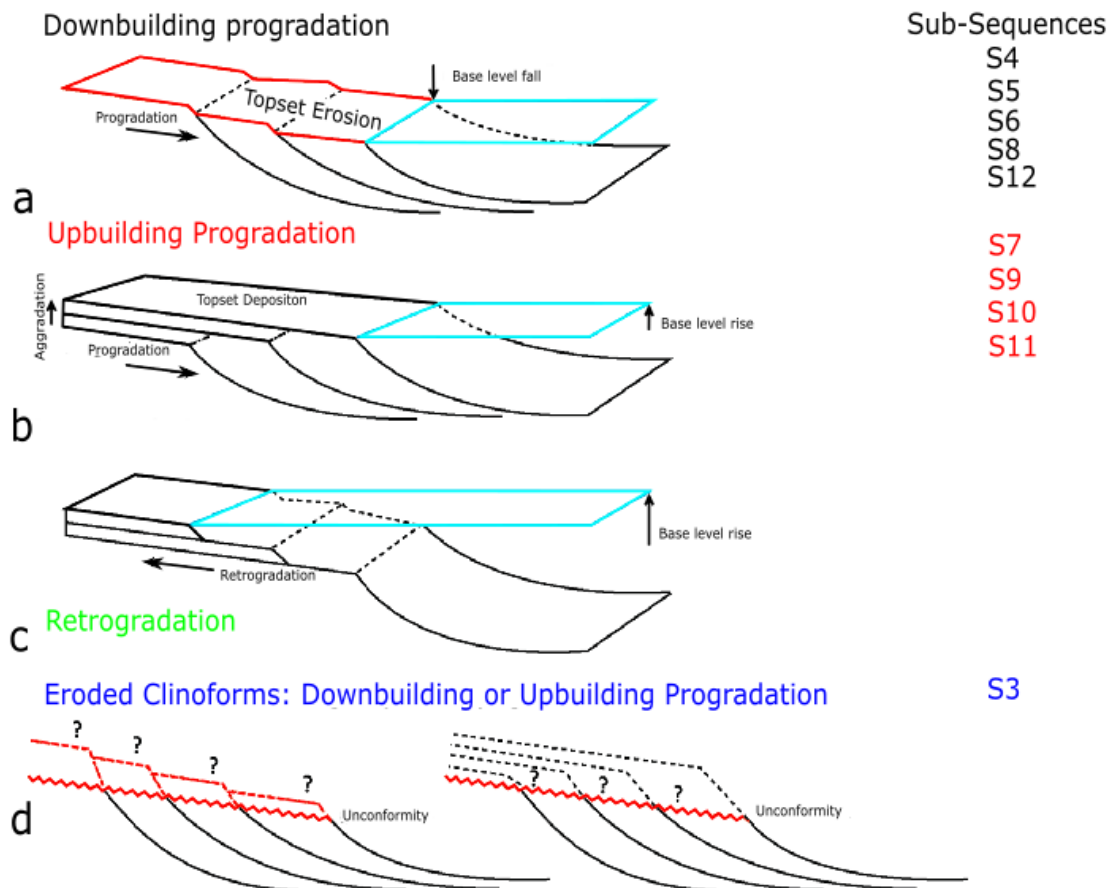


Figure 30: Staratal Associations as a consequence of accommodation and sedimentation (Modified from Franzel and Back, 2019)

Base level rise and migration to basinward results in downbuilding progradation and is not associated with sediment supply. Upbuilding progradation is associated with sediment supply and is observed when the sedimentation rate is higher in base level rise. Conversely, retrogradation is observed when the sedimentation rate is higher than the base level (Catuneanu, 2006).

4.4.1. Sub-Sequence-1(S1)

It is the lowermost and the oldest sub-sequences after basement. It is located above the acoustic basement and its base of depth around 2,500 ms (TWT) in the SE and around 2,200 ms (TWT) in the NW. This package shows aggradation meaning that the sediment influx and relative sea level are equal (Posamentier and Allen, 1999). This section is identified as belonging to the Kapuni Group based on the well data, and this group is represented by transgression. The TST is dominant in this package (Baur et al. 2014).

4.4.2. Sub- Sequence-2(S2)

Horizon 2 defines the base of this sub-sequence. This sequence lies between horizon 2 and 3 as previously mentioned. Horizon 2 defines the base of these sub-sequences. Its base of depth is around 2,300 ms (TWT) in the SE and around 2,000 ms (TWT) in the NW. The sequence is ending with sediments which belongs to the Mokau group. According to Holt and Stern (1994), this group is Early Miocene aged. In the Oligocene period, this basin was under water. Horizon 2 belongs to Kapuni Group (Paleocene- Eocene). Between this two horizon Oligocene sedimen deposited. As a result, the terrestrial sediments have started to be deposited in the basin during this period. In the lower part of this sequence, it is observed that some reflections may indicate carbonate (high amplitude-low frequency reflectors). Therefore, this sequence may indicate that terrestrial sediments are being deposited in the system.

This sub-sequence indicates the aggradational pattern of the HST. This sub-sequence is bounded with horizon 2 and 3. Horizon 3 defines as a entire clinoform system's downlapping surface.

4.4.3. Sub- Sequence-3 (S3)

Horizon 3 defines the base of sub-sequence 3 and its base of depth around 1.600 ms (TWT) in the SE and is around 1.650 ms (TWT) in the NW. In it is most proximal section, this subsequence corresponds to erosional surface and it is conformable in distal section. This sub-sequence bounded with horizon 3 and 4 and this is the oldest unit in clinoform system and Horizon 3 define as a base of this sub-sequence. Reflectors can be seen downlapping horizon 3 (Figure 25).

The base is defined as a local downlapping surface. The upper one was defined as the local downlap surface of sub-sequence 4. Horizon 3, especially in Figure 25 and 26, incision valley in this sub-sequence shows the early TST.

4.4.4. Sub- Sequence-4(S4)

Horizon 4 defines the base of sub-sequence 4 and its base depth is around 1.200 ms (TWT) in the SE and is around 1.600 ms (TWT) in the NW. It is located above sub-sequence 3, the

oldest unit in clinoform system (sub-sequence 3). It also extends from the proximal section to the distal section. Sub-sequence 4 is bounded by horizons 4 and 5. Horizon 4 defines the base of this sub-sequence. The local downlap surface is located at the base and the local onlap surface is located at the top (Figure 26).

4.4.5. Sub- Sequence-5 (S5)

The base of this sub-sequence is Horizon 5. Its base depth is around 0.800 ms (TWT) in the SE and is around 1.590 ms (TWT) in the NW. Sub-sequence 5 bounded by horizon 5 and horizon 6. It has a local downlap surface at the base and a local onlap surface at the top. The base of sub-sequence 5 is horizon 5 (Figure 28).

4.4.6. Sub- Sequence-6 (S6)

Horizon 6 is the base of sub-sequence 6. The base of this sub-sequence is horizon 6 and its base depth is around 0.710 ms (TWT) in the SE and 1570 ms (TWT) in the NW. Sub-sequence 6 bounded by horizons 6 and 7. Local downlap surfaces are located at the base and the top. Reflectors are also downlapping horizon 6.

4.4.7. Sub- Sequence-7(S7)

Local downlap surfaces are located at the base and above. The base of this sub-sequences is Horizon 7. Horizon 7 defines the base of this sub-sequence and its base depth is around 0.700 ms (TWT) in SE and around 1.550 ms (TWT) in the NW. Sub-sequence 7 is deposited between horizons 7 and 8. Some seismic lines show aggradational patterns in the upper parts; however the progradational pattern is generally dominant. The aggradational pattern observed upper part of the forsets and topsets point to HST.

4.4.8. Sub- Sequence-8(S8)

Horizon 8 is the base of the sub-sequence and its base depth is around 1.540 ms (TWT) in the NW. Reflectors on the surface show downlap. Sub-sequence 8 can be defined as a FSST due to falling sea level and toplapping horizon 9. Horizon 9 represents the end of FSST horizon 9 so the top of sub-sequence 8 can be defined as a maximum regressive surface.

4.4.9. Sub- Sequence-9(S9)

Horizon 9 is this sub-sequence base and the reflectors are both downlapping and onlapping at the base of this unit. In some intervals reflectors show retrogradational patterns so those reflectors point to early TST. Sub-sequence 9 was developed between local downlap surfaces. Its base depth is around 0.600 ms (TWT) in the SE and around 1,520 ms (TWT) in the NW.

4.4.10. Sub- Sequence-10(S10)

Horizon 10 defines the base of sub-sequences 10 and its base depth is around 0.550 ms (TWT) in the SE and around 1,500 ms (TWT) in the NW. Sub-sequence 10 shows different characteristics in different seismic lines. These are characteristic of the channel structure they display. There are local downlap surfaces at the top and bottom of this sub-sequences.

4.4.11. Sub- Sequence-11(S11)

This sub-sequence was found only in Figure 25 and 26. The top of this sub sequence eroded. Erosion may be the reason we see these lines only north of the basin. Even if sub-sequence 11 shows erosion its top, it assumed as a upbuilding progradation. Because it shows high sediment supply in figure 37b. The reflectors shows toplap and downlap.

4.4.12. Sub-Sequence-12(S12)

DTB01-31 and DTB08043 are located in the south of the study area where Horizon 12 forms the base of sub-sequence 12. The development of horizon 12 was not observed in seismic lines in the North, so horizon 11 forms the base of sub-sequence 12 in these regions. Horizon 12 defined as a base of this sub-sequence at the southern part. Channels are observed in sub-sequence 12 in Northern areas of basin. Sub-sequence 12 can be defined as a FSST due to falling sea level. The other reason is some reflectors toplaping horizon 13. The top of this subsequence is horizon 13 and that can be defined as a maximum regressive surface.

4.5. Trajectory Analysis

Trajectory analysis is an essential method to understand the depositional process of the clinoforms and their lateral and vertical migration. Sediment supply and 4th-5th order sea

level changes are important in defining the shoreline trajectory (Helland-Hansen and Gjølberg, 1994; Helland-Hansen and Martinsen, 1996). The analysis was applied on seismic lines DTB01-31, DTB08043, SUNZ-91-136, SUNZ-91-143-TIK09-08 (Figure 31, 32, 33, 34, 35). The results which created with using Helland-Hansen and Martinsen (1996) shoreline trajectory classification for each line are given in Table 3. There are 10 roll over points identified due to their offlap break. It is difficult to see some roll over points due to erosion in some lines (Figure 32, 33, 35). In the light of the results obtained, the general trend starts with low angle ascending regressive, followed by stationary and high angle ascending regressive. When determining system tracts, Low angle ascending regressive-early TST, high angle ascending regressive-HST and descending regressive FSST were defined.

