Anatomy and allostratigraphy of deep-marine Mount Messenger Formation (Miocene), eastern-margin Taranaki Basin, New Zealand

Thesis for partial fulfillment of
Candidatus Scientiarum degree
in
sedimentology/petroleum geology
for

Kristian Helle

Department of Geoscience
University of Bergen
2003

Summary

Title: Anatomy and allostratigraphy of deep-marine Mount Messenger Formation (Miocene), eastern-margin Taranaki Basin, New Zealand.
Purpose of study: Sedimentological description of outcropping deep-water clastics within Mount Messenger Formation.
Study area: North-Taranaki coastal region, North Island, New Zealand.
Methodology: Mapping on foot and sedimentary logging.
Geological setting: The basin-floor fans and channel levee complexes of Miocene Mount Messenger Formation were deposited in fore-deep, intra (sub) continental Taranaki Basin. The basin is mainly submarine, but Mount Messenger Formation crops out in the study area with a thickness of approximately 700m. The lower part is dominated by mid fan deposits, the middle part by lower fan deposits, and the upper part by channel-levee deposits.
Lithofacies and lithofacies associations: 4 lithofacies associations have been recognized in the lower and middle part of Mount Messenger Formation; 1) *massive sandstone association* consist of thick beds of massive very fine to fine grained sandstone interbedded with very thin beds of mudstone interpreted as deposits from gravity-flows with laminar flow component interbedded with hemipelagic mud; 2) *heterolithic association* consist of interbedded thin beds of very fine to fine grained sandstone and mudstone interpreted as high-density turbidity current or sandy debris-flow deposits interbedded with hemipelagic mud; 3) *finely-laminated association* consist of thick beds of finely-laminated very fine to fine grained sandstone interpreted as turbidity current deposits; 4) *deformed association* consist of very thick-bedded, heavily deformed interval interpreted as slump-flow deposits.
Architectural elements: 3 types of architectural elements are recognized; 1) massive sandstone association or finely-laminated sandstone association dominated *sandstone elements* interpreted as mid fan deposits; 2) heterolithic association dominated *heterolithic elements* interpreted as lower fan deposits; and 3) deformed association dominated *deformed elements* interpreted as deposits from slope failure.
Allostratigraphic units: The architectural elements are stacked in successions of *sandstone element* — *heterolithic element* — *deformed element* which each define an allostratigraphic unit bounded by the lower erosive surface of sandstone elements (cycle boundaries). A total of 4 units are recognized.
Allostratigraphic architecture: The sandstone elements at the base of each allostratigraphic unit are interpreted to represent different depositional environments within the mid fan setting. The depositional environment changes with time from outer mid fan to middle mid fan to inner mid fan, reflecting the overall progradation of the depositional system into the study area. Paleocurrent measurements indicate the direction of progradation was towards the north-west.
Paleogeography: Mount Messenger Formation is interpreted as multiple sourced, moderately efficient, shallow incised, channel attached depositional system. Paleocurrent measurements indicate that Allostratigraphic Unit 1 and 2 were fed from 2 sources; slump-flows from the north and sandy gravity-flows from the south-east. Allostratigraphic Unit 3 and 4 were fed from a source located to the south. The formation can be classified as a hybrid between a sand-rich slope apron and a mixed sand-mud slope apron depositional system in the classification introduced by Reading & Richards (1994).
Controls on stratigraphic architecture: 3 stratigraphic time hierarchies are recognized within the studied deposits; 1) onset of Mount Messenger deposition representing a *low-frequency hierarchy* with several million years or more duration interpreted to result from interacting factors of sediment supply, subsidence and eustasy, but ultimately controlled by the uplift in the south-east; 2) rhythmic stacking of architectural elements representing a *medium-frequency hierarchy* with 100-200 thousand years duration interpreted to result from tectonic processes; and 3) thinning-up successions within architectural elements representing a *high-frequency hierarchy* with 10's of thousands years duration interpreted to result from autogenic processes.

Acknowledgements

This study is a result of a cooperation project between BP Norge AS, University of Bergen (UiB) and Institute of Geological and Nuclear Sciences (IGNS), Lower Hutt, New Zealand. The project was funded by the former two whereas IGNS organized the field work.

The thesis was supervised by Professor Dr. philos. William Helland-Hansen (UiB) who coordinated the project; Dr's Greg Browne, Peter King and Malcolm Arnot (IGNS) introduced the study area and assisted during field work; Co-supervisors at BP Norge AS were Cand. scient. Kristin Nyberg and Dr. scient Tina R. Olsen. The help and support received during field work and writing of the thesis has been highly appreciated.

The land owners in Tongaporutu District are acknowledged for general information about the area and kindly giving permission to enter land.

I also wish to thank my fellow students; Cand. mag. Ingine Kristin Strømsøyen for general discussions and cooperation in the field; and Cand. scient. Morgan Ganerød for help with computer -and software related problems.

My girlfriend Ellinore B. Vipond is thanked for flexibility, help and support during final days of writing the thesis. Finally, I wish to express my gratitude to my family for interest in my education and financial support during my studies.

Kristian Helle

Bergen, December 2003

Table of Contents

Front page photo; thinning up from mid-fan to lower fan environment. Photo taken looking south from Tongaporutu River estuary at high tides. Volcano Mount Taranaki in far distance.

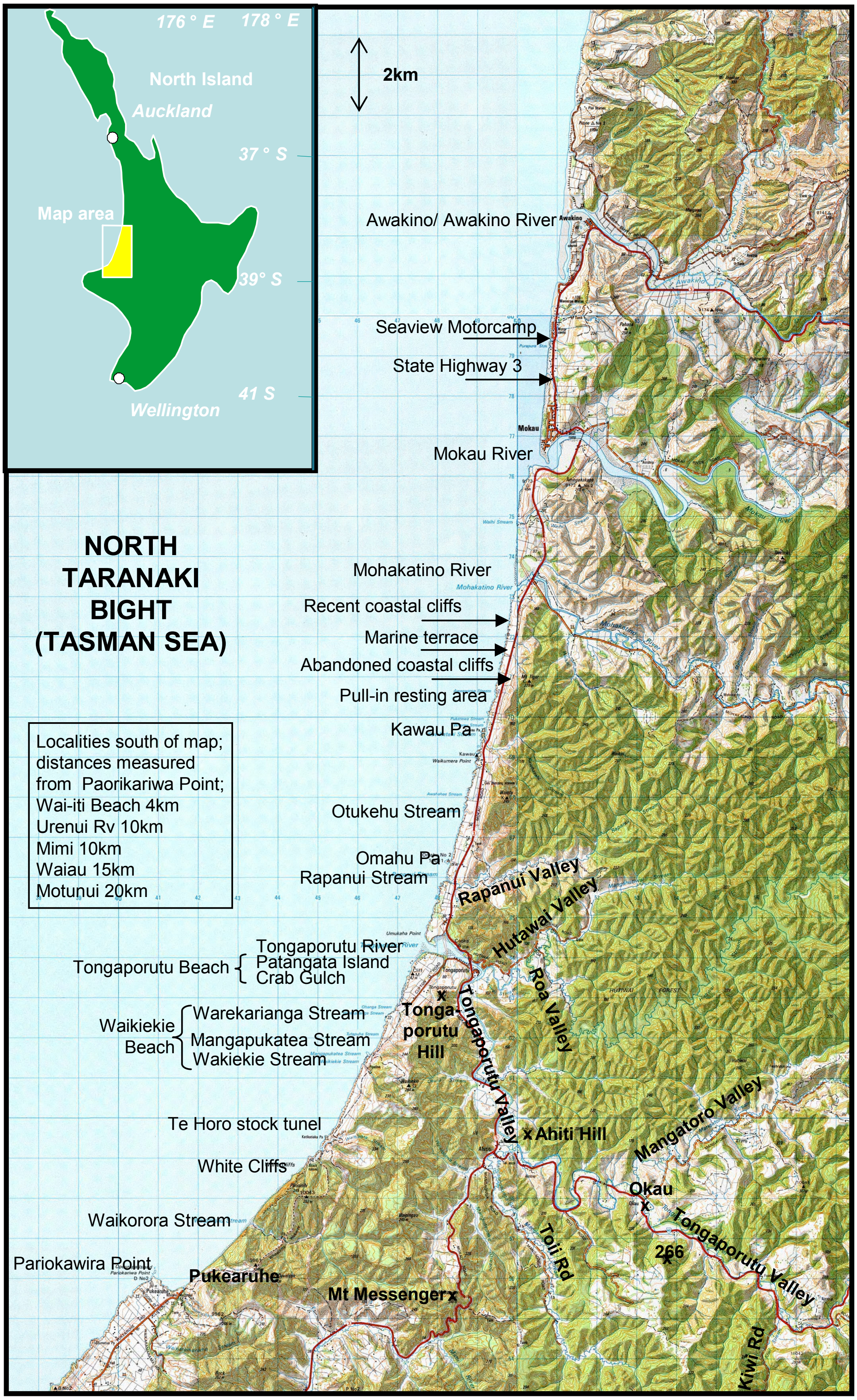


Figure 1.1 Position of study area and key localities; north-Taranaki coastal region, eastern-margin Taranaki Basin, New Zealand. Map modified from NZMS 260 Q18 Tongaporutu Edition 1 by Department of Lands & Survey, New Zealand.

1. Introduction

1.1. *Purpose of study*

The main purpose of this study has been to describe the sedimentology, 3D geometry and architecture of architectural elements within the outcropping deep-water clastics of Late Miocene Mount Messenger Formation, eastern-margin Taranaki Basin, New Zealand (Figure 1.1). The results were used to build a depositional model for the system.

The regional paleogeographic setting with erosion of tectonically uplifted areas supplying sediments to a sandy deep-marine system prograding into a fault bounded basin, strongly resembles the Cretaceous development of deep-marine systems in the Norwegian Sea. This project was therefore initiated by BP Norge AS for the purpose of using the study area as potential analogue for hydro-carbon fields in the Norwegian Sea deep marine depositional systems.

1.2. *Study area*

The study area is located in the coastal area between Awakino in the north and White Cliffs in the south, a distance of 25km in the north-Taranaki coastal region, New Zealand (Figure 1.1). The approximately 90km^2 study area lies between 0-400m above sea-level and is dominated by fluvial incised valleys and heavy forest vegetation. At the coast, a recent relative sea-level fall has moved the coastal cliff transect 0.1-1km seawards and left marine terraces in front of the here called "abandoned coastal cliffs" transect.

The outcrop-quality along the coastal cliffs is excellent due to the ongoing wave-erosion which keeps the rock surfaces fresh from vegetation and weathering. However, the 5-20 meter high coastal cliffs fall straight into the inter-tidal zone and make the outcrops accessible during medium to low-tides only. The 3 kilometers long coastal cliff transects between Tongaporutu River estuary and Waikiekie Stream outlet is easily accessible and represents a continuous well exposed stratigraphic succession. This coastal cliff transect was therefore chosen as a detailed study area for description of lithofacies and lithofacies associations.

Due to the heavy vegetation inland of the north-Taranaki coast, there are few possibilities for inland correlation of the architectural elements cropping out in the coastal cliffs. However, the Tongaporutu catchment area is cultivated and has a network of sealed and dirt roads that make it possible to trace strata towards the east and south-east in a scale of 10- 10’s of meters. It is also possible to map strata along the roughly north-south oriented abandoned coastal cliffs.

1.3. Methodology

The field work was carried out during the New Zealand autumn in 2002 and 2003 over a period of totally 4 months. In the detailed study area, the rock succession was measured bed-by-bed in a scale of 1: 10 or 1:20 and lithofacies described based on grain size, sedimentary structures, textures, mineralogy and color. Beds were classified as *very thin beds* if thickness between 1-5cm; *thin-beds* if thickness between 5-60cm, *medium beds* if thickness between 60-100cm, *thick beds* if thicker than 100cm and *very thick beds* if thicker than 400cm (McKee & Weir, 1953). Plane orientations were noted on the form strike/dip → XX, where XX refers to the dip direction of the plane and strike is noted using the right hand rule. Further, the stratigraphic grouping of lithofacies was used to distinguish lithofacies associations.

The sedimentary log from the detailed study area is included in the Enclosures 1-4 (separate volume) in a scale of 1:200 whereas examples of the different lithofacies and lithofacies associations are integrated in the text. Sedimentary raw logs are included in Appendix II.

The stratigraphy of the study area was divided into 3D architectural elements based on the dominant lithofacies associations within stratigraphic intervals. The mapping of these were carried out by driving on sealed -and dirt roads to come as close as possible to the area of interest, and then to walk out the surfaces to reconstruct the geometry of the depositional system. Detailed correlation across faults dissecting the study area are included in Appendix I

Equipment used was; mm-paper, 1:50.000 topographical maps, tape-measure, compass, GPS, binoculars and an air-pressure based altimeter. In addition, a digital camera was used to document individual lithofacies, lithofacies associations and large scale architectural elements in both inland and coastal areas.

The architectural elements are presented with a summary log from the studied coastal transect whereas their geometry and distribution are presented on outcrop maps integrated in the text and on a maps and profiles in Enclosure 5-9 (separate volume).

In deep-marine systems, the same depositional processes may work in different depositional settings. A channel fill in upper mid fan setting might for example consist of the same lithofacies association as unchannelised sheet sand in outer mid-fan setting. The interpretation of depositional setting is therefore largely dependent on the larger scale geometries of the lithofacies associations (architectural elements). In this thesis, the description and process-based interpretation of lithofacies and lithofacies associations is presented separately from the description and environmental-based interpretation of architectural elements.

The architectural elements were grouped into allostratigraphic units based on stacking pattern and erosional surfaces. These are presented on a topographical map and a summary log of the studied coastal transect. The architecture of allostratigraphic units further formed the base for interpreting the evolution of the depositional system. The data was then combined to build a paleogeographic model for the Mount Messenger depositional system. Possible controls on stratigraphic architecture are discussed in Chapter 7.

1.4. Previous work

The earliest mapping and description of strata cropping out in the coastal cliffs between Awakino and Motunui was made by Clarke (1912), Grange (1922), Henderson & Ongley (1923), Morgan & Gibson (1927) and Grange (1927). The bio -and lithostratigraphy was later refined by Gibson (1963) and Hay (1967).

Gibson (1963), Glennie (1958) and Quennel (1938) each compiled a composite measured section for the Awakino-Motunui interval. However, with the exception of Glennie (1958) little attention was paid to its depositional history until the recent regional studies by King et al. (1993 & 1994), Jordan et al. (1994), King & Thrasher (1996), Hansen (1996), Lindsay (1996) and Brown et al. (1996, 1997 & 2000).

1.5. Geological setting

The New Zealand sub-continent is dissected by the Pacific-Australian plate boundary that places most of North Island on the Australian Plate, and most of South Island on the Pacific Plate (Figure 1.2). 100.000 square kilometers large Taranaki Basin is an intra (sub) continental basin (King & Thrasher, 1996) located in a back-arc setting (Bennett

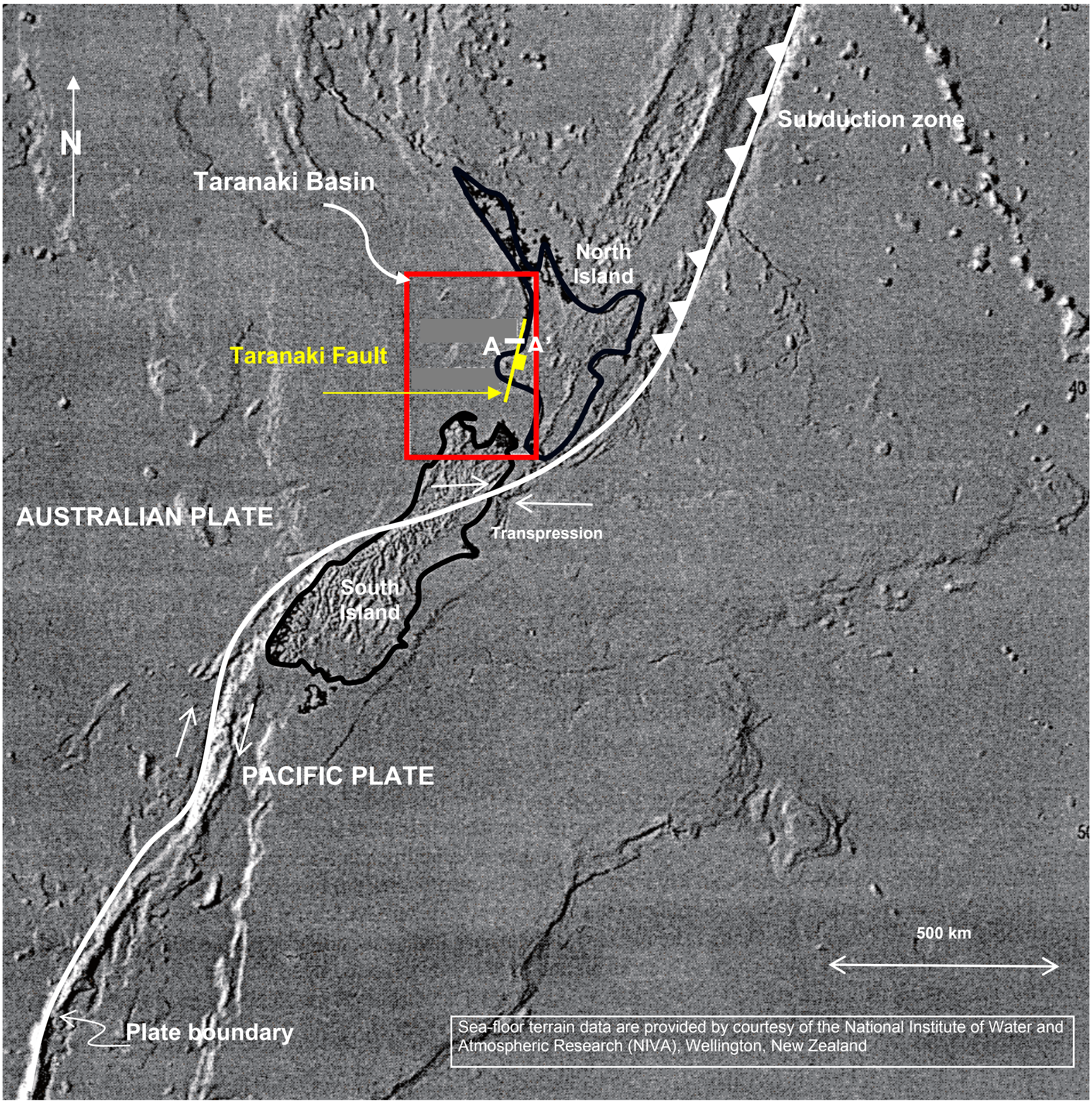


Figure 1.2 Regional setting of New Zealand and Taranaki Basin. New Zealand is dissected by the Australian-Pacific plate boundary. A subduction zone has since Miocene time been located the in the north-east, whereas strike-slip movement dominates in the south-west. Early Miocene transpression between the plates resulted in overthrusting along Taranaki Fault and initiated a 3rd order regression into Taranaki Basin. A-A' represents profile line in Figure 1.3. Modified from King & Thrasher (1996).

et al., 1992) on the west side of North Island. The basin started to subside in Late Cretaceous time and has primarily evolved as a marine basin being open to the sea in the north and west (King & Thrasher, 1996). In Early Miocene time, initiation of oblique convergence between the Australian and Pacific Plate led to westwards overthrusting of Mesozoic basement rocks along roughly north-south trending Taranaki Fault (Figure 1.2 & 1.3) (King & Thrasher, 1992). This resulted in asymmetric foreland subsidence in Taranaki Basin to the west (Holt & Stern, 1994). The uplift initiated a major, still ongoing regression which was associated with a change in sedimentation from carbonate dominated Tikorangi and Taimana Formation in Oligocene time, to clastic dominated Wai-iti Group in Miocene time (King et al., 1993).

In proximal areas to the south-east, Wai-iti Group represents a clastic wedge prograding into a mud and volcaniclastic dominated deep-water environment (Manganui and Mohakatino Formation) with basin-floor fans and channel-levee complexes (Mount Messenger Formation) being deposited in front of the prograding slope (Urenui Formation) (Figure 1.3) (King et al., 1993).

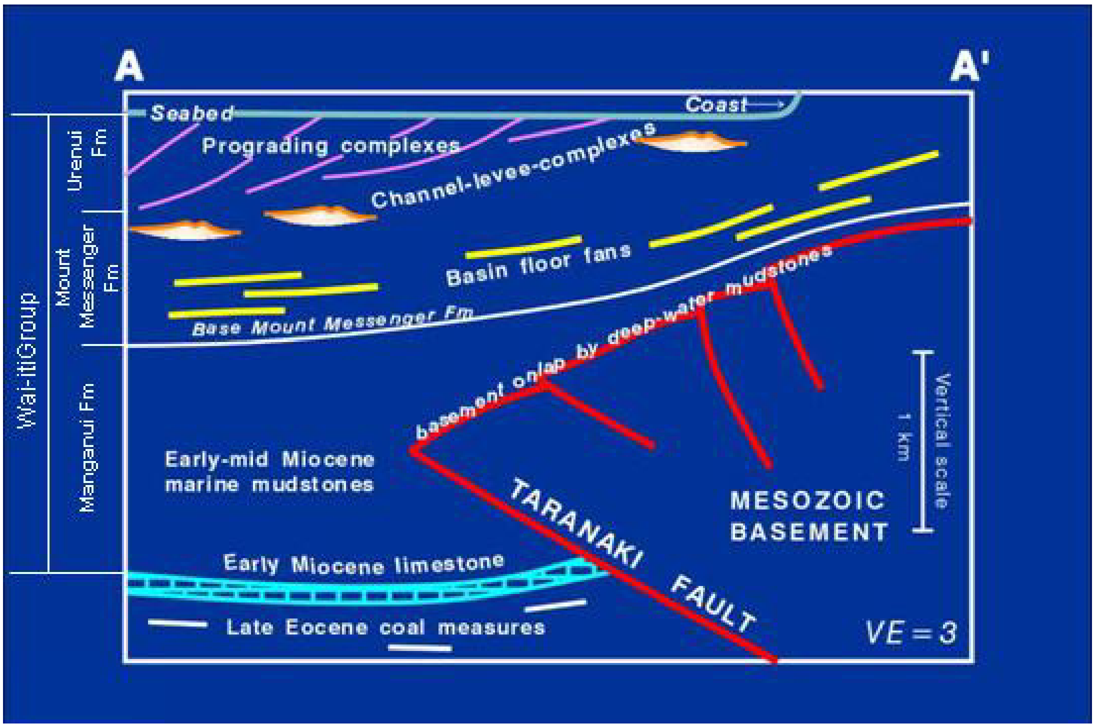


Figure 1.3 Tectono-stratigraphic framework for eastern-margin of Taranaki Basin. In Miocene time, sediments provided from erosion of uplifted hinterlands in the south and south-east changed the sedimentation on the basin-floor from mainly limestone to mainly clastic. The deep-marine mud of Manganui Formation was successively overlain by the basin-floor fans and slope fans of Mount Messenger Formation, later followed by the slope deposits of Urenui Formation. Position of profile A-A’ shown in Figure 1.2. and 1.5. Slightly modified from King & Thrasher (1993).

To the east, Mount Messenger Formation onlap Herangi High whereas both onlap and overtop sub-surface Patea-Tongaporutu High located further to the south (King et al., 1993) (Figure 1.4). In the north, the siliciclastic deposits of Mount Messenger Formation interfinger with the volcaniclastic deposits of Mohakatino Formation.

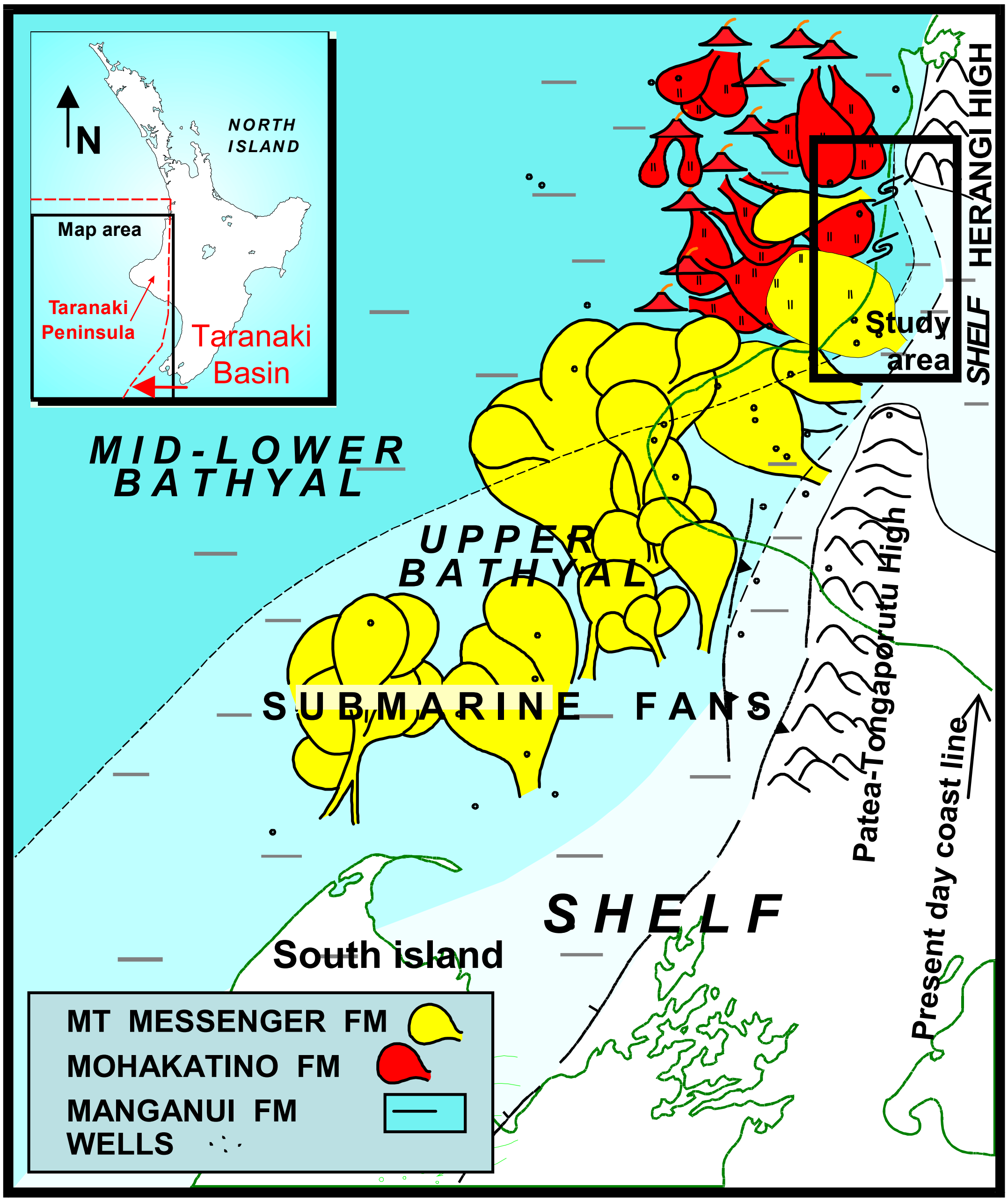


Figure 1.4 Late Miocene paleogeography. Sand was transported to the basin-floor from the south and south-east from multiple sources. In the north, Mount Messenger Formation interfingers with the volcaniclastic basin–floor fans of Mohakatino Formation. Black frame indicate position of study area. Slightly modified from King & Thrasher (1993).

Taranaki Basin is mainly submarine, but a phase of Neogene uplift has exposed the eastern margin on the west side of North Island (King et al., 1993). Wai-iti- Group crops out in the north-Taranaki coastal region where the regional structural strike makes the semi-consolidated strata dip gently down towards the south-west (Figure 1.5).

Approximately 700m thick Mount Messenger Formation was deposited over a period of 1-2 Ma (King et al., 1994) and crops out in the coast near areas between Mokau River and Pariokariwa Point (Figure 1.5) (King & Thrasher, 1996).

