CHAPTER 1

Introduction

1.1 Introduction

The Giant Foresets Formation (GFF) is a thick progradational sequence formed during the latest Miocene to Pleistocene, overlying the continental margin of the northern Taranaki Basin, along the western margin of North Island, New Zealand (Fig. 1.1). The characteristics of the GFF are primarily recognized from the seismic data by its large-relief and basinward prograding clinoforms (Hansen and Kamp, 2002). Studying of the stratigraphic framework of the progradational GFF offers an opportunity to understand the relationship of the progradational facies to various factors such as the basin structure, sedimentation rate, subsidence and eustatic sea level change. Application of sequence stratigraphic principles to study the GFF in the shelf-slope-basin succession provides insight into their depositional history, areal extent, palaeogeography and genetic relationships. The evolution of the GFF has been studied based on 2D seismic data (Hansen and Kamp, 2002; 2004; 2006). Therefore, the interpretations in the current study were limited to medium to large scale features viewed in 2D sections. Consequently, there is a scope for exploring spatial distribution of depositional facies, other geologic features if present and interpret finer scale characteristics associated with the GFF.

Recent research (Morley and Naghadeh, 2016) documented early stage development of isolated listric normal faults that formed at the base of the GFF, not within the deltaic prograding sediment. The growth faults formed during Pliocene shelf edge clinoform progradation, and fault initiation near the base of the slope was inferred to be transient caused by an increased in pore fluid pressure due to lateral expulsion of fluids from beneath the prograding GFF. In their study, two growth faults, Karewa and Mangaa, show no evidence of mobile shale being present, and there is no obvious loading trigger for the faulting or significant slope or asymmetric uplift that would have gravity sliding. Within the growth faults section, the chaotic reflections are present in the hanging wall area and interpreted to represent mass transport complexes (MTC).It is uncertain whether fault displacement created a depression for MTC fill, or whether loading by the MTC helps trigger fault movement. Thus, understanding the depositional history as well as the timing by which the GFF prograded relative to the underlying structures such as the growth faults and mass transport complex (MTC) may provide valuable information on the kinematics of these compressional structures. This study aims to analyze the high resolution depositional features within the GFF by means of mapping, using both 2D and 3D data, available in the study area (Fig. 1.2B). Integration of a sequence stratigraphic model-based on high quality seismic data provides an opportunity to understand the depositional development, especially the timing when the movement on gravity-driven normal faults was triggered, thus understand better the causes of growth fault initiation.

The scope of this study is to construct a stratigraphic framework of the Pliocene-Pleistocene prograding facies (the Giant Foresets Formation) of the northern Taranaki Basin and establish its relationships to base-level changes and sediment supply, as well as the timing of the growth fault initiation. The stratigraphic framework includes identification of stratal termination and stacking pattern, seismic facies analysis and subdivision of genetic units, which help in the interpretation of the depositional settings, sequence boundaries and depositional trends. Some key stratigraphic features can also be highlighted by attribute extraction. Key objectives for this research include:

- Mapping selected horizons in the Pliocene-Pleistocene prograding facies from 3D seismic data (Karewa) and correlating with 2D seismic lines and well data.
- Interpretation of higher order sequences (3^{rd} or higher) and subdivision of genetic units (i.e. systems tracts) in the GFF section.
- Fitting a sequence stratigraphic model in order to correlate depositional trends associated with subsidence and sea-level changes.
- Understanding of the timing of the GFF and syn-kinematic fills (mass transport complex) relates to the underlying fault structures.

- Identification of geologic features (i.e. mass transport deposit, channels, submarine fans) using attribute extraction.
- Develope a chronostratigraphic chart (Wheeler diagram) of the GFF section.
- Determine which stage or stages of the GFF triggered growth fault formation. Is there any identifiable sedimentary event that initiated growth fault movement?

1.2 Geologic setting

The Taranaki Basin is a Late Mesozoic extensional basin, covering a total area of 330,000 km^2. The basin is bounded by the Taranaki Fault on the eastern side, which marks a convergent boundary between the Australian and Pacific plates (King & Thrasher, 1992). The structural development of the Taranaki Basin has been reviewed by King and Thrasher (1996). It is broadly subdivided into two distinct tectonic regions: the Eastern Mobile Belt and the Western Stable Platform. The tectonically active Eastern Mobile Belt, including the Northern Graben which underwent overthrusting, folding and uplifting. Conversely, the Western Platform of the Taranaki Basin is considered as a relatively stable and structurally simple region.

Extension in the Taranaki Basin during the Late Cretaceous is associated with spreading of the Tasman Sea. During the Latest Cretaceous to Early Oligocene, the basin accumulated sediments in a type of passive margin setting under a regional transgression, where subsidence rate outpaced sedimentation rate. From the Middle to Late Oligocene the eastern part of the basin started to rapidly subside, due to convergence of the Australian and the Pacific plates. During the Late Oligocene to Early Miocene, the basin involved overthrusting of the basement on the Taranaki fault. By the Middle Miocene, compression within the northern part of the basin and along its eastern margin was diminished. This is followed by the onset of volcanism within the northern part of the basin. The volcanic arc was parallel to the trend of the convergent zone and continued activity until about 7-8 Ma. The volcanic arc remained as a topographic high and influenced the sediment pattern until the late Pliocene (King and Thrasher, 1996). During the Pliocene the volcanic arc migrated southeastward onshore. The northern parts of Taranaki Basin experienced back-arc extension and formed large depocenters such as the Northern and Central Graben, which were filled by progradational sequences (Hansen and Kamp, 2004).

The study area is located along the northern margin the Northern Graben (Fig. 1.2), which is a wide depocenter bounded by the Cape Egmont and the Turi fault zones , that constitute its western and eastern boundaries (Fig.1.2A). In general, the Taranaki Basin later stage of the basin development occurred in a foreland basin setting, overprinted associated with volcanic activity related to convergence of the Pacific and the Australian plates (King & Thrasher, 1996). However, the northern part of the basin was subjected to distinct tectonism compared to other parts of the basin. The Northern Graben has undergone back-arc rifting from the Miocene to Recent (King and Thrasher, 1996; Giba et al., 2010). Concurrently, the eastern side of the Northern Graben (Turi Fault Zone) was accompanied by fault block tilting due to the extension and forming the Manganui Platform (King and Thrasher, 1996). Due to the down-faulting and rapid progradation in this structure, the Northern Graben was filled with syn-sedimentary units and then overstepped by the Giant Foresets Formation (Hansen and Kamp, 2006).