	Rollover Points Between	Shoreline Trajectory Class
DTB01-31	1-3	Low Angle Ascending Regressive
	3-4	Stationary
	4-5	High Angle Ascending Regressive
	5-6	Descending Regressive
	6-9	Low Angle Ascending Regressive
	9-10	Descending Regressive
DTB08043	2-3	Low Angle Ascending Regressive
	3-4	Stationary
	4-5	High Angle Ascending Regressive
	5-6	Descending Regressive
	6-9	Low Angle Ascending Regressive
	9-10	Descending Regressive
SUNZ-91-136	1-3	Low Angle Ascending Regressive
	3-4	Stationary
	4-5	Low Angle Ascending Regressive
	5-6	Descending Regressive
	6-8	High Angle Ascending Regressive
	8-10	Low Angle Ascending Regressive
SUNZ-91-143	1-3	Low Angle Ascending Regressive
	3-4	Stationary
	4-5	Low Angle Ascending Regressive
	5-6	Descending Regressive
	6-8	High Angle Ascending Regressive
TIK09-08	2-3	Low Angle Ascending Regressive
	3-4	Stationary
	4-5	Low Angle Ascending Regressive
	5-6	Descending Regressive
	6-7	Low Angle Ascending Regressive
	7-10	High Angle Ascending Regressive

Table 3: The results of trajectory classification on selected seismic surveys in Taranaki Basin

In general, Low angle ascending regressive progrades farther than the previous clinoform system and develops in a basinward direction. Such environments are indicative of a rise in relative sea level. High angle ascending regressive, show both aggradation and progradation basinward. Accommodation space and sediment supply ratio is higher than low angle ascending regressive and the sediment supply ratio is higher. Stationary Trajectories generally refer to sediment bypass on the basin floor (Bullimore et al. 2005: Helland-Hansen and Hampson, 2009).



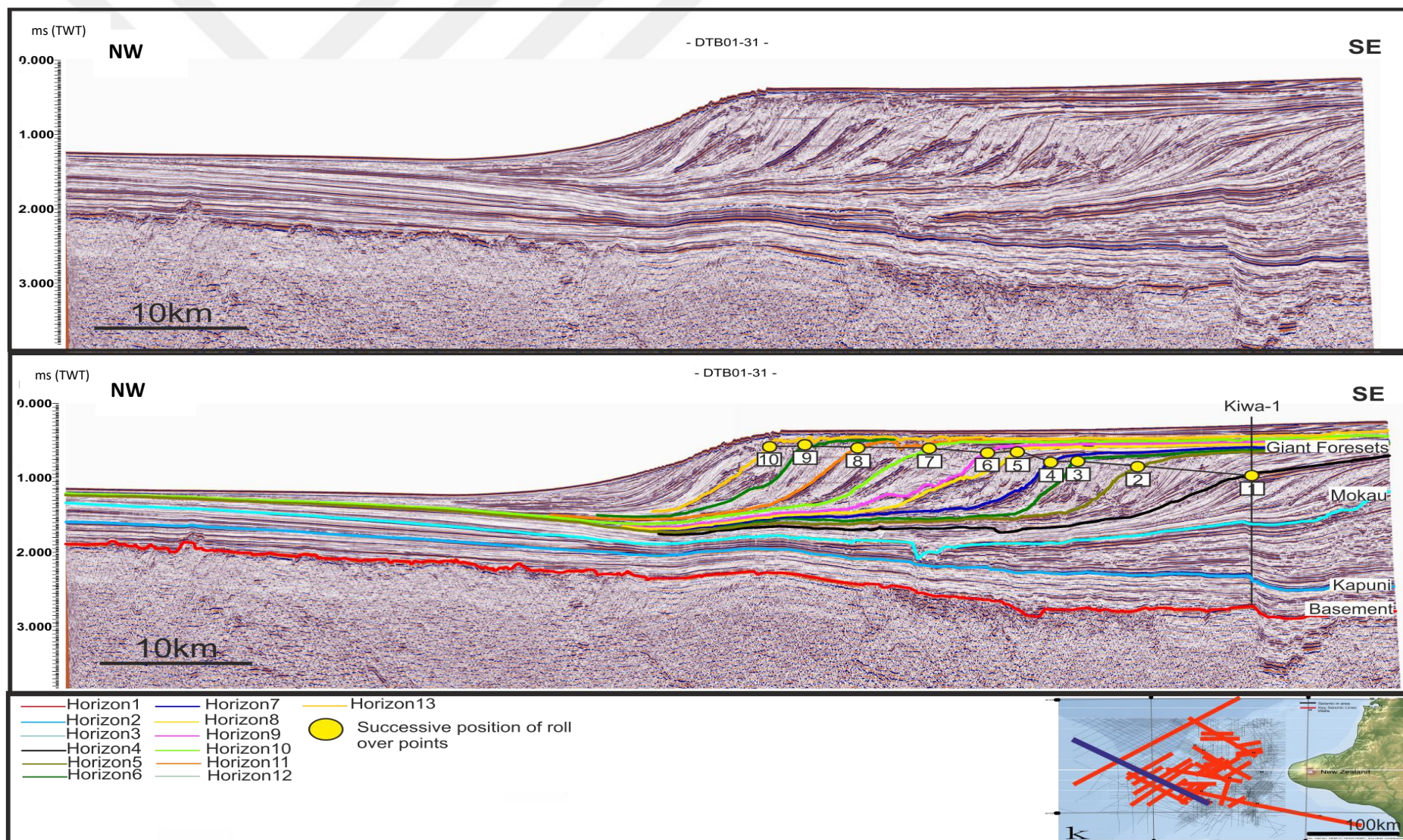


Figure 31: DTB01-31 Trajectory Analysis Rollover Points and Trajectory Line (Age of; Giant Foreset Formation: Plio-Pleistocene, Mokau Group: Early Miocene, Kapuni Group: Paleocene-Eocene)

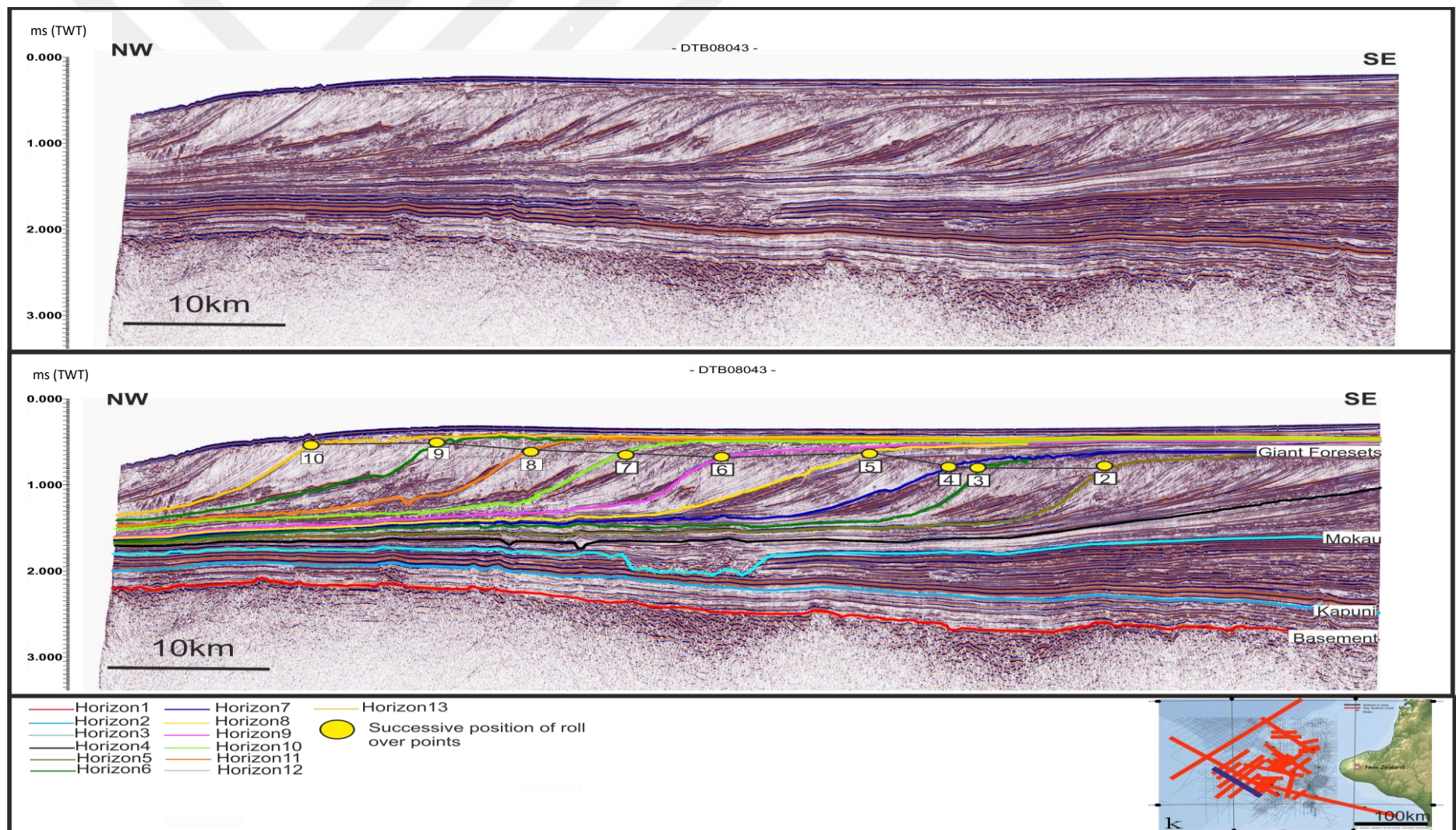


Figure 32: DTB08043 Trajectory Analysis Rollover Points and Trajectory Line (Age of; Giant Foreset Formation: Plio-Pleistocene, Mokau Group: Early Miocene, Kapuni Group: Paleocene-Eocene)