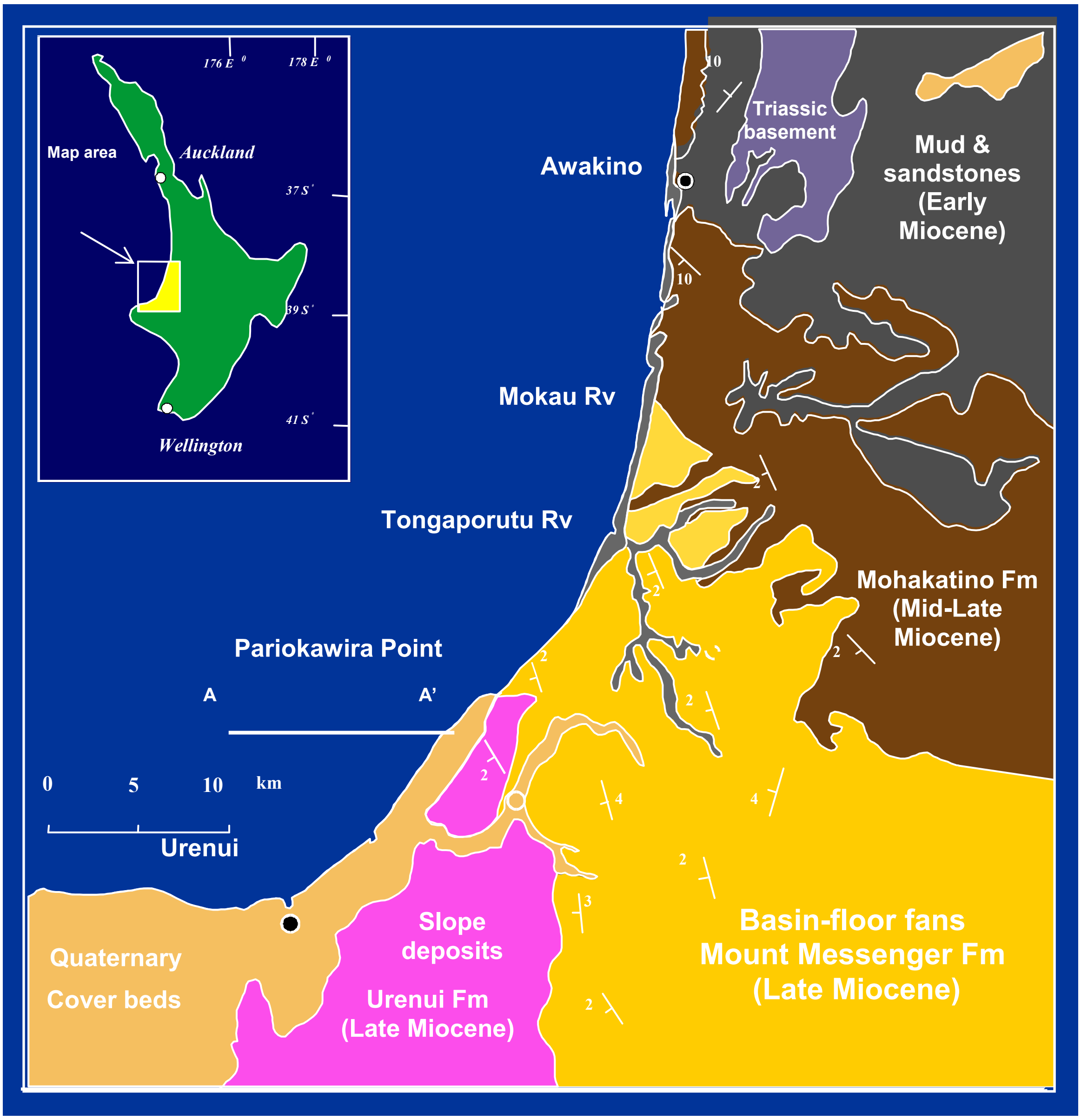


Figure 1.5 Geological map of the study area. The regional structural strike makes successively younger strata dip gently down towards the south-west. The basin-floor fans and slope fans of Mount Messenger Formation is overlain by the slope deposits of Urenui Formation. Profile A-A' represent profile line in Figure 1.3. Slightly modified from King & Thrasher (1993).

Mount Messenger Formation is divided into three; 1) an approximately 200m thick *lower sandstone unit* mainly consisting of sheet sands; 2) an approximately 400m thick *middle thin-bedded unit* mainly consisting of interbedded thin-beds of sandstone and mudstone; and 3) an approximately 100m thick *upper sandstone unit* consisting of channel-levee deposits (Figure 1.6) (King et al., 1993). Based on foraminiferal microfauna, King et al. (1993) concluded that the strata cropping out between Awakino -and Waikiekie Beach (lower and middle units) was deposited in lower to middle bathyal depths.

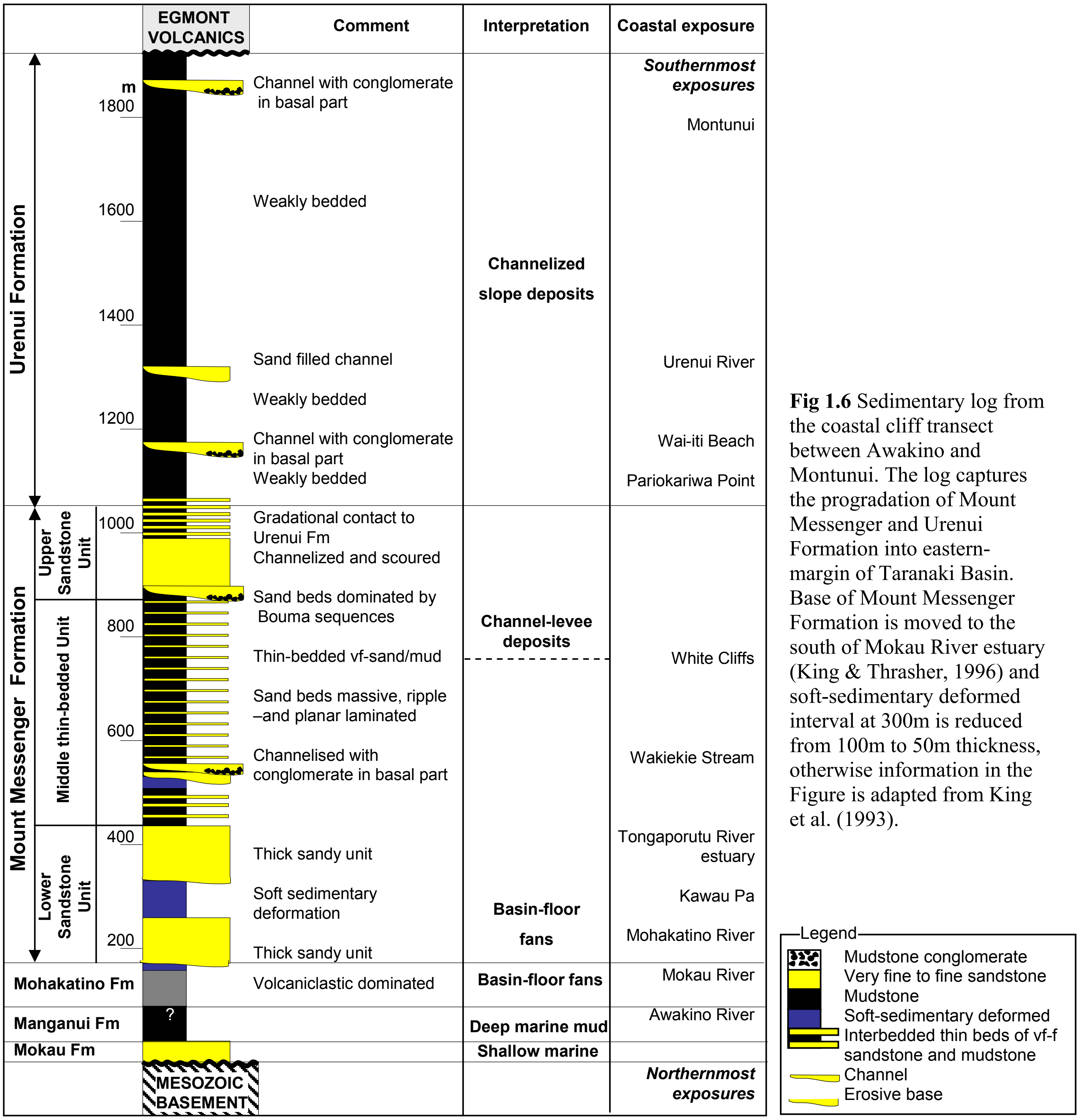


Fig 1.6 Sedimentary log from the coastal cliff transect between Awakino and Montunui. The log captures the progradation of Mount Messenger and Urenui Formation into eastern-margin of Taranaki Basin. Base of Mount Messenger Formation is moved to the south of Mokau River estuary (King & Thrasher, 1996) and soft-sedimentary deformed interval at 300m is reduced from 100m to 50m thickness, otherwise information in the Figure is adapted from King et al. (1993).

2. Lithofacies and lithofacies associations

A total of 4 lithofacies associations are recognized; 1) *massive sandstone association (MSA);* 2) *heterolithic association (HA);* 3) *finely-laminated sandstone association (FLSA);* and 4) *deformed association (DA)* (Enclosure 1-4). The detailed study area has earlier been described by (King et al., 1993, 1994).

2.1. Massive sandstone association

Medium to thick beds of massive very fine to fine grained sandstone interbedded with very thin to thin beds of mudstone interpreted as deposits from gravity-flows with a laminar flow component interbedded with hemipelagic background sedimentation.

Description; The massive sandstone association (Figure 2.1, Enclosure 1 & 2) has a sandstone: mudstone ratio of approximately 9:1 (Browne et al., 2000) and consists of thick-bedded sandstone lithofacies, mudstone conglomerate lithofacies and mudstone lithofacies (Table 2.1). The association is underlain by the deformed association (Enclosure 1 A) and grades upwards into the heterolithic association or is erosively overlain by the deformed association.

Thick-bedded sandstone lithofacies; the lithofacies consists of dark grey, medium to thick-beds (typically 0.7m, max thickness of approximately 4.0m) of well sorted, very fine to fine grained sandstone (Figure 2.1). The beds have sharp to erosive bases (Figure 2.1 B) and tops and are in places amalgamated (Enclosure 1 D). Where erosive, the relief of is commonly 10cm, but relief of up to 1 meter occurs. Non-erosive relief are expressed as dewatering structures (centimeters to 10's of centimeters scale, Enclosure 1 B) and flame/load structures (centimeters scale).

The beds are generally massive, but weak planar lamination (Figure 2.1 C), rare convoluted bedding and rare ripple topped beds occur. There is little grain-size variation within and between beds. Sub-angular to sub-rounded, individual floating, millimeters to centimeters scale mudstone clasts with longest apparent axis oriented parallel to bedding are frequent at all levels in sandstone beds.

Table 2-1 Description and interpretation of lithofacies.

Lithofacies	Lithology	Sedimentary structures	Bouma divisions	Sedimentary texture/ mineralogy	Thickness	Geometry	Color	Bounding surfaces	Interpretation
Thick-bedded sandstone lithofacies (S_{TK})	Very fine to fine grained sandstone	Commonly massive (non-graded). Rare current rippled tops and weak planar lamination. Convoluted bedding, some scours. Dewatering structures. Mudstone clasts with longest axis parallel to bedding	A , (B)	Mostly quartz, microcline, some mica, angular, clast supported grains.	Medium to thick bedded. Up to 400cm thick packages caused by amalgamation	Sheet/lobe shaped, individual beds pinch out in outcrop, others are truncated by or onlap scours and channel margins.	Dark colored	Sharp to erosive bases and tops with erosive relief of up to 1m. Flame/load structures with relief of a few cm, dewatering processes have caused relief up to 40cm	Laminar flow component; deposits of high-density turbidity currents, liquefied-flow, debris flows or aggradation under turbulent flow
Thin-bedded sandstone lithofacies (S_{TN})	Very fine to fine grained sandstone	Massive, planar laminated, current ripple lamination with rare climbing ripples. Few classical Bouma sequences	A, B, C	Mostly quartz, microcline, some mica, angular, clast supported grains	Very thin to thin bedded	Sheet or lobe shaped, compensation style bedding	Dark colored	Sharp to occasionally erosive bases and tops. Relief commonly a few cm	High-density turbidity current or debris flow deposits
Finely-laminated sandstone lithofacies (S_{FL})	Coarse silt to fine grained sandstone. Dominated by very fine to fine grained sandstone	Planar, ripple –and climbing ripple laminated, occasional normal graded beds	A, B, C	Mostly quartz, microcline, some mica, $CaCO_3$. Angular, clast supported grains	Thin to thick bedded	Individual beds often difficult to detect, scours common	Grey/green colored	Difficult to detect, tops and bases sharp to erosive	Deposition from turbulent flows
Mudstone lithofacies (M)	Mudstone	Few depositional structures, intensely bioturbated. Occasional planar lamination.			Very thin to thin bedded	Tabular, beds completely eroded in places	Light colored	Sharp to erosive tops and sharp bases. Flame/load structures, relief range from mm to a few 10's of cm	Hemipelagic settling or fall-out of sediments brought into suspension by gravity flows
Mudstone conglo-merate lithofacies (CGL)	Sandy, mudstone conglomerate, shell fragments in places	Apparent longest axis parallel to bedding		Sub-angular to subrounded, matrix and clast supported	Thin to thick bedded	Commonly confined within scours width 10cm to 100m, depth 10cm to 3m	Clasts light colored, matrix dark colored	Erosive bases and tops	Ripped-up from underlying mud by erosive gravity-flows and deposited a short distance down-dip
Deformed lithofacies (D)	Mud dominated, blocks of very fine to fine grained sandstone	Soft-sedimentary deformation expressed as folding and faulting			Thick to very thick bedded	Confined within slump scar or convex upper surface	Mudstone light colored. Sandstone blocks dark colored	Erosive bases and tops	Slump-flow deposits
Tuffaceous lithofacies (T)	Very fine to medium grained tuff	Intensely bioturbated, occasional preserved normal grading		Sub-rounded	Very thin bedded	Panar, beds traceable for 100's of m, lithofacies locally eroded	White	Sharp	Fall-out of suspended volcaniclastics following a volcanic eruption

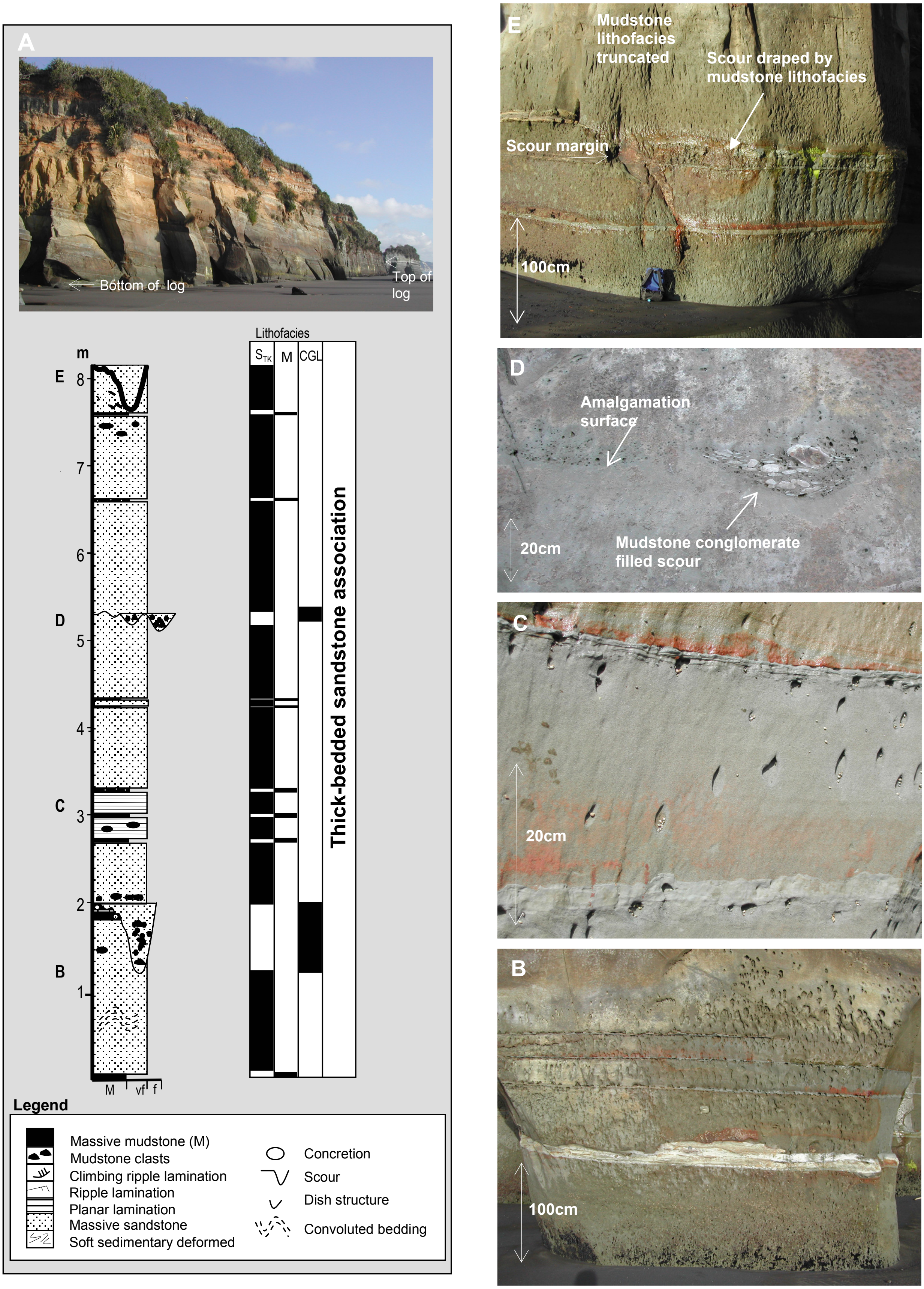


Fig. 2.1 Sedimentary log of the massive sandstone association <u>**A:**</u> Sedimentary log and overview of locality at Tongaporutu Beach. Cliff 15m high. B-E on log refer to photos B-E. <u>**B:**</u> Top of mudstone lithofacies commonly have erosive relief. <u>**C:**</u> Thick-bedded sandstone lithofacies are mainly massive, but weak planar lamination occur. <u>**D:**</u> Mudstone conglomerate lithofacies filled scour grading laterally over to amalgamation surface. <u>**E:**</u> Thick-bedded sandstone lithofacies in scour draped by mudstone lithofacies. Mudstone lithofacies truncated.

Individual beds are traceable for over 100m, but the minor 3D control limits the possibility to document the full geometry. However, individual sandstone beds are observed to pinch-out and they are therefore likely to construct sheet or lobe shapes. At some localities, beds are truncated by, or onlap scours or channel margins (Enclosure 1 C).

Mudstone conglomerate lithofacies; the lithofacies consist of very thin to thick-bedded, clast/matrix supported mudstone conglomerate with a matrix of very fine to fine grained sandstone (Figure 2.1 D, Enclosure 2 A). The lithofacies commonly has low matrix content. Clasts are sub-angular to sub-rounded and have spherical to elongated shapes. Clast sizes are in the scale of millimeters to 10's of centimeters and commonly have longest apparent axis oriented parallel to bedding. The mudstone conglomerates are confined within scours (width=0.3-100m, depth=0.2-3m)

Mudstone lithofacies; the mudstone lithofacies consist of very thin-bedded to thin-bedded (typically 7cm), light colored, bioturbated mudstone beds without depositional structures.

The lithofacies has sharp bases and sharp to erosive tops. The erosive relief is commonly a few centimeters but mudstones are locally completely eroded. Non-erosive relief of tops and bases are expressed as dewatering structures (centimeters to 10's of centimeters scale) (Enclosure 1 B) and flame/load structures (centimeters scale).

Laterally, mudstone beds commonly change to amalgamation surfaces (Figure 2.1 D), mudstone clast horizons or are truncated by scours (Figure 2.1 E). At one locality, the mudstone lithofacies drape the base of a scour, being under and overlain by thick-bedded sandstone lithofacies (Figure 2.1 E).

Interpretation; *Thick-bedded sandstone lithofacies;* The mudstone clasts were ripped up from the sea-floor by erosive gravity-flows. These clasts, the erosive lower contact and the local deformation/erosion of the underlying mudstone lithofacies suggest deposition from a high energy flow.

The un-graded beds and orientation of the clasts suggest the lithofacies was deposited from a flow (or from a part of a flow) with laminar flow component (i.e. high-density turbidity current (sensu Lowe, 1982), liquefied-flows, sandy debris-flows (Shanmugam, 2000), or aggradation below a bypassing turbulent flow (Kneller & Branney, 1995)).

The non-erosive relief is a result of loading of the underlying sediments during and after deposition of a gravity flow. The weak ripple laminated tops may indicate post-depositional reworking by bottom currents or represent reworking by the waning tail or suspension cloud of the gravity-flow (Jordan et al., 1994).

Mudstone conglomerate lithofacies; The immaturity of the mudstone conglomerates and low matrix content reflect short transport. The mudstone clasts are likely to have been ripped-up from underlying mud layers by erosive gravity-flows and deposited after being transported a short distance down-dip.

The *mudstone lithofacies* represent hemipelagic background sedimentation deposited during interflow periods. The truncation and lateral change of mudstone lithofacies into amalgamation surfaces and surfaces with lined rip-up clasts is a result of the different flow modes and erosive strength existing in time and space during transport and deposition of the overlying gravity-flow. The non-erosive relief is a result of loading and water-escape processes generated during and after deposition.

The mudstone lithofacies draped base of scour indicates the flow cutting the scour was bypassing. The mud drape represents background sedimentation deposited between cutting the scour and filling the scour.

2.2. Heterolithic association

Thin beds of very fine to fine grained sandstone interbedded with very thin to thin beds of mudstone interpreted as high-density turbidity current or sandy debris-flow deposits interbedded with hemipelagic mud.

Description; The heterolithic association (Figure 2.2, Enclosure 2 & 3) has a sandstone: mudstone ratio of 7:3 to 6:4 (Browne et al., 2000) and consist of the thin-bedded sandstone lithofacies, mudstone lithofacies and tuffaceous lithofacies (Table 2.1). The association has a gradual lower contact (typically over a few meters) to the underlying massive sandstone association and is overlain by the deformed association.

Thin-bedded sandstone lithofacies: the lithofacies consist of very thin to thin beds of very fine to fine grained sandstone. The beds have sharp to occasionally erosive bases and tops. Where erosive, the contact appears scoured with a relief of up to 30cm. Non-erosive relief are in a scale of millimeters to a few centimeters and is expressed as flame/load structures and dewatering structures (Figure 2.2 D).

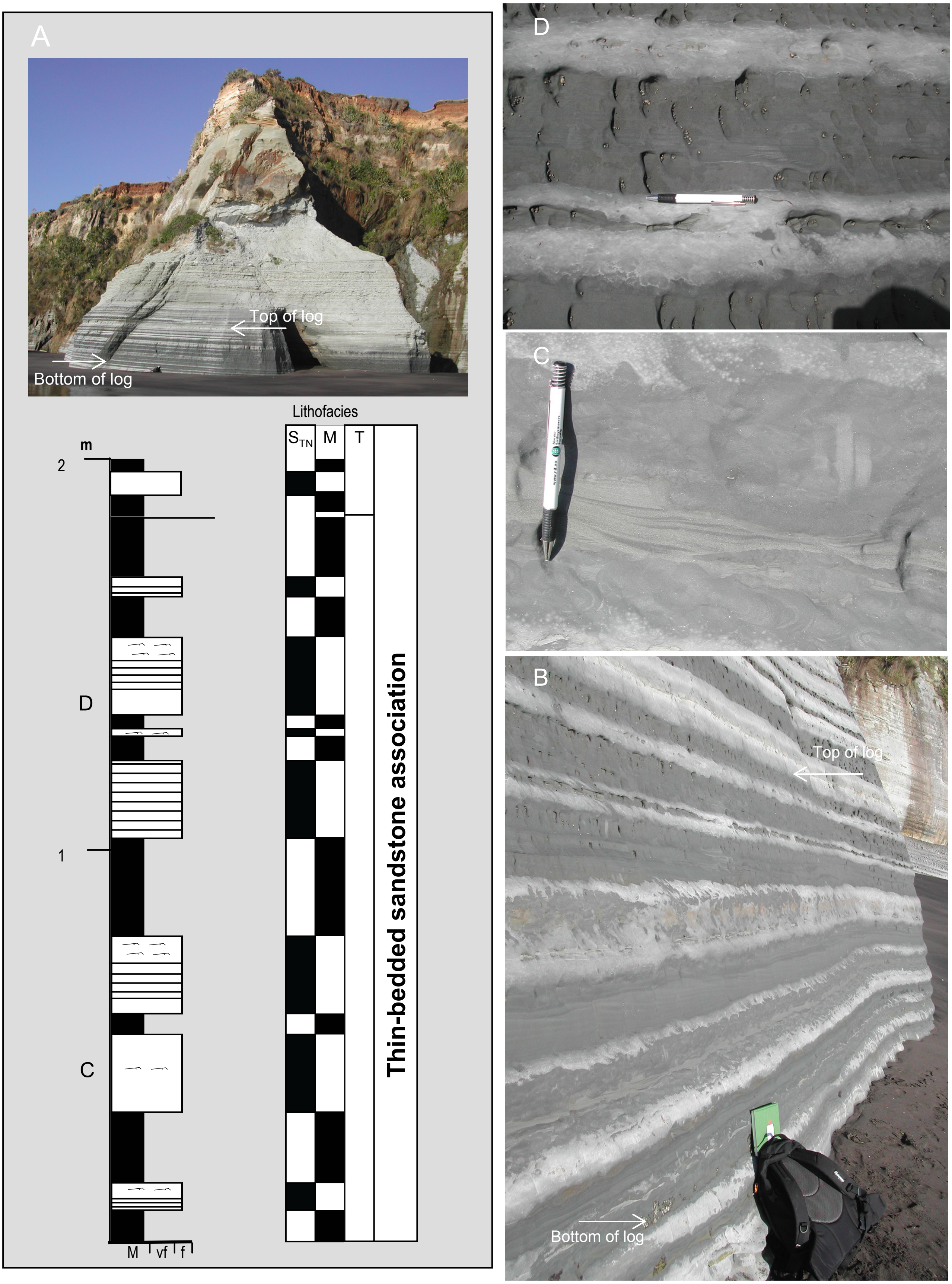


Figure 2.2 Sedimentary log of the heterolithic association. Sandstone dark colored. **A:** Sedimentary log and overview of locality at Waikiekie Beach. C and D on log refer to photo C and D. **B:** Close-up of logged section, fine lamination evident. **C:** Ripple laminated thin-bedded sandstone lithofacies, bioturbation. **D:** Sharp contacts between thin-bedded sandstone lithofacies and mudstone lithofacies. Gentle relief due to loading. See Figure 2.1 for legend.

Sedimentary structures in sandstone beds range from massive, planar lamination, ripple lamination (Figure 2.2 C), and rare climbing ripple lamination, but classical Bouma-sequences are uncommon. The ripple lamination is positioned on top of sandstone beds (Enclosure 2 E). Occasional, individual floating rounded mudstone clasts with radii in a scale of millimeters to a few centimeters occur. There is little grain-size variation within and between sandstone beds.

In the heterolithic association, the beds are commonly stacked in compensation style bedding (Enclosure 2 F) and Browne et al. (1996) found, in a detailed study area at Tongaporutu Beach that approximately 50% of the sandstone beds pinches-out over a distance of less than 100m and that only a few sandstone beds can be traced for more than 200m. Also, the sandstone beds are overall upwards thinning with, in places, minor upwards thinning intervals superimposed (Enclosure 3 A).

Mudstone lithofacies: The *mudstone lithofacies* is very thin-bedded to thin-bedded, light colored, bioturbated and contain rare planar lamination. Tops of mudstone beds are sharp to occasionally erosive with erosive relief of typically a few centimeters, but mudstones are occasionally locally eroded. Non-erosive relief on tops and bases are expressed as flame/load structures, dewatering structures in a scale of millimeters to a few centimeters. White mudstone beds react to HCl acid indicating $CaCO_3$ and some horizons have developed $CaCO_3$-concretions.

In the heterolithic association, the mudstone beds are overall thickening-upwards with, in places, minor upwards thickening intervals of mudstone beds superimposed.

Tuffaceous lithofacies; The tuffaceous lithofacies is very-thin bedded and overlain and underlain by mudstone lithofacies. The lithofacies is very fine to medium grained and intensely bioturbated, however, normal grading is evident in places.

Interpretation; *Thin-bedded sandstone lithofacies:* The low erosion and few mudstone clasts within sandstone beds suggest deposition by low energy flows. The sharp upper contact and lack of normal grading within sandstone beds suggests deposition from a flow with a stepped density profile (sandy debris flow, Shanmugam, 2000) or that the lithofacies represent the basal deposits of a flow bypassing down-dip (high-density turbidity current, sensu Lowe, 1982).

The ripple laminated top of sandstone beds may reflect a change in hydraulic regime during deposition or represent post-depositional bottom-current reworking

(Jordan et al., 1994). The non-erosive relief is likely to have been generated by loading, water-escape processes during and after deposition of the overlying gravity-flow.

The compensational style bedding of sandstone beds results from gravity-flows filling-in topographical lows on the contemporaneous sea-floor. The upwards thinning intervals of sandstone beds each represent waning flow strength in the study area with time.

The few mudstone clasts present and the occasional scoured relief may reflect the up-dip erosive strength of the flow. Further, the gradual transition from the massive sandstone association to the upwards thinning sandstone beds of the heterolithic association suggest a gradual shift in deposition. The thin-bedded sandstone lithofacies may therefore be genetically related to the thick-bedded sandstone lithofacies.

Mudstone lithofacies: The mudstone is interpreted as hemipelagic background sedimentation where the planar lamination represents short variation in amount and type of suspended particles in the water column. The non-erosive relief is a result of loading and water-escape processes generated during and after deposition of the overlying gravity-flow.