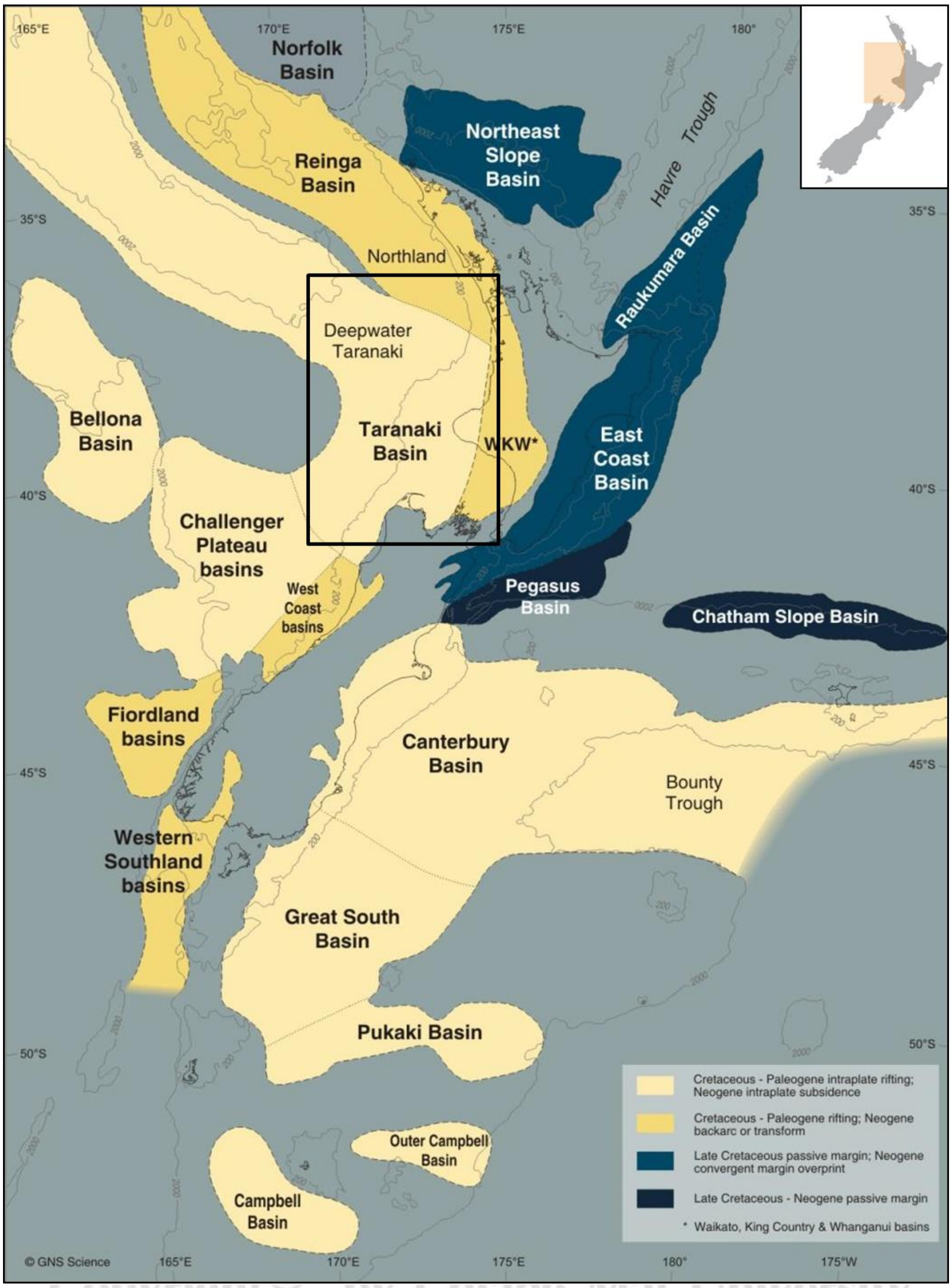

Figure 1.1: Distribution of the sedimentary basins in New Zealand, and the location of the study area (black rectangle) in the Taranaki Basin (GNS Science, 2013).