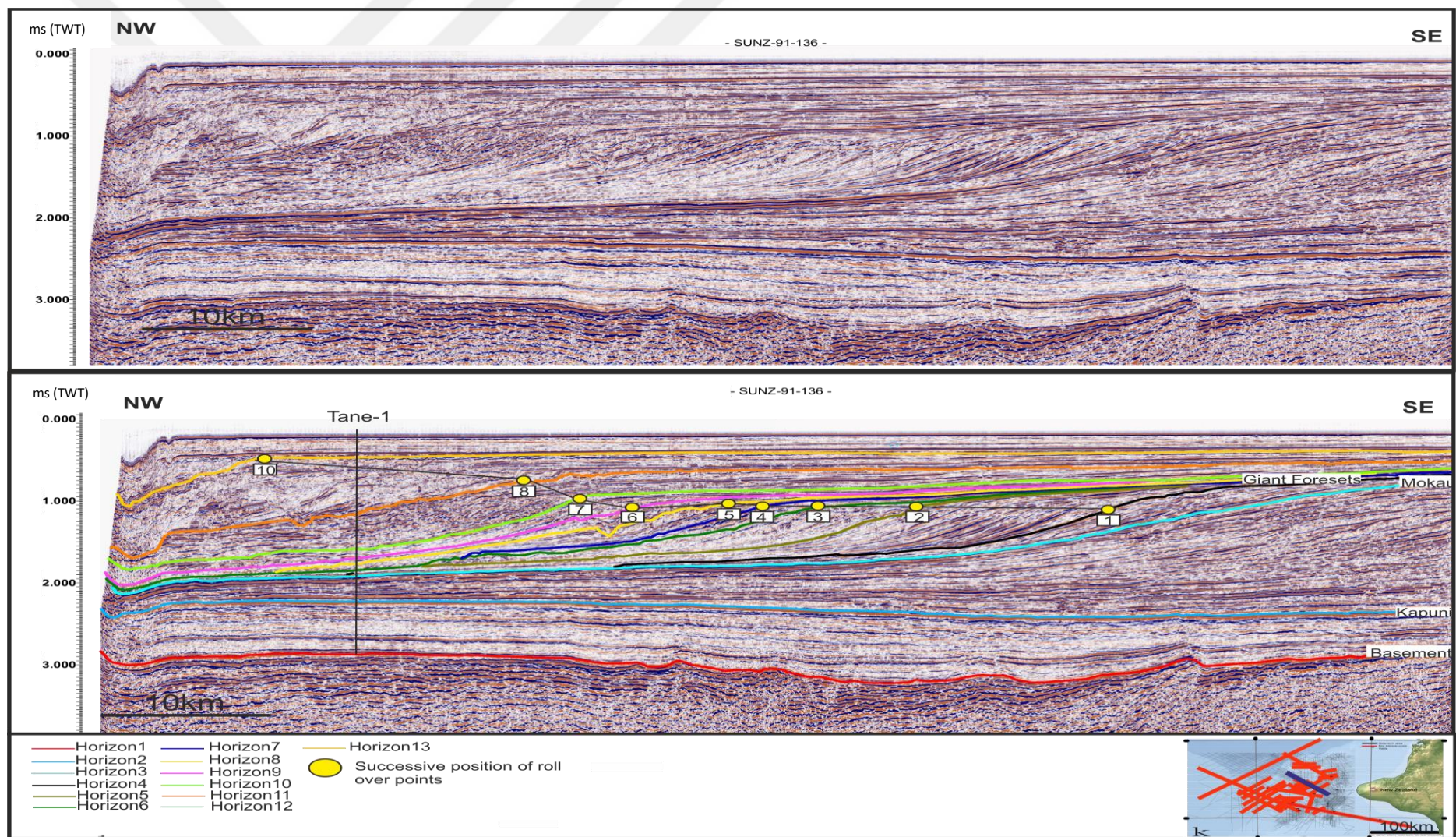


Figure 33: SUNZ-91-136 Trajectory Analysis Rollover Points and Trajectory Line (Age of; Giant Foreset Formation: Plio-Pleistocene, Mokau Group: Early Miocene, Kapuni Group: Paleocene-Eocene)

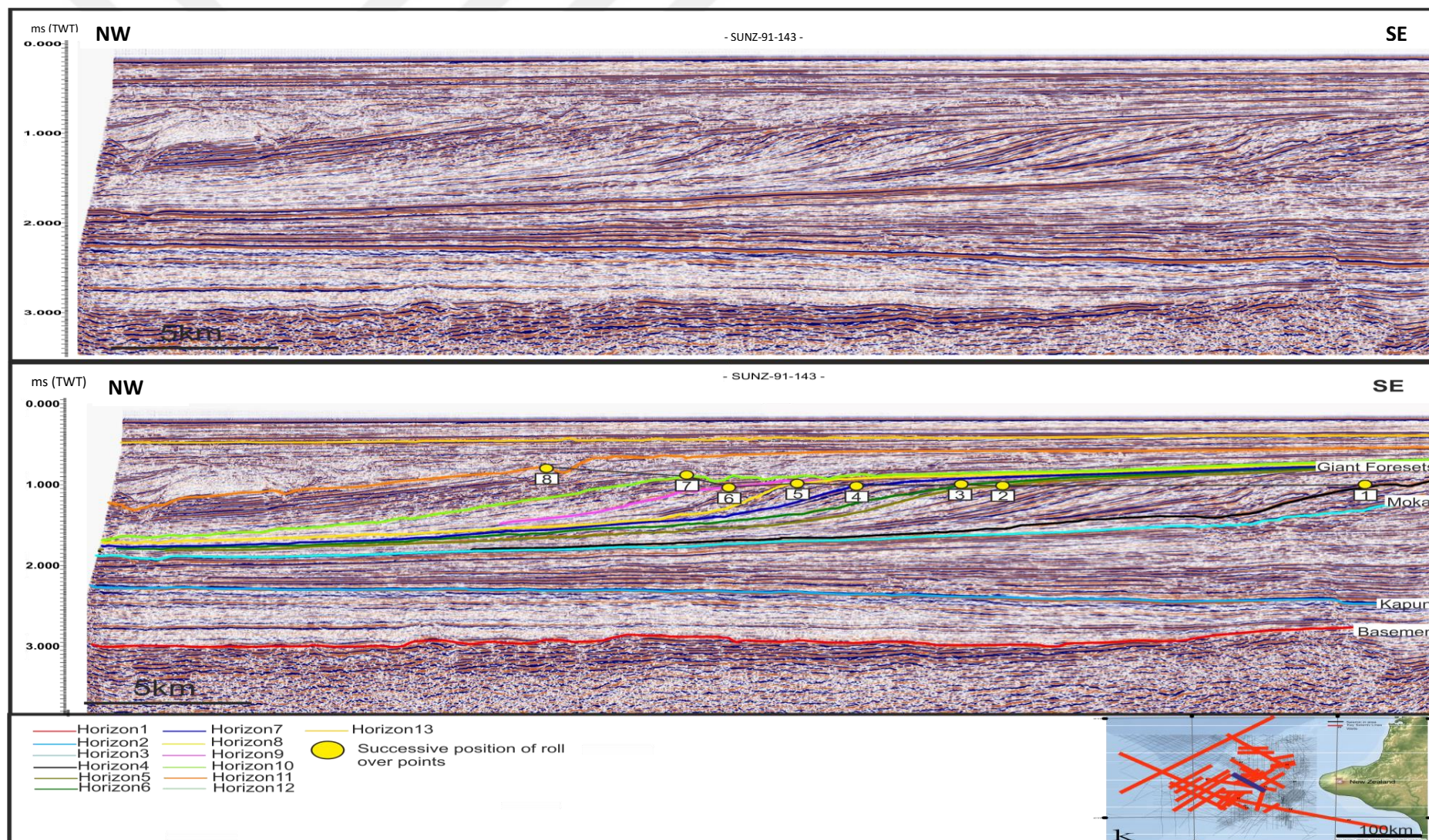


Figure 34: SUNZ-91-143 Trajectory Analysis Rollover Points and Trajectory Line (Age of; Giant Foreset Formation: Plio-Pleistocene, Mokau Group: Early Miocene, Kapuni Group: Paleocene-Eocene)

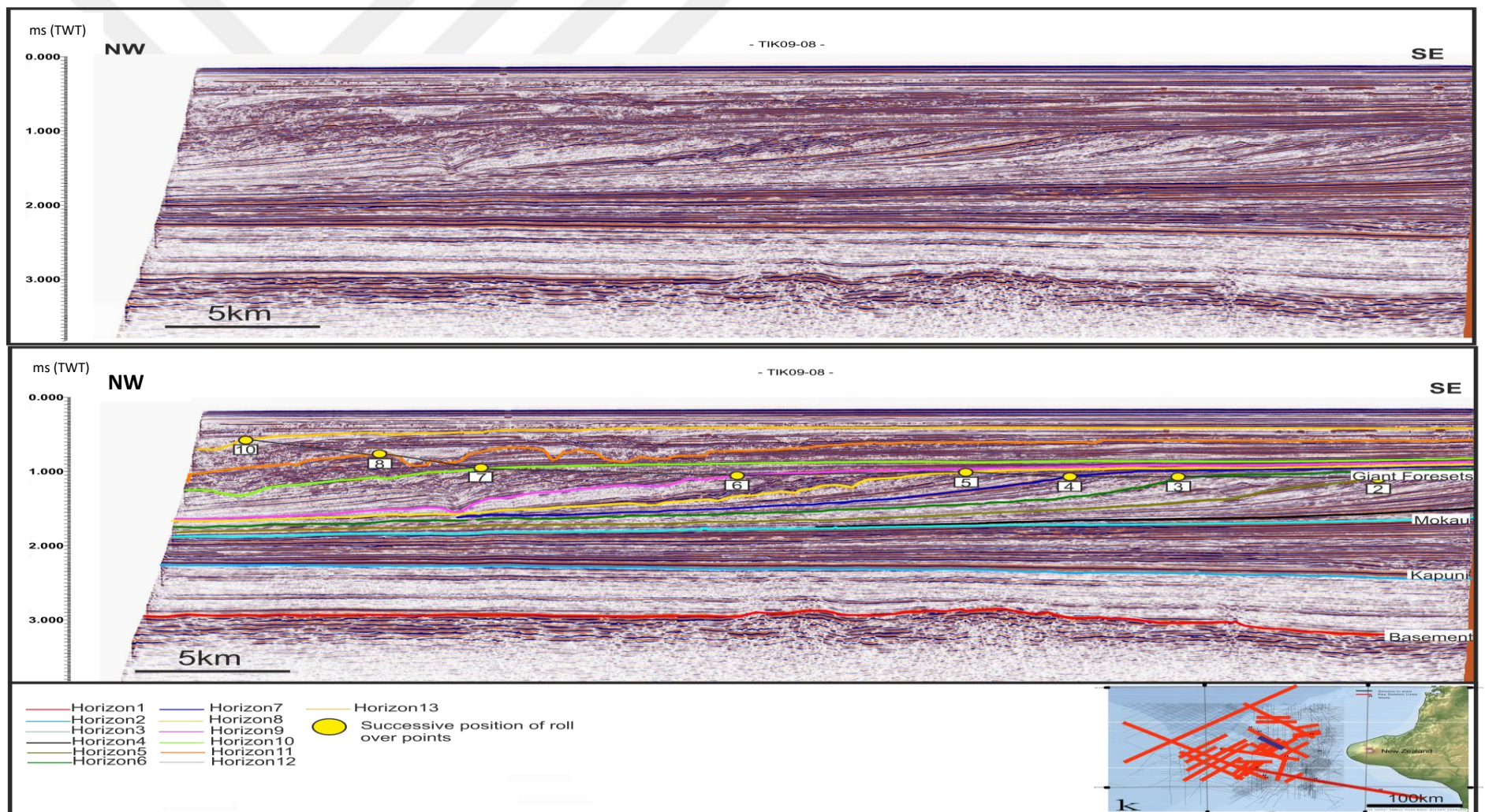


Figure 35: TIK09-08 Trajectory Analysis Rollover Points and Trajectory Line (Age of; Giant Foreset Formation: Plio-Pleistocene, Mokau Group: Early Miocene, Kapuni Group: Paleocene-Eocene)

4.6. Grid Maps

While creating grid maps, horizons interpreted on seismic lines were used. The aim of this study is to understand the development of the basin. These maps also show thickness. In the region downbuilding, upbuilding progradation and eroded clinoforms systems were observed as outlined in Figure 30. While creating the following figures, the grid map of the old horizon is located at the bottom and the younger one is at the top. The young horizon shows a transparent pattern. In this section, we tried to make a relation between progradation type (Figure 30) and grid maps. As we mentioned before upbuilding progradation is related with sediment supply and base level rise so when basin prograding further we can infer during this stage sediment supply is high.