Tuffaceous lithofacies; The lithofacies is a result of suspension settling of volcaniclastic material resulting from volcanic eruptions. The deposits were originally normal graded due to different rate of settling with respect to grain size, but were later bioturbated and the grading erased.

2.3. Finely-laminated sandstone association

Finely laminated very fine to fine grained sandstone interpreted as deposits from turbulent flows.

Description; The finely-laminated association (Figure 2.3, Enclosure 4) consists of the finely-laminated sandstone lithofacies and mudstone lithofacies (Table 2.1). The association consists of an approximately 15m thick succession observed north of Waikiekie Stream only. The association has an erosive base with relief of typically 3-5m (max 10’s of meters) expressed as large sand filled scours and injections of sand into the underlying lithology. The section reacts to HCl acid throughout, indicating $CaCO_3$. The succession is over –and underlain by the deformed association but the relief of the upper contact is weathered.

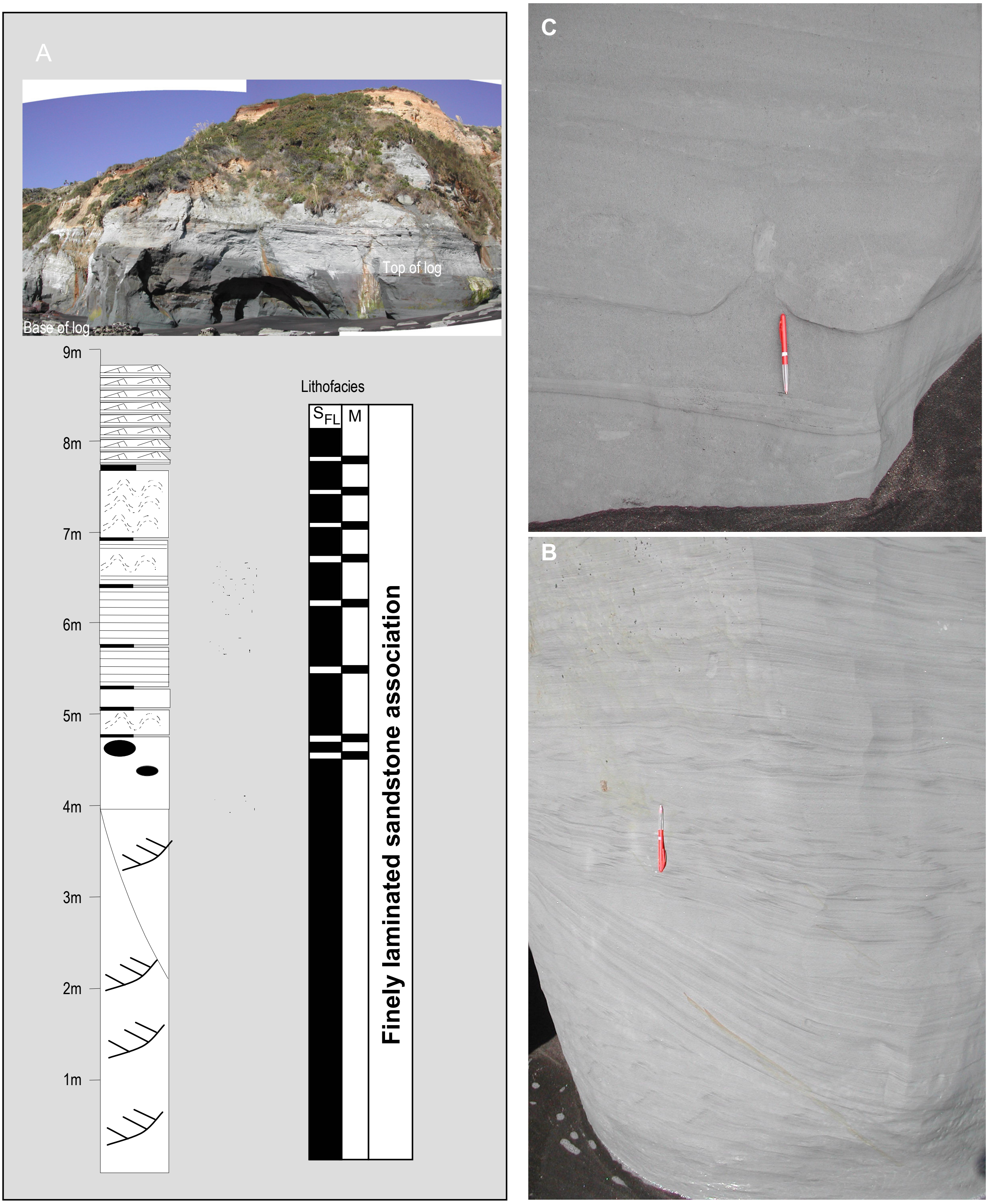


Figure 2.3 Sedimentary log of the finely-laminated sandstone association. **A:** Sedimentary log and overview of locality at Waikiekie Beach. **B:** Scour, ripple and climbing ripple lamination of finely-laminated sandstone lithofacies. **C:** Planar laminated finely laminated sandstone lithofacies. Mudstone lilthofacies are deformed by water-escape processes. See Figure 2.1 for legend.

Finely-laminated sandstone lithofacies: The lithofacies consist of medium to thick-bedded, grey-green, well-sorted finely-laminated coarse-silt to fine grained sandstone. The lowermost interval is dominated by planar lamination where no obvious bedding planes were detected, but scours (width 10's of centimeters scale, depth few centimeters to 10's of centimeters scale) are common. In this interval, concretions reacting to HCl acid, indicating $CaCO_3$, are frequent. The section grades over to a ripple and climbing ripple laminated dominated interval with very fine to fine grained sand filled scours (width centimeters to meters scale, depth centimeters to meters scale).

Above this, beds are distinguishable, have sharp tops and bases that in places are disturbed by dewatering structures and flame/load structures. The beds are planar laminated, contains dish structures, water-escape structures and convoluted bedding. The interval is capped by a few beds with sharp bases and tops grading upwards from planar laminated fine grained sandstone to ripple laminated coarse siltstone.

Mudstone lithofacies: Mudstone lithofacies are absent in the lower interval, but some beds of massive, very thin-bedded mudstone lithofacies are present in the uppermost part of the association. Beds have sharp tops and bases which in places are disturbed by dewatering structures and flame/load structures.

Interpretation; *Finely-laminated sandstone lithofacies:* The scours and injection of the association's lower boundary suggests the lowermost planar laminated interval represents traction structures of high energy flows. The lack of clear bedding planes may either indicate the beds are amalgamated or was aggrading under a continuous flow (steady state flows (Kneller & Branney, 1995)). The scours may either represent erosive pulses within the continuous flow, or actual bedding surfaces of amalgamating surge flows.

The climbing-ripple interval were formed during deposition of turbulent flows and the presence of theses are interpreted to reflect a substantial reduction in the capacity of the flows to carry sand resulting in rapid deposition (Sanders, 1963, 1965). The flows are therefore likely to have been deposited rapidly, possibly by pulsed flows just before, during or just after a hydraulic jump (Browne pers. com, 2003). The scours throughout the section is likely to result from sea-floor erosion of flows in intense turbulence during a hydraulic jump (as suggested by Mutti & Normark (1987) for parts of the Hecho group in Spain). The dish and water-escape structures are likely to have developed as a result of upwards moving water during and after deposition of a flow.

The normal graded beds are indicative of deposition from turbulence and the non-erosive bases suggest deposition from low-energy flows. The overall development from scoured planar lamination to climbing ripple lamination to detectable bedding and non-erosive graded beds may indicate a reduction in flow strength with time.

Mudstone lithofacies; The mudstone lithofacies probably represent settling of suspended material introduced by gravity-flows. The high sandstone: mudstone ratio is either a result of insufficient time to accumulate mud, or that the mud was initially deposited but later eroded by succeeding flows causing amalgamation of sandstone beds.

2.4. Deformed association

Heavily deformed interval commonly overlain by un-deformed, tuffaceous stratified mudstone interpreted as slump-flow deposits draped by slump-flow generated suspended mud stratified with sediments derived from volcanic eruptions.

Description; The deformed association (Figure 2.4, 2.5, Enclosure 3 & 4) consists of deformed lithofacies, mudstone lithofacies and tuffaceous lithofacies (Table 2.1). The deformed association is erosively overlain by the massive sandstone association and commonly erosively overlies the heterolithic association.

Deformed lithofacies; The deformed lithofacies is 0.2-10m thick, commonly mudstone-dominated and contain deformation structures expressed as open, overturned folds (fold width in decimeters to meters scale) (Figure 2.4 C, 2.5) as well as syn-sedimentary normal and compressional faults. The underlying lithology commonly contains up to 0.5m deep mudstone injections and compressional faults with upwards decreasing throw (Enclosure 3 C & D).

In places, the deformed lithofacies contain rounded blocks of massive very fine to fine grained sandstone with radii in a scale of decimeters to meters. The deformed lithofacies is commonly overlain by tuffaceous stratified mudstone (mudstone lithofacies and tuffaceous lithofacies) containing shell fragments, or more rarely, by massive sandstone association. The top of the deformed lithofacies is difficult to detect where overlain by mudstone lithofacies but is sharp and planar where observed. Where overlain by massive sandstone association, the contact is erosive. The lithofacies has an erosive base with relief of commonly a few meters (Enclosure 4 D & E).

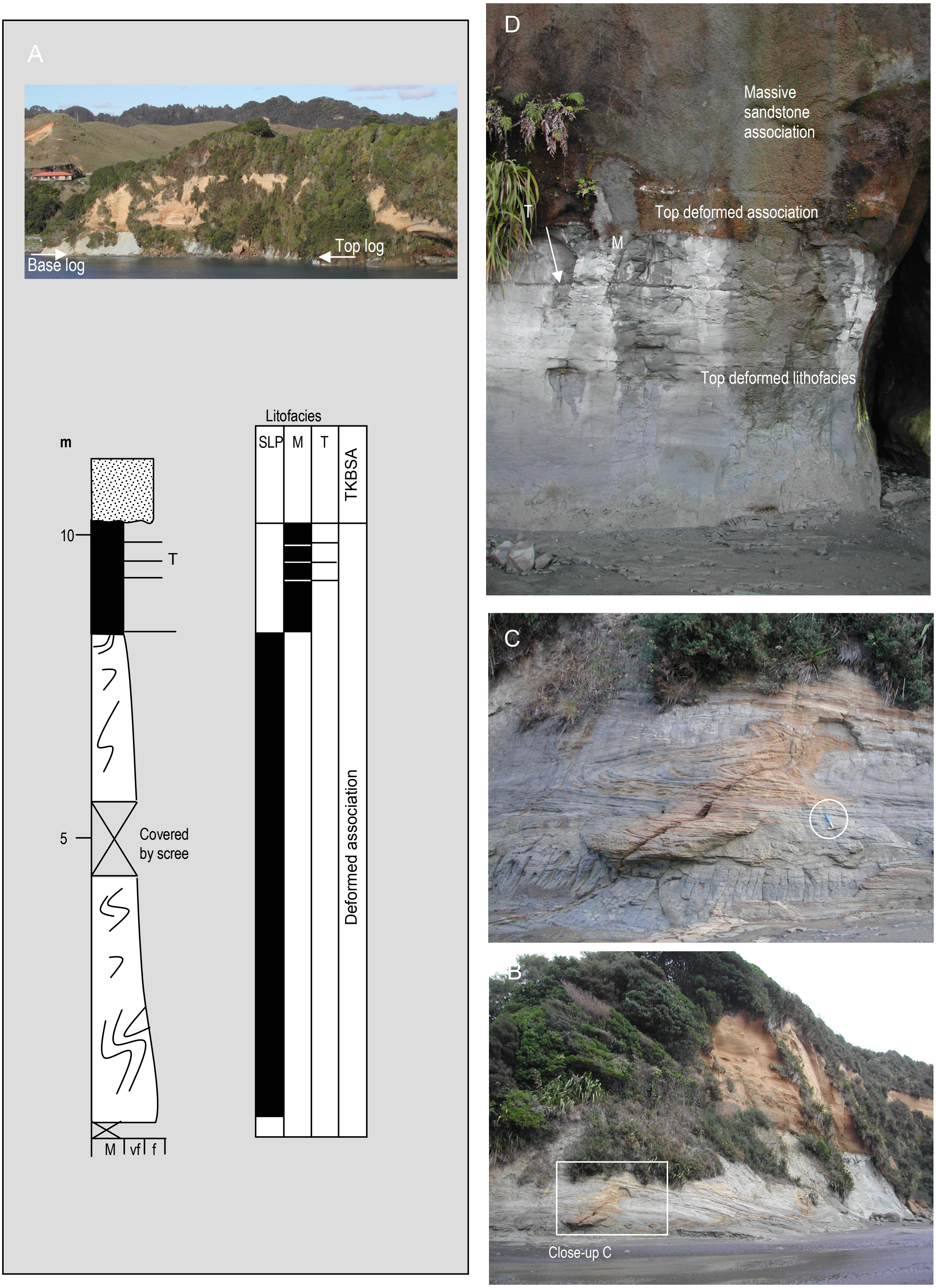


Figure 2.4 Sedimentary log of the deformed association. **A:** Sedimentary log and overview of locality at Tongaporutu River estuary. **B:** Close+up of locality **C:** Overturned fold in deformed lithofacies **D:** Deformed lithofacies is capped by tuffaceous stratified mudstone. See Figure 2.1 for legend.

Figure 2.5 Soft-sedimentary folding of the deformed association. Locality just north of Omahu Pa.

Mudstone lithofacies; The mudstone lithofacies consist of very-thin to thin-bedded, light colored mudstones with shell fragments. The lithofacies contain weak planar lamination and has sharp tops where overlain by tuffaceous lithofacies, or erosive tops where overlain by massive sandstone association (Enclosure 1 A). The base is difficult to detect where underlain by deformed lithofacies, but is planar and sharp where observed.

Tuffaceous lithofacies; The tuffaceous lithofacies is very-thin bedded, very fine to medium grained, intensely bioturbated and overlain and underlain by mudstone lithofacies (Figure 2.4).

Interpretation; *Deformed lithofacies;* The overturned folds and erosive base indicate transport and deposition of a flow. The high mud content, deformed internal stratification and large sandstone blocks suggests deposition of semi-consolidated sediments from a cohesive flow. It is therefore likely the deformed association represent deposits from a slump-flow. However, some of the soft-sediment deformation in upper part of the association may be attributed to loading by the overlying massive sandstone association. The erosive relief of the deformed association's lower contact and the injections, deformation and compressional faults in the underlying strata suggest deposition from a slump-flow with relative high competence.

Mudstone and tuffaceous lithofacies; The tuffaceous stratified mudstones are un-deformed and may have been deposited over a long period of time or as several shorter events. In the former alternative, the mud drape might be interpreted as background deposition interbedded with deposits from volcanic eruptions. In the latter alternative, the lowest part of the stratified mudstone might have been deposited from the suspension cloud generated by the underlying slump itself. After a volcanic eruption - (also possibly triggering slumping) - and deposition of the tuffaceous lithofacies, slumping occurs in a different area. The extensive suspension cloud generated drapes over a large area including the area for the first slumping.

Provenance area; Slump-flows may travel long distances on low angle slopes during hydroplaning or if they have a pseudo-plastic rheology, they may deposit on the same gradient as the gradient of the area were initiated. This makes it difficult to estimate the actual travel distance for slump-flows based on their deposits, especially as the up-dip slump scars are not exposed/preserved and the depositional dip on the paleo basin-floor is unknown.

However, slump-flows are gravity driven and therefore dependant on a certain sea-floor gradient to be initiated and transported. Also, the abundance of mudstone in the deformed associations reflects a mud dominated provenance area. Further, the association contains rafted blocks of sandstone, is commonly underlain by the heterolithic association and overlain by the massive sandstone association. The latter suggests that the onset of sand deposition and the onset of slumping have the same genetic origin, - *or* that the slumping controlled where sand deposition in the basin occurred. Both alternatives include proximity to a system transporting sand from the shelf and continental areas to the basin-floor (i.e. the slope). It is therefore unlikely that the slump-flows were initiated at sub-marine highs on the basin-floor as no sand would be expected on such highs. The slump-flows was probably initiated on the time-equivalent, mud-rich slope similar to younger Urenui Formation which therefore represent a good analogue for the provenance area for the slumps of Mount Messenger Formation.

3. Architectural elements

3 types of 3D architectural elements are recognized; 1) massive sandstone association or finely laminated sandstone association dominated *sandstone elements (SE);* 2) heterolithic association dominated *heterolithic elements (HE);* and 3) deformed association dominated *deformed elements (DE)* (Figure 3.1). A total of 12 architectural elements and 4 architectural sub-elements are recognized (Figure 3.2).

Figure 3.1 Aerial photo showing a selection of architectural elements and their appearance in the coast near outcrops just south of Tongaporutu River estuary. Photo by Peter King.

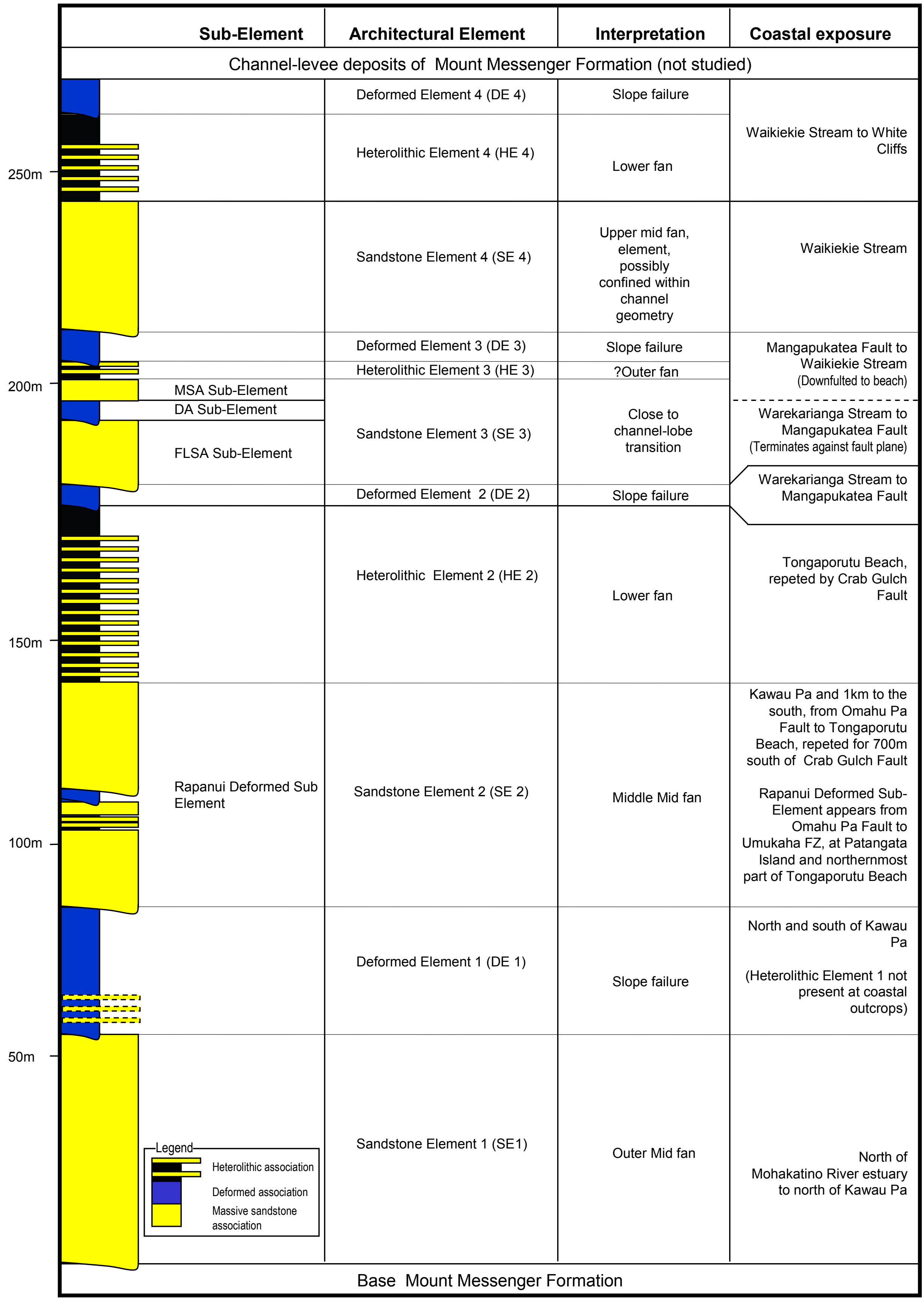


Figure 3.2 Summary log of architectural elements cropping out between Mokau River estuary and White Cliffs. Modified from King et al. (1993, 1994). Faults and locations referred to in figure marked on Figure 3.3.

The mapping of architectural elements is largely based on the distinct and extensive traceable deposits of the deformed elements. The sharp boundary between the deformed elements and the overlying sandstone elements can be traced over distances for up to 10's of kilometers and has been used as stratigraphic markers to correlate inland from the coastal outcrops.

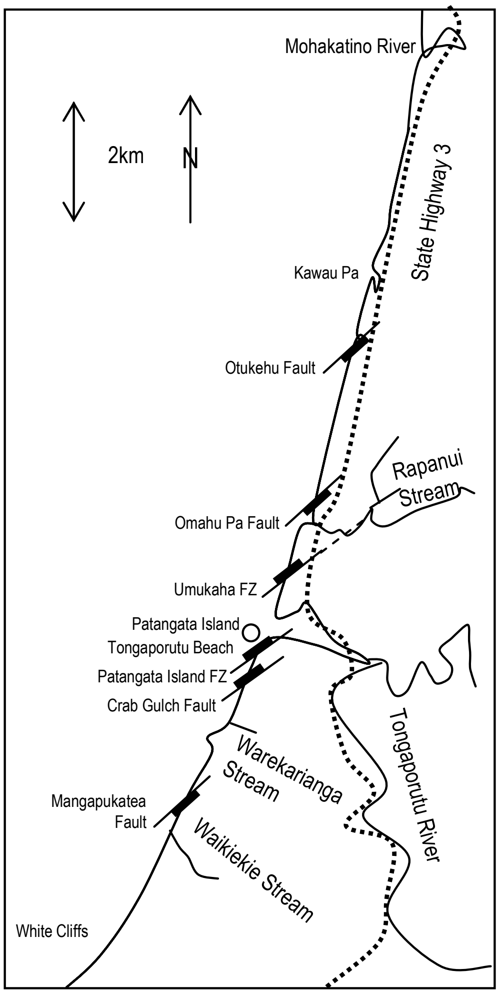


Figure 3.3 Map of faults dissecting the coast

The study area is dissected by several north-east — south-west striking extensional faults with up to 50m throw that locally repeats sections. These include, from the north toward the south; Otukehu Fault (050/60→SE), Omahu Pa Fault (050/60→SE), Umukaha Fault Zone (230/60→NW), Patangata Island Fault Zone (230/60→NW), Crab Culch Fault (230/60→NW) and Mangapukatea Fault (050/60→SE) (Figure 3.3, Enclosure 6). These faults add an extra element of uncertainty to correlations within the study area. With the exception of Mangapukatea Fault, the faults dissect the coastal exposures of Sandstone Element 2 and are described in this chapter (Chapter 3.4). Beds on either side of Mangapukatea Fault cannot be correlated in the coastal cliffs.

Even if Walker's (1978) and Normark's (1978) classic model for basin-floor fans not necessary applies to the Mount Messenger depositional system, Walker's (1978) and Normark's (1978) terminology has been used for interpreting mid fan and lower fan environments. In this model, the *upper mid fan* is dominated by relatively deep channel geometries; the *middle mid fan* by shallow channel geometries; the *outer mid fan* by unchannelised thick-bedded sheet sandstone; and the *lower fan* by unchannelised interbedded thin beds of sandstone and mudstones. The following description is presented from the north towards the south and in stratigraphically ascending order;

3.1. Sandstone Element 1

Un-channelised, massive sandstone association dominated architectural element thinning towards the north and south-east interpreted as a basin-floor fan. Coastal outcrops interpreted as outer mid-fan environment.

Description; Sandstone Element 1 is dominated by the massive sandstone association (Figure 3.2). The northernmost exposures of Sandstone Element 1 are located in the hillsides just south of Awakino, inland of Seaview Motorcamp where it interfingers with the volcaniclastics of Mohakatino Formation and crops-out with an estimated thickness of 15m (Figure 3.4, Enclosure 5 A). Sandstone Element 1 thickens towards the south and has an estimated thickness of 60m at Mokau River (Enclosure 5 B) and 80m at Hutawai/Roa Valleys. From these localities, the element thins towards the south-east up Tongaporutu Valley and has an estimated thickness of 15m in the in the Mangatoro Valley and 5m just north of Kiwi Road (Enclosure 6). Sandstone Element 1 therefore has a minimum extent of 25km in the north-south direction and 14km in the east-west direction.

At the coastal cliffs, the element erosively overlies the estimated 7m thick base Mount Messenger slump and is exposed from just north of *Mokau River estuary to Kawau Pa* (Enclosure 5 C). Here the element is dominated by sheet sand with rare, shallow channel geometries (meter deep). The lower boundary of Sandstone Element 1 appears to be planar in outcrop scale, however, the 3D control is limited.

Interpretation; The thinning toward the north and south-east suggests Sandstone Element 1 has sheet or lobe shaped geometry

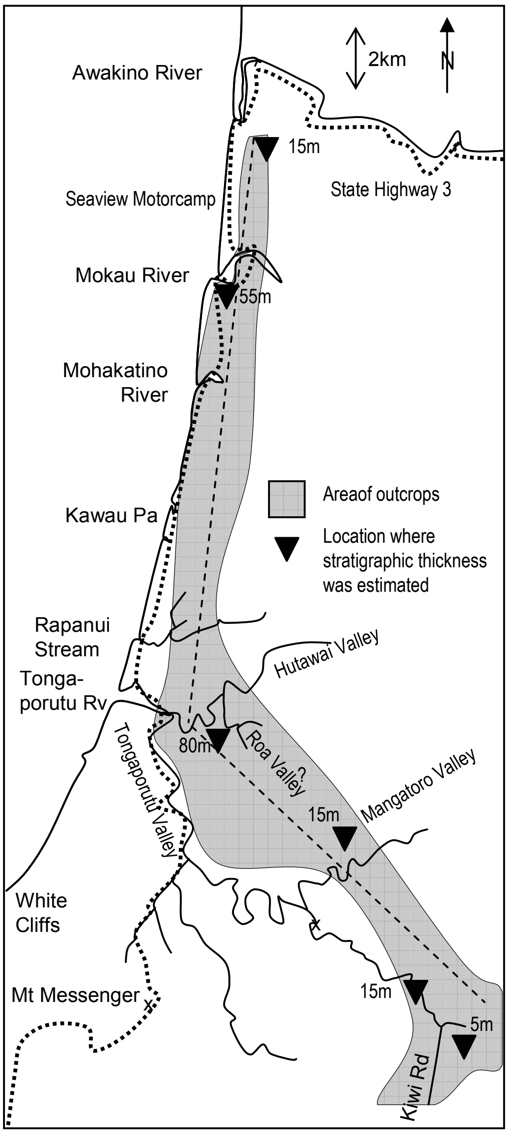


Figure 3.4 Outcrop map of Sandstone Element 1.

and is therefore interpreted as a basin-floor fan. The positions to the north and south-west, where the element is thin are likely to represent marginal positions of the fan. The element is thickest at the Hutawai/Roa Valley and these areas are likely to represent axial positions of the fan.

In the coastal outcrops, the dominance of sheet sand and the absence of channel geometries is interpreted to reflect an outer mid-fan depositional environment in the terminology of Normark (1978) and Walker (1978).

3.2. Heterolithic Element 1

Heterolithic association dominated, laterally confined architectural element interpreted as lower-fan deposits.

Description; Heterolithic Element 1 is dominated by the heterolithic association (Figure 3.2). The only exposure of Heterolithic Element 1 is located along State Highway 3, south of Tongaporutu River estuary where it is approximately 15m thick (Figure 3.5 & 3.6). The element can be traced a few kilometers up Tongaporutu Valley as a vegetated flattening of topography, however, the element is not present at north side of Tongaporutu River estuary (Figure 3.7) or the coastal cliff transect north of Tongaporutu River estuary. The element might be present in Rapanui Valley but was not observed, possibly due to vegetation.