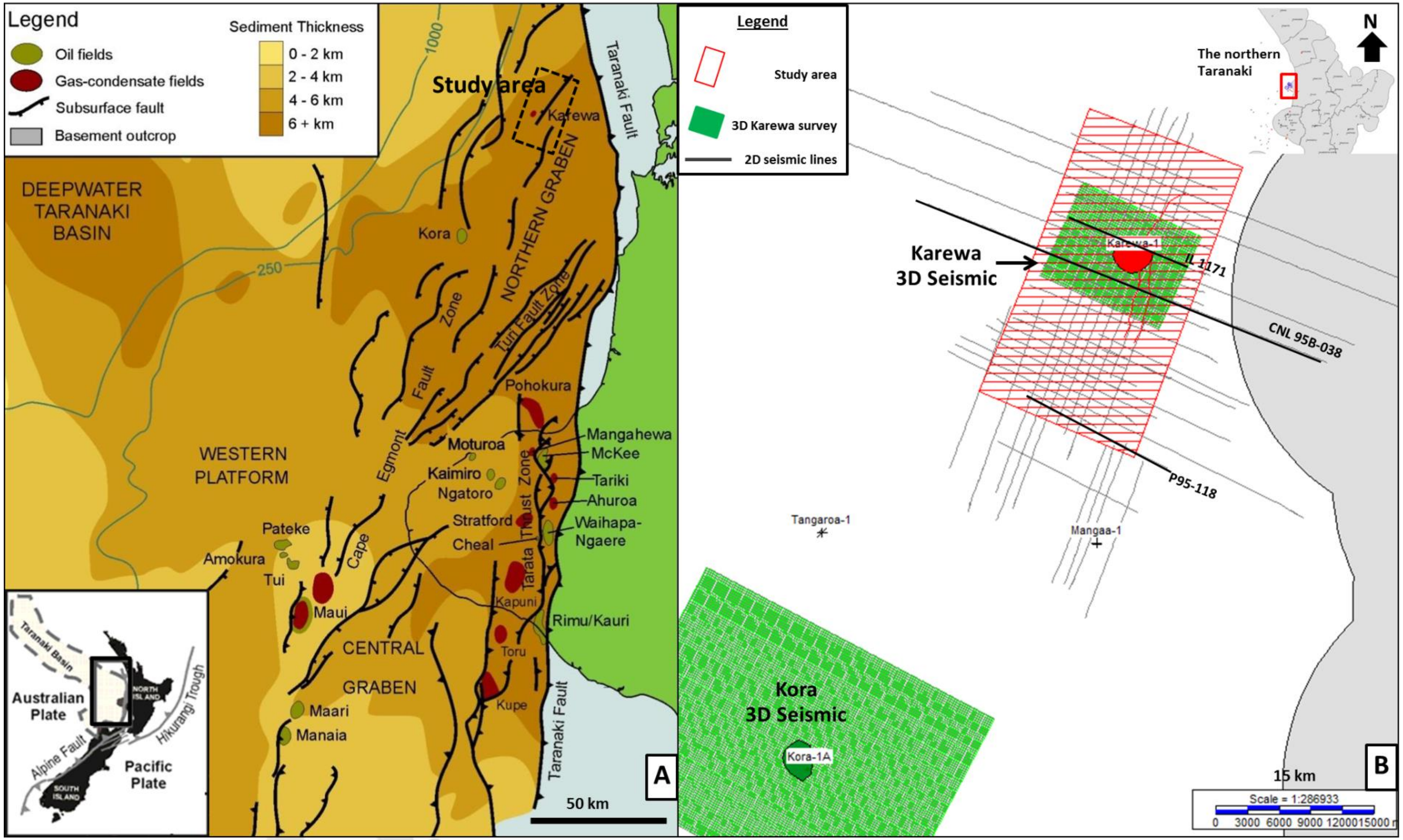

Figure 1.2: (A) General structural geology of the study area in the Northern Taranaki Basin, New Zealand (Modified from New Zealand Petroleum and Minerals, 2013); (B) The study

1.3 Stratigraphy of the Northern Taranaki Basin

The sedimentary section within the Taranaki Basin can be divided into four units affected by four distinct tectonic regimes (Fig. 1.3). These are broadly (Aaron, 2014):

1. Late Cretaceous to Early Paleogene syn-rift sequence.
2. Paleocene-Eocene late-rift and post-rift transgressive sequence.
3. Oligocene-Miocene foredeep and distal sediment starved shelf and slope sequence and Miocene regressive sequence.
4. Pliocene-Pleistocene regressive sequence (the Giant Foresets Formation)

The basement and the earliest basin-fill are believed to have formed during the Jurassic to Early Cretaceous (NZPAM, 2013). Rifting during the Late Cretaceous and Early Paleogene produced localized faulting and subsidence within the Taranaki Basin. During this age, the basin was dominated by fluvial to deltaic deposits. Coals of the Rakopi Formation formed as an important source rock while the fluvial sandstone in this age formed a potential reservoir. During the Latest Cretaceous, the basin was filled with transgressive shallow marine deposits. Although no production occurred from this level, sandstone facies of the North Cape Formation was considered to have good reservoir potential.

Stogen et al. (2012) investigated the Taranaki basin through new basin-wide seismic mapping, biostratigrahy, facies analysis, and basin modelling. Their study suggests passive subsidence occurred during the Mid-to-Late Paleocene with some development of the Late Paleocene marine source rocks in the distal areas (Waipawa Formation).The good reservoir of this interval was produced in the Tui, Maui and Kupe fields. During the Late Eocene, there was widespread non-marine deposition in the southern sub-basin and extensional faulting in the south. During this age, deep marine fan sandstone of Tangaroa Formation formed a good potential reservoir in the northern part of the basin. Late Oligocene-Earliest Miocene was marked by the onset of fault reactivation, followed by transgression. Distal facies deposits of the (Otaraoa and Tikorangi formations) form a good seals across the basin.

In the middle Miocene, there was significant inversion in the southwest and onset of progradation of shelf and shoreline towards the north. The basin was dominated by slope to basinal muds and basin floor fans (Moki Formation) in this age. During the Late Miocene, slope-shelf system rapidly prograded out into the deep basin the sediment source transport direction was from the northwest, instead of the previous northward direction. During Early Pliocene, the Northern Graben underwent major subsidence with deposition of slope-basinal muds, submarine fans and condensed marls in the northwest. The Mangaa Formation exhibits a series of basin floor fan deposits and is the lowermost stratigraphic unit within the Northern Graben. The sandstones of the Mangaa Formation are considered as good potential reservoirs in the Karewa field. During Oligocene-Miocene, compressional thrust loading along the Taranaki fault in the foreland side produced widespread subsidence of the continental crust. The accommodation space of the basin was subsequently filled by the Giant Foresets Formation, which comprised a thick shelf-to-basin succession of fine-grained sediments fed by uplift of the Southern Alps (Hansen and Kamp, 2002). The Giant Foresets Formation overlies the top of the stratigraphic section and covers the northern part of the Taranaki basin, Central Graben and the northwestern part of the Western Stable Platform. The GFF overlies the Ariki-Mangaa Formations and Mohakatino-Manganui Formations in some areas.

The offshore North Taranaki Graben has been considered as a highly prospective area for oil and gas. In 2003, Karewa-1 well was drilled within the study area (Fig. 1.2B), with small gas shows from the Mangaa Formation turbidite sands of earliest Pliocene age, which underlies the GFF. To the south of the study area, there was an oil discovery in the Miocene reservoir at Kora-1 well, drilled in 1988, at the margin of the Northern Graben (NZPAM, 2013). Those discoveries confirmed that the Northern Graben can be prospective oil and gas zones within the Taranaki Basin. Therefore, a detailed investigation of the stratigraphic framework can help in understanding the prospect potential in the study area.