Sub-sequence-4, sub-sequences-5 and sub-sequence-6 illustrate the downbuilding progradation (The grid map of sub-sequence-4 is given in appx1, the grid map of sub-sequences-5 is given in appx2 and the grid map of sub-sequence-6 is given in appx3). These sub-sequences indicate a base level fall. Sub-sequence-7 (Figure 36a) shows significant sea level rising and during deposition of sub-sequence-7, sediments prograding South part of basin but sub-sequence 8 (The Grid map of S8 given in appx4) shows sea level falling this stage is related with forced regression and after this basin also slightly started to prograde at the North, sub-sequence-9, sub-sequence-10 show the upbuilding progradation and after the deposition S9, sediments started to prograding both North and South part of the basin (Figure 37a). These sub-sequences indicate a high sediment supply ratio. In addition, the sediment supply ratio is higher than the base level rise.

The sub-sequence-11 shows the upbuilding progradation again, and we can see that the high sediment supply at this point. During that time sediments still prograding both North and South (Figure 37 b). Generally, North-west progradation was observed in the south of the basin until basin sub-sequence-9, but after this sub-sequence, progradation continued in the south and North of the basin. Horizon 12 was observed only on seismic lines DTB01-031 and DTB08043. Therefore, grid maps of horizon 12 are subject to a higher level of uncertainty, and multiple hypothesis can be formed. Appendix 5, show the development of S12. It shows downbuilding progradation. It should be noted that S11 and S12 have contact with horizon 12. This is why these two grid maps show uncertainty.

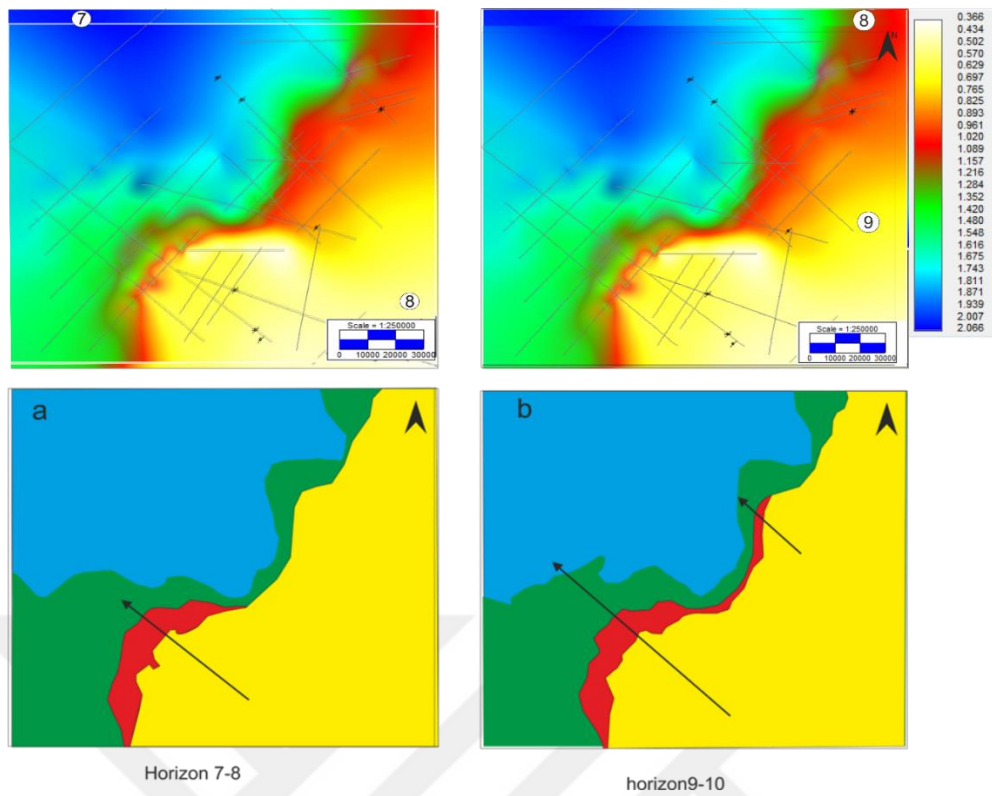


Figure 36: Development of basin ((a: Horizon 7-8(S7), b: Horizon9-10(S9)) the red area shows to space between two horizon, arrow show direction of progradation.

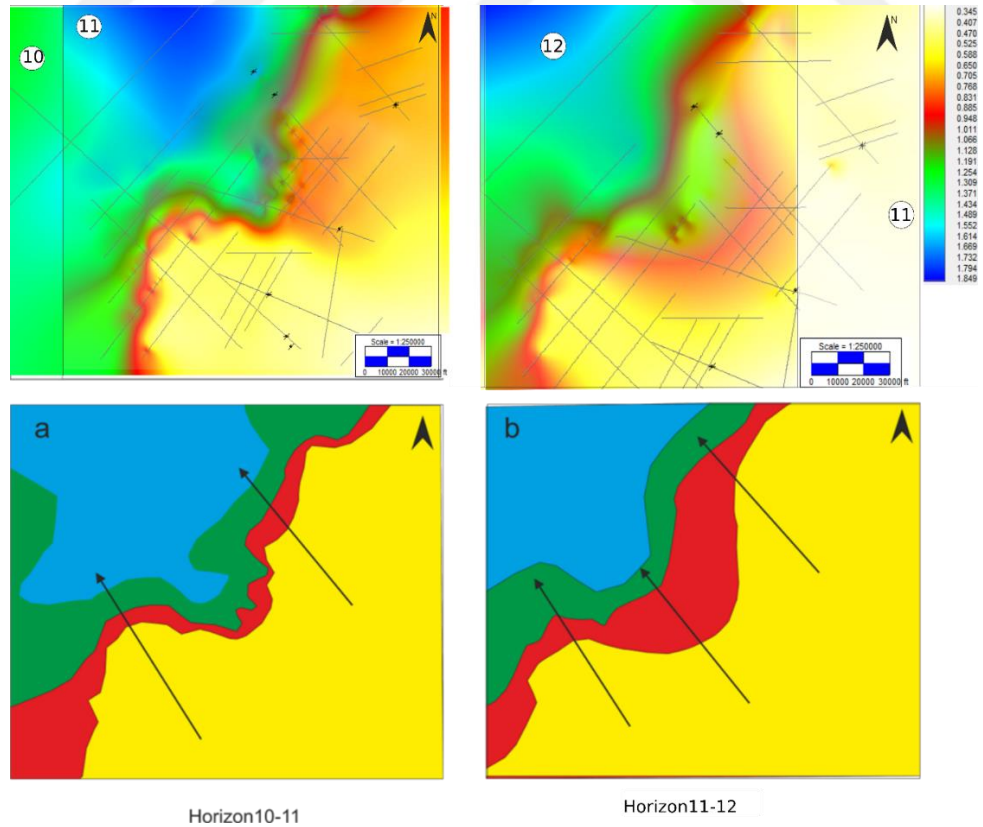


Figure 37: Development of basin (a: Horizon 10-11(S10), b: Horizon11-12(S11)) the red area shows to space between two horizon, arrow show direction of progradation.

5. Discussion

5.1. The introduction

The aim of this section is to interpret the results and compare them with other studies. One of the main and important objectives of the study is to determine reservoirs in the study area. Sequence stratigraphy concept and trajectory analysis have an essential place in the study of determining the presence and distribution of reservoirs.

5.2. Reservoir Distribution

Climoform was first described in 1951 by John Rich. According to Rich (1951), clinoforms are basin margin strata with a sigmoid geometry. The upper part of these structures is called topset and they point to shallow marine regions. The lower part of this structure is called the bottomset and points to deep marine regions. The results of the analysis performed on the clinoforms shown in the previous section are given below as a summary in Table 4. According to Johannessen and Steel (2005), the rise in sea level in systems characterized by high sediment supply causes muddy slope formation in the bottomset of the clinoforms. The aggrading coastal and shelf regions of such systems have a large part of the sediment budget. A: S ratio is high in the topset. Catuneanu (2006) defined such systems as Highstand tract and stated that the most important reservoirs in this system would be shoreline and shoreface. He also stated that these reservoirs had high sand \ mud ratio and showed good lateral continuity. Reservoir formations may also be observed in HST-related fluvial systems, but the reservoir quality is defined as moderate. Catuneanu (2006) stated that the most important of the HST reservoirs will occur in the proximal parts. S7 has reservoir of HST (Figure 38). Probable reservoirs of other seismic lines are given in appendix 6, 7, 8, 9.

According to Steel and Olsen (2002), flat or slightly downward trajectories are the markers of sea level falling and precipitation is observed in deep water environment. They also reported that fluvial channel structures could be observed. In this study, channel structures are seen in Figure 27 and 29 during the deposition of sub-sequence8 and sub-sequence12. Catuneanu (2006) described these systems as Falling Stage systems tracts and evaluated the reservoir potential of these systems in two different aspects: early FSST and late FSST. Early FSST is represented by the first stages of falling base level. This stage shows

progradation and offlap fluvial erosion or sediment bypass. According to Catuneanu (2006), reservoirs in this phase are observed in offlapping, shoreline and downstepping regions in shoreface. In Early FSST, the likelihood of a fluvial reservoir is very low because the non-marine part of the basin is exposed to sediment by-pass.

Late FSST is represented by the late stages of the falling base level. In the late FSST phase, sand bodies that occur in the early FSST lose their shape. Lack of accommodation space in fluvial and shoreline systems causes turbidites in deep water environment. Turbidites occurring at this stage are the best reservoirs related to deep water submarine fans in Late FSST. These turbidites formations have high sand / mud and sediment / water ratio. The reason for this is that they contain terrestrial sediment (Catuneanu, 2006). Sub-sequence-8 and sub-sequence-12 have reservoirs of this systems tract (Figure 38).

Bullimore et al. (2005) described the characteristics of low angle positive shelf edge trajectory and stated that they were positioned higher than the previous clinoform systems that preceded them and they were oriented towards more basinward. Bullimore et al. (2005) also emphasized that such systems would point to the early stages of sea level rise and deltaic units. In these systems, especially in the topset parts, A: S ratio is low. According to Catuneanu (2006), reservoirs of Early TST systems may be related to continental shelf based transgressive wedges or deep water wedges. The best reservoirs related to the Continental shelf; estuary-mouth complexes, backstepping beaches, prograding delta or even retrograding bayhead deltas. Wave energy is one of the biggest obstacles in the formation of coastal reservoirs and this reduces the likelihood of detecting possible reservoirs in landward to shoreline. S3, S4, S5, S9, S10, S11 have the reservoir potential of this systems tract. In 2D seismic lines, no reservoir of early TST was found.

Lowstand systems tract and Late stage Transgressive systems tract were not observed on the seismic lines, so no associated reservoir formation was observed. Sequence stratigraphy is very important in determining budget and petroleum plays. The results obtained after these analyzes are outlined in the Table 4. However, in general, it can be stated that the probable reservoirs in the study area develop mostly in the early TST zones but the best quality probable reservoirs in the region develop in the HST zones.