Interpretation; Based on the low sandstone: mudstone content of the heterolithic association, the lack of observed channel-levee geometries and the interpretation of Sandstone Element 1 as

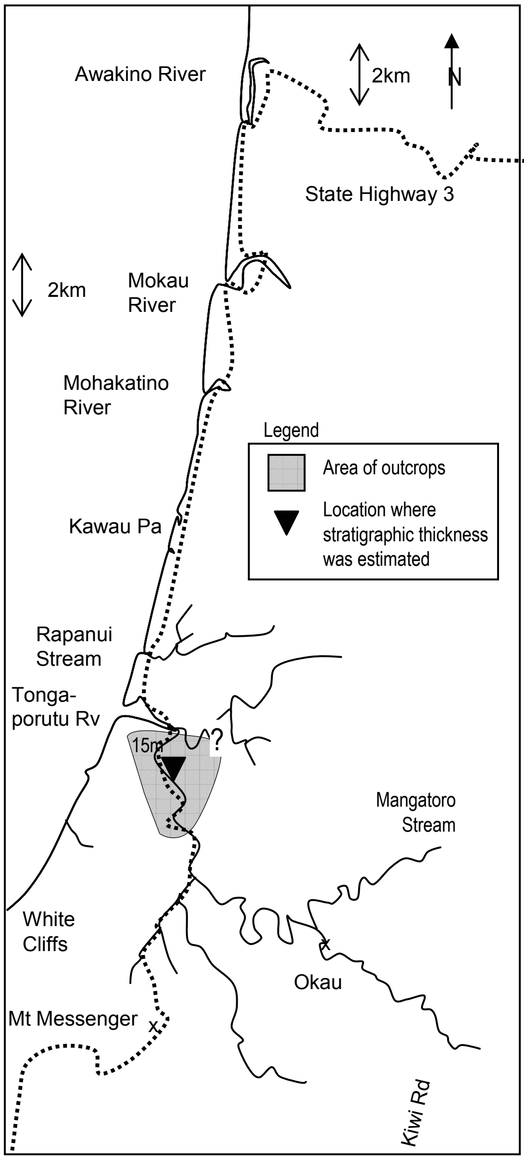
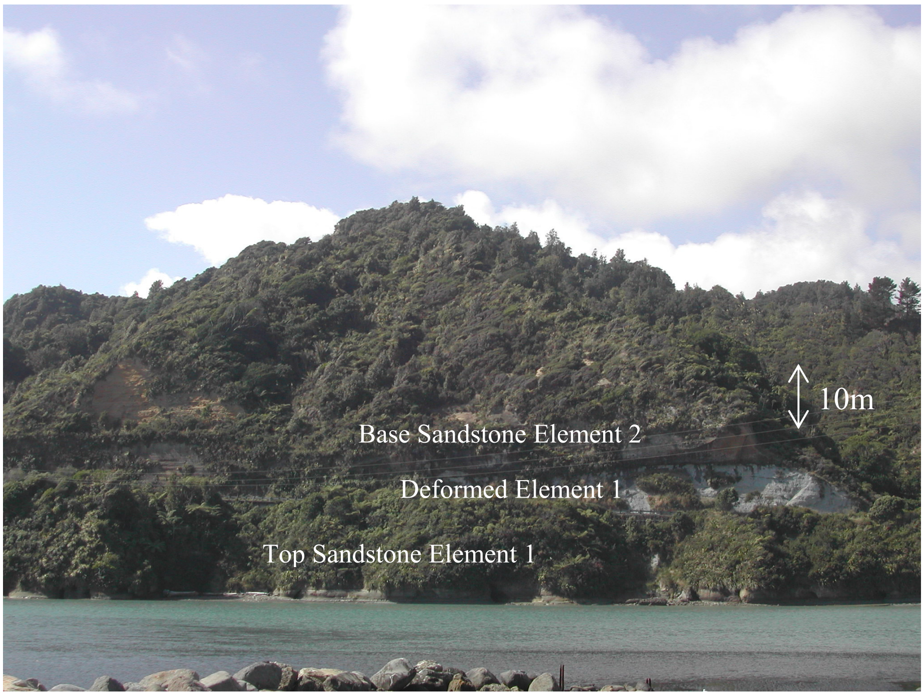


Figure 3.5 Outcrop map of Heteregeneous Element 1.

outer mid-fan deposits, Heterolithic Element 1 is interpreted to represent lower-fan environment. As the element is not observed to the north, it is either laterally equivalent to the massive sandstone association at top of Sandstone Element 1, or has been eroded by the overlying Deformed Element 1.

Figure 3.6 Exposure of Heterolithic Element 1 at State Highway 3, just south of Tongaporutu River estuary.

Figure 3.7 Heterolithic Element 1 is not present at northern bank of Tongaporutu of Tongaporutu River estuary.



3.3. Deformed Element 1

Deformed association dominated architectural element thinning toward the south interpreted as deposits resulting from slope failure. The element is laterally confined with axial positions to the north.

Description; Deformed Element 1 is dominated by the deformed association (Figure 3.2). The northernmost exposures of Deformed Element 1 are located in the hillside above the southern bank of Mohakatino River estuary where it has as estimated thickness of 30m (Figure 3.8, Enclosure 5 D1 & D2). However, the element has not been traced further towards the north and its relation to Mohakatino Formation is not documented.

The section along the abandoned coastal cliffs just south of Mohakatino River is tectonically complex with tilted blocks of massive sandstone association, but the vegetation makes it difficult to decide if the rotation is syn -or post-sedimentary. However, based on the structural strike of the area (170-180°) it seems likely that the section exposes to the upper part of Deformed Element 1.

At the coastal cliffs, the element erosively overlies Sandstone Element 1 (Enclosure 5 E) and is exposed north and south of *Kawau Pa* (Enclosures 5 G). Here, structural analysis indicates Deformed Element 1 was traveling towards the south-west (King pers. com, 2003).

At State Highway 3 just south of Tongaporutu River estuary, Deformed

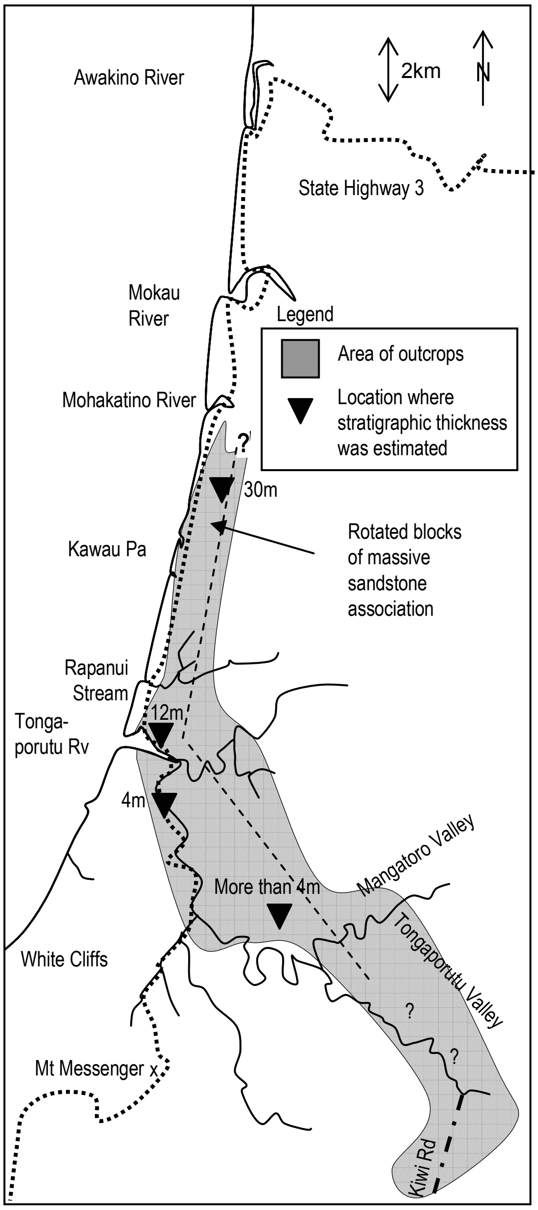


Figure 3.8 Outcrop map of Deformed Element 1.

Element 1 is much thinner (4m) and overlies Heterolithic Element 1 (Figure 3.7).

The element can be traced discontinuously for 12km towards the south-east up Tongaporutu Valley (Enclosure 6). If these correlations are correct element has a minimum surface area of 45km^2.

Interpretation; The thinning toward the south suggest an axial position for the element close to or north of Kawau Pa, whereas more marginal positions are believed to occupy the localities at, and south of, the exposures along State Highway 3. The highly erosive lower boundary suggests the element is at least partially confined within a slump scar.

The element may have eroded through an initially underlying Heterolithic Element 1 in axial parts whereas Heterolithic Element 1 was preserved in more marginal positions *or* Heterolithic Element 1 is laterally equivalent to uppermost part of Sandtone Element 1. As the element was traveling towards the south-west (King pers. com, 2003), the north-south trending coastal transect represent a section oblique to the slump scar axis. The element is interpreted as deposits resulting from slope failure (see chapter 3.4).

The large deformed blocks of massive sandstone association in the upper part of Deformed Element 1 suggest the sand was deposited on the basin-floor before being deformed. The deformation may be a result of direct seismic disturbance of the sea-bed (King pers. com. 2003) -*or* renewed movement along the underlying slump scar due to seismic activity or oversteepening.

If the time of Deformed Element 1 deposition in general was a time of slumping, the exposures of deformed associations up Tongaporutu Valley might be time equivalent, but may not represent the same slump-flow. This makes the actual extent of the element uncertain.

3.4. Sandstone Element 2

Partly channelised, massive sandstone association dominated architectural element thinning toward the north and south-east interpreted as a basin-floor fan. Coast near outcrops interpreted as middle mid-fan environment.

Description; Sandstone Element 2 is dominated by the massive sandstone association and the deformed association (Figure 3.2). The northernmost exposures of Sandstone Element 2 are located in the hillsides above the southern bank of Mokau River estuary where it interfingers with the volcaniclastics of Mohakatino Formation and has an estimated thickness of 25m (Figure 3.9, Enclosure 5 B).

Further to the south, at the pull-in resting area just north of Kawau Pa there is a massive sandstone association filled channel complex (Enclosure 5 F). The channels are a few meters deep and the lower boundaries of channels have erosional relief of a few meters.

The abandoned coastal cliffs transect between Kawau Pa and Rapanui Valley is exposed along strike (180°) and possibly channelised but this is not documented due to vegetation. Sandstone Element 2 is exposed in Rapanui Valley where some meters deep channel geometries occur on the south side of the valley.

At the coastal cliffs, the element appears from Kawau Pa (Enclosure 5 H) to 1 kilometer toward the south, between Omahu Pa Fault and Tongaporutu Beach and is repeated along a short stretch south of

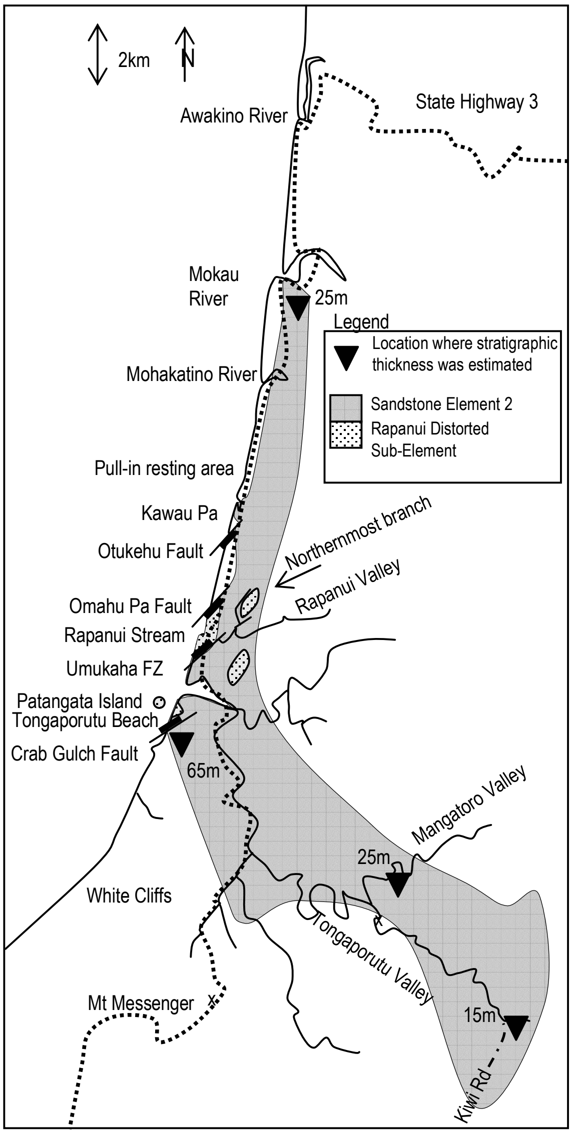


Figure 3.9 Outcrop map of Sandstone Element 2. Dotted area represents exposures of Rapanui Deformed Sub-Element.

Crab Gulch Fault (Figure 3.1 & 3.9, Enclosure 5). The section is dominated by sheet sands with occasional scours. 3 paleocurrent measurements from scour axis trend roughly south-east — north-west whereas 1 paleocurrent measurement from climbing ripples within scour indicate transport of sediments towards the north- west.

Parts of Sandstone Element 2 are more or less continuously exposed from Tongaporutu River estuary towards the south-east to north of Kiwi Road, 15km up Tongaporutu Valley where it crops out with a thickness of about 15m (Enclosure 6). The element therefore has an extent of 25 kilometers in the north-south direction and 14 kilometers in the east-west direction. Sandstone Element 2 has a gradual contact to the overlying Heterolithic Element 2. The lower contact of Sandstone element 2 may have a concave down lower contact in the area near Tongaporutu River estuary, however, the 3D control is limited (see discussion later this chapter).

Rapanui Deformed Sub-Element; the sub-element is dominated by the deformed association. The northernmost exposure of the sub-element is located in the northern branch of Rapanui Valley where it is partly exposed and has an estimated thickness of 5-10m (Figure 3.9, Enclosure 5 I). The element is poorly exposed/preserved elsewhere in Rapanui Valley.

At the coastal cliffs, the sub-element appears between Omahu Pa Fault and Umukaha Fault Zone, at Patangata Island and at northern end of Tongaporutu Beach (Figure 3.9). The sub-element thins from being about 6m at Rapanui Stream, to 2-3m at Patangata Island and pinches-out to a 30cm mudstone horizon at northern end of Tongaporutu Beach (Figure 3.10). The sub-element was not observed in Tongaporutu Valley, which may indicate it was a traveling toward south-west, as Deformed Element 1, however, vegetation makes this uncertain.

The sub-element thickens more than it erodes down towards stratigraphic lower lying heterolithic association exposed both at Rapanui Stream and Patangata Island. Consequently the upper contact is likely to have a convex-up profile. Also, the erosional relief of the upper boundary increases with the thickness of the sub-element; from being sub-planar in the south to 10 centimeters in the north. Some structures (planar laminated deformed mudstone lithofacies) are preserved at Patangata Island (Figure 3.10 B).

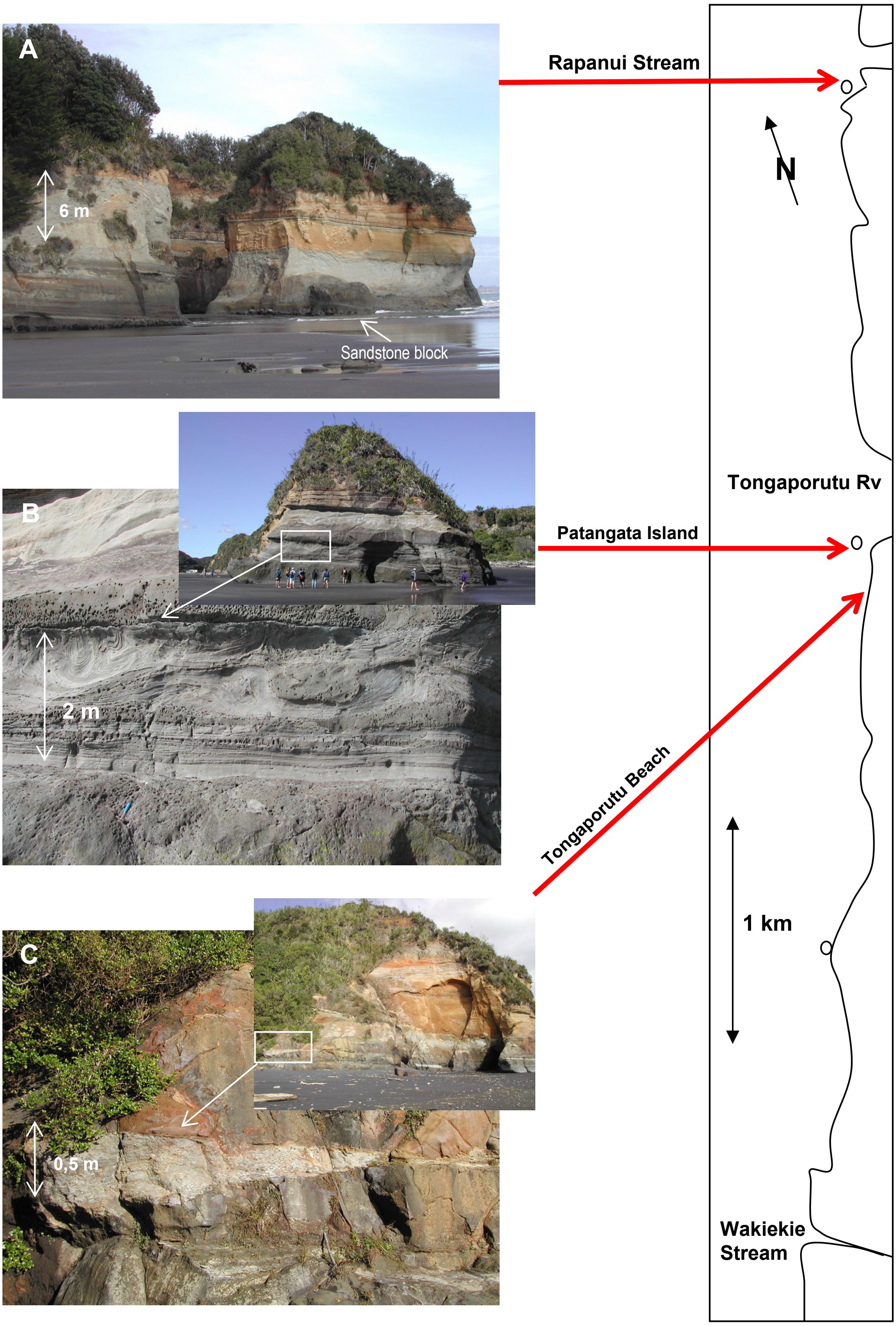


Figure 3.10 Lateral development (north-south) of Rapanui Deformed Sub-Element over a distance of 2.5km. **A:** At Rapanui Stream, the sub-element is 6m thick and contains large (radii in the scale of meters) rounded boulders of very fine to fine sandstone. **B:** At Patangata Island, the sub-element is 2-3m thick and contains deformed planar lamination in lower part (planar laminated interval part of a fold). **C:** At Tongaporutu Beach, the sub-element wedges-out into a 30cm thick mudstone horizon.

The internal deformation of the sub-element increases with the thickness toward the north, where large rounded (radii=metres) rafted sandstone boulders are present. Unlike most deformed associations, Rapanui Deformed Sub-Element is underlain by the massive sandstone association and has no tuffaceous stratified mud drape.

Interpretation; The thinning of Sandstone Element 2 toward the north and south-east suggests a sheet or lobe shaped geometry and the element is interpreted as a basin-floor fan. The positions to the north and south-west, where the element is thin are likely to represent marginal positions of the fan. In the coast near areas between Mohakatino River and Tongaporutu River, where the element is thickest and channelised are likely to represent axial positions of the fan. These areas have been interpreted to represent middle mid fan environment due to the migrating channel complex just north of Kawau Pa.

Rapanui Deformed Sub-Element; At Rapanui Stream, where the sub-element is thickest is considered to represent axial positions compared to the exposures at Patangata Island and Tongaporutu Beach. The sub-element's convex-up upper surface suggests that it represented positive relief on the contemporaneous sea-floor and the locations at Rapanui Stream probably represented a higher point on the sea-floor than the lower lying margins. At Rapanui Stream, the upper boundary of the sub-element has therefore been subject to a higher degree of erosion resulting in the higher erosional relief.

The lack of stratified mud drape of Rapanui Deformed Sub-Element may be due to that the only accessible suspended mud was the background sedimentation and the suspended mud generated by Rapanui Deformed Sub-Element itself (see interpretation of stratified mud drape in chapter 2.4). This may indicate there were few other slumping events in this part of Taranaki Basin at the time, possibly implying that Rapanui Deformed Sub-Element represent an independent event of slope failure, not initiated by the same mechanisms as the mud draped slumps.

However, the lack of stratified mud drape may simply be due to that there was no time for accumulation of suspended mud *or* the drape was later subject to a high degree of erosion due to the sub-element's positive relief on the sea-floor. It is difficult to distinguish between different triggering mechanisms for slumping based on slump-flow deposits and it is presently not possible to distinguish between the above models. The sub-element is interpreted as deposits resulting from slope failure.

Correlation between Kawau Pa and Tongaporutu River estuary; *Kawau Pa to Omahu Pa Fault (Enclosure 7);* The coastal cliff transect section from Kawau Pa to Omahu Pa Fault (Figure 3.11) is dominated by deformed element(s) containing intra-formational deformation of massive sandstone association and sandstone element(s) (Enclosure 7 A1 & A2) (King et al., 1993). Also, the area is tectonically complex with dissecting faults and the stretch between Otukehu Fault and

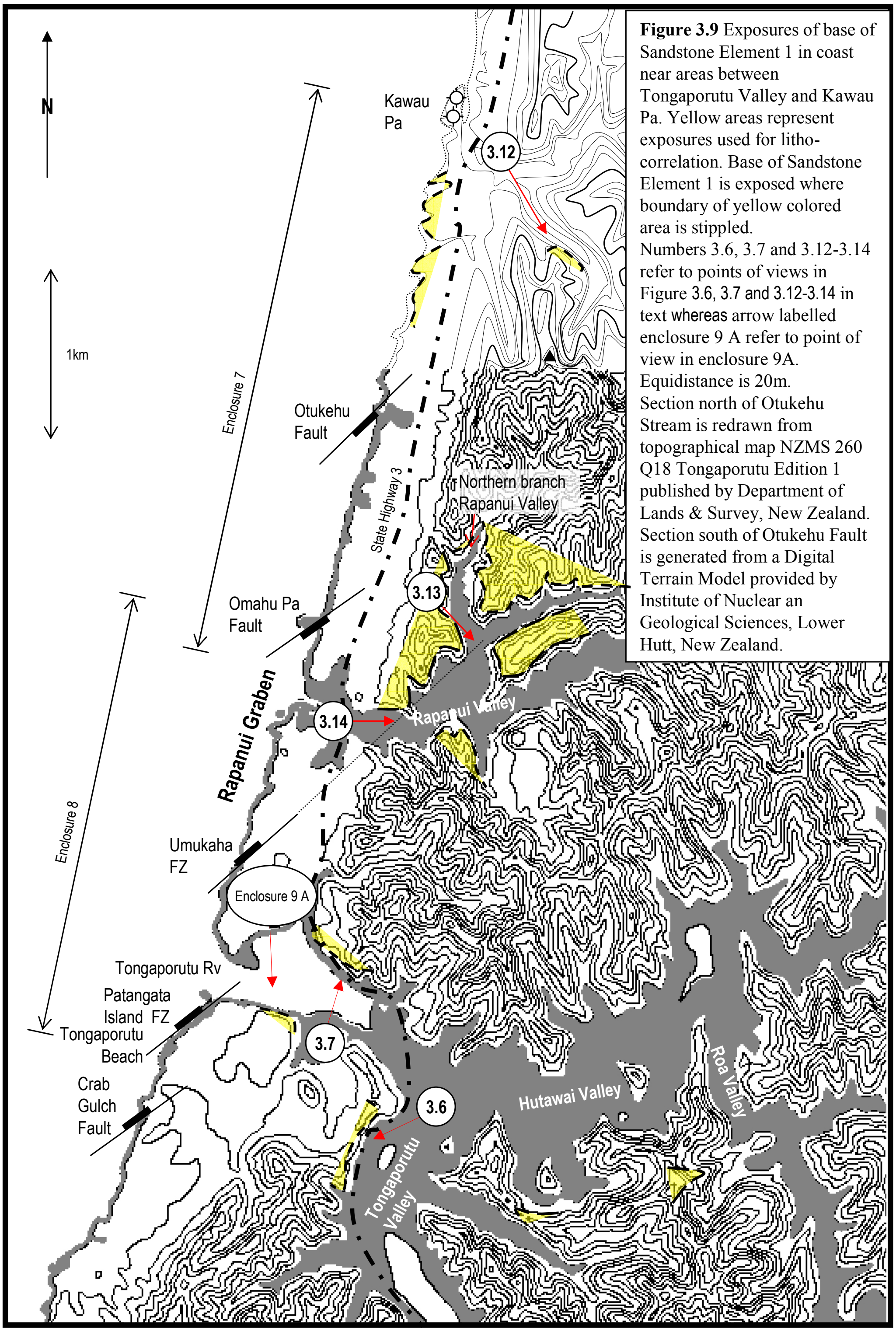


Figure 3.9 Exposures of base of Sandstone Element 1 in coast near areas between Tongaporutu Valley and Kawau Pa. Yellow areas represent exposures used for litho-correlation. Base of Sandstone Element 1 is exposed where boundary of yellow colored area is stippled. Numbers 3.6, 3.7 and 3.12-3.14 refer to points of views in Figure 3.6, 3.7 and 3.12-3.14 in text whereas arrow labelled enclosure 9 A refer to point of view in enclosure 9A. Equidistance is 20m. Section north of Otukehu Stream is redrawn from topographical map NZMS 260 Q18 Tongaporutu Edition 1 published by Department of Lands & Survey, New Zealand. Section south of Otukehu Fault is generated from a Digital Terrain Model provided by Institute of Nuclear an Geological Sciences, Lower Hutt, New Zealand.

Omahu Pa Fault constructing an anticlinal (Enclosure 7). This makes stratigraphic correlations along the low (<10m) coastal cliffs difficult. At least 2 faults dissect this section; *Otukehu Fault* and *Omahu Pa Fault*.

However, even if the stratigraphy along the coastal cliffs from Kawau Pa to Omahu Pa Fault is uncertain, the basal part of Sandstone Element 2 can be traced from the coastal exposure at Kawau Pa, up to the abandoned coastal cliffs (Figure 3.12), toward the south across the inland projections of Otukehu -and Omahu Pa Faults to Rapanui Valley (Figure 3.13) and down Rapanui Stream (Figure 3.14) to the south side of Omahu Pa Fault's coastal exposure (Enclosure 7). No displacement was observed across these faults inland projections making large throws (100-100's of meters) on the faults unlikely.

No direct correlation has been made at the coastal transect due to lack of stratigraphic markers. However, the footwall of Omahu Pa Fault and the footwall of Otukehu Fault both contain deformed blocks of massive sandstone association (Enclosure 7 B, C1 & C2) similar to the rotated and deformed blocks at the abandoned cliffs south of Mohakatino River (see above). It is possible that these all are laterally equivalent but further field work is needed to document this.

The stratigraphy between Kawau Pa to Omahu Pa Fault remains somewhat uncertain but it seems that the coastal cliffs transect is sub-parallel to the structural strike - (as observed at the abandoned coastal cliffs inland of the section) - and exposes to the boundary between Sandstone Element 2 and underlying Deformed Element 1.

Omahu Pa Fault to Umukaha Fault Zone (Rapanui Graben, Enclosure 8); Seen from the west, Omahu Pa seems to be a big, over 10m high deformed block of massive sandstone association that is far to big to fit into the 6m thick Rapanui Deformed Sub-Element exposed on the south side of Omahu Pa Fault (Enclosure 8 F). The fault plane is highly deformed and its orientation indicates that Omahu Pa block is up-thrown to the north-west (Enclosure 8 E). It is therefore likely that the fault juxtaposes two different deformed elements; Rapanui Deformed Sub-Element south of the fault plane and a stratigraphic lower deformed element north of the fault plane (probably Deformed Element 1).

Figure 3.12 Base of Sandstone Element 2 as exposed inland of Kawau Pa, see Figure 3.9 for location.

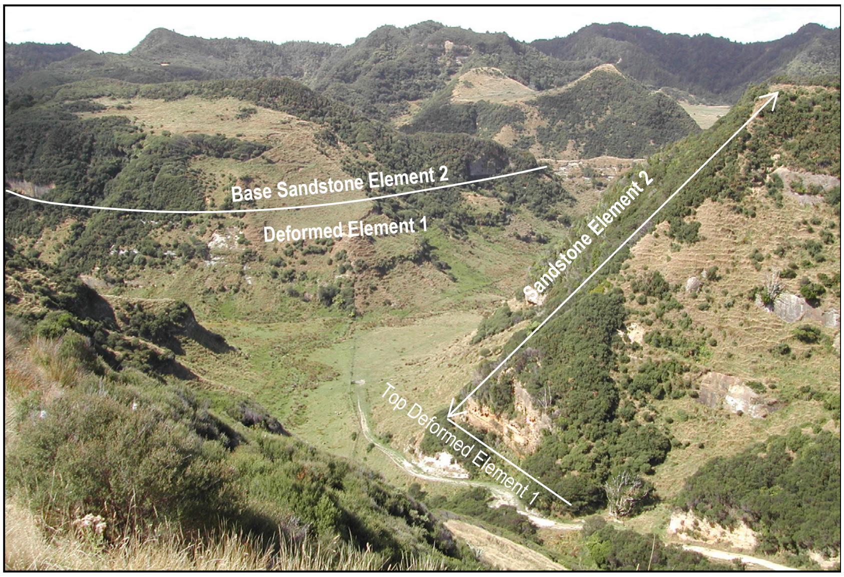


Figure 3.13 Base of Sandstone Element 2 as exposed in northern branch of Rapanui Valley, see Figure 3.9 for location.