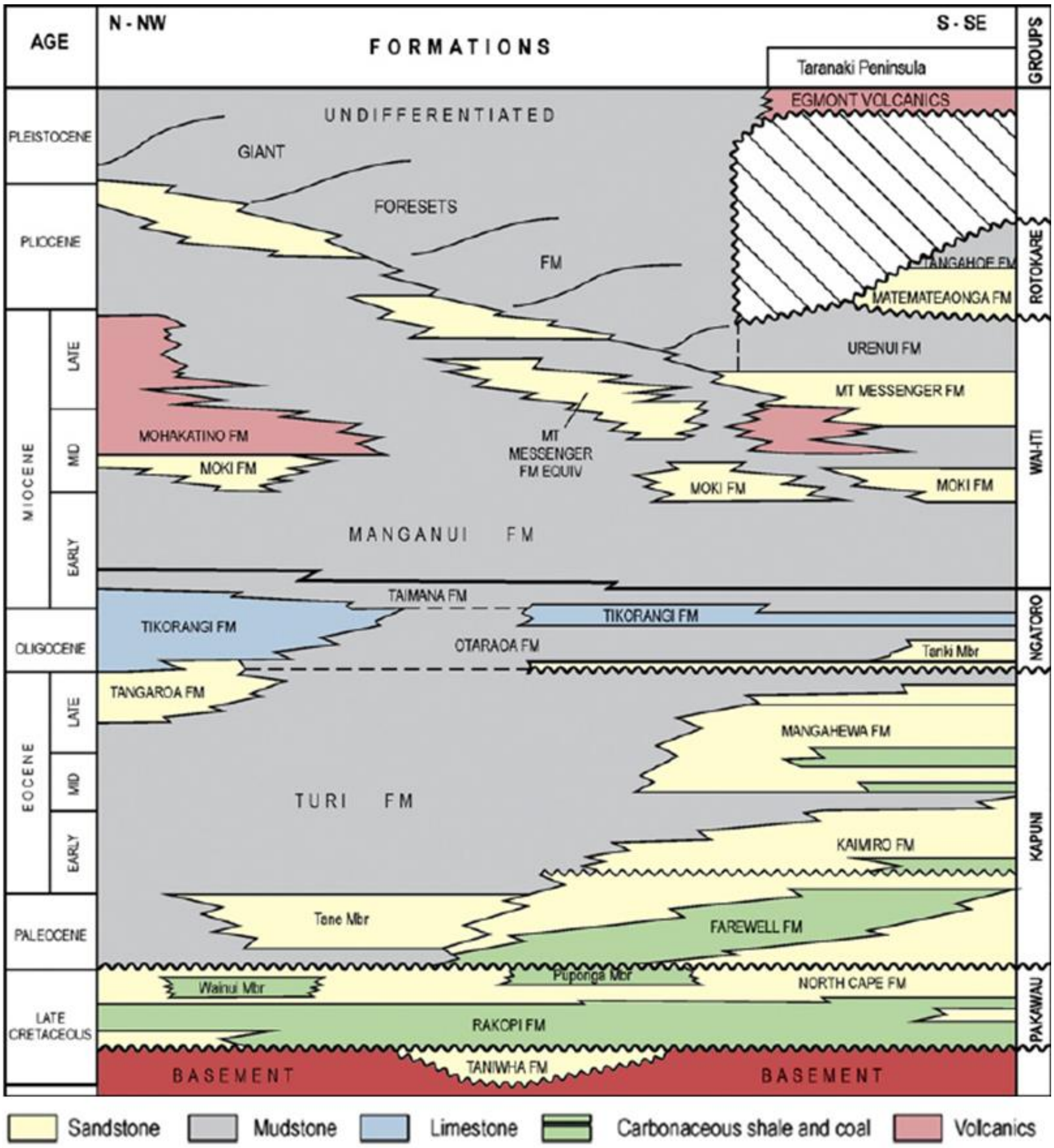

Figure 1.3: Schematic chronostratigraphy of the Taranaki Basin (Source: Kroeger (2012), modified from King and Thrasher, 1996).

1.4 The Giant Foresets Formation

The Giant Forsets Formation (GFF) is recognized by its bold, high relief clinoforms offlapping the Mangaa Formation in the basinward direction. The GFF comprises a shelf-slope-basin succession of fine muds through silts and sands. It is the building block of most of the modern continental shelf and slope was resulted from rapid progradation together with rapid down-faulting during the Pliocene, yielding thickness of about 2200 m in places (Hansen and Kamp, 2002). The GFF has been documented by several workers, e.g. the geometry and internal reflection character of the GFF within the Northern Graben has been documented using 2D regional lines (Hansen and Kamp, 2006) and from the Parihaka 3D seismic data located towards southwest (Salazar et al., 2015). In the Central Graben, the GFF was also imaged, e.g. Maui and Turi 3D seismic surveys (Shumaker et al., 2016), where numerous submarine gullies were investigated within the GFF interval.

The sediment distribution patterns of the Pliocene succession were greatly influenced by the Latest Miocene extension in the Northern Taranaki Basin. The initial extension of the Northern Graben was suggested to occur before the GFF progradation. Sediment supply was sourced from the erosion towards the east, followed by filling of the progradational sequences in the Northern Graben during the Late Miocene and Early Pliocene. In the same period, the north and the west of the graben underwent a period of sediment starvation. During the Pliocene to Pleistocene, sedimentation rate outpaced the accommodation space created by graben extension. Thus, the graben was overtopped by the progradational sequences with the progradational front building out northward. Progradation on the shelf has migrated rapidly until the present day (Hansen and Kamp, 2002; 2004; 2006).

The sedimentary succession during the Pliocene-Pleistocene comprises the mud-dominated package of the Giant Foresets Formation and underlying sand-dominated package of Mangaa Formation (Fig. 1.4). Although the Mangaa Formation has been the exploration target, the Giant Foresets Formation has never been considered for exploration by the petroleum companies (Hansen and Kamp, 2004). However, over 15% of the world oil reserves come from clastic-dominated depositional systems (Richard et al, 1998). Therefore, it would be useful to investigate architectural elements of this depositional system and constrain the possible reservoir facies (i.e. channel sands, levees (thin beds), mass transport deposits, etc.) and extent of seal facies.