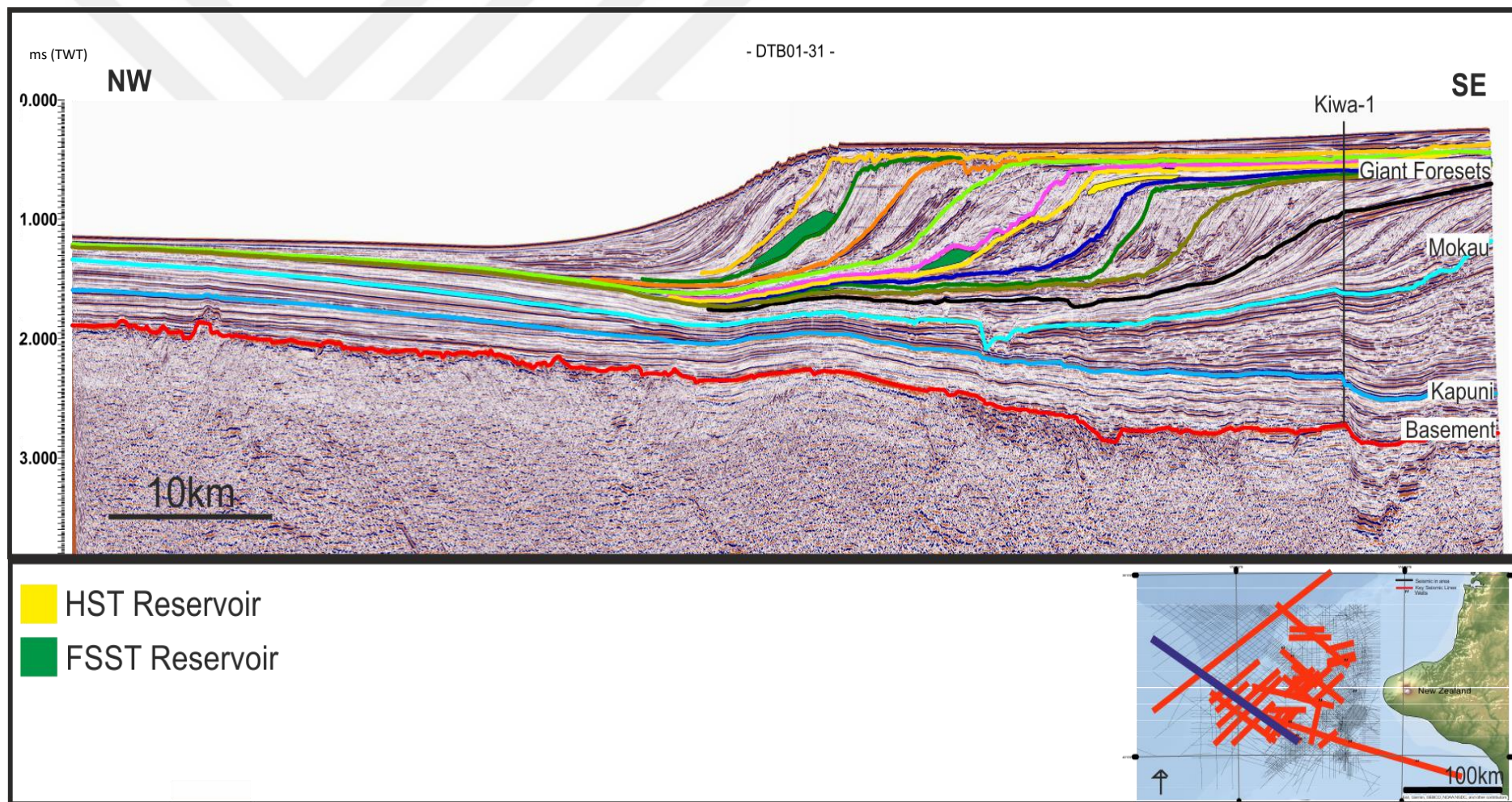


Figure 38: Section illustrating the occurrence of a probable reservoir related to FSST and HSST (DTB01-31)

	TRAJECTORIES		SYSTEMS	UPBUILDING/ DOWNBUILDING PROGRADATION	CONFIGURATION	RESERVOIR
	Hellan-Hensen and Martinsen(1996)	Bullimore et al., (2005)	TRACT			Catuneanu (2006)
S1					PARALLEL	
S2					PARALLEL	
S3			EARLY TST	ERODED	OBLIQUE	EUSTUARY MOUNT, COMPLEXES, BACKSTEPPING BEACHES, PROGRADING DELTA OR EVEN RETROGRADING BAYHEAD DELTAS SHOW GOOD QUALITY
S4	LOW ANGLE ASCENDING REGRESSIVE	LOW ANGLE POSITIVE TRAJECTORY		DOWNBUILDING PROGRADATION	COMPLEX SIGMOID- OBLIQUE	
S5				DOWNBUILDING PROGRADATION	COMPLEX SIGMOID- OBLIQUE	
S6	STATIONARY			DOWNBUILDING PROGRADATION	COMPLEX SIGMOID- OBLIQUE	
S7	HIGH ANGLE ASCENDING REGRESSIVE	HIGH ANGLE POSITIVE TRAJECTORY	HST	UPBUILDING PROGRADATION	SIGMOID	SHORELINE SHORFACE GOOD RESERVOIR QUALITY, MODERTE IN FLUVIAL SYSTEMS
S8	DESCENDING REGRESSIVE	LOW ANGLE NEGATIVE TRAJECTORY	FSST	DOWNBUILDING PROGRADATION	OBLIQUE	SHORELINE AND SHOREFACE DOWN STEPPING AREAS(EARLY FSST), DEEP WATER SUBMARINE FANS(LATE FSST)
S9	LOW ANGLE ASCENDING REGRESSIVE	LOW ANGLE POSITIVE TRAJECTORY	EARLY TST	UPBUILDING PROGRADATION	SIGMOID	EUSTUARY MOUNT, COMPLEXES, BACKSTEPPING BEACHES, PROGRADING DELTA OR EVEN RETROGRADING BAYHEAD DELTAS SHOW GOOD QUALITY
S10				UPBUILDING PROGRADATION	SIGMOID	
S11				UPBUILDING PROGRADATION	OBLIQUE	
S12	DESCENDING REGRESSIVE	LOW ANGLE NEGATIVE TRAJECTORY	FSST	DOWNBUILDING PROGRADATION	SIGMOID	SHORELINE AND SHOREFACE DOWN STEPPING AREAS(EARLY FSST), DEEP WATER SUBMARINE FANS(LATE FSST)

Table 4: The analysis summary of sub-sequences

5.3. Comparison With Other Papers

Salazar et al. (2016) divided the development of the Taranaki basin into 3 different phases using shelf edge trajectory and geomorphological pattern and observed 9 different sub-sequences (Figure 39). During Stage 1 (Early Pliocene), he discovered that the shelf edge was stable. He also pointed to the increase of rollover points at a low angle during this phase. Stage 2 (Early-Late Pliocene), on the other hand, mentioned that clinoforms show concave geometry and in addition, relative sea level fall at this stage. Specifically, in this zone, the canyon incision and sediment bypass along the basin indicated. Stage 3 (Late Pliocene-Recent) clinoforms usually show sigmoid configuration and observed a higher architecture. At this stage, increased sediment supply and accommodation space was observed.

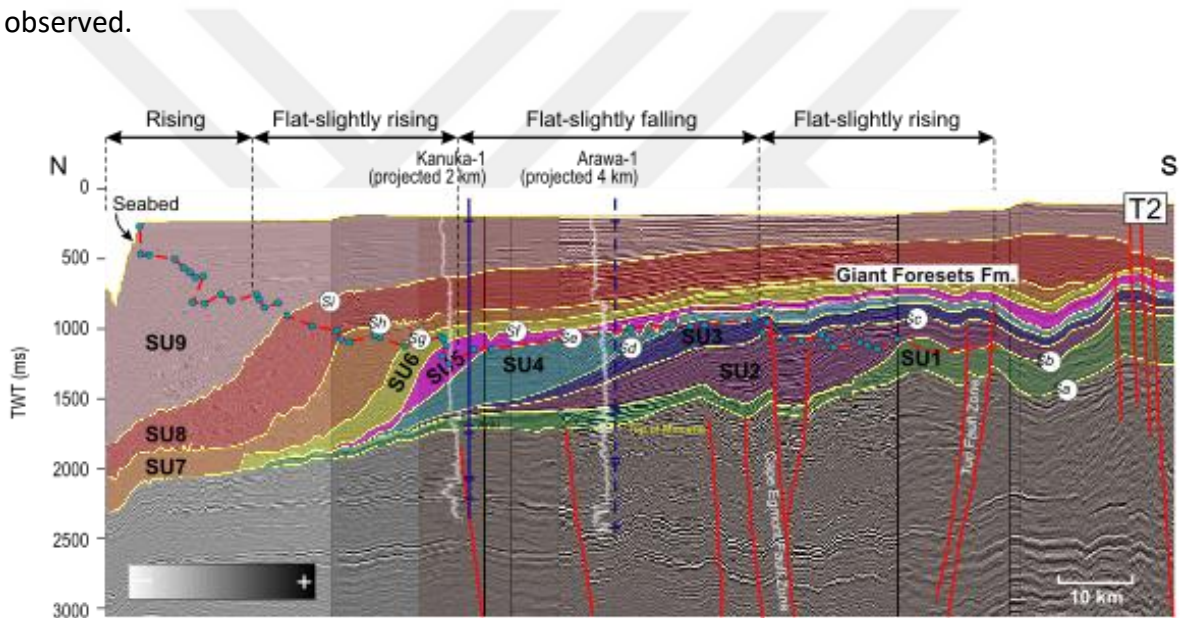


Figure 39: According to Salazar et al (2006) interpretation of evolution of clinoform units in Taranaki Basin

Franzel and Back (2019) examined the Taranaki Basin from four different angles, namely, clinoform, downbuilding and upbuilding progradation, retrogradation and eroded clinoforms. During their study, they observed 9 different sub-sequences with the base (Figure 40). They emphasized that downbuilding progradation is related to falling in base level and upbuilding progradation is related to high sediment supply and sea level rise.