Figure 3.14 Base of Sandstone Element 2 as exposed in lower part of Rapanui Valley, State Highway 3 in front, see Figure 3.9 for location.

Rapanui Deformed Sub-Element is over -and underlain by the massive sandstone association and can be traced along the coastal cliffs from Omahu Pa Fault to Umukaha Fault Zone (Enclosure 8). The Omahu Pa Fault plane dips toward the south-east whereas the fault planes of Umukaha Fault Zone dip toward the north-west, suggesting the section is confined within a graben structure (here called Rapanui Graben). Umukaha Fault Zone juxtaposes Rapanui Deformed Sub-Element in the hanging-wall with the massive sandstone association in the foot-wall (Enclosure 8 A1 & A2).

Umukaha Fault Zone to Tongaporutu Beach (Enclosure 8); litho-correlation across Umukaha Fault Zone (Figure 3.15) shows that strata from Umukaha Fault Zone to Tongaporutu River estuary exposes to Sandstone Element 2 and makes it possible to correlate Deformed Element 1, Sandstone Element 2 and Rapanui Deformed Sub-Element to exposures along the southern bank Tongaporutu River estuary (Enclosure 9 A). This makes it possible to measure the stratigraphic thickness between Deformed Element 1 and Rapanui Deformed Sub-Element and further to estimate the throw of Umukaha Fault Zone;

- *Minimum throw;* In the coastal cliffs, Umukaha Fault Zone juxtaposes Rapanui Deformed Sub-Element in the hanging-wall with massive sandstone association in the foot-wall. This imply that the throw of Umukaha Fault Zone is more than the cliff face, i.e. >10m.
- *Maximum throw;* The strata on the south side of Umukaha Fault Zone can be traced and correlated to the southern bank of Tongaporutu River estuary (Enclosure 9 A). The marker beds present on both sides of the fault zone (Figure 3.15) therefore exclude a throw of more than the stratigraphic thickness between Deformed Element 1 and the marker beds. This stratigraphic thickness is estimated to be 45-50m at the southern bank of Tongaporutu River estuary. (See appendix I for detailed calculations).
- *Estimated throw;* The throw of Umukaha Fault Zone is likely to be 10-50m.

The correlation and suggested throw on Umukaha Fault Zone makes it possible to estimate the throw on Omahu Pa Fault; An asymmetric Rapanui Graben with a big throw (>100m) on Omahu Pa Fault would be accompanied by strata in the Rapanui Graben dipping *toward* Omahu Pa Fault and/or strata in the footwall dipping *away* from the fault plane.

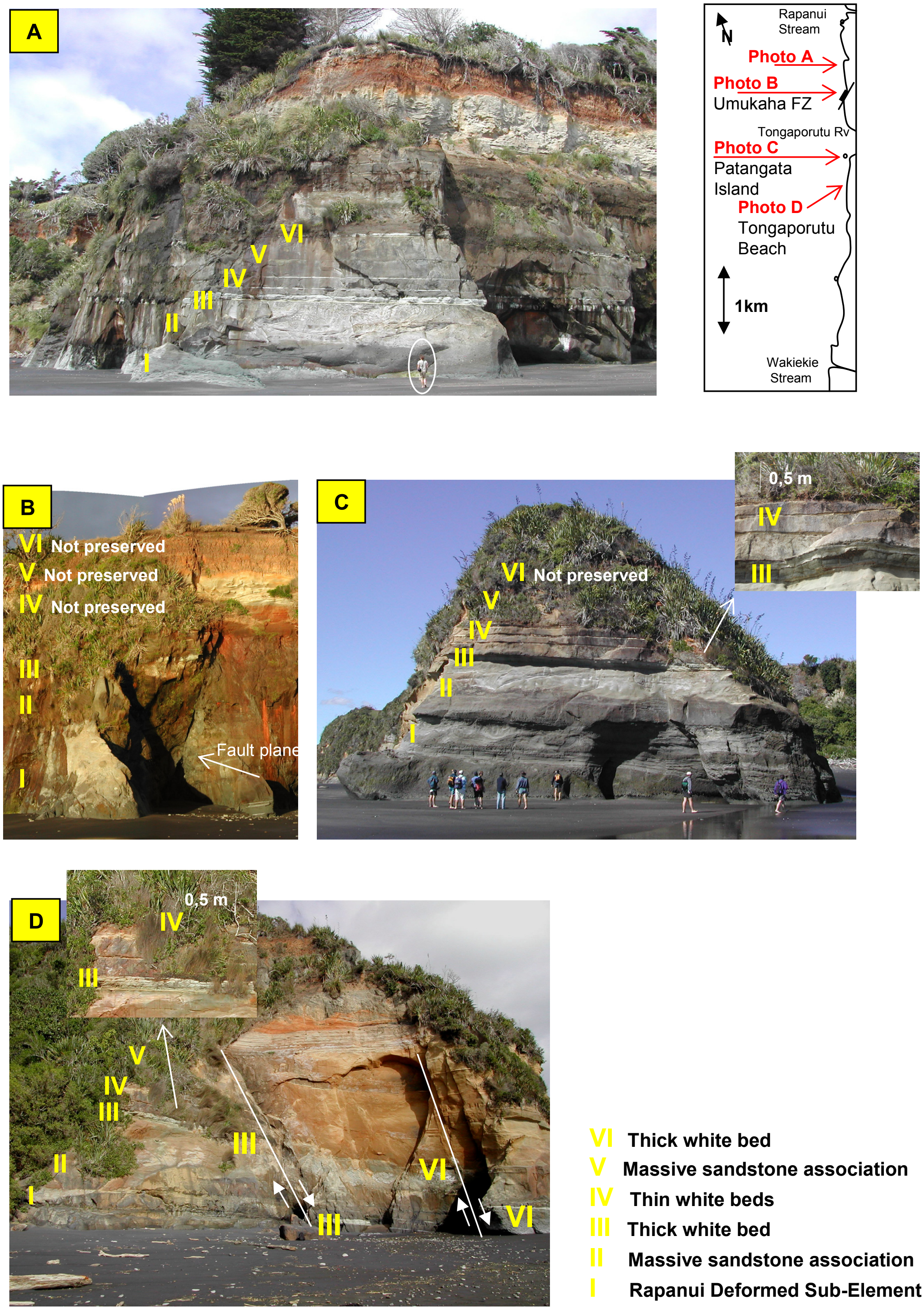


Figure 3.15 Detailed lithologic correlation across Umukaha Fault Zone. I-VI represent beds or bed sets recognized on both north and south side of Umukaha Fault Zone. Map shows position for photos A-D. **A:** Marker beds as exposed just south of Rapanui Stream. **B:** Marker beds as exposed at Umukaha Fault Zone. **C:** Marker beds as exposed at Patangata Island. **D:** Marker beds as exposed at Tongaporutu Beach. Coastal cliffs are approximately 15m high.

However, Umukaha –and Omahu Pa Fault dissect the coast without affecting the strike in Rapanui Graben markedly compared to the regional strike. Moreover, the strata in the footwall dip gently *toward* the Omahu Pa Fault plane. The throw of the two faults would therefore be expected to be approximately the same, with an additional throw of approximately 10m on Omahu Pa Fault due to the structural strike and thickness difference between the elements, i.e. throw of 20-55m (see appendix I for detailed calculations).

Tongaporutu River estuary to east side of Tongaporutu Valley (Figure 3.16); the lower boundary of Sandstone Element 2 can be correlated from the southern bank to the northern bank of Tongaporutu River estuary (Enclosure 9 A, Figure ??). The boundary is also exposed toward south along State Highway 3, in the lowermost parts of Tongaporutu Valley (Figure 3.7).

Heterolithic Element 1 is exposed at localities south of Tongaporutu River, but is not present at north side of the river. This suggests either that the element is laterally equivalent to the top of Sandstone Element 1, or the element is eroded by the overlying Deformed Element 1 (Figure 3.16). Deformed Element 1 thickens less the toward north than the thickness of Heterolithic Element 1 at exposed locality, and if Deformed Element 1 has eroded Heterolithic Element 1, this implies Sandstone Element 2 has a concave-down lower surface (at least locally). On the other hand, if Heterolithic Element 1 is laterally equivalent to top of Sandstone Element 1, Sandstone Element 2 has a convex-up surface (at least locally).

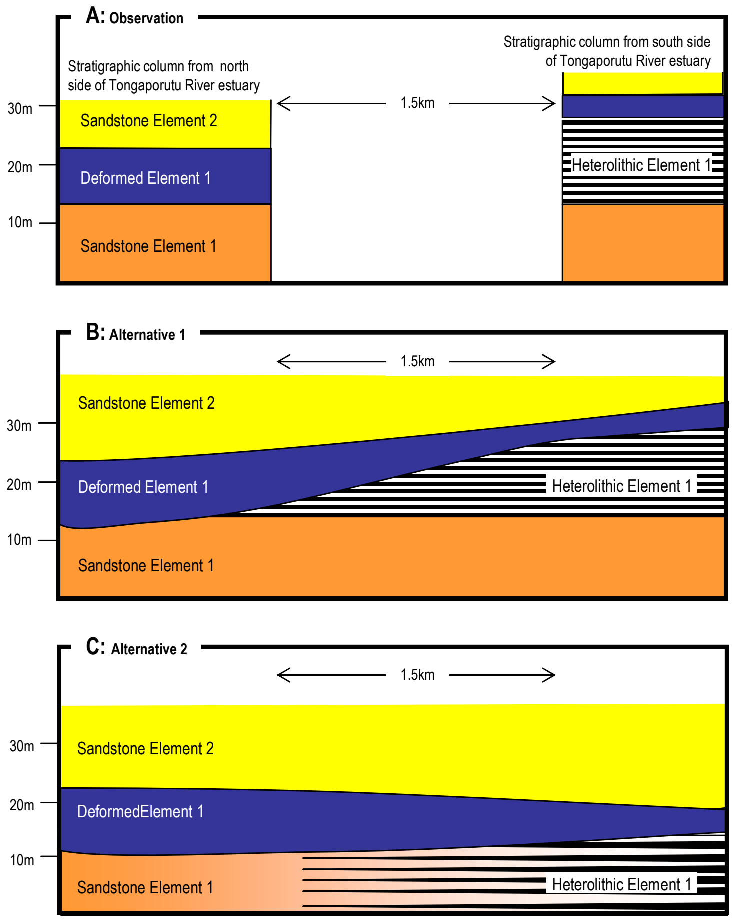


Figure 3.16 Possible geometries of architectural elements cropping out at Tongaporutu River estuary. **A:**Observed stratigraphy on the north and south side of Tongaporutu River estuary (localities at State Highway 3). **B:** *Alternative 1*, Deformed Element erodes Heterolithic Element 1, implying a concave-up lower surface of Sandstone Element 2. *Alternative 2*, top of Sandstone Element 1 is laterally equivalent to Heterolithic Element 1 implying a concave-up lower surface of Sandstone Element 2. However, the alternatives can be combined to give Deformed Element 1 a planar upper surface.

3.5. Heterolithic Element 2

Heterolithic association dominated architectural element thickening toward the south-east interpreted as lower-fan deposits.

Description: Heterolithic Element 2 is dominated by the heterolithic association (Figure 3.2). The northernmost exposures of Heterolithic Element 2 are located in the northernmost branch of the Rapanui Valley (Figure 3.16, Enclosure 5 I) where it has an estimated thickness of 10m but is erosively overlain by Quaternary deposits. Heterolithic Element 2 is also exposed at top of the hillside north of Tongaporutu River estuary, and at Tongaporutu Hill.

At the coastal cliffs, the element is exposed along the southernmost part of the section from *Tongaporutu River estuary to Crab Gulch Fault* where it has a gradual contact over 2m to the underlying Sandstone Element 2 (Enclosure 9 B). The transition is repeated by Crab Gulch Fault and Heterolithic Element 2 reappears along the southern part of the stretch from *Crab Gulch Fault to Warekarianga Stream* where it has a thickness of approximately 40m (Figure 3.1). Here, 2 paleocurrent measurements from ripple lamination trends roughly towards the north-west.

Heterolithic Element 2 is poorly exposed in the lower part of Tongaporutu Valley, but is exposed at Okau, 9km up Tongaporutu Valley. Here the transition from Sandstone Element 2 to Heterolithic Element 2 consists of interfingering between 10m thick intervals of massive sandstone association and heterolithic association (at tunnel). Also, Heterolithic Element 2 thickens from 40m at the coast to 250-300m thick in outcrops at Okau (Enclosure 6). East of point 266 the element has a thickness of estimated 100m. No channels were observed,

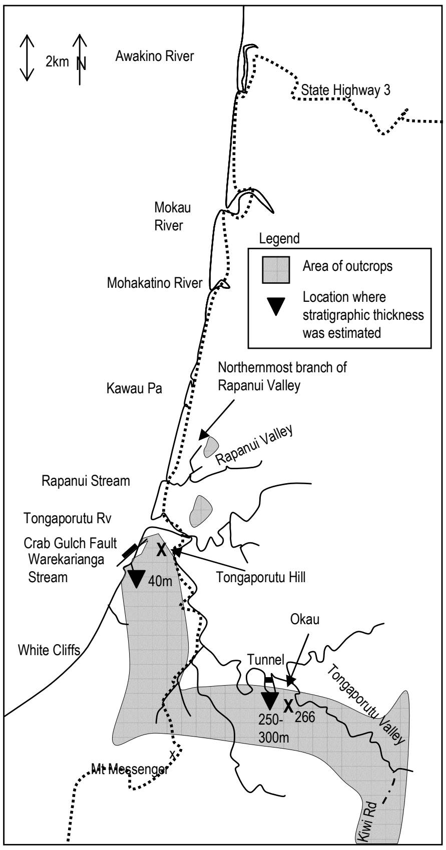


Figure 3.16 Outcrop map of Heterolithic Element 2.

however, the mapped area trends south-east — north-west and there is minor 3D control.

Interpretation: At the coast, Heterolithic Element 2 may represent lower-fan, distal overbank or the proximal background deposition on the basin-floor (King et al., 1994). There are no simple criteria to distinguish between these on a lithofacies level in the studied outcrops. However, in Tanqua Karoo Basin (South-Africa), Basu & Bouma (2000) found that base truncated Bouma Sequences (T_c, T_{cd}, T_{cde}) are dominant in levee-overbank deposits whereas top-truncated Bouma Sequences (T_a, T_{ab}, T_{abc}) characterize channel-sheet transition and distal sheet. The lack of T_a for the former is a result of deposition of "bodyspill" from channelised turbidity currents or lagging tails of degenerating turbidity currents (Basu & Bouma, 2000). If assuming the same trend is present in Mount Messenger Formation, the element would be expected to represent lower fan deposits as the association is dominated by T_{abc} divisions. Also, as no channel-levee geometries were observed, an interpretation of the coastal exposures of Heterolithic Element 2 as lower fan deposits is preferred (King et al., 1993, 1994).

In the inland areas, the strike line of base Sandstone Element 2 does an S-bend (Enclosure 6) which may be related to the thickness changes of Heterolithic Element 2 toward south-east. This may reflect infilling of a tectonically inactive depression on the contemporaneous sea-floor or syn-sedimentary subsidence of a sub-basin. Due to the abrupt thinning of the element from east side to west side of 266 an interpretation of the element being deposited in a syn-sedimentary sub-basin (here called Okau Sub-Basin) is preferred (Figure 3.17). However, the correlation of the upper surface of Heterolithic Element 2 (i.e. Sandstone Element 3) is uncertain. The sandstone element exposed east of 266 may not correlate Sandstone Element 3, but represent an element not exposed or preserved to the west. If so, this reflects that the eastern boundary of Okau Sub-Basin is located farther to the east or that the basin is symmetric.

Alternatively, the observations may therefore be without inferring a sub-basin. The regional structural dip is commonly 1-3 degrees which would give subtle post-depositional deformation of strata a relatively large topographical effect and the S-shape of base Sandstone Element 1 strike line may represent a synclinal. The thickness change might reflect up-dip transition from lower fan environment at the coastal transect to slope-fan environment toward the south-east. Ot the Heterolithic Element 2 and 4 may amalgamate toward south-east.

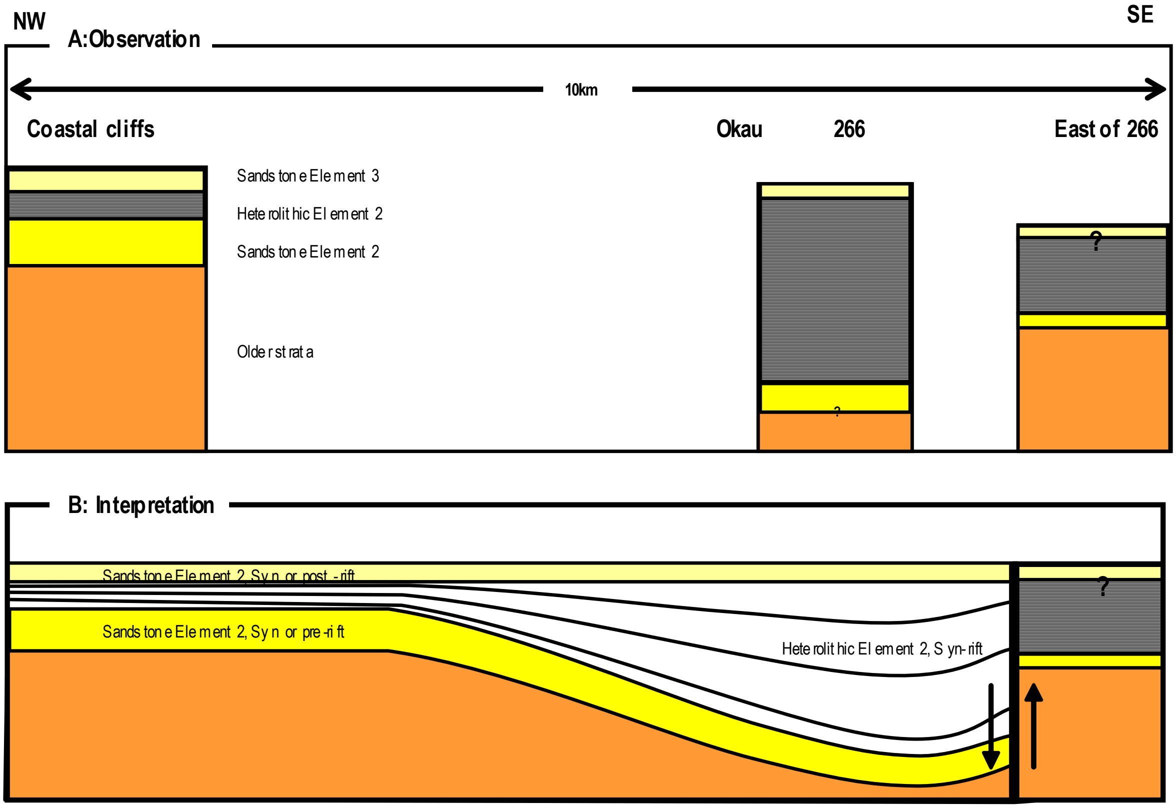


Figure 3.17 Interpreted tectono-stratigraphic framework for inland exposures of Heterolithic Element 2. <u>A:</u> Observed stratigraphy from coastal cliffs to east of 266. <u>**B:**</u> Interpreted syn-rift sedimentation of Heterolithic Element 2. Interpretation also based on base of Sandstone Element 2's strike line (Enclosure 5). Deformed elements not marked on profile due to reasons of space.

3.6. Deformed Element 2

Deformed association dominated architectural element thinning toward the north interpreted as deposits resulting from slope failure. The element is laterally confined within slump scar with axial positions to the south.

Description; Deformed Element 2 is dominated by the deformed association (Figure 3.2): The northernmost exposures of Deformed Element 2 are located at Tongaporutu Hill where it has a thickness of approximately 5m (Figure 3.1, 3.16, Enclosure 5 & 6).

At the coastal cliffs, the element is exposed from *Warekarianga Stream to Mangapukatea Fault.* The element thickens and erodes down toward the south and subcrops beach-level with an estimated thickness of 15m (Enclosure 9 C). The slump scar trends toward the north-west.

Interpretation:

Deformed Element 2 has a lower contact with erosive relief which indicates it is at least partially confined within a depression. As the element thickens towards the south it is likely that the axial position of the slump is located to the south in the study area. The element is interpreted as deposit resulting from slope failure.

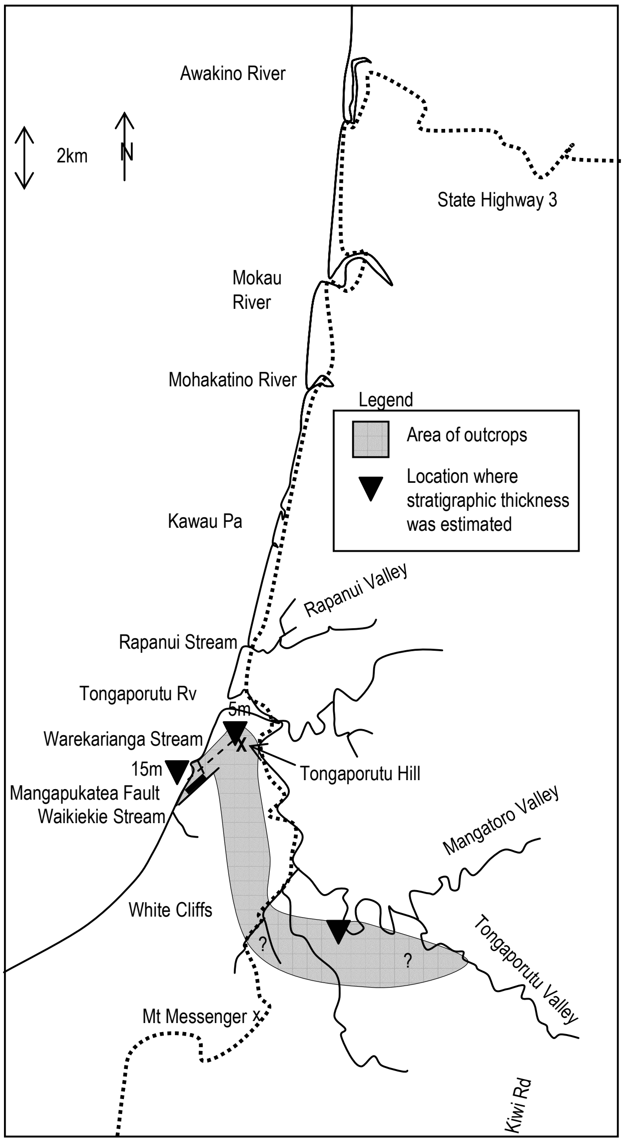


Figure 3.18 Outcrop map of Deformed Element 2

3.7. Sandstone Element 3

Partly channelized FLSA/MSA/DA -dominated architectural element interpreted as upper mid-fan environment. Coast near outcrops has high basal relief interpreted as channel-lobe transition.

Description: Sandstone Element 3 is dominated by the finely-laminated association, massive sandstone association and the deformed association (Figure 3.2). The northernmost exposures of Sandstone Element 3 are located in the hillsides of Tongaporutu Hill (Figure 3.1 & 3.19). The element is poorly exposed elsewhere in the lower parts of Tongaporutu Valley; however, a roughly estimated 50m thick sandy interval is poorly exposed along the ascent of State Highway 3 from Tongaporutu Valley to Mount Messenger (from 50m above sea-level). Also, an approximately 10m thick interval of massive sandstone association with a sub-planar lower contact is under -and overlain by the heterolithic association between Toii Rd and Okau, - 9km south-east from the coast.

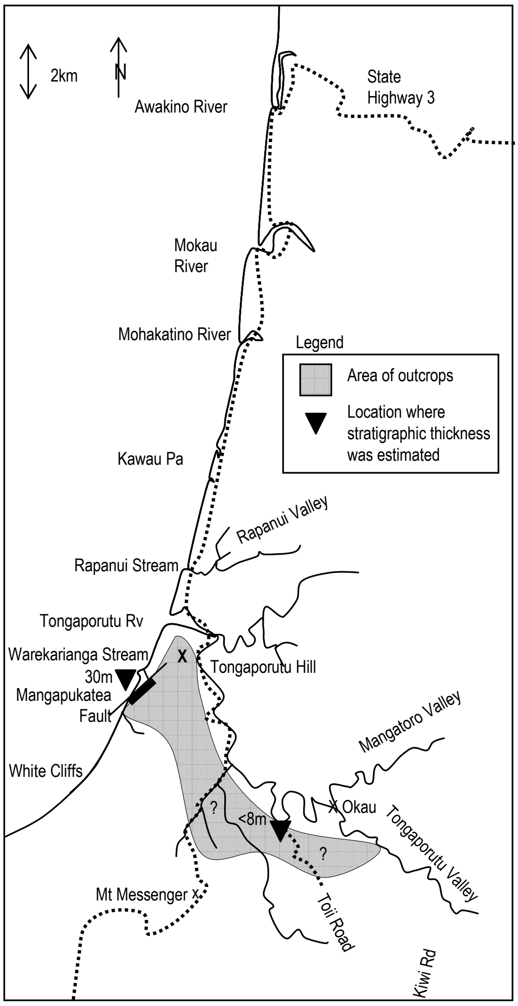


Figure 3.19 Outcrop map of Sandstone Element 3.

These inland exposures probably correlate the Sandstone Element 3 exposures at the coast. The element has then a minimum extent of 8 kilometers in the north-south direction and 9 kilometers in the east-west direction.

In the coast near areas, the outcrops allow a 3-fold division of Sandstone Element 3 (Enclosure 9 D);

1) *Finely-Laminated Sandstone Association Sub-Element;* the sub-element's northernmost exposures is located at Tongaporutu Hill where it is approximately 15m thick and has a basal relief of 4m. The sub-element is poorly exposed southwards along

Figure 3.20 Erosive relief of FLSA Sub-Element. Note flame structure in middle right. Cliff approximately 20m high.

the abandoned coastal cliffs but appears along the coastal cliffs from *Warekarianga Stream to Mangapukatea Fault.* Here the lower boundary has relief of typically 5 meters, but relief of up to 10's of meters occur (Figure 3.21). The relief is expressed as scours and injections into the underlying Deformed Element 2. The relief of the lower boundary then has a minimum extent of 1kilometer in the north-sosuth direction and 1kilometer in the east-west direction. The sub-element terminates against Mangapukatea Fault and cannot be traced further towards the south (Enclosure 9 D). 2 paleocurrent measurements from scour axis trend roughly towards south east — north-west. Finely-Laminated Sub-Element is overlain by Deformed Association Sub-Element;

2) *Deformed Association Sub-Element;* the sub-element was not observed at Tongaporutu Hill or at the abandoned cliffs, probably due to vegetation.

At the coastal cliffs, the sub-element is exposed along a short stretch (few 100's of meters) just north of Mangapukatea Fault only (Enclosure 9 D). The sub-element terminates against Mangapukatea Fault plane and cannot be traced further toward the south. It was therefore not possible to detect the geometry of the sub-element. Deformed Association Sub-Element is overlain by Massive Sandstone Association Sub-Element;

3) *Massive Sandstone Association Sub-Element;* the sub-element is dominated by the massive sandstone association. The sub-element is present but poorly exposed at Tongaporutu Hill and southwards along the abandoned coastal cliffs.

At the coastal cliffs, the sub-element is down-faulted to beach-level by Mangapukatea Fault and exposed from *Mangapukatea Fault to Waikiekie Stream* (Enclosure 9 D). Beds cannot be correlated across Mangapukatea Fault.

Interpretation: The larger scale geometry of Sandstone Element 3 remains undecided, but the extent of the element suggests deposition on the basin-floor. Further, the relief on the base of the element suggests a depositional setting of middle mid fan environment.

Finely-Laminated Sandstone Association Sub-Element; The rapid dumping of the finely-laminated sandstone association was probably related to a change from a relatively high-energy hydraulic regime to a relatively low-energy hydraulic regime. This change is likely to occur were gravity-flows pass from a relatively high gradient and channelised conditions to flatter and locally unchannelised areas of the basin-floor fan (i.e. channel-lobe transition) (Mutti & Normark, 1987); Gravity-flows that are exiting channel mouths loses competence and deposit excess sediments rapidly in front of the channel due to dissipation of energy caused by increased internal turbulence and/or enlargement and dilution of the flow (Menard, 1964), (Middleton, 1970) & (Komar, 1973). Also, the overlying Sandstone Element 4 is intensely channelised (see subchapter 3.10) whereas the underlying Sandstone Element 2 is dominated by sheet sands. It is therefore likely that the injections, scouring and channels at the base of Sandstone Element 3 relates to the chaotic nature and pulsed flows expected at the channel-lobe transition (Brown pers.com, 2002).