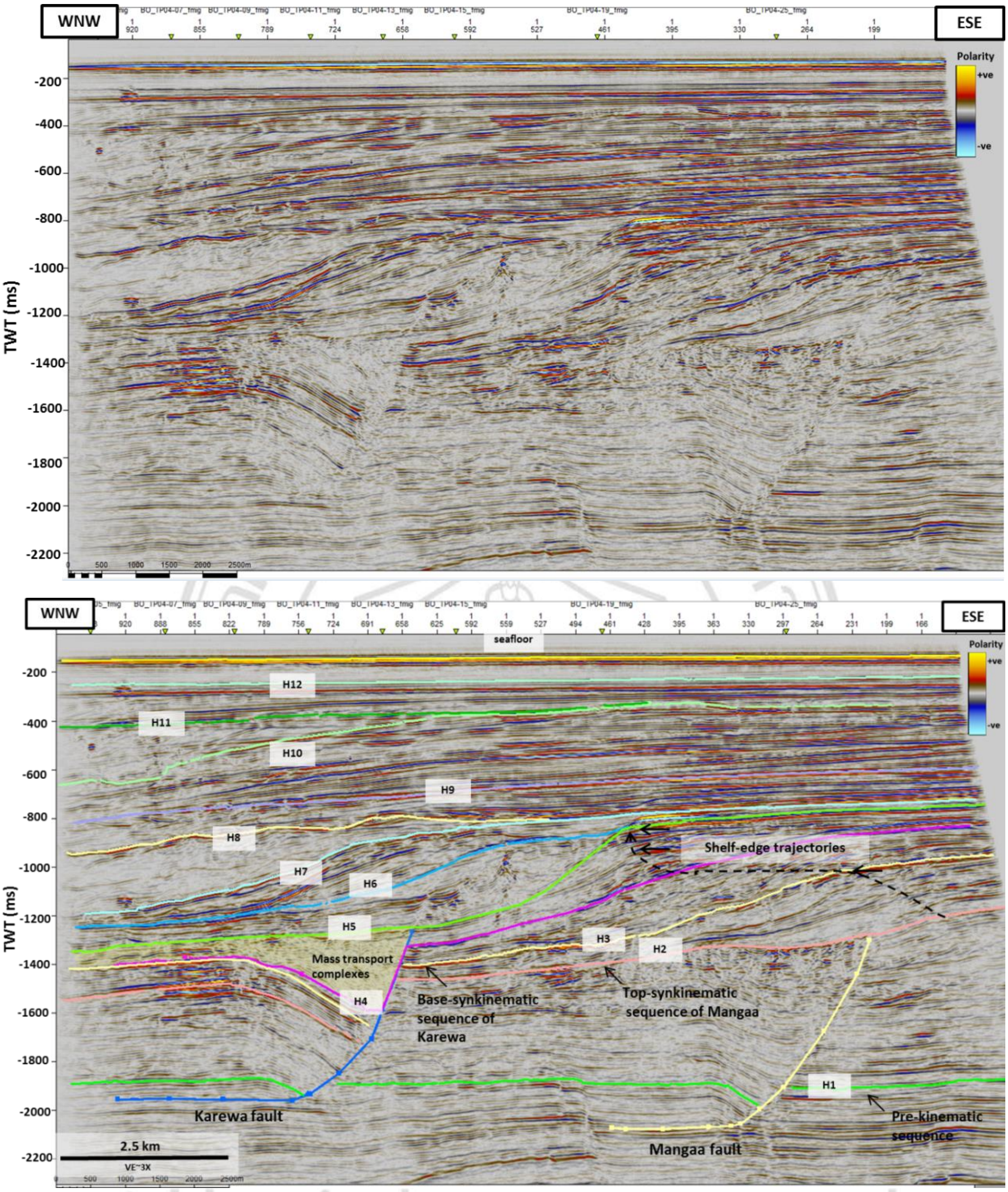

Figure 1.4: Uninterpreted and interpreted vertical seismic section of 2D line P95-118 along depositional dip (See. Figure 1.2 for location). a) Uninterpreted seismic section from the Karewa 3D seismic, shows well-defined progradational sequnces of the Giant Foresets Formation. b) Same seismic section shows interpreted horizons and two main growth faults, Karewa and Mangaa, named after Morley and Naghadeh (2016).

1.5 Sequence Stratigraphic Principles

Sequence stratigraphy is a methodology that provides a framework for the elements of any depositional setting. This framework ties changes in stratal stacking patterns in response to varying accommodation (sea level, tectonic subsidence changes) and sediment supply though time, and provides the genetic context in which event-significant surfaces and the strata they separate are placed into a coherent model (Cataneanu, 2006; 2011). The scope of this stratigraphic concepts used in this study are discussed in Catuneanu (2006) and Sepmstrata.org. The concept of sequence stratigraphy is relatively new and is under much debate. In spite of its popularity among academic and industry organizations, sequence stratigraphy remains a method that has no formalized definition in stratigraphic guides or codes (Catuneanu, 2011). This reflects the existence of a variety of alternative approaches (Fig. 1.5 and 1.6).

The main tool used in sequence stratigraphic analysis is the stacking pattern of strata and key surfaces that bound successions defined by upstepping, forestepping, and downstepping patterns (Fig. 1.7). A sequence stratigraphic framework may consist of three different types of sequence stratigraphic unit, namely sequences, system tracts, and parasequences. Each type of unit is defined by specific stratal stacking pattern and bounding surfaces. The definition of these units is independent of temporal and spatial scale, and also, the mechanism of formation (Catuneanu, 2011). As previously stated, a concept of a sequence is not fully formalized. However, all current stratigraphic approaches include a common set of fundamental principles and concepts which can be standardized as a model-independent methodology (Catuneanu, 2009). Beyond this model-independent methodology, the interpreter may make model-dependent choices with respect to nomenclature of preference that is best adapted to the depositional system and the selection of surfaces to be elevated to sequence boundaries (Fig. 1.6 and 1.8).

The sequence stratigraphic workflow applied in this research begins with analysis of seismic facies based on seismic reflection characteristics. The objective of seismic facies analysis is to define the depositional environment in the sense of sediment depositional characteristics. Concurrently, the bounding horizons were identified based on erosional truncation, onlap and/or downlap surfaces which helped to build the chronostratigraphic framework for the targeted sedimentary succession. Such surfaces define the container for intervening depositional sequence units forming during a full cycle of change in accommodation or sediment supply. The accommodation involves both increase (positive) and decrease (negative) in the space available for sediment to fill (Catuneanu, 2006; 2009; 2011). Ultimately, the sequences were characterized and interpreted in genetic term (i.e. systems tracts). A systems tract is defined as 'a linkage of contemporaneous depositional systems forming the subdivision of a sequence' (Brown and Fisher, 1977), and is interpreted on the basis of stratal stacking patterns, position within the sequence, and types of bounding surfaces (Van Wagoner 1995; Posamentier and Allen 1999). Systems tracts in the study area are shoreline-related in this case (Catuneunu, 2011), where their origin can be linked to particular types of shoreline trajectories. Each identification will contribute useful information towards the recognition of depositional trend of the prograding facies within the studyarea.