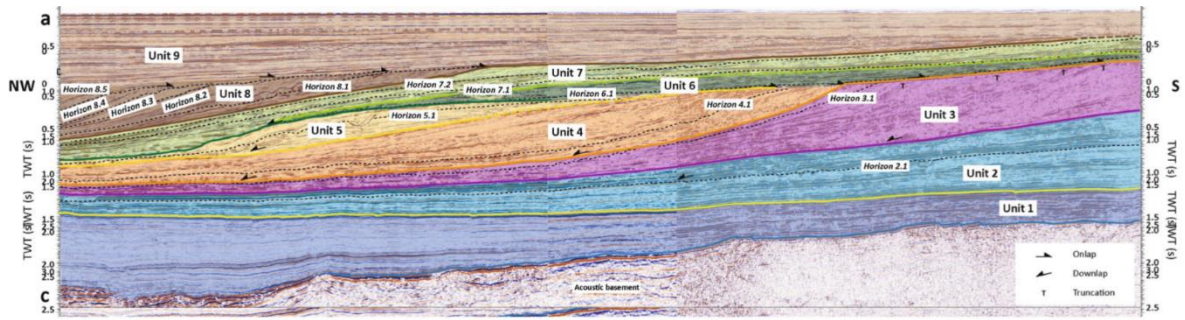


Figure 40: According to Franzel and Back (2019) interpretation of evolution of clinoform units in Taranaki Basin

When comparing the two studies above, 12 different sub-sequences with base were observed in this study (Figure 41). In this study, the classification made by Franzel and Back (2019) was used. In this study, S3-S7 stage 1, S8 stage 2, S9-S11 stage 3 and S12 stage 4 can be classified according to changes in sea level and systems tracts. Sea level increased during stage 1 and slightly decreased in stage 2. In Stage 3, rising at sea level was observed more than Stage 1. In Stage 4, there is a falling again at sea level. It also makes sense to discuss the horizon 12 under this title. Topset preserved well during the Stage 3 as comparison the other stages. The Foresets southern regions are thicker in the Northern region and thinner in the Northern region. This may possibly indicate a change in sediment supply and system. Failure to identify horizon 12 may be related to erosional scours or Mass Transport Deposits. This is the reason why this horizon is not easily identified.

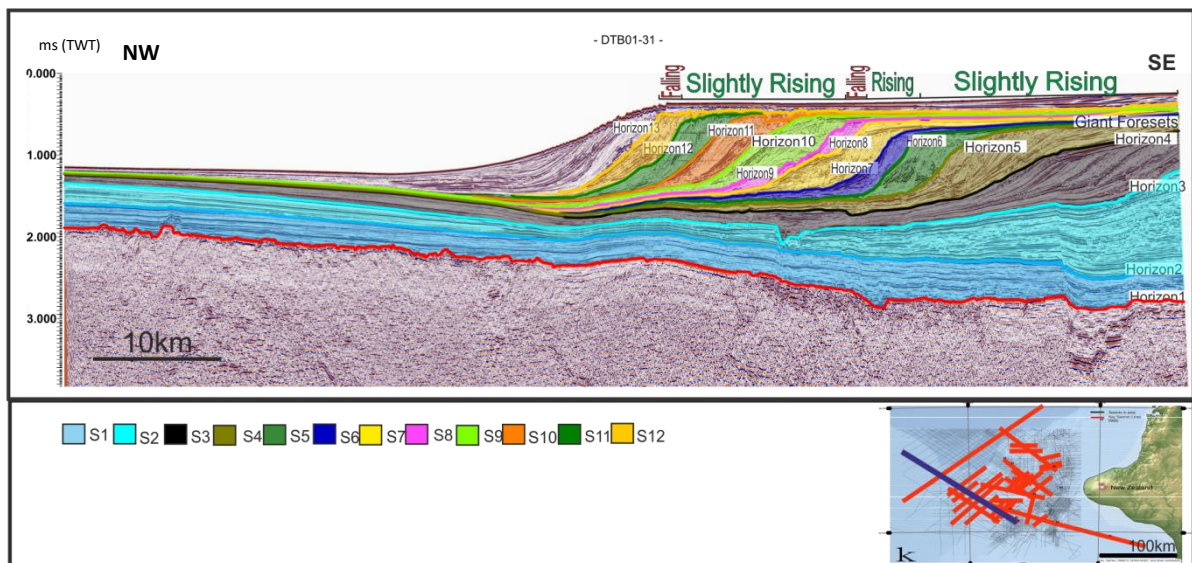


Figure 41: Section showing Sea Level Changes in DTB01-31

5.4. Global Sea Level Curve Comparison with Taranaki Basin Sea Level Changes

Sea level falling in S4-S5 range followed by increase in sea level is related to early TST. There was no change in the sea level during S6, which proves that the S6 point assigned as stationary in the trajectory analysis section is correct. The observed decrease in sea level during sub-sequence-8 following sub-sequence-7 is associated with the FSST. Increased sea level during S9, S10 and S11 may be associated with early TST. We can associate the falling sea level with FSST during S12 storage. In the Table 5 below, the relative sea level rise scenarios taken from Catuneanu (2002) were compared with the sub-sequences detected in this study.

The well data on the seismic lines interpreted during this study give us only a limited age range (Early Miocene-Plio-Pleistocene). Franzel and Back (2019) compared the sub-sequences they found with the Cape Egmont Fault development. They then correlated each sub-sequence with specific events that occurred during the development of Cape Egmont Fault. The same application can be used during this study to get more detailed information about the age of the sub-sequences, but first of all we need to know the history of development of Cape Egmont Fault (Figure 42).

The Cape Egmont Fault zone is very close to the study area and is therefore thought to have affected the study area. This zone has been activated several times. In the area where this zone intersects with the age range of the study area, reverse displacement is between 11-5.5 ma, inactive between 5.5-3.7 ma and the last reactivation observed is normal fault in the 3.7ma-Recent range (King and Trasher, 1996; Reilly et al. 2016; Franzel and Back, 2019).

As already mentioned, downbuilding progradation develops in relation to base level fall. The development of S12 and S8 with downbuilding progradation may be affected by tectonic or eustatic conditions. The basinward progradation of the clinoforms of S12 and S8, together with the base level falling, may be related to the uplift or global sea level falling or it can be related with both factor. in the proximal zone. Naish and Camp (1997) reported high frequency eustatic changes during the Pliocene period and reported that the overall trend was decreasing sea level. From Figure 42, we can say that S12 is Pliocene aged. Although S8 shows FSST, we can associate the progradation with the tectonic uplift

observed in the grid map in the appendix 4. According to Strogon (2011), the Taranaki basin was exposed to the uplift associated with back-arc basin collision during Late Miocene. For this reason, S8 Late Miocene may be considered older. The age of these sub-sequences may range from 5.5 to 3.7 Ma, where the Cape Egmont Fault is inactive. Franzel and Back (2019) reported that sea level was stable during Late Miocene. Here we can say that S2-S3-S4-S5-S6 and S7 are late Miocene aged.

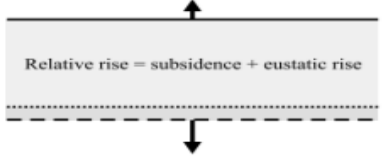
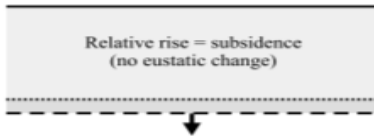
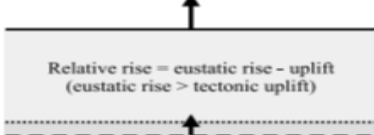
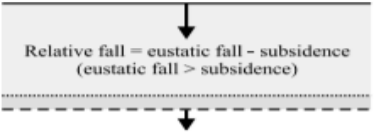
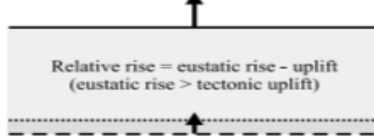
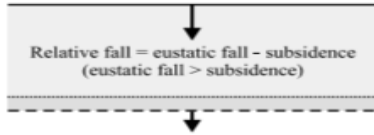
S4-S5 sea level sea floor datum water sediments	
S6	
S7	
S8	
S9-S10-S11	
S12	

Table 5: Possible scenerios for each Sub-Sequences (Scenerios adapted from Catuneanu, 2002)

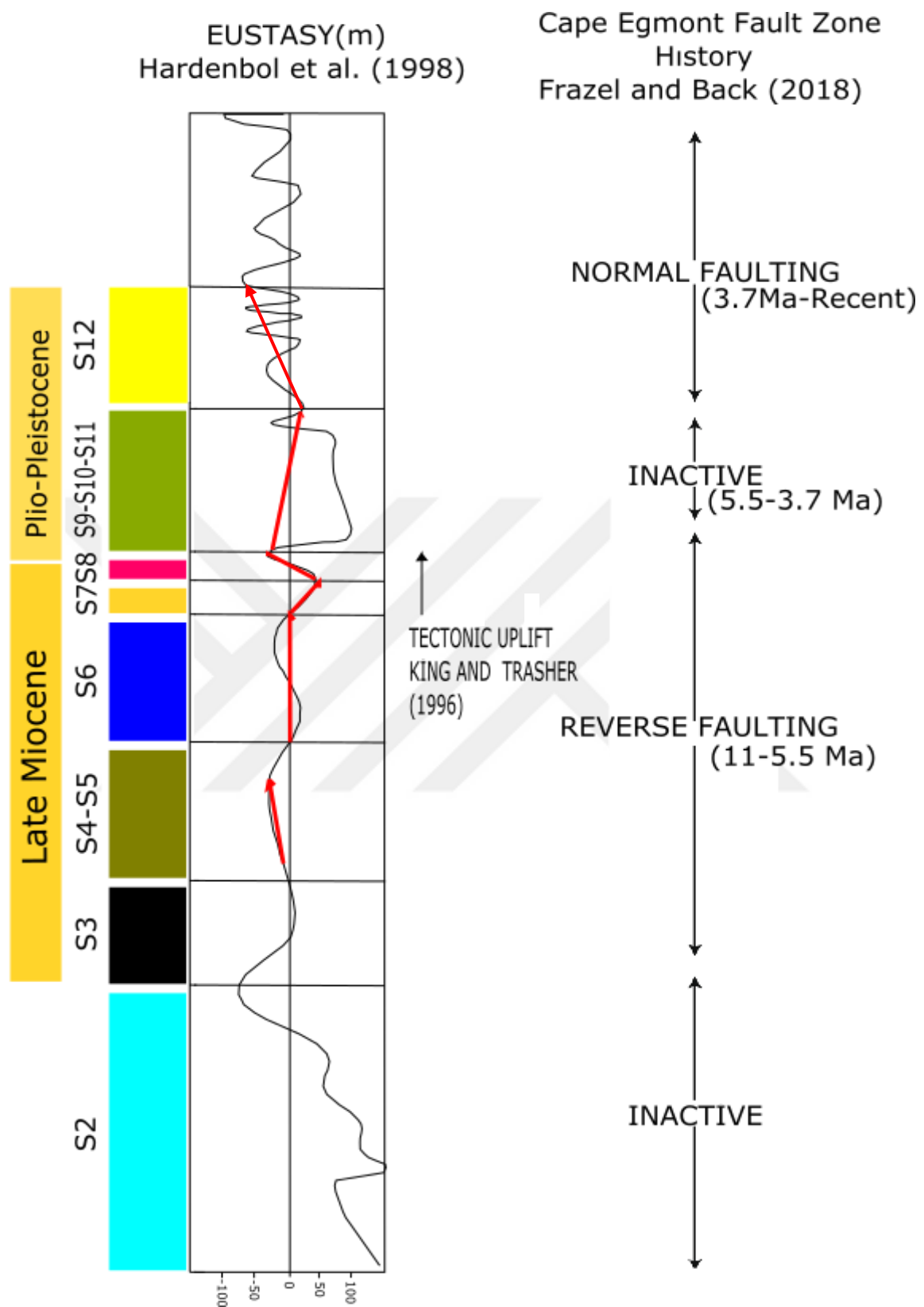


Figure 42: Global Sea Level Comparison with Relative Sea Level Change in the Taranaki Basin
(modified from Franzel and Back, 2019)