General remarks; The turbidites in the channelised Sandstone Element 3 might indicate that the sand was transported to the basin-floor by turbidity currents.

Deformed Association Sub-Element; It was not possible to interpret axial and marginal positions due to lack of 3D control. The sub-element is interpreted as deposits resulting from slope failure.

Massive Sandstone Association Sub-Element; the sub-element could either be lobe, sheet or confined within a channel geometry. It is not possible to distinguish between these geometries in outcrop due to vegetation.

3.8. Heterolithic Element 3

Heterolithic association dominated architectural element interpreted as lower-fan deposits.

Description; Heterolithic Element 3 is dominated by the heterolithic association (Figure 3.2) and is exposed along a short stretch just north of Waikiekie Stream only (Figure 3.21, Enclosure 9 D). The uppermost part of the element is truncated by the erosive relief of the overlying Deformed Element 3, otherwise the no information about the geometry or lateral variations was possible to detect due to vegetation.

Interpretation; Based on interpretations of similar facies in Heterolithic Element 2, the element is interpreted as lower fan deposits. However, as long as the larger scale geometry and lateral development of the element is undecided, this should be regarded as an uncertain interpretation. Both the underlying and overlying sandstone elements are channelised and Heterolithic Element 3 might be laterally confined within a channel geometry or represent overbank deposits.

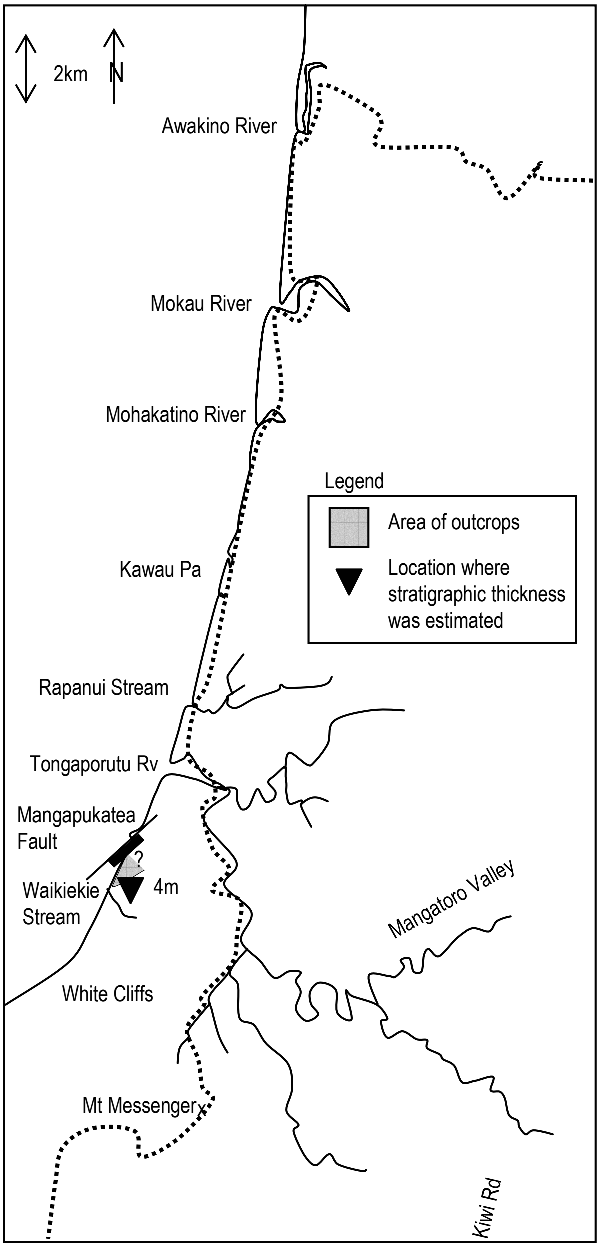


Figure 3.21 Outcrop map of Heterolithic Element 3

3.9. Deformed Element 3

Deformed association dominated architectural element thinning toward the north interpreted as deposits resulting from slope failure. The element laterally confined within slump scar with axial positions to the south.

Description: Deformed Element 3 is dominated by the deformed association (Figure 3.2). The northernmost exposures of Deformed Element 3 are located at the coastal cliffs south of Mangapukatea Fault (Figure 3.22, Enclosure 9 D). The element erodes down with a few meters toward the south and is 7m thick where it subcrops beach-level, just south of Waikiekie Stream outlet.

Interpretation: The erosive relief on the lower contact indicates the element is at least partially confined within a depression. As the element erodes down towards the south it is likely that the axial position of the slump is located to the south of the study area. The element is interpreted as deposits resulting from slope failure.

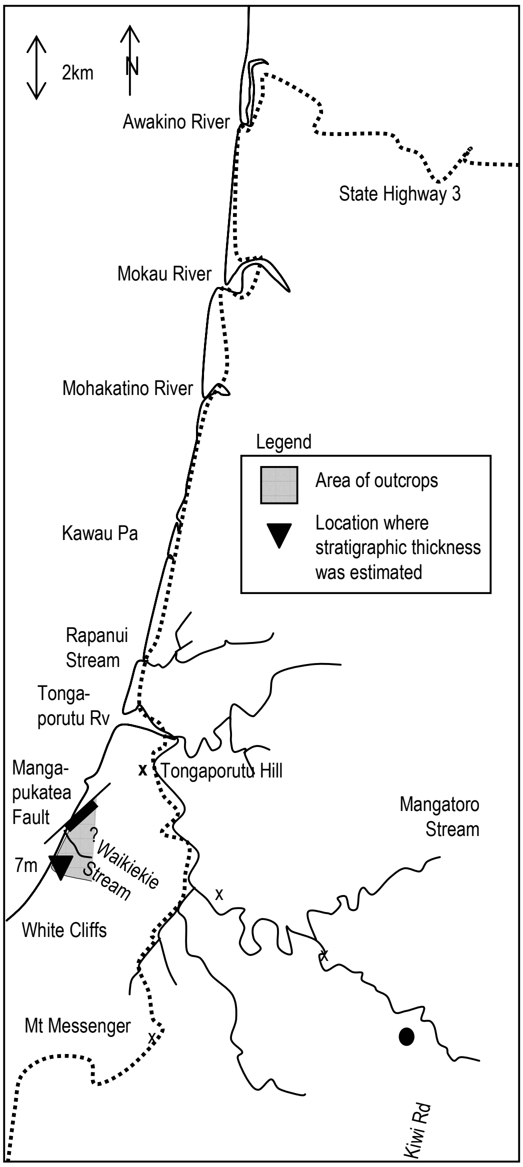


Figure 3.22 Outcrop map of Deformed Element 3.

3.10. Sandstone Element 4

Laterally confined massive sandstone element dominated architectural element with basal mudstone conglomerate lithofacies grading upwards to thick-bedded sandstone lithofacies interpreted as a channel fill sequence in upper mid fan environment.

Description: Sandstone Element 4 is dominated by the massive sandstone association (Figure 3.2). The northernmost exposures of the element are located in the hillsides north of Waikiekie Stream where it is channelised (100's of meter wide) (Figure 3.23). It was not possible to trace the element further towards the north and it is not present at the expected stratigraphic position south of Tongaporutu Hill. The element might therefore be laterally confined. However, Mangapukatea Fault might dissect the area south of Tongaporutu Hill and displace the element into a vegetated area. No such fault was observed, but a fault with 10-15m throw occurs in Tongaporutu Valley which might represent the extension of Mangapukatea Fault.

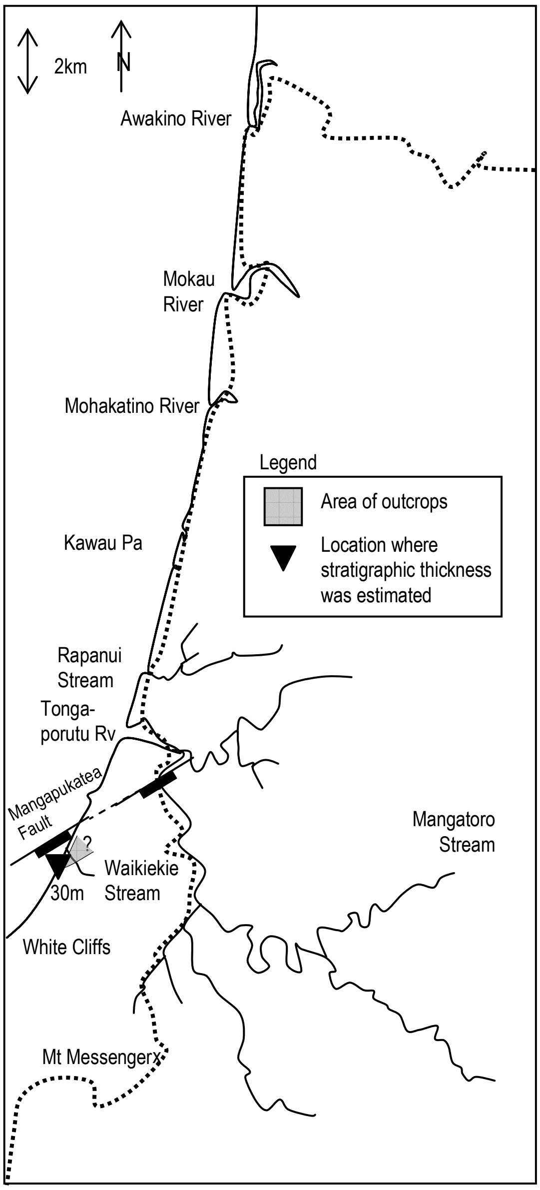


Figure 3.23 Outcrop map of Sandstone Element 4.

At the coast, Sandstone Element 4 is exposed along the northernmost part of the section from *Waikiekie Stream to White Cliffs* where it has an estimated thickness of 30m (Enclosure 9 E). Here, the element is intensely channelised and the basal contact erodes meters down into the underlying Deformed Element 3 toward south.

The lowermost part of the element consists of a 1m thick interval of planar laminated thick-bedded sandstone. This interval is erosively overlain by an approximately 5m thick interval of multi-storey scours filled with mudstone conglomerate lithofacies and thick-bedded sandstone lithofacies (Figure 3.24). The conglomerate filled scours have various sizes ranging from a few meters to 100m wide, and a few 10's of centimeters to a few meters deep. The sand filled scours tend to be of more limited lateral extent (10's of meters) and are typically a few meters deep.

The overlying interval consists of thick-bedded sandstone lithofacies cut by channels 100 meters wide and 10's of meters deep (Figure 3.25). Shell fragments are abundant throughout the entire succession.

Interpretation; The succession at Waikiekie Stream is interpreted to represent a mixed channel fill sequence (terminology after Mutti & Normark, 1987); These are characterized by lithofacies associations that record an erosional stage – here represented by the clast-supported mudstone conglomerate– followed by a period of sand deposition directly in the channel system during backfilling, here represented by the overlying thick-bedded sandstone lithofacies. The planar laminated sandstone at the base might represent the first stage of backfilling after cutting of a channel. Channels 10-10's of meters deep are expected to occur in upper mid fan setting.

Sandstone Element 4 might be laterally confined and may therefore be interpreted as a kilometer wide channel belt. A possible analogue to the geometry of the element is the Kanalkopf exposure in Karoo Basin, South-Africa (Figure 3.26). However, due to the low control on Mangapukatea Fault, the interpretation of Sandstone Element 4 being laterally confined is uncertain.

Figure 3.24 Lower part of Sandstone Element 4.Close up of section in Enclosure 9 E. Vertical section in photo about 6m high **A:** Section is dominated by thick-bedded sandstone lithofacies and mudstone conglomerate lithofacies filled scours. **B:** Scour margins marked.

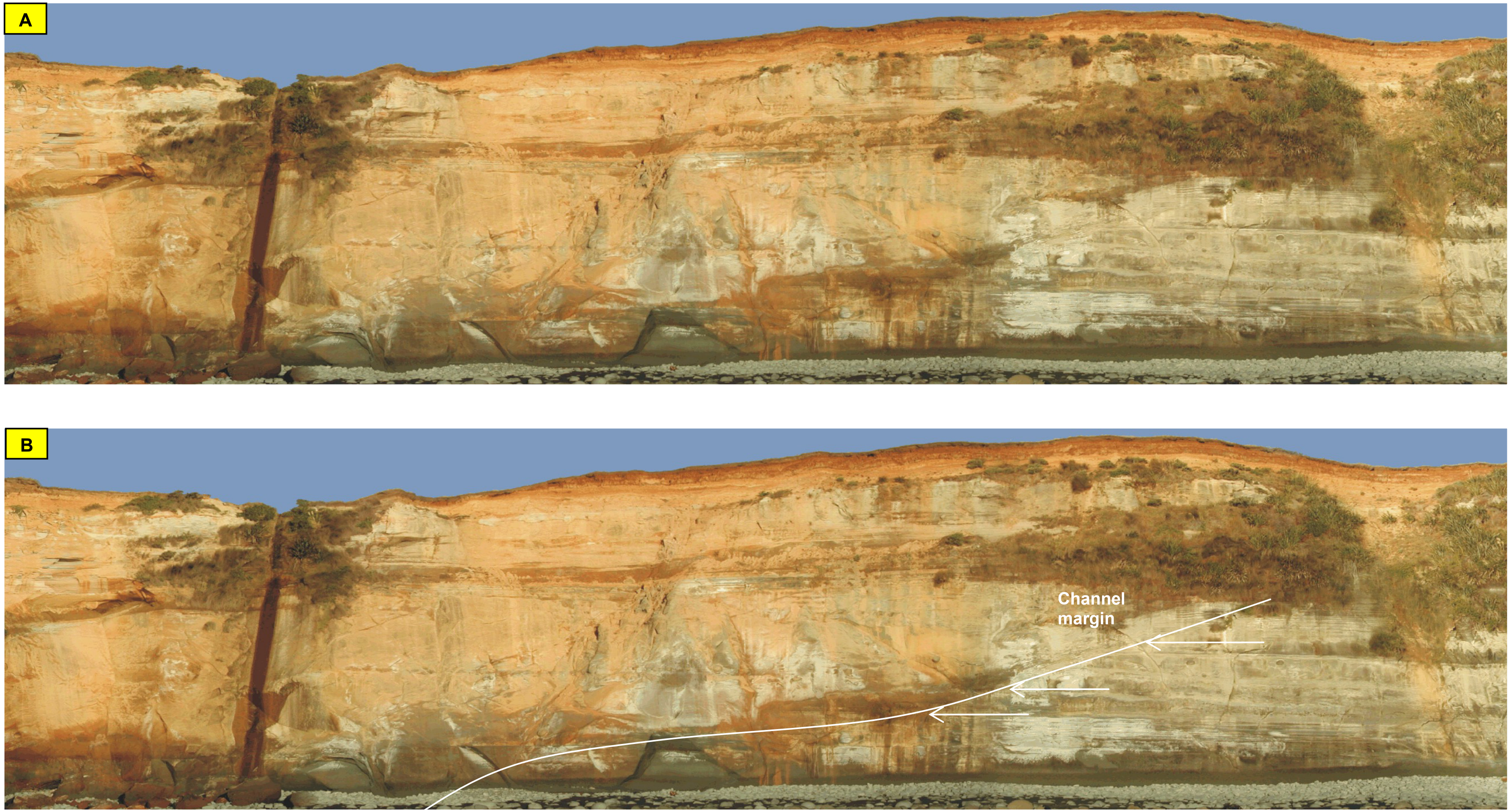


Figure 3.25 Close up of sections in Enclosure 9 E. Vertical section in photo about 6m high **A:** Upper part is dominated by deep thick-bedded sandstone lithofacies filled channels. **B:** Channel margin marked.

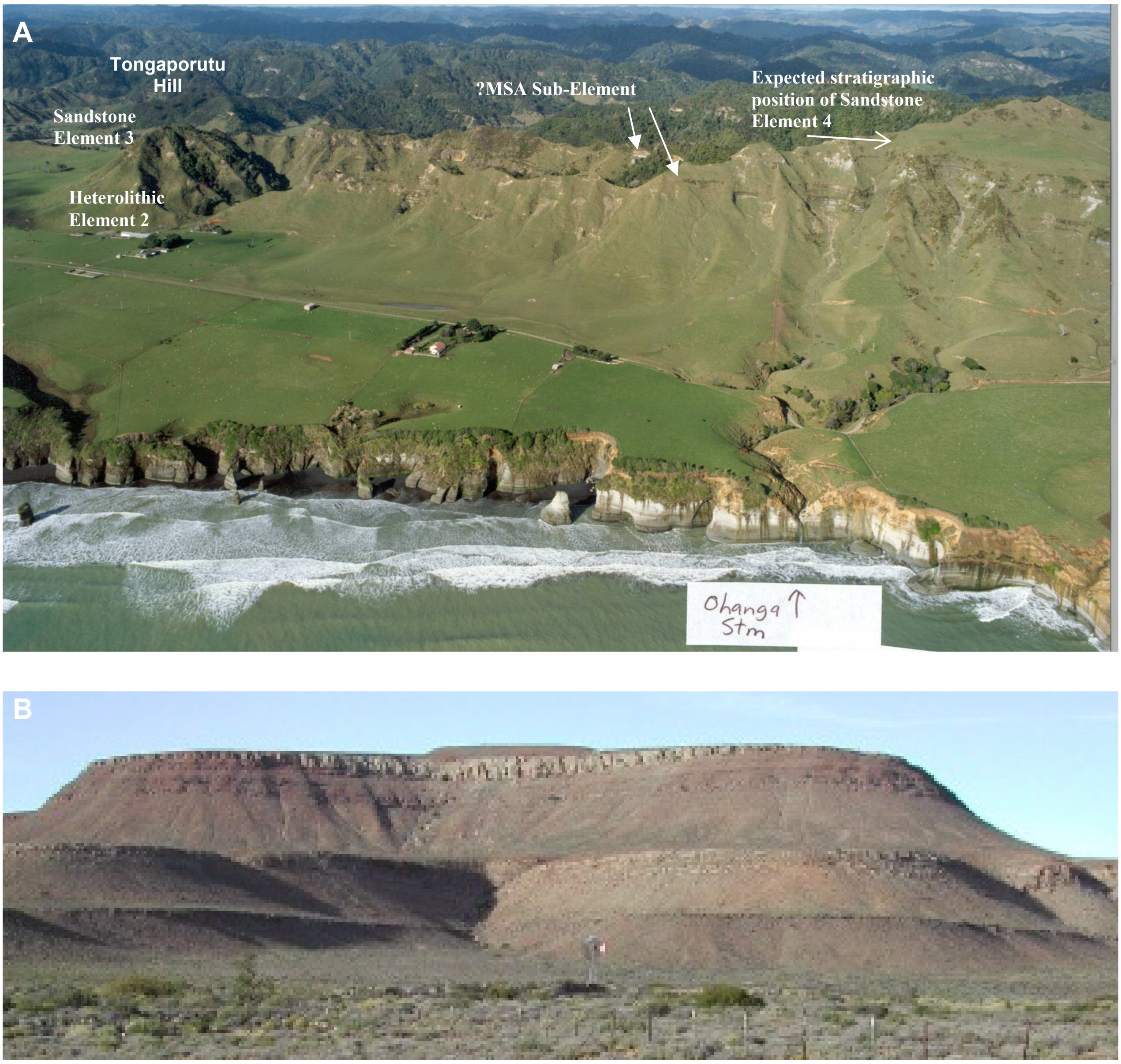


Figure 3.26 **A:** Aerial photo of abandoned coastal cliffs south of Tongaporutu Hill (photo by Peter King). Sandstone Element 4 was not found at expected stratigraphic position just south of Tongaporutu Hill (white arrow) and the Element might therefore be laterally confined. However, due to the low 3D control on Manggapukatea Fult, this remains uncertain. **B:** Possible analogue to Sandstone Element 4; the channel geometry of the Kanaalkopf localitiy, Karoo Basin, South Africa.

3.11. Heterolithic Element 4

HA-dominated architectural element interpreted as lower-fan deposits.

Description: Heterolithic Element 4 is dominated by the heterolithic association (Figure 3.2). The geometry and extent was not mapped due to vegetation but the element has a thickness of 40m at the coastal outcrops (Figure 3.27, Enclosure 5, 9 F) (thickness adapted from sedimentary log in King et al., 1994).

Interpretation: Based on the high mud content of the heterolithic association, the interpretation of Heterolithic Element 2 and the lack of observed channel-levee geometries, Heterolithic Element 1 is interpreted to represent lower-fan environment.

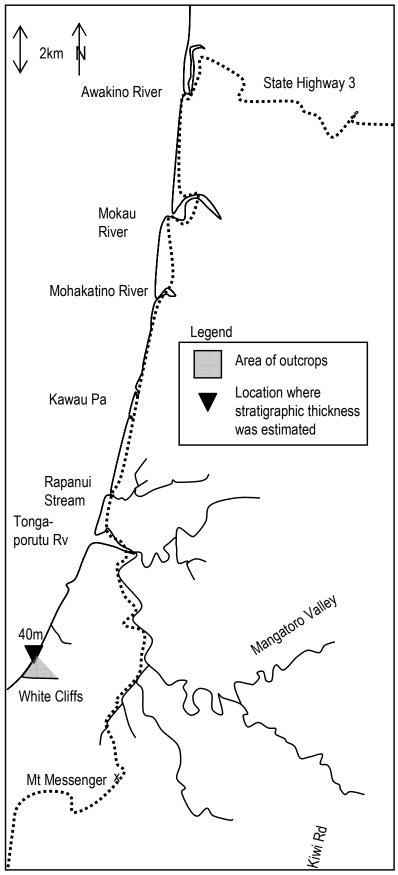


Figure 3.27 Outcrop map of Heterolithic Element 4.

3.12. Deformed Element 4

DA-dominated architectural element interpreted as deposits resulting from slope failure.

Description; Deformed Element 3 is dominated by the deformed association (Figure 3.2). The element is approximately 15m thick and erosively overlies Heterolithic Element 4 (Enclosure 5). (Description adapted from King et al., 1994)

Interpretation; The element is interpreted as deposit resulting from slope failure.

4. Allostratigraphic units

An allostratigraphic unit is defined as *"…a mappable stratiform body of sedimentary rock defined and identified on the basis of their bounding discontinuities"* (North American Commission on Stratigraphic Nomenclature, 1983). An ideal allostratigraphic unit is here defined as stratigraphic succession consisting of a sandstone element grading upwards into a heterogeneous element that is capped by a deformed element (identical to a sequence in King et al., 1994) (Figure 4.1). The cycle boundaries are placed at the erosive base of the sandstone elements due to the marked and easy recognizable break in lithology. A total of 4 allostratigraphic units are recognized (Figure 4.2 & 4.3). Table 4.1 compares the division used in this study with previous studies.

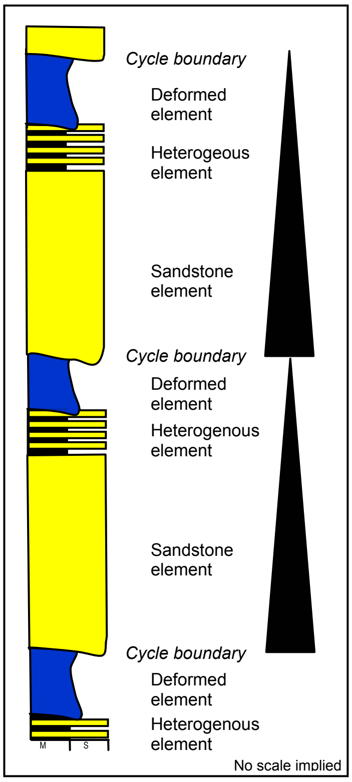


Figure 4.1 Idealized sedimentary log of the rhythmic lithology in the study area. Log redrawn from Brown (pers.com, 2003). See Figure 1.6 for legend.

Table 4.1 Comparison of stratigraphic division of Mount Messenger Formation in this study and by other studies. Black line indicates stratigraphic position of base of Mount Messenger Formation.

<table>
<tr><th colspan="2">King et al. (1993)</th><th colspan="2">This study</th><th>King et al. (1994)</th><th>King & Thrasher (1996)</th></tr>
<tr><td colspan="2">Urenui Formation</td><td colspan="2">Not studied</td><td>Not studied</td><td>Urenui Formation</td></tr>
<tr><td rowspan="10">Mount Messenger Formation</td><td>Upper sandstone unit</td><td colspan="2">Not studied</td><td>Sequence 4 & 5</td><td rowspan="13">Mount Messenger Formation</td></tr>
<tr><td rowspan="8">Middle interbedded unit</td><td>Deformed Element 4</td><td rowspan="3">Allostratigraphic Unit 4</td><td rowspan="3">Sequence 3</td></tr>
<tr><td>Heterolithic Element 4</td></tr>
<tr><td>Sandstone Element 5</td></tr>
<tr><td>Deformed Element 4</td><td rowspan="3">Allostratigraphic Unit 3</td><td rowspan="3">Sequence 2</td></tr>
<tr><td>Heterolithic Element 3</td></tr>
<tr><td>Sandstone Element 3</td></tr>
<tr><td>Deformed Element 2</td><td rowspan="3">Allostratigraphic Unit 2</td><td rowspan="3">Sequence 1</td></tr>
<tr><td>Heterolithic Element 2</td></tr>
<tr><td>Lower sandstone unit</td><td>Sandstone Element 2</td></tr>
<tr><td rowspan="5">Mohakatino Formation</td><td>Tawariki Slitstone Member</td><td>Deformed Element 1</td><td rowspan="3">Allostratigraphic Unit 1</td><td rowspan="3">Not studied</td></tr>
<tr><td>Not present in study area</td><td>Heterolithic Element 1</td></tr>
<tr><td>Ferry Sandstone Member</td><td>Sandstone Element 1</td></tr>
<tr><td>Purupuru Tuff Member</td><td colspan="2" rowspan="2">Mohakatino Formation</td><td rowspan="2">Not studied</td><td rowspan="2">Mohakatino Formation</td></tr>
<tr><td>Mangarara Sandstone Member</td></tr>
</table>

4.1. Allostratigraphic Unit 1

Allostratigraphic unit consisting of Sandstone Element 1, Heterolithic Element 1 and Deformed Element 1, representing a shift from outer mid-fan to lower-fan depositional environment.

The base of Allostratigraphic Unit 1 corresponds to the base of Mount Messenger Formation as defined by King & Thrasher (1996) (Table 4.1 & Figure 4.2).

At the coast, Sandstone Element 1 and 2 are separated by Deformed Element 1 which either locally eroded an originally underlying Heterolithic Element 1 *or* was a catastrophic event during continuous deposition of a sandstone element. In the latter alternative, Sandstone Element 1, Deformed Element 1 and Sandstone Element 2 may be regarded as a major sandstone element. This element would grade into Heterolithic Element 2 which is capped by Deformed Element 2 and the whole succession might be viewed to represent the lowermost allostratigraphic unit.

However, Sandstone Element 1 is overlain by Heterolithic Element 1 south of Tongaporutu River and the Deformed Element 1 thickens toward the north. At the coast, the exposures of Sandstone Element 1 and Deformed Element 1 are therefore regarded as a locally incomplete Allostratigraphic Unit 1.

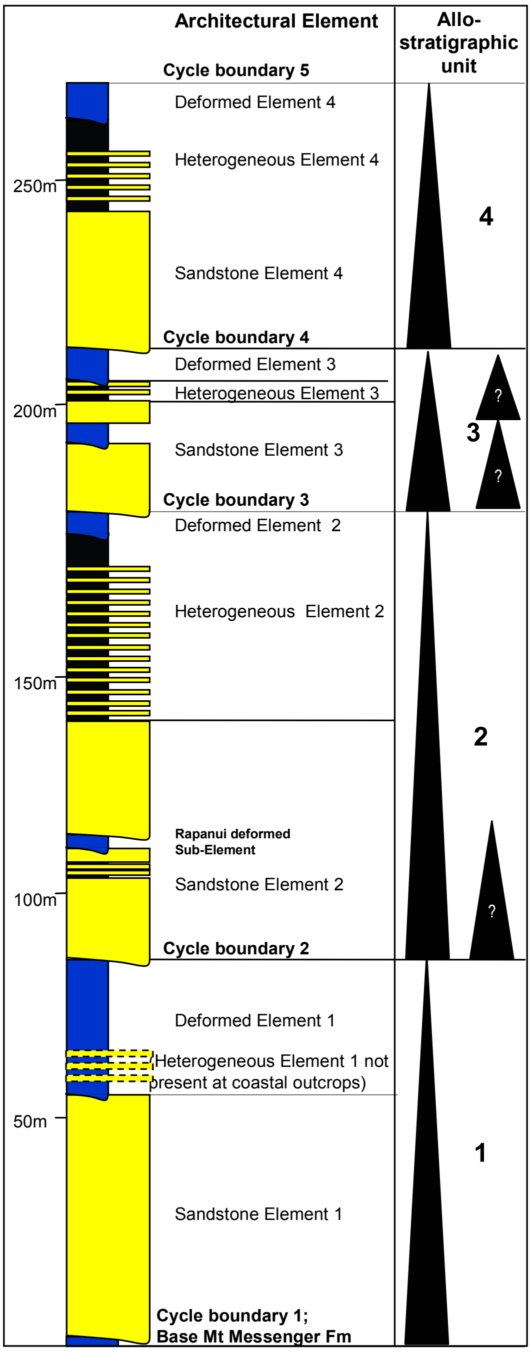


Figure 4.2 Sketch log of architectural elements and allostratigrphic units in the studied coastal cliff transect Modified from King et al. (1993, 1994). See Figure 1.6 for legend.