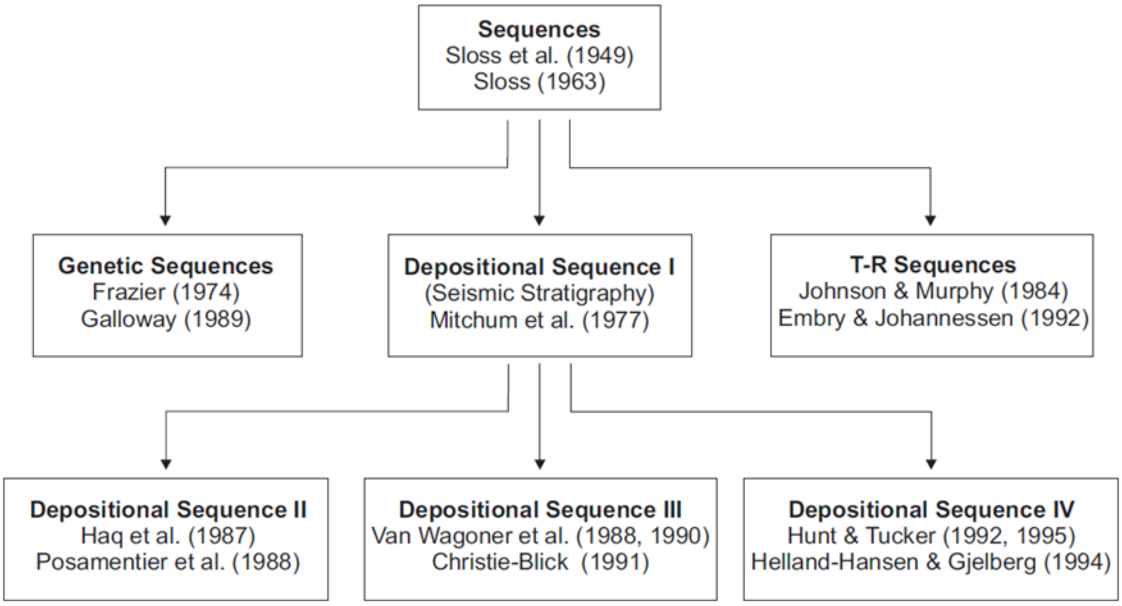

Figure 1.5: Evolution of sequence stratigraphic approaches (Catuneanu et al., 2011).

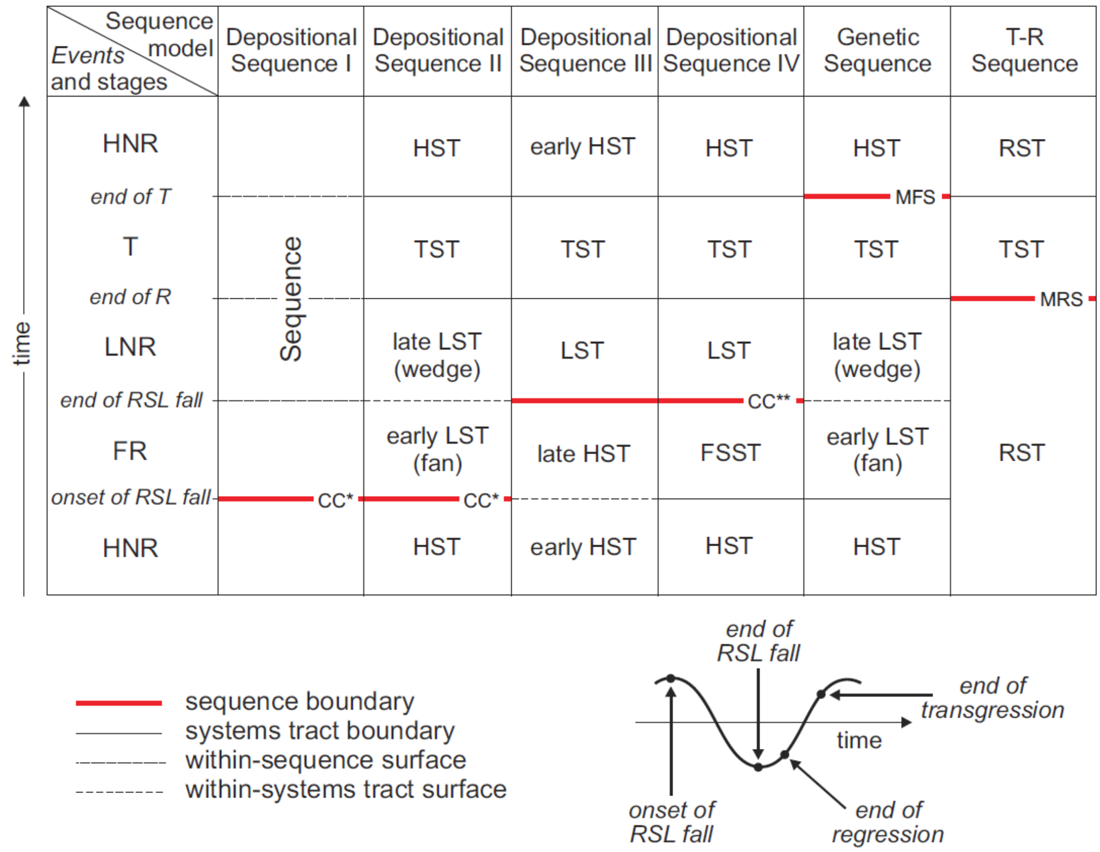

Figure 1.6: Nomenclature of systems tracts, and timing of sequence boundaries for the various sequence stratigraphic approaches (Catuneanu et al., 2011). Abbreviations: RSL – relative sea level; T – transgression; R – regression; FR – forced regression; LNR – lowstand normal regression; HNR – highstand normal regression; LST – lowstand systems tract; TST – transgressive systems tract; HST – highstand systems tract; FSST – falling-stage systems tract; RST – regressive systems tract; T-R – transgressive-regressive; CC* – correlative conformity in the sense of Posamentier and Allen (1999); CC** – correlative conformity in the sense of Hunt and Tucker (1992); MFS – maximum flooding surface; MRS –maximum regressive surface. References for the proponents of the various sequence models are provided in Figure 1.5.