6. Conclusions

- Twelve different sub-sequences were found after stratal terminations. Sub-sequence 1 is associated with the basement. Time interval of study has not include Sub-sequence 1. Sea level changes define with using Trajectory analysis. Four different stages were determined according to sea level changes. S3-S7 stage 1, S8 stage2, S9-S10-S11 Stage 3 and S12 stage 4 were determined. Stage 1 and Stage 3 have a slightly rising Sea level. Stage 2 and Stage 4 show sea level falling. Topset preserved well during the stage 3 as comparison the other stages.
- Stage 1 and 3 can be associated with normal regression and Stage 2 and 4 can be associated with forced regression. It is evidence of erosion and oblique pattern forced regression observed in sub-sequence 8 and sub-sequence 12. Horizon 9 and Horizon 13 were identified as maximum regressive surface.
- Early TST has been observed until deposition of sub-sequence 7 has started. HST is dominant with the development of sub-sequence 7. FSST develops during sub-sequence 8 and Early TST occurs during S9-S10-S11.
- Configuration (oblique, sigmoid etc.) patterns of the identified sub-sequences, grid maps, and during the development of Sub sequence 10 (Stage3), show different developments in the southern and Northern part of the study area. Forsets are thicker in the Northern area and it is thinner in the southern area. This may indicate a change in sediment supply or system. In addition, the fact that horizon 12 appears only in the southern area can be associated with this.
- Trajectories show a trend in the region as low angle ascending regressive, stationary, high angle ascending regressive and descending regressive.
- Horizon 2 is the top part of the Kapuni group (Paleocene-Eocene). Horizon 3 is the top part of the Mokau (Early Miocene) group. It was previously said that the region was under water during the Oligocene period. For this reason, the first terrestrial sediments entered the region between horizon 2 and 3.

- Well data is not sufficient to provide information about the age of each clinoform due to a lack of biostratigraphic information. Naish and Camp (1997) stated that during the Pliocene period the sea level had a high frequency and showed a generally decreasing trend. Therefore, based on the sea level curves and available data, the best interpretation is that sub-sequence 12 is Pliocene aged. In addition, Franzel and Back (2018) reported that sea level was stable during Late Miocene. That is why S2-S3-S4-S5-S6 and S7 are Late Miocene aged as they show similar patterns.
- In the basin, sub-sequence 7 contains HST reservoirs. The best reservoirs of this Systems tract are located in the shore and shoreface section. sub-sequence 12 and sub-sequence 8 are likely to show reservoirs of the FSST systems tract and are usually related to deep water submarine fans. S3-S4-S5-S9-S10 and S11 show reservoirs of the early TST systems tract. Possible reservoirs are in the early TST phase developed in debris flow and back stepping beaches, estuarine deltas and low density turbidity flows. The problem related with early TST is that they cannot preserve reservoir due to the high energy. Early TST reservoirs could not define in 2D seismic survey in this study.

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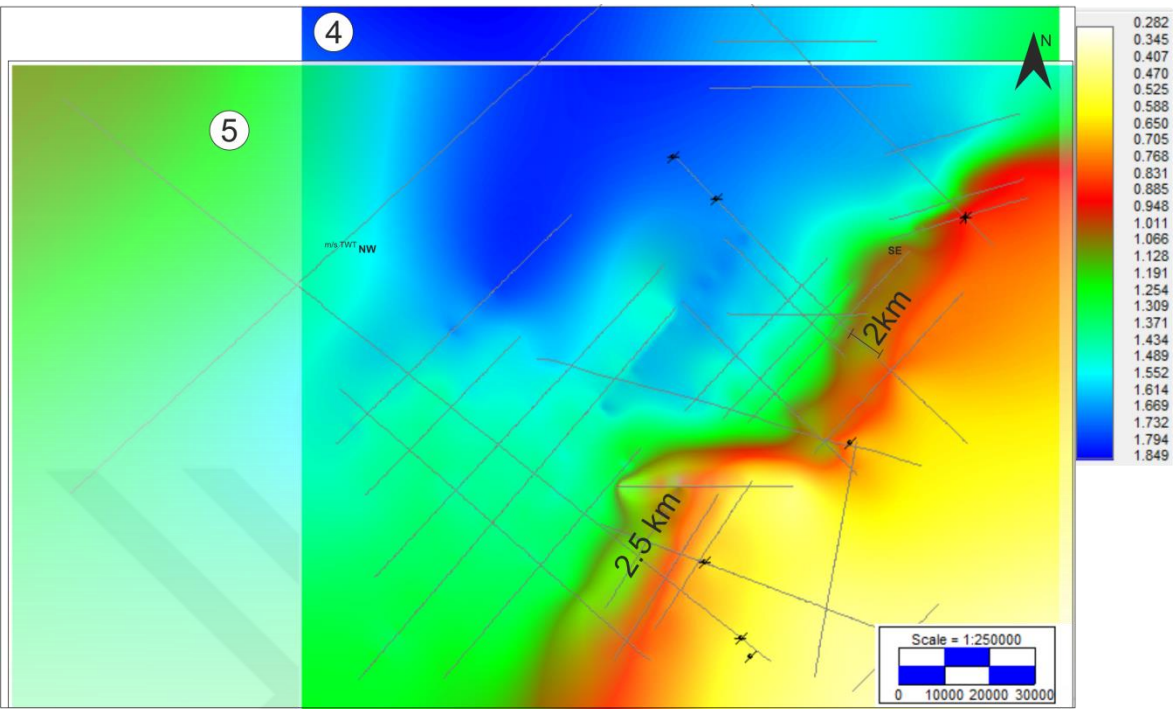
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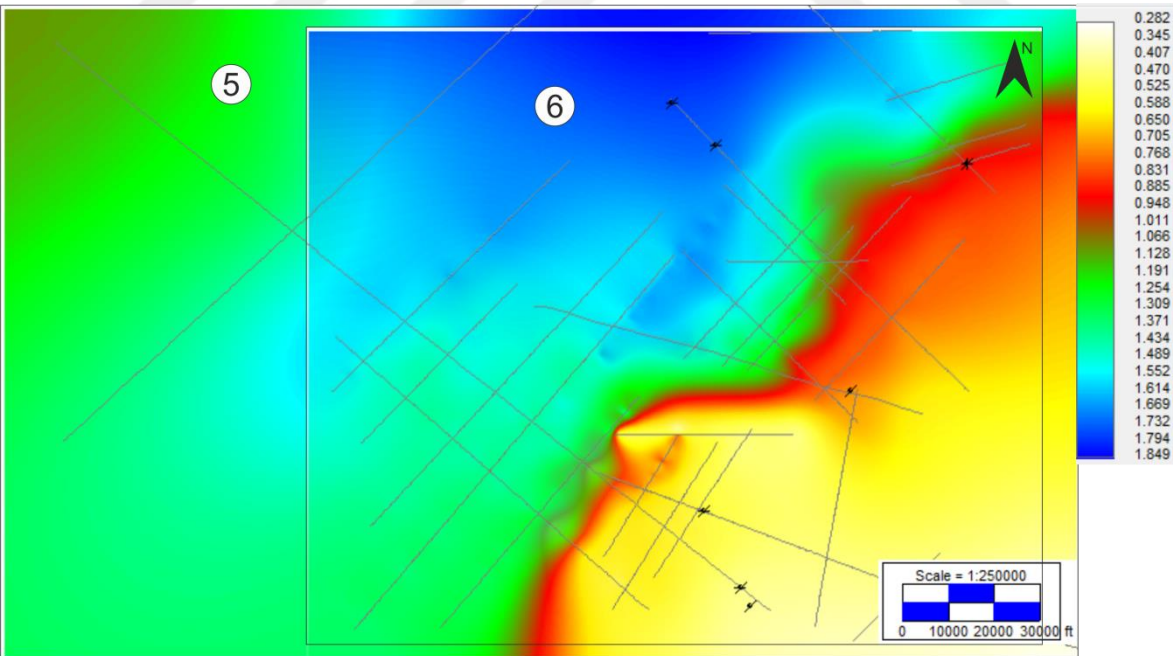
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8. Appendix