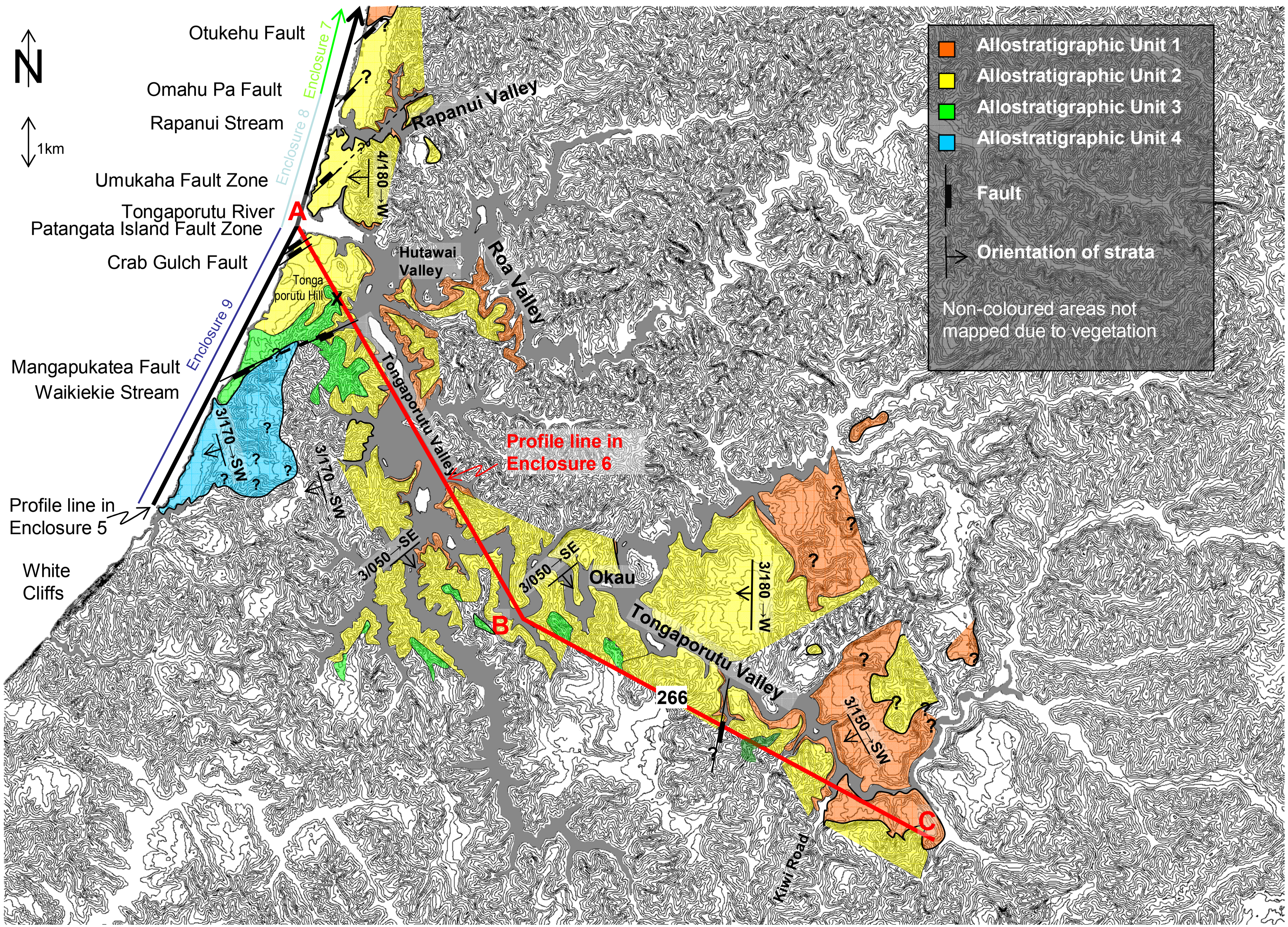


Figure 4.3 Map of allostratigraphic units. Positions for profiles shown in Chapter 3 marked. Allostratigraphic Unit 1 and 2 can be traced over a large area whereas for units 3 and 4, the outcrop control is much less. Map just extends as far north as Kawau Pa as no Digital Terrain Model was available for areas further north. Also, the mapped area north of Kawau Pa is close to 2D and stratigraphy is shown in Enclosure 5

Allostratigraphic Unit 1 can be traced a considerable distance in the study area, however, there is minor 3D control due to vegetation and erosion (Figure 4.3).

In summary, the unit represents a change from mid-fan sedimentation to lower-fan sedimentation capped by deposits from slope failure.

4.2. Allostratigraphic Unit 2

Allostratigraphic unit consisting of Sandstone Element 2, Heterolithic Element 2 and Deformed Element 2, representing a shift from mid-fan to lower-fan depositional environment.

The section between base of Sandstone Element 2 and top of Rapanui Deformed Sub-Element might be regarded as an allostratigraphic unit due to the thin interval of heterolithic association just below Rapanui Deformed Sub-Element (Figure 4.2). However, the interval of heterolithic association and Rapanui Deformed Sub-Element is separated by an interval of massive sandstone association. Moreover, Rapanui Deformed Sub-Element has characteristics different of the other deformed association dominated architectural elements (see chapter 3.4) and this interval has therefore not been recognized as an independent allostratigraphic unit. Allostratigraphic Unit 2 is therefore regarded to consist of Sandstone Element 2, Heterolithic Element 2 and Deformed Element 2 (Figure 4.2). Allostratigraphic Unit 2 can be traced a considerable distance in the study area, however, there is minor 3D control due to vegetation and erosion (Figure 4.3).

In summary, Allostratigraphic Unit 2 represent a change from mid-fan sedimentation to lower-fan sedimentation capped by deposits from slope failure (King et al., 1994).

4.3. Allostratigraphic Unit 3

Allostratigraphic unit consisting of Sandstone Element 3, Heterolithic Element 3 and Deformed Element 3, representing a shift from channel lobe transition to lower-fan depositional environment.

Sandstone Element 3 has a complex architecture, but is condensed and does not contain heterogeneous sub-elements. The whole succession is therefore included as a sandstone element in Allostratigraphic Unit 3 (Figure 4.2). Allsotratigraphic Unit 3 is poorly exposed inland of the coastal outcrops but can be discontinuously traced up

Tongaporutu Valley. The structural orientation makes it likely that the unit crop out in a vegetated area south of Tongaporutu Valley (Figure 4.3).

In summary, Sandstone Element 3 grades over to the thin Heterolithic Element 3 which represent a shift from channel-lobe transition to lower fan environments. Alternatively, this represents a shift from channel-lobe transition to overbank deposits. The unit is capped by Deformed Element 3 which is interpreted to have resulted from slope failure (King et al., 1994).

4.4. Allostratigraphic Unit 4

Allostratigraphic unit consisting of Sandstone Element 4, Heterolithic Element 4 and Deformed Element 4, representing a shift from channel to lower-fan depositional environment.

Allostratigraphic Unit 4 consists of Sandstone Element 4, Heterolithic Element 4 and Deformed Element 4 (Figure 4.2). The unit is only exposed in the coast near outcrops at Waikiekie Stream due to vegetation (Figure 4.3).

In summary, the unit reflects the abandonment of a channel belt and onset of lower-fan deposition and is capped by deposits from slope failure.

5. Allostratigraphic architecture

The depositional environment of the sandstone elements becomes more proximal with time, interpreted to reflect the overall progradation of the depositional system.

The sandstone elements at the base of each allostratigraphic unit have been interpreted to represent different depositional environments (Table 5.1). The stacking of these reflects the overall evolution of the Mount Messenger depositional system in the study area.

Table 5-1 Table of geometry and interpretation of sandstone elements

Architectural Element	Relative age	Observation	Depositional setting
Sandstone Element 4	Youngest	Deeper channels	Inner mid fan
Sandstone Element 3		Scours and injections	Channel-lobe transition
Sandstone Element 2		Fan, local channel complex	Middle mid fan
Sandstone Element 1	Oldest	Fan, occasional scours	Outer mid fan
Base Mount Messenger Formation			

Sandstone Element 1 occupies marginal and axial positions in the same areas as Sandstone Element 2. Further, the coastal exposures of Sandstone Element 1 have been interpreted to represent uchannelised mid-fan deposits whereas the coastal exposures of younger Sandstone Element 2 represent partly channelised mid-fan deposits. The Allostratigraphic Unit 1 and 2 are therefore likely to be aggradational to slightly progradationally stacked.

It is not possible to document the stacking pattern of Allostratigraphic Unit 3 and 4 due to the limited 3D control. However, the bases Sandstone Element 1 and 2 are sub-planar, the base of Sandstone Element 3 has meters deep scours and injections whereas Sandstone Element 4 is cut by 10's of meters deep channels. This overall stratigraphic development represent a shift from basal geometries expected *down-dip* of the channel-lobe transition to geometries expected *at* the channel-lobe transition to geometries expected *up-dip* of the channel-lobe transition and reflects the depositional system's progradation into the study area (Figure 5.1).

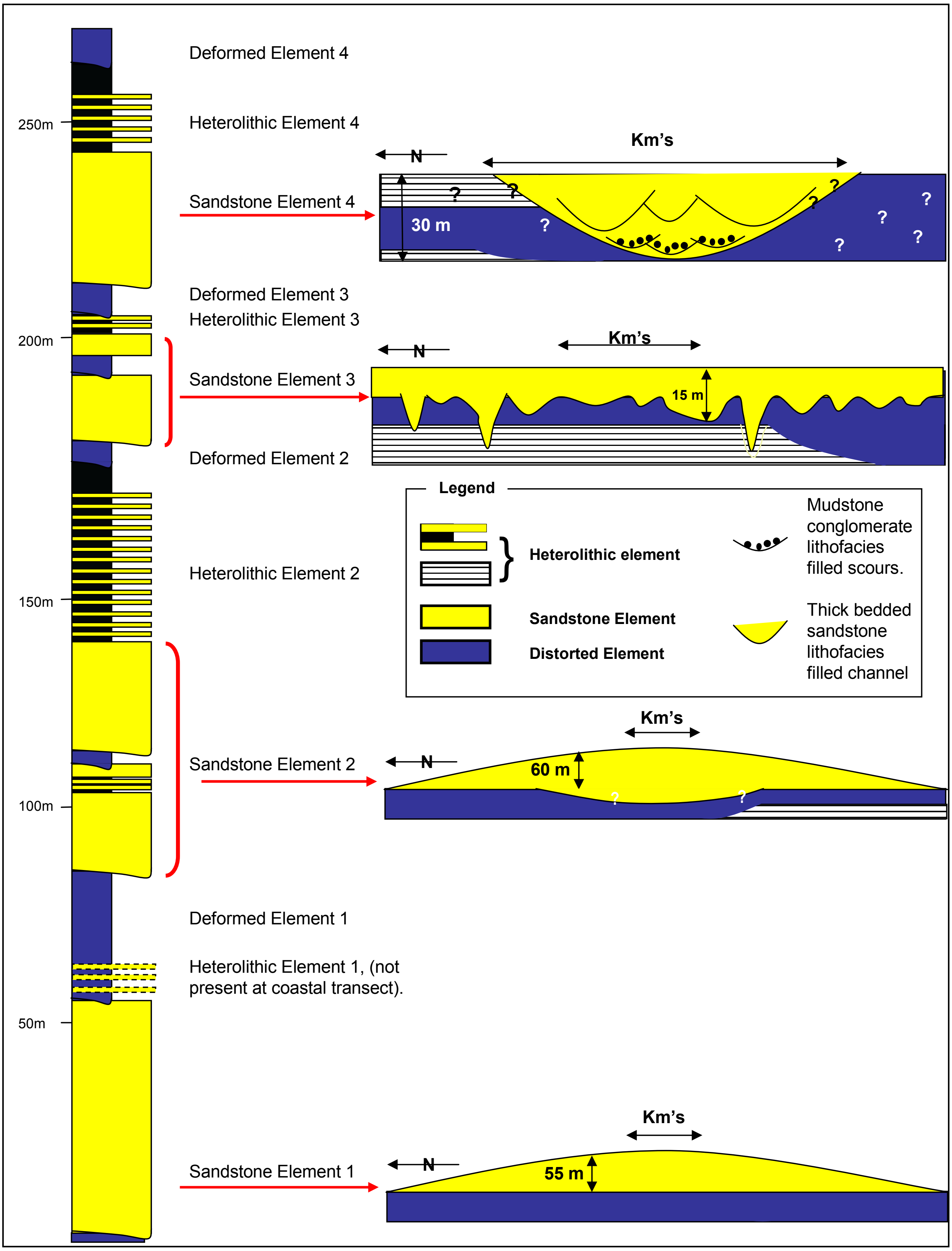


Figure 5.1 The basal relief of the allostratigraphic units (i.e. base of sandstone elements) increases with time from 1) sub-planar (traceable for 10's of km), 2) scoured and channelised (width 10's of m, depth 5m) to 3) a kilometre wide channel. This represent a shift from basal geometries expected *down-dip* of the channel-lobe transition to geometries expected *at* the channel lobe transition to geometries expected *up-dip* of the channel-lobe transition. This transition with time reflects the depositional system's progradation into the study area. See figure1.6 for legend.

Paleocurrent measurements determined from channel axis (Figure 5.2) and ripple –and climbing ripple lamination (Figure 5.3) at Tongaporutu Beach and Waikiekie Beach trend roughly towards the western half circle. Following King et al. (1993), it is therefore concluded the depositional system had a westerly to north-westerly direction of progradation.

Figure 5.2 Summary rose plot of channel axis directions. N =5.

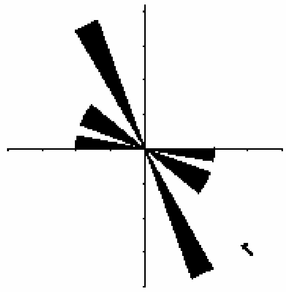
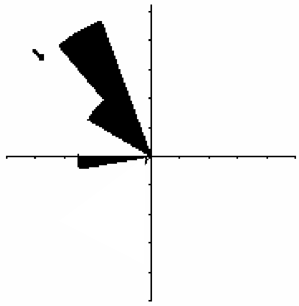


Figure 5.3 Summary rose plot of polar measurement s in architectural elements. N=6.



Mutti's (1985) depositional model for Hecho Group in Spain might represent a good analogue for the up-dip development of the Mount Messenger Formation (Figure 5.4). The *thick-bedded sandstone lobes is* represented by sandstone elements 1 and 2 whereas the *channel lobe transition* is represented by Sandstone Element 3 and the *thick-bedded channel fill sandstone* is represented by Sandstone Element 4.

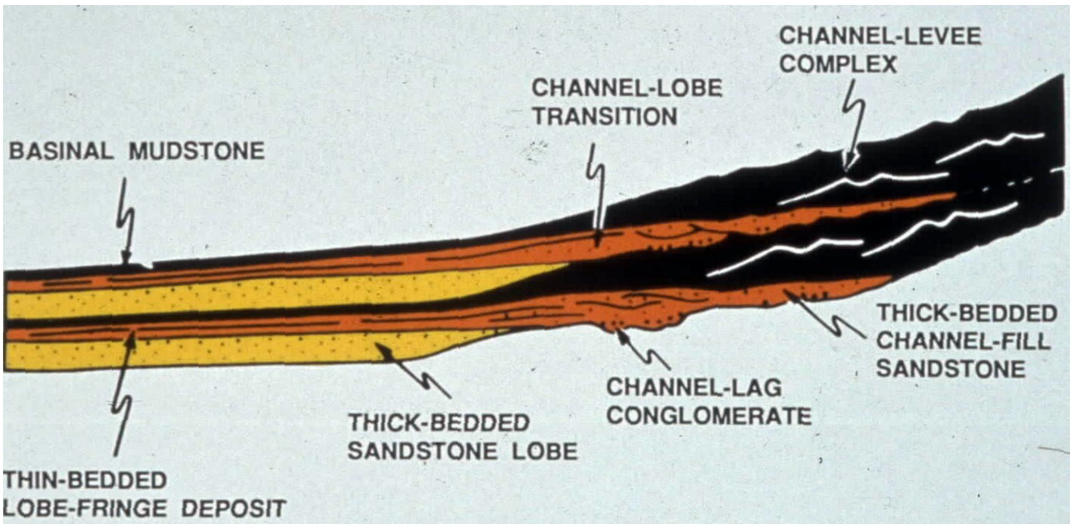


Figure 5.4 Possible analogue for the Mount Messenger depositional system: The deep-water expression of depositional sequences in the Eocene Hecho Group, south-central Pyrenees (After Mutti 1985). Thick- and heterolithic deposited down-dip of channel-lobe transition. Thick-bedded channel-fill sandstone with channel lag conglomerate deposited up-dip of channel-lobe transition.

6. Paleogeography

Mount Messenger Formation is interpreted as multiple sourced, moderately efficient, shallow incised, channel attached depositional system. The formation has been classified as a hybrid between a *sand-rich slope apron* and a *mixed sand-mud slope apron* depositional system.

In Miocene time, the deep-sea was separated from the rapidly rising hinterland to the south and south-east by a narrow paleo-shelf (Figure 6.1) (King et al., 1993). The paleogeography of the hinterland may have been quite similar of today, with meandering rivers transporting sediments from uplifted areas to a retreating coastline. However, the uplift could have favored establishment of braided rivers.

The very fine to fine grain size of the sandy facies remains largely constant throughout Mount Messenger Formation (Brown pers. com, 2003). According to Richards et al. (1998), this is typical for relict shelfal and marginal marine sand source whereas a wide range of grain sizes and mineralogy are indicative for fluvial or fluvio-

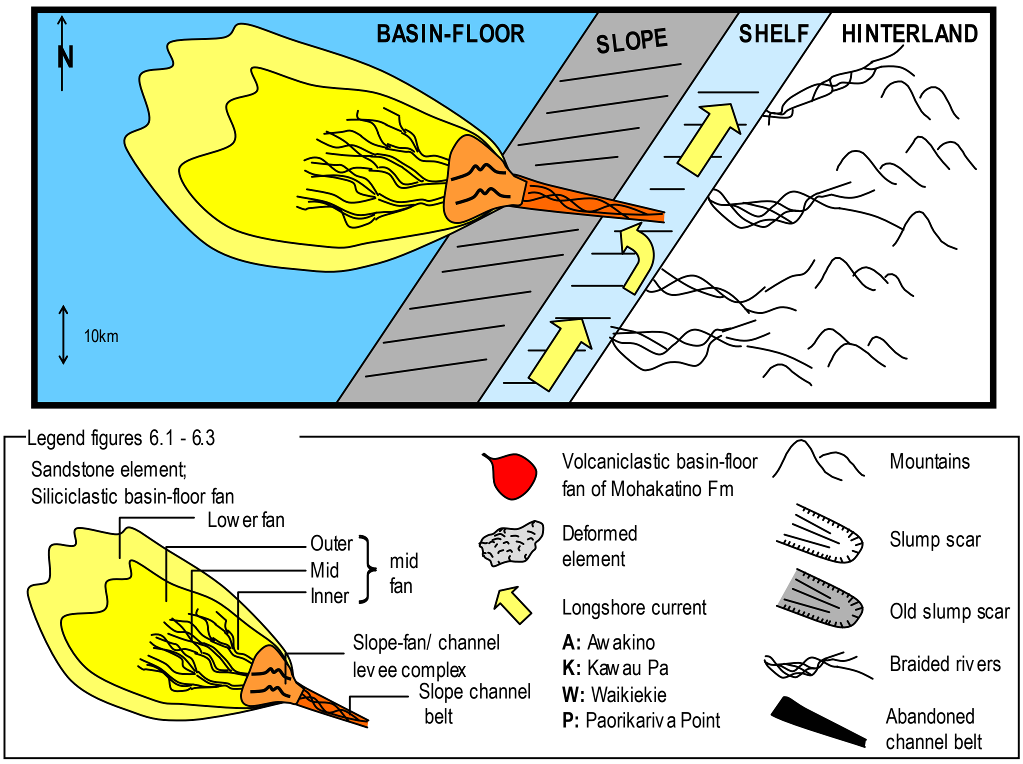


Figure 6.1 Paleogeographic framework for the eastern-margin of Taranaki Basin in Miocene time; Braided rivers extending from uplifted areas in the east and south-east supplied sediments to the narrow shelf. On the shelf, sediments were reworked by longshore currents and transported to shallow, cross-shelf channels leading to the basin-floor. The basin-floor fans were channel attached and mid/lower fan environments occur in front of channel-levee deposits (Model by King et al.,1993).

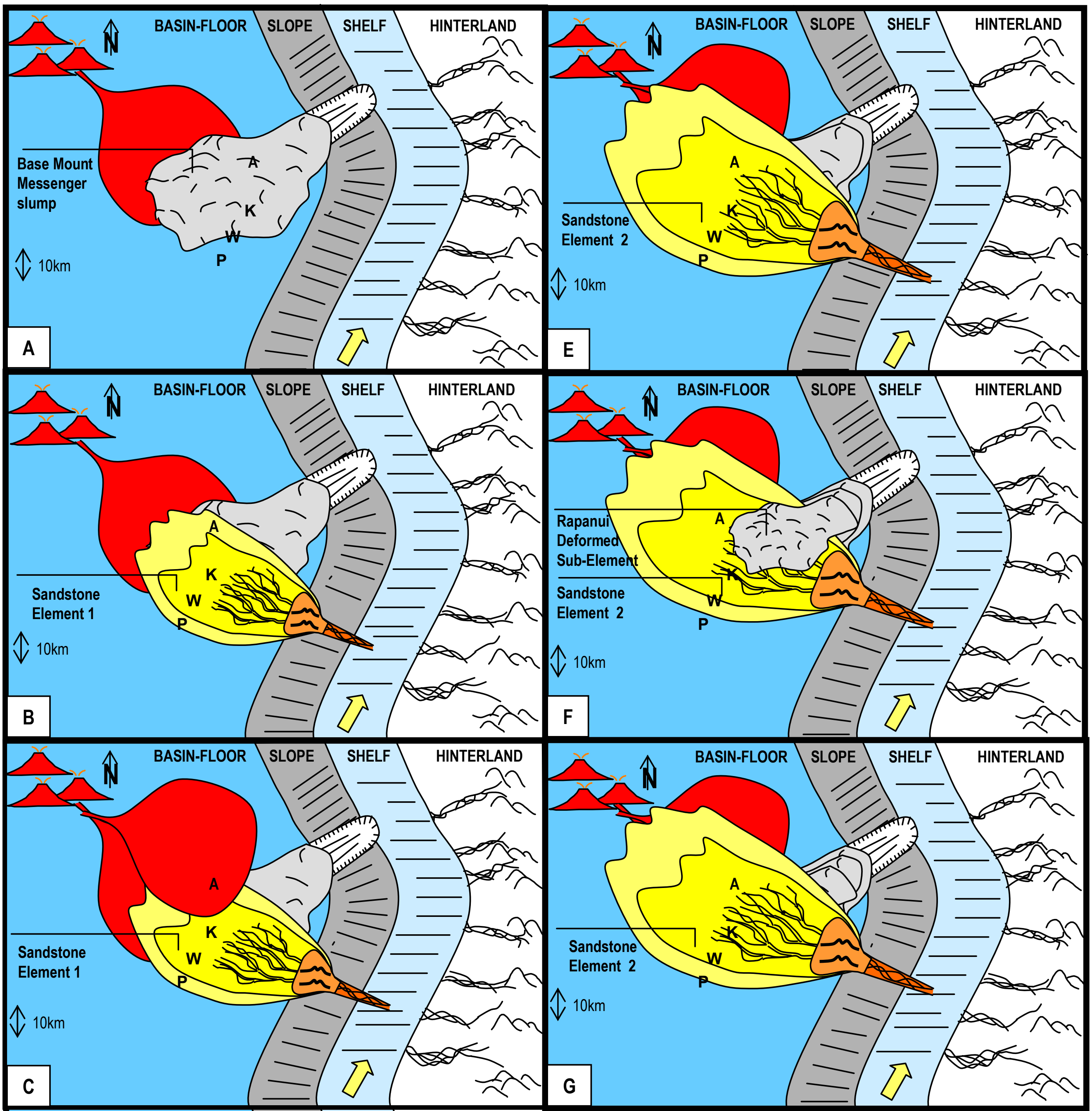
deltaic source. Further, the sandy facies of Mount Messenger Formation has low-grade meta-sedimentary rocks of Mesozoic age as origin (Nodder et al., 1990b, Jordan et al., 1994). King et al. (1993) and King & Thrasher (1996) suggested a source area to the south and south-east of the study area. Marine erosion of uplifted areas and marine reworking of fluvially introduced sediments provided a source for the Mount Messenger depositional system. King et al. (1993) further suggested sediments were transported by longshore currents to cross-shelf channels leading to the basin floor.

The slope deposits of Urenui Formation are cut by 30-40m deep channels that bypassed sediments to the basin-floor fans (King et al., 1993). It is reasonable to assume the same type of channels where feeding the studied part of Mount Messenger Formation. The Mount Messenger depositional system was therefore probably fed through a shallow channel system.

The shallow channels in Sandstone Element 2 might represent an analogue to the down-dip geometry of the deeper channels in Sandstone Element 4. These channels most likely extended to the slope and were probably connected to the shallow slope channels. The basin-floor fans are therefore likely to have been channel attached.

The rapid uplift of hinterland might have resulted in that the fans were deposited as aprons. However, King et al. (1994) interpreted the deposits overlying the studied stratigraphic interval as channel-levee complexes and further suggested that channel-levee deposits would be expected up depositional dip of the studied basin-floor fans. If this is correct, the stabilizing effect of the levees would contribute to transporting sediments some distance onto the basin-floor. The depositional system is therefore likely to represent a moderately efficient system (terminology from Mutti, 1979).

Deformed Element 1 was traveling towards the south-west (King pers. com, 2003) whereas Sandstone Element 1 and 2 were prograding towards the north-west. This may indicate the slope was turning from facing north-west in the southern part of the study area to facing south-west in the northern parts of the study area. This further suggests 2 sources of sediments for Allostratigraphic Unit 1 and 2; slump-flows represented by Deformed Element 1, 2 and Rapanui Deformed Sub-Element from the north-east and basin-floor fans represented by Sandstone Element 1 and 2 from the south-east (Figure 6.2). Sandstone Element 1 occupies marginal and axial positions in the same areas as Sandstone Element 2, suggesting they were fed by the same point source(s). In the north, Allostratigraphic Unit 1 and 2 interfinger with the volcaniclastics of Mohakatino Formation.



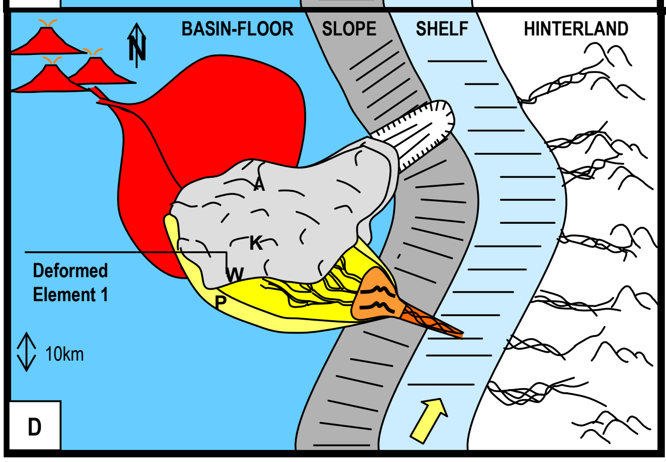


Figure 6.2 Paleogeographic evolution of Mt Messenger Formation.
A: Prior to Mount Messenger deposition; volcaniclastics of Mohakatino Formation; Slope failure in the north-east and deposition of the base Mount Messenger slump.
B: Onset of Mount Messenger deposition; Sandstone Element 1 progrades toward the north-west.
C: In the north, Sandstone Element 1 interfinger with the volcaniclastics of Mohakatino Formation.
D: Slope failure in the north-east and deposition of Deformed Element 1.
E: Continued progradation of the Mount Messenger basin-floor fans; deposition of Sandstone Element 2.
F: Slope failure in the north-east and deposition of Rapanui Deformed Sub-Element.
G: Continued progradation of the Mount Messenger basin-floor fans; deposition of Sandstone Element 2. Maps partly based on King (1993) and Brown & King pers. com., 2003.