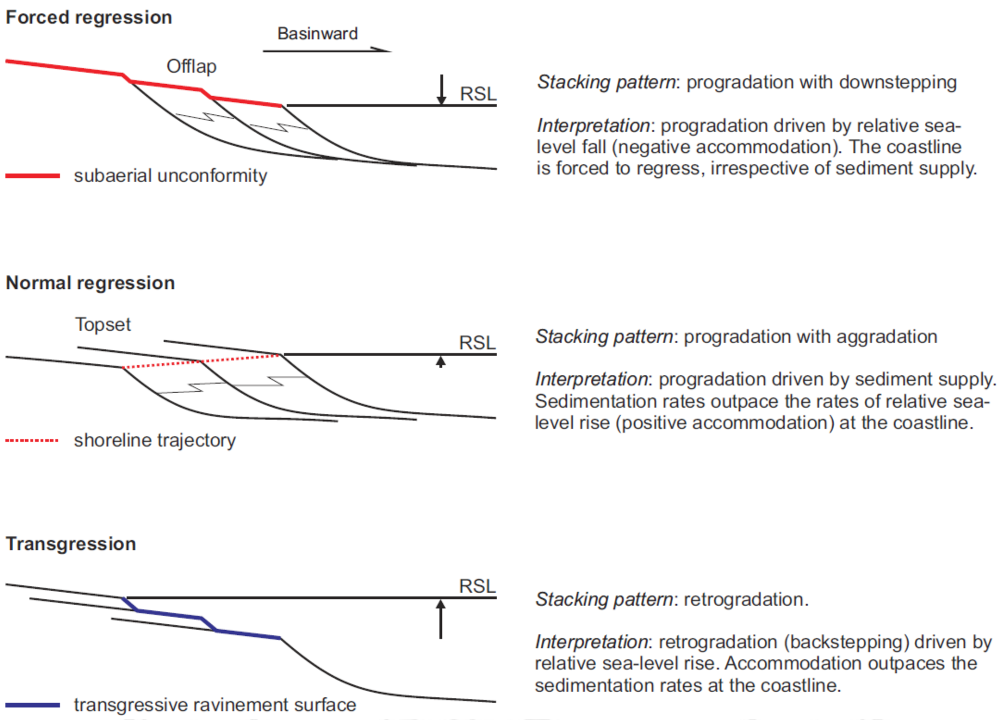

Figure 1.7: Stratal stacking patterns related to shoreline trajectories (from Catuneanu et al. 2010): forced regression (forestepping and downstepping at the shoreline) , normal regression (forestepping and upstepping at the shoreline), transgression (backstepping at the shoreline).

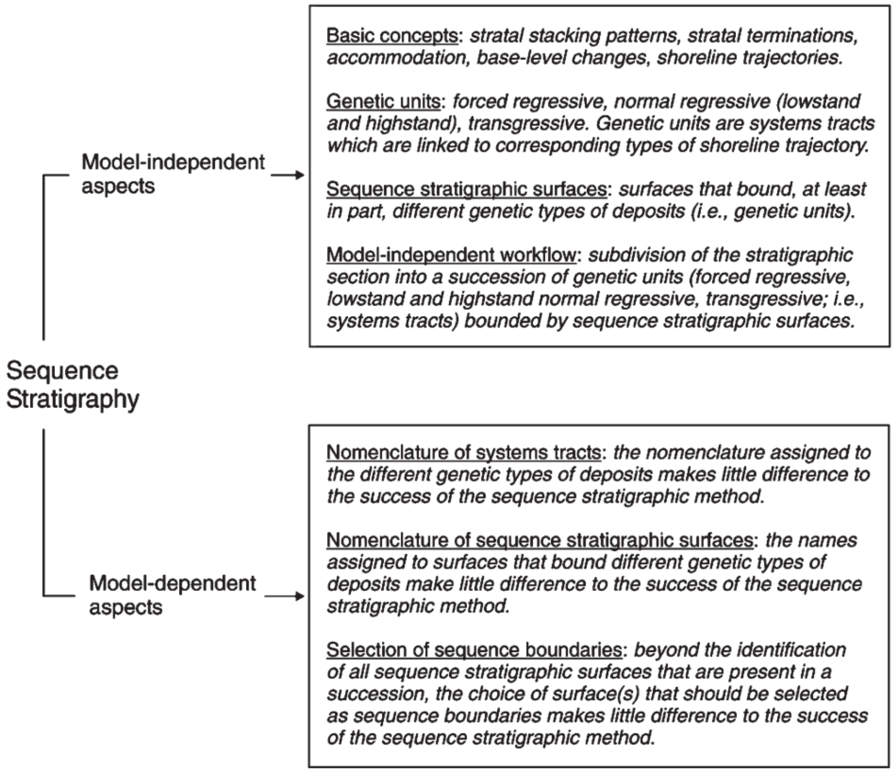

Figure 1.8: Model-independent versus model-dependent aspects of sequence stratigraphy. The model-independent aspects form the core platform of the method that is validated by all "schools." The model-dependent aspects can be left to the discretion of the practitioner; such flexibility allows one to adapt more easily to the particularities of each case study (Source: Catuneanu, 2011).

1.6 Mass Transport Complex (MTC)

Much research has been done on Mass Transport Complexes (MTCs) (Armandita, 2015; Bull, 2009; Frey-Martinez, 2006; 2010). The MTCs are generally recognized as zones of chaotic or highly disrupted seismic facies (Frey-Martinez, 2010). Most of the MTCs in marine settings have been primarily studied through shallow imaging techniques (i.e. multibeam bathymetry, sidescan sonar) and high-resolution seismic data (Canals et al., 2004, and references therein). 3D seismic data has many proven advantages over other methods. For example, 3D seismic data can provide useful information about the MTC geometry by using techniques such as detailed correlation between vertical and horizontal seismic sections, attribute extraction, and flattening of horizon slices. Bull (2009) grouped the various kinematic indicators into three distinct domain in which they are most likely to occur within the MTC: the headwall domain, translation domain and the toe domain (Fig. 1.9).