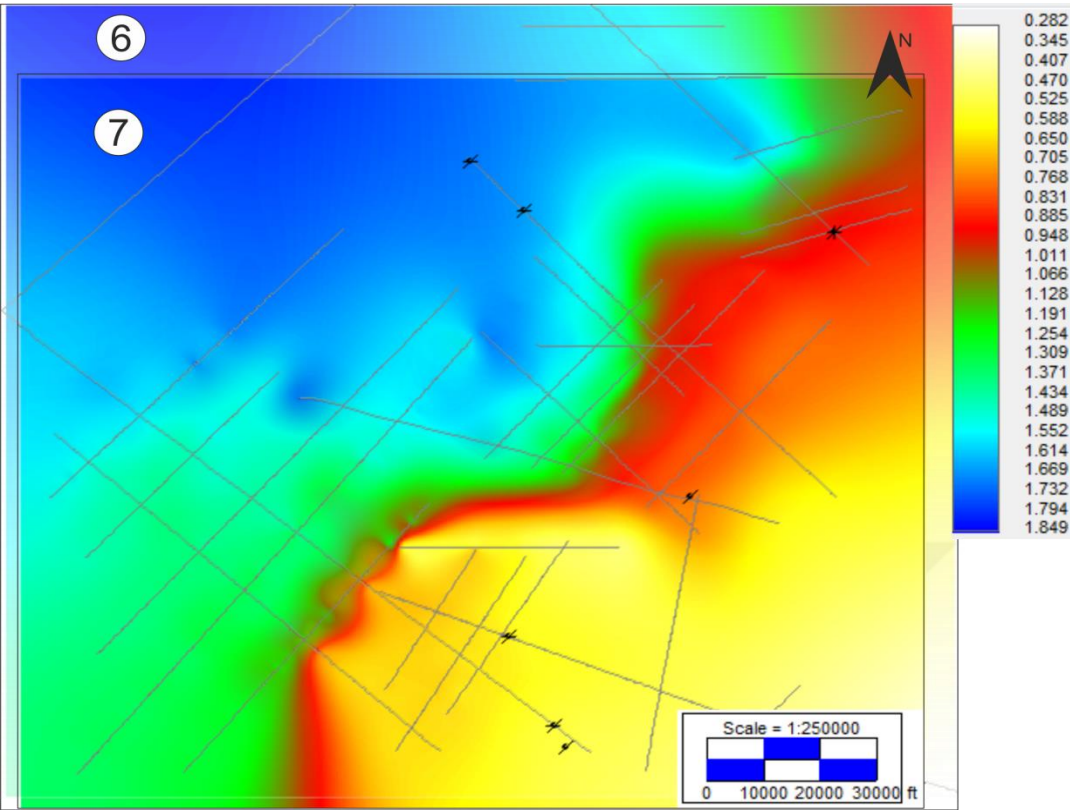
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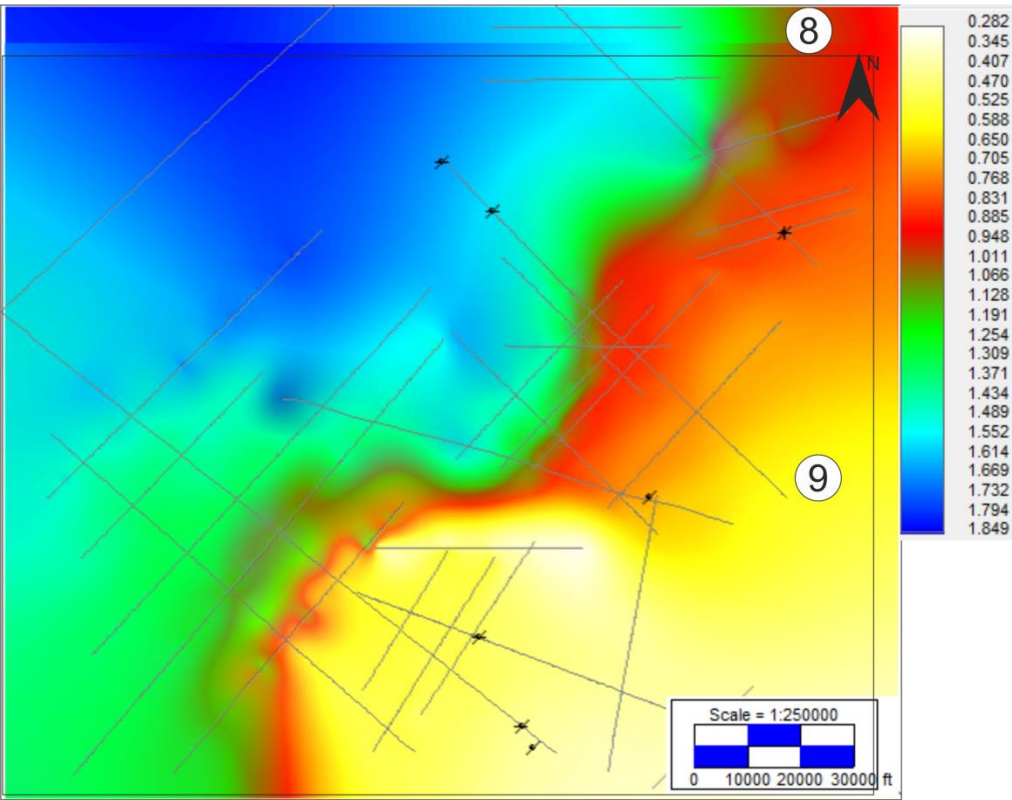
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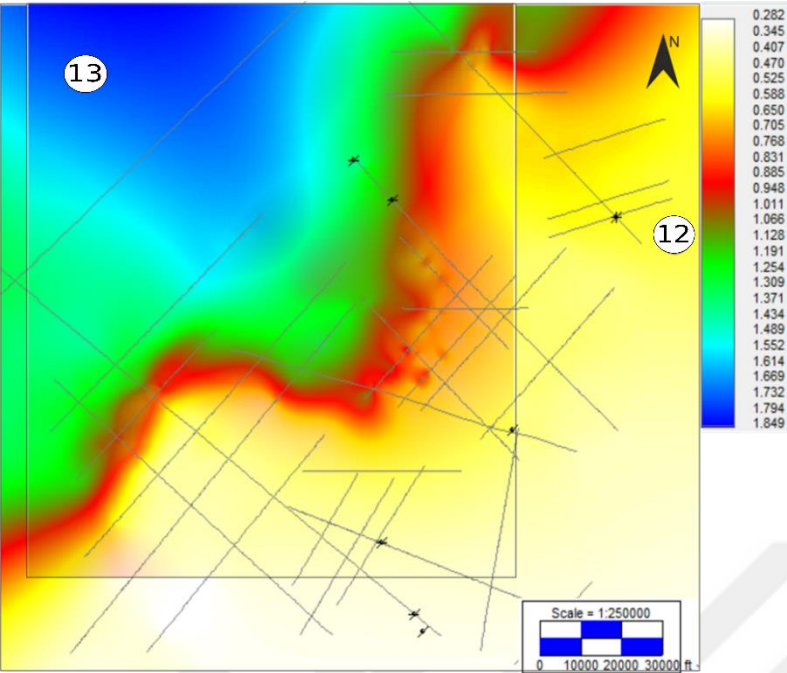
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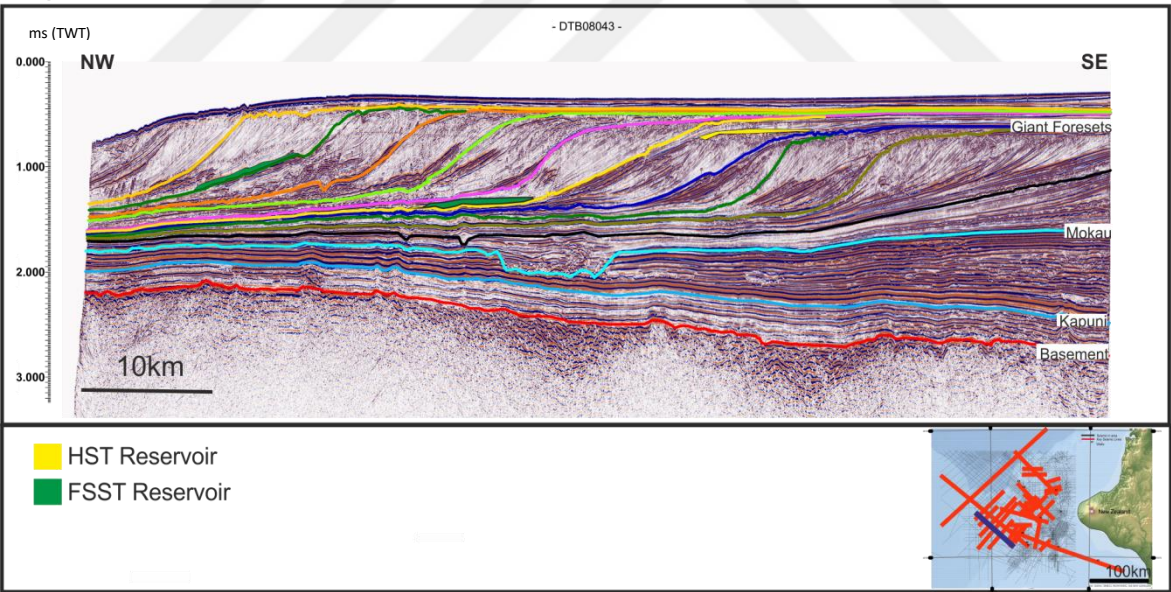
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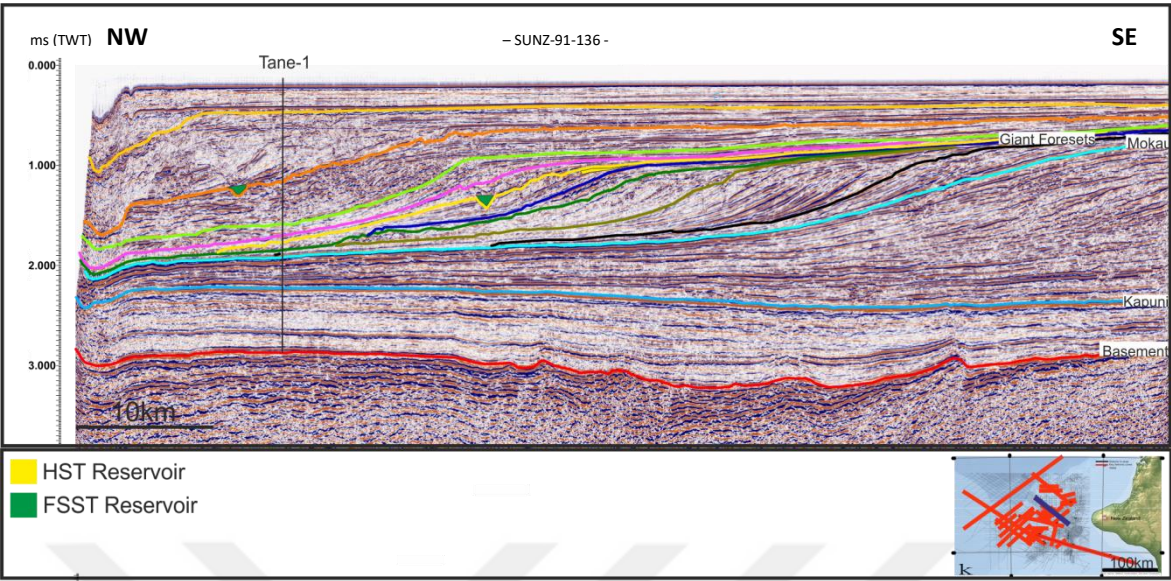
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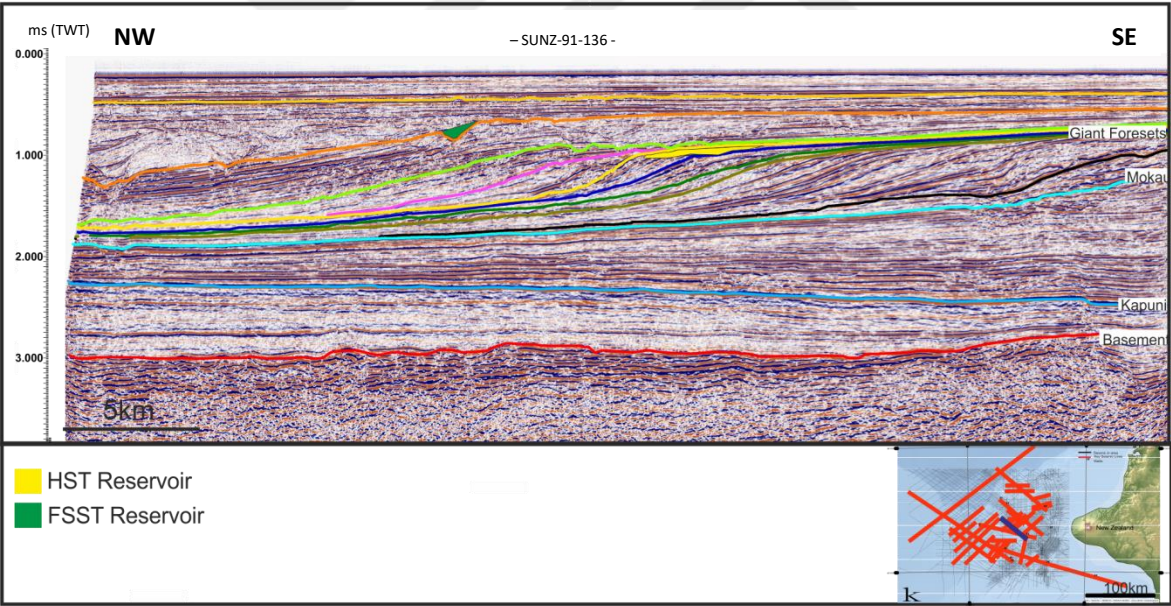
Appendix 6: Probable reservoir highlights DTB08043



Appendix 7: Probable reservoir highlights SUNZ-91-136



Appendix 8: Probable reservoir highlights SUNZ-91-143



Appendix9: Probable reservoir highlights TIK09-08