Deformed Element 2 and 3 erodes down toward the south, in an area located south of the interpreted axial position of Sandstone Element 1 and 2. Also, the slump scar of Deformed Element 2 exposed at Waikiekie Beach trend towards the north-west. This may indicate Allostratigraphic Unit 3 and 4 were fed through a point source located further south (Figure 6.2). In this area, the preference of sandstone elements to overlie deformed elements may indicate the slope channels initially were slump scars that later was used as conduits for sandy gravity flows. However, these lateral variations may also be explained by compensational response on the basin-floor.

These 3 point sources were probably a few of numerous point sources feeding the basin-floor as suggested by King et al. (1993) (Figure 1.4).

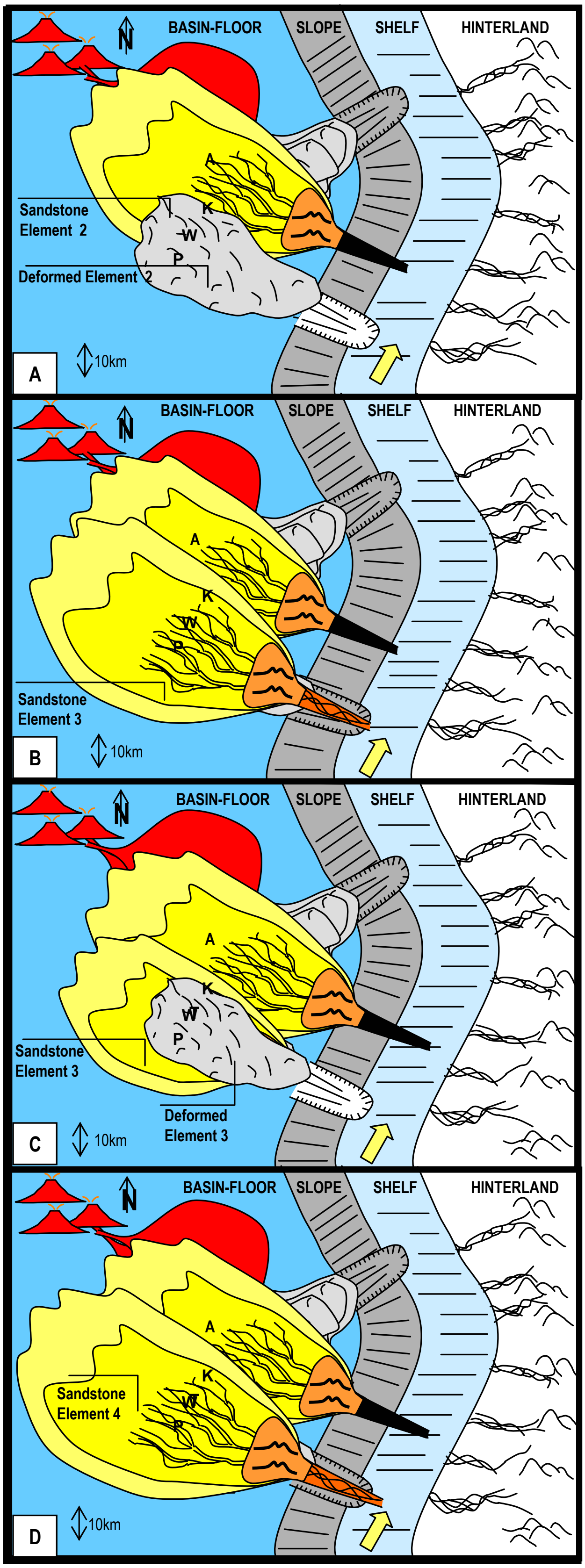


Figure 6.3 Paleogeographic evolution of Mount Messenger Formation
A: Slope failure in the south and deposition of Deformed Element 2.
B: Continued progradation of the Mount Messenger basin-floor fans; deposition of Sandstone Element 3. Slump scar from Deformed Element 2 possibly being used as a conduit for sandy gravity flows feeding Sandstone Element 3.
C: Slope failure in the south and deposition of Deformed Element 3.
D: Continued progradation of the Mount Messenger basin-floor fans; deposition of Sandstone Element 4. Slump scar from Deformed Element 3 possibly being used as a conduit for sandy gravity flows feeding Sandstone Element 4.
Maps partly based on King et al. (1993) and King & Brown pers. com, 2003.

Based on the discussion above and the terminology introduced by Reading & Richards (1994), the depositional system may be classified as a hybrid between the *sand-rich slope apron* with braided rivers in the hinterland and sediments dumped close to the slope (Figure 6.4) and the *mixed sand-mud slope apron* with shallow channels transporting sand some distance onto the basin-floor and slope failures resulting in deposition of deformed elements (Figure 6.5).

.

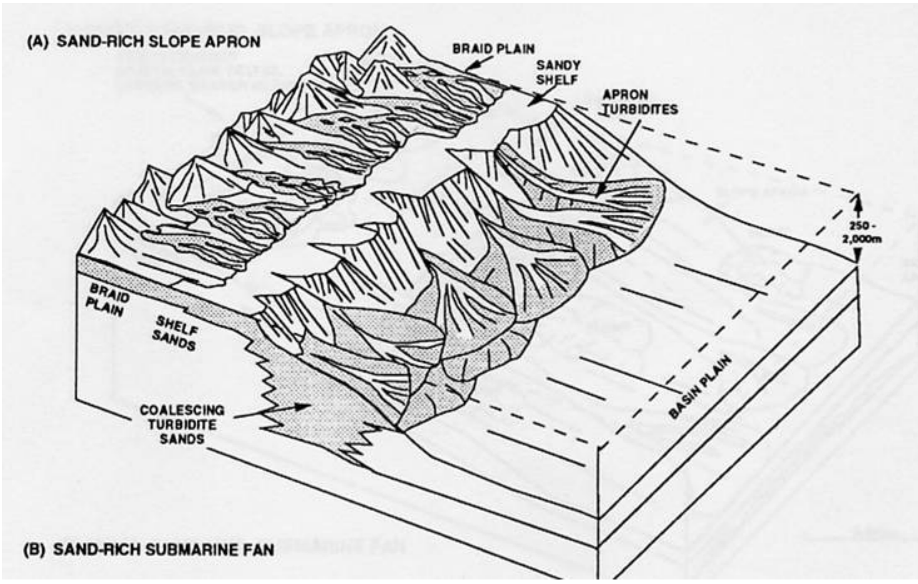


Figure 6.4 *Sand-rich slope apron* in Reading & Richards' (1994) classification of deep-marine clastic depositional systems. Sediments are delivered by braided rivers along a broad front adjacent to the submarine slope. The sediments are mainly transported to the basin-floor by deeply incised channels (compared to model in Figure 6.12).

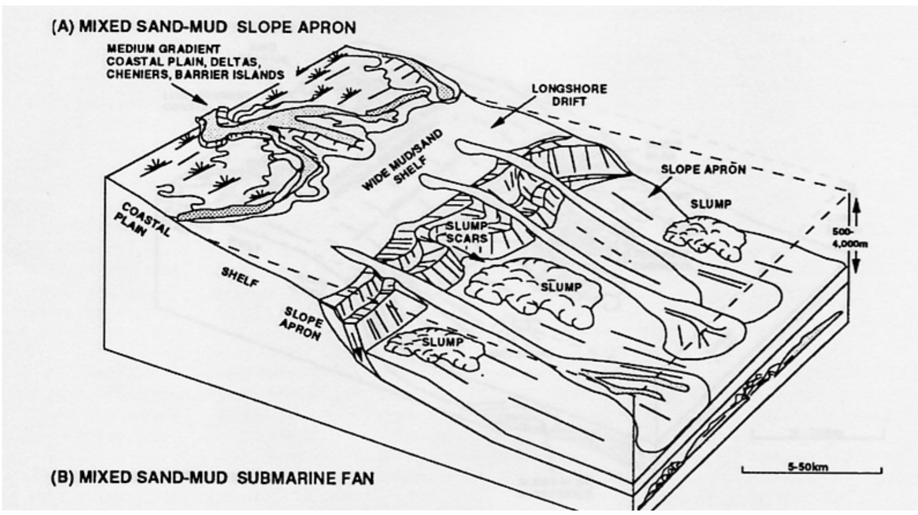


Figure 6.5 *Mixed sand-mud slope apron* in Reading & Richards' (1994) classification of deep-marine clastic depositional systems. The sediments are transported to the basin-floor by shallowly incised channels (compared to model in Figure 6.11).

7. Controls on stratigraphic architecture

The age control through the studied stratigraphic interval is limited but allows some speculative comparison between stratigraphic architecture and potential driving mechanisms with known rates and duration (Figure 7.1 & Table 7.1). 3 time hierarchies are recognized in the studied deposits; 1) *low-frequency* hierarchy with several million years or longer duration; 2) *medium-frequency* hierarchy with 100-200 thousands years duration; and 3) *high-frequency* hierarchy with 10's of thousands years duration (King et al., 1993, 1994).

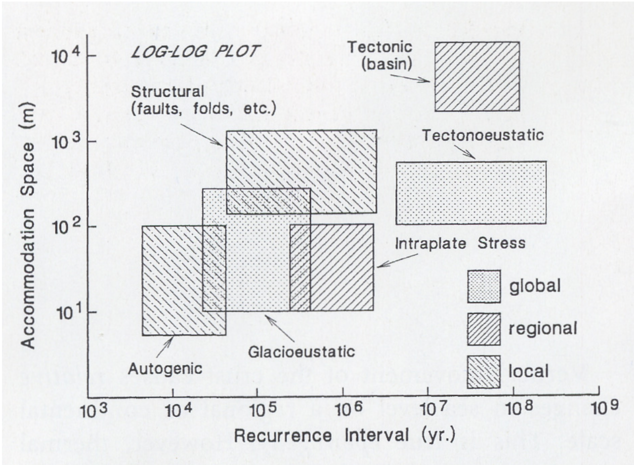


Figure 7.1 Estimated ranges in accommodation space versus recurrence interval for various processes that generate stratigraphic cyclicity. The regional extent of the processes is indicated by internal ornamentation of each box (adapted from Dickinson et al., 1994).

Table 7-1 The relationship between tectonic processes and stratigraphic signatures in foreland basins, at different time scales

Duration (Ma)	Scale	Tectonic process	Stratigraphic signature
>50	Entire tectonic belt	Regional flexural loading, imbricate stacking	Regional fore-deep basin
10-50	Regional	Terrane docking and accretion	Multiple ”molasse” pulses
10-50	Regional	Effects of basement heterogeneities during crustal shortening	Local variations in subsidence rate; may lead to local transgressions/regressions
>5	Regional	Fault-propagation anticline and foreland syncline	Sub-basin filled by sequence sets bounded by major enhanced unconformities
5-0.5	Local	Thrust overstep branches developing inside fault propagation anticline	Enhanced sequence boundaries; structural truncation and rotation; decreasing upwards dips; sharp onlaps; thick lowstands, syntectonic facies
<0.5	Local	Movement of individual thrust plates; normal listric faults; minor folds	Depositional systems and bedsets geometrically controlled by tectonism and bounded by unconformable bedding-plane surfaces; maximum flooding surfaces superimposed on growth fault scarps; shelf perched lowstand deposits

Table adapted mainly from (Deramond et al., 1993) with additional data from (Waschbusch & Royden, 1992) and (Stockmal et al., 1992). Table constructed by (Miall, 1997)

7.1. Low-frequency architecture

Onset and progradation of the Mount Messenger depositional system caused by interacting factors of sediment supply, subsidence and eustasy.

The deposition of Mount Messenger Formation took place over a time period of 1-2 million years and represent the basin-floor response to the 3rd order (1-10Ma) progradation into Taranaki Basin before being overlain by the Urenui deposits (King et al., 1993, 1994). Driving mechanisms operating on this time scale are mainly tectonic (Figure 7.1 & Table 7.1). King et al. (1993) concluded that the basinal change from carbonate to clastic dominated sedimentation was ultimately controlled by tectonic processes in the rising hinterland to the south and south-east. However, King et al. (1993) points out that, in the study area,*"...it is not essential to invoke a solely tectonic (uplifted source) origin for Mount Messenger sediments. Instead, or as well as, the formation probably reflects a changing balance locally between sediment budget and accommodation space, and consequent shift in depositional environment".* The onset of Mount Messenger deposition in the study area may merely mark the onset of progradation into this particular area (King et al., 1993) and may have been a result of gradual progradation or shift the locus of deposition due to for example local and semi-regional source area tectonics.

Further, King et al. (1993) points out that the onset of Mount Messenger sedimentation roughly correspond in time with a major eustatic sea-level fall of around 150m in Late Miocene time (c. 10Ma, Haq et al., 1987) (Figure 7.2) and suggest that the deposition of Mount Messenger Formation was controlled by interacting factors of sediment supply, subsidence and eustasy.

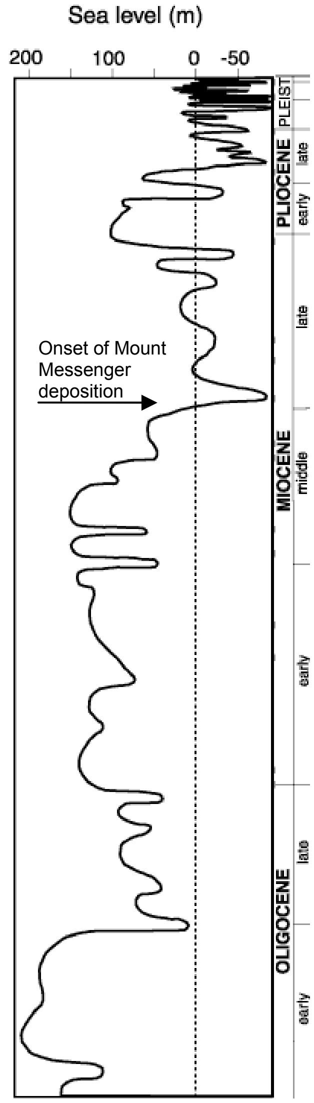


Figure 7.2 Haq et al.'s (1987) eustatic sea-level curve from Oligocene until present.

7.2. Medium-frequency architecture

The rhythmic stacking of architectural elements in Allostratigraphic Unit 1-4 has possible interpretations ranging from completely controlled by sediment supply, relative sea-level or tectonic processes.

The allostratigraphic units are bounded by erosional discontinuities and Aubry (1995) states that in some deep water deposits there is almost as much geological time represented by unconformities as there is time represented by sediments. The deformed elements may accommodate a considerable time interval and the allostratigraphic units may be highly diachronous. However, as long as there is no age control above and below the deformed elements this time interval remains undecided. This further makes it uncertain what time interval an allostratigraphic unit represents. However, based on the time interval of Mount Messenger deposition in the study area, King et al. (1994) suggested that each allostratigraphic unit represents 100-200 thousands years. There are a number of processes operating on this time scale (Figure 7.1 & 7.2, Table 7.1 & 7.2) and the rhythmic stacking of architectural elements in the Allostratigraphic Unit 1-4 either results from rhythmical allo/autogenic processes or un-rhythmical generated allo/autogenic processes.

In Miocene time, possible rhythmical allogenic driving mechanisms with 100's of thousands years duration include tectonic processes (Table 7.1) and Milankovitch processes (Table 7.2) (Miall, 1997). The study area is located in a highly tectonic active region where local and regional tectonic processes would be expected to have an impact on sediment supply and relative sea-level (King et al., 1993, 1994). Further, Milankovitch processes are widely accepted as the dominant control on climate variations with 10's and 100's of thousands years duration. Milankovitch processes may have had a major influence on sediment supply from the hinterland and/or may have

Table 7-2 Duration and type of Milankovitch processes

Milankovitch Process	Major periods (ka)	Minor periods (ka)
Eccentricity	413 & 100	2035, 128 & 54
Obliquity	41	54 & 40
Precession	24	-

caused repeated glacio-eustatic sea-level falls resulting in relative sea-level falls in the study area.

King et al. (1994) preferred to interpret the rhythmic stratigraphy of the Allostratigraphic Unit 2-4 (sequence 1-3 in King et al., 1994) to reflect relative sea-level cycles with 100-200 thousands years duration and that the units comprises mainly, if not entirely, lowstand sediments. In the terminology of Posamentier et al. (1991), King et al. (1994) (Figure 7.3) interpreted the sandstone elements and the lower part of the heterolithic elements as basin-floor fans. The upper part of the heterolithic elements was interpreted as possible channel-levee –or prograding complexes whereas the overlying deformed elements were interpreted as prograding complexes or highstand system tract deposits. The sequence boundaries (SB) were placed at the erosive base of the basin-

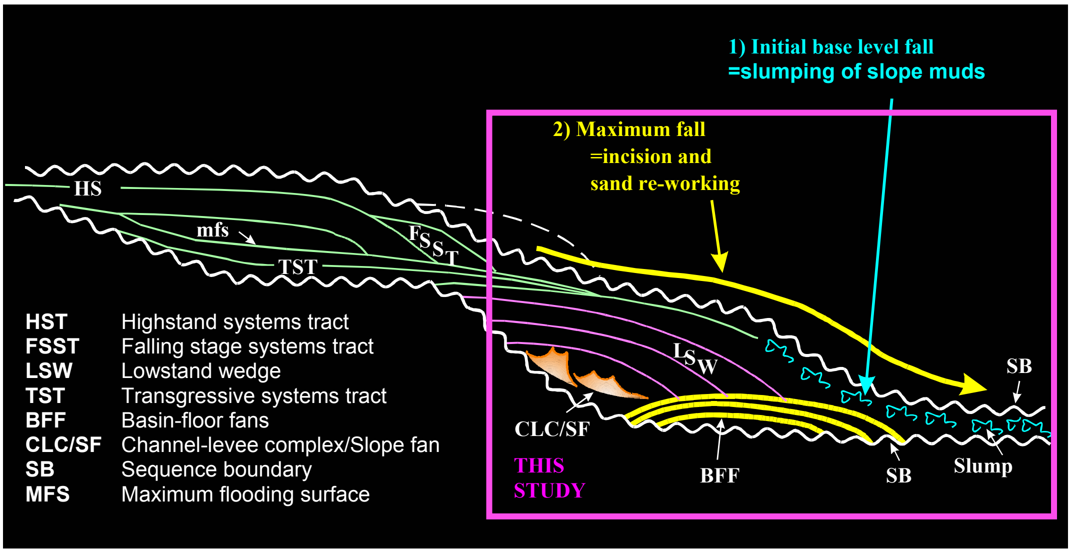


Figure 7.3 General sequence stratigraphic model for deep-water settings. Slumps are deposited during late highstand and initial relative sea-level fall, BFF deposition during relative sea-level low and TST deposition during sea-level rise and highstand. Slightly modified from presentation by Brown and King at University of Bergen, 2003.

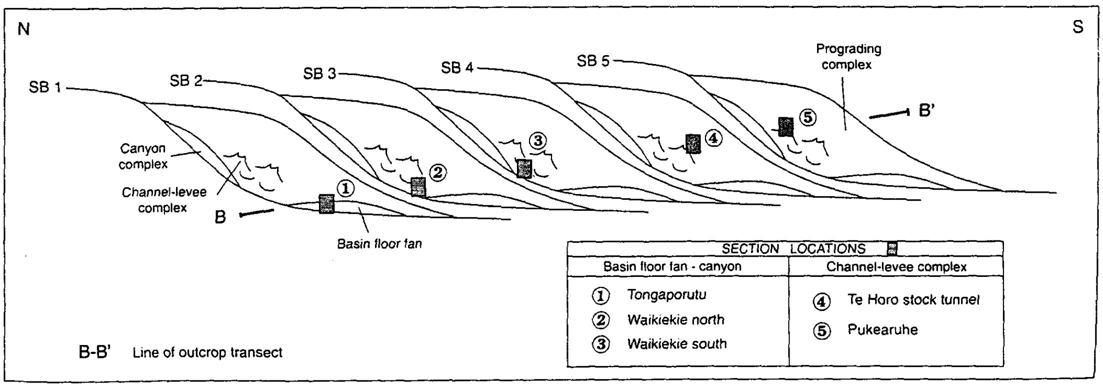


Figure 7.4 Summary sequence stratigraphic model for deposition of Mount Messenger succession in coastal cliff transect between Tongaporutu River estuary and Pukearuhe (King et al. 1994). SB 1-4 corresponds to CB 2-4 in this study.

floor fans (interpreted as Type I, after Posamentier & Vail (1988), Van Wagoner et al. (1988), Van Wagoner et al. (1990), and Posamentier & James (1993)) and SB 1-4 in King et al. (1994) are equivalent to this study's cycle boundary 2 as exposed at Tongaporutu River estuary and coastal exposures of cycle boundaries 3, 4 and 5 (Figure 4.2 & 7.2).

Late Miocene time was a period of major 4th order eustatic sea-level changes (Figure 7.1) (Haq et al., 1987). Further, the slope-deposits of Urenui Formation which overlies Mount Messenger Formation are cut by channels at several stratigraphic levels inferred to have been incised at different times of relative sea-level lows (King et al., 1993). This suggests that relative sea-level influenced Late Miocene deposition in Taranki Basin and may indicate a relative sea-level influence during deposition of Mount Messenger Formation.

On the other hand, the time equivalent shelf was narrow (King et al., 1993) and this would have made the sedimentation on the basin-floor easily affected by changes in hinterland sediment supply. Based on estimated time 24 modern river systems would use to form shelf edge deltas, Burgess & Hovius (1998) concluded that *"…transport of sand to deep marine systems is likely to be significant during third order highstands of relative sea-level."* and further that *…interpreting ancient sand-rich deep marine strata as lowstand deposits without sufficient paleogeographic information may not therefore always be appropriate".* Milankovitch processes may have caused changes in source area climate with 100's of thousands years duration without associated relative sea-level change. This may have resulted in more sediments being eroded and transported into Taranaki Basin during humid climate periods than during dry periods.

Also, local source area tectonics (Table 7.1) may have shifted the position of major river outlets and changed the entry points of sediments to the marine environment or tectonic pulses within the orogenic belt may locally have increased erosion and sediment supply to Taranaki Basin.

However, the poor age-control through this stratigraphic interval makes correlation with Milankovitch and independent relative -or eustatic sea-level curves speculative. Further, it is not possible to correlate the strata to relative sea-level indicators on the time-equivalent shelf/coast (e.g. incised valleys) as the shelf deposits are not preserved. This makes it difficult to compare the relative sea-level controlled incisions in the slope deposits of Urenui Formation to the older basin-floor deposits of

Mount Messenger Formation. Also, the hinterland is not preserved and the amount of tectonic control on sedimentation remains undecided.

The uplift of the hinterland to the east and the south-east was rapid and an extensive erosion and transport of sediments into Taranaki basin followed (King et al., 1993). It is possible that allogenic factors did *not* have a strong influence on the Mount Messenger depositional system, but that the system was overwhelmed by high sediment supply. The 3rd order progradation might be viewed as a front of major lateral variations in lithofacies associations caused by rhythmic autogenic processes on the shelf, deltaic lobe shifts, slope channel avulsion and basin-floor compensational response may have resulted in cyclic lithological response reflecting the onset, maximum -and termination of deposition in an area. A preserved example of this may be Rapanui Deformed Sub-Element; the sub-element pinches out to a mudstone horizon and in principle any mudstone horizon may be laterally equivalent to a deformed element. This may indicate a chaotic system where . However, Rapanui Deformed Sub-Element may reflect single event into a stable and predictive system.

Alternatively, the cyclic architecture may merely reflect the depositional system's response to un-rhythmic allogenic events as slope failure triggered by global and regional seismic activity and/or un-rhythmic autogenic slope failure triggered by e.g. gas-escape rather than relative sea-level fluctuations or Milankovitch processes. Slumping may have resulted in slump scars extending land -and basinward of the position of the channel lobe transition, later laterally confining gravity-flows and making massive sandstone association able to reach positions of previous distal deposition (heterolithic association). This may be in lower-fan or distal overbank settings, however, if the basin-floor by far was covered by the heterolithic association the slump would likely be deposited on top of this association. When the conduit is abandoned the distal deposition of the thin bedded sandstone association commences.

It is not presently possible to distinguish between these models due to the low time and up-dip control, but the narrow shelf (King et al., 1993) would make the depositional system easily influenced by several processes. As the study area is located in a very tectonically active area it seems likely that this had a major influence on the depositional system evolution on 100's of thousands years scale.

7.3. High-frequency architecture

Rhythmic stratigraphy within architectural elements results from autogenic shifts in deposition.

Smaller scale rhythmic stratigraphy occur superimposed on the interpreted 100-200 thousands years cycles in many places along the coast (King et al., 1994). As these are superimposed on cycles interpreted to have durations of 100-200 thousands years, they are presumably related to variation in deposition on a few 10's of thousands years scale.

Only autogenic processes operate on this time scale (Figure 7.1) and King et al. (1994) interpreted this rhythmic stratigraphy as autocyclic depositional adjustments, e.g., lobe switching, compensation bedding and channel-levee migration.

7.4. Further work

This thesis presents large scale mapping and litho-correlation of the strata outcropping between Awakino River and Waikiekie Stream and up Tongaporutu Valley. Further work could include detailed sedimentary logging and thickness measurements of architectural elements at Hutawai Valley, Rapanui Valley, Mokau River, Awakino River and along the abandoned coastal cliffs. Detailed studies of the geometries, stratigraphic position and lateral extent of the channel complex exposed at the pull-in resting area just north of Kawau Pa might refine the understanding of lateral development of Sandstone Element 2. Also, detailed correlation and mapping of strata inland of the coastal cliff transect between Kawau Pa and Omahu Pa Fault could refine the understanding of stratigraphy of the study area.

More paleocurrent measurement from all architectural elements would refine the understanding of the paleogeographic evolution of Mount Messenger Formation. Further, detailed mapping of lower contacts of sandstone elements and seismic interpretation of offshore lines might help define seismic scale geometries of the Mount Messenger depositional system.

8. Conclusion

1. Studies between Kawau Pa and Waikiekie Stream enables correlation between time equivalent strata from Awakino to Tongaporutu River estuary and further up the Tongaporutu catchment area. This makes it possible to reconstruct the minimum dimensions and larger scale geometry of the architectural elements within the study area.
2. The bases of sandstone elements change with time from; 1) sub-planar; 2) channelised and scoured; 3) to deeper channels. The change likely reflects systematic changes of the Mount Messenger depositional system through time. In the study area, a progradation of the depositional system has been documented down-dip of the channel-lobe transition to geometries expected up-dip of the channel-lobe transition and reflects the depositional system's progradation into the study area (King et al., 1993).
3. Mount Messenger Formation is interpreted as multiple sourced, moderately efficient, shallow incised, channel attached depositional system. Paleocurrent measurements indicate that Allostratigraphic Unit 1 and 2 were fed from 2 sources; slump-flows from the north and sandy gravity-flows from the south-east; Allostratigraphic Unit 3 and 4 were fed from a source located to the south. The formation can be classified as a hybrid between the sand-rich slope apron and the mixed sand-mud slope apron depositional system in the classification introduced by Reading & Richards (1994).
4. 3 stratigraphic time hierarchies are recognized within the studied deposits; 1) onset of Mount Messenger deposition representing a *low-frequency hierarchy* with several million years or more duration interpreted to result from interacting factors of sediment supply, subsidence and eustasy, but ultimately controlled by the uplift in the south-east; 2) rhythmic stacking of architectural elements representing a *medium-frequency hierarchy* with 100-200 thousand years duration interpreted to result from tectonic processes; and 3) thinning-up successions within architectural elements representing a *high-frequency hierarchy* with 10's of thousands years duration interpreted to result from autogenic processes (King et al., 1994)

References Cited

Aubry, M. P., 1995; *From chronology to stratigraphy: interpreting the lower and middel eocene stratigraphic record in the Atlantic Ocean.* ***IN;*** Berggrren, W.A., Kent, D.V., Aubry, M-P., Hardenbol, J. (eds.) Geochronology, time scales and global stratigraphic correlation. Society of Sedimentary Geology Special Publication 54, p. 213-274.

Basu, D. & Bouma, A. H., 2000; *Thin-bedded turbidites of the Tanqua Karoo: physical and depositional characteristics.* ***IN;*** A.H. Bouma and C.G. Stone, (eds.), Fine-grained turbidite systems, AAPG Memoir 72/SEPM Special Publication No. 68, p. 263-278.

Bennett, C., Gregg, R. & King P.R., 1992; *Petroleum geology of the Taranaki Basin, with emphasis on the north-eastern quadrant.* ***IN;*** Petroleum exploration in New Zealand news 32, p. 14-32.

Browne, G. H., McAlpine, A. & King, P. R., 1996; *An outcrop study of bed thickness, continuity and permeability in reservoir facies of the Mt Messenger Formation, north Taranaki.* ***IN;*** New Zealand Petroleum Conferance Proceedings Volume 1, p. 154-163.

Browne, G. H., Slatt, R. M. & King, P. R., 2000; *Contrasting Styles of Basin-Floor Fan and Slope Fan Deposition: Mount Messenger Formation, New Zealand.* ***IN;*** Bouma, A.H. and Stone, C.G. (eds.), Fine-grained turbidite systems, AAPG Memoir 72/SEPM Special Publication 68, p. 143-152.

Browne, G. H. & Slatt. R. M., 1997; *Thin-bedded Slope Fan (Channel