1.6.1 Headwall domain

This area encompasses the upslope, extension region of the MTC. The main kinematic indicators found in this domain are headwall scarps and extensional ridges and blocks. A headwall scarp essentially represents an extensional failure surface, and therefore forms in the same way as extensional faults. It is a high-slope surface marking the shallowest portion of the MTC, where sediment evacuation initiates (Fig. 1.9). On seismic cross-sections, it is recognized as an excisional feature with abrupt reduction of stratigraphic section in a downslope direction. Depending on the nature of MTC, the headwall may represent translated block with preserved high degree of coherency.

1.6.2 Translation domain

This domain comprises the main translated body of the MTC, between the upslope and downslope area (Fig. 1.9). The material translate downslope across the basal shear surface can lead to intense deformation (Martinsen, 1994), this resulted in formation of the features which can provide kinematic information of the MTC. The kinematic indicators that typically occur in association with this domain include lateral margins, basal shear surface, internal body and top surface of the MTC.

1.6.3 Toe domain

The toe domain includes the downslope termination point, or ‘toe’ (Fig. 1.9). The main kinematic indicators contained within them are pressure ridges, thrust and fold systems. Frey-Martinez et al. (2006) subdivided the toe domain (Fig. 1.10) into those which are ‘frontally confined,’ where the translated mass is buttressed downslope against stratigraphically equivalent undisturbed strata; and ‘frontally emergent,’ occurring when the translated mass is able to ramp up from the original level of the basal shear surface and move freely across undisturbed strata.

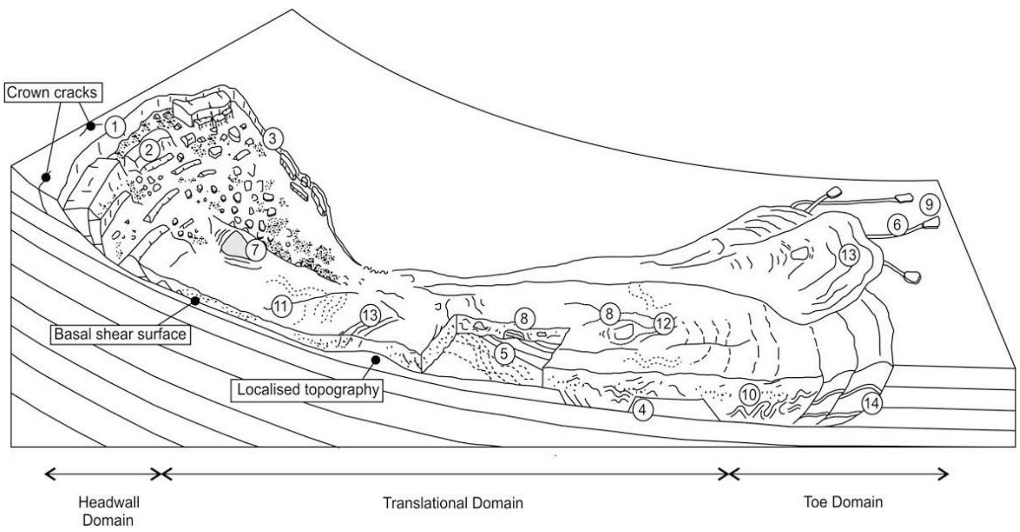

Figure 1.9: Schematic representation of a MTC and the likely occurrence and associations of kinematic indicators relative to the various domains. (1) Headwall scarp. (2) Extensional ridges and blocks. (3) Lateral margins. (4) Basal shear surface ramps and flats. (5) Basal shear surface grooves. (6) Basal shear surface striations. (7) Remnant blocks. (8) Translated blocks. (9) Out-runner blocks. (10) Folds. (11) Longitudinal shears/first order flow fabric. (12) Second order flow fabric. (13) Pressure ridges. (14) Fold and thrust systems. (Source: Bull et al (2009), modified after Prior et al. (1984).

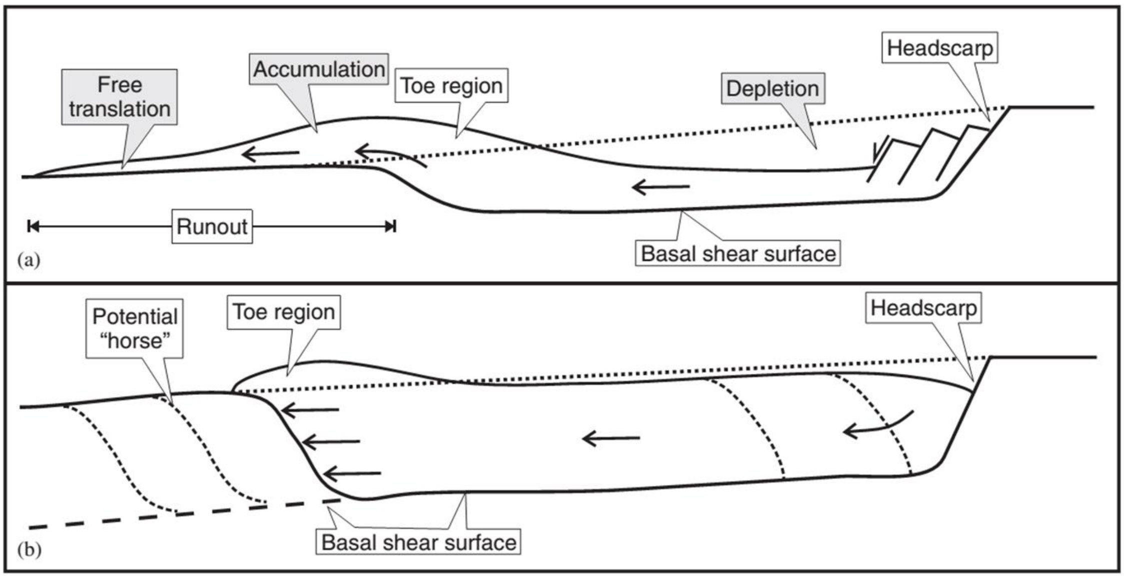

Figure 1.10: Schematic depiction of the two main types of submarine landslides according to their frontal emplacement: (a) Frontally emergent landslide. Note that the material ramps out from the basal shear surface onto the seabed and is free to travel considerable distances over the undeformed slope position. (b) Frontally confined landslide. The mass is buttressed against the frontal ramp and does not abandon the original basal shear surface. (Source: Frey-Martinez et al. (2006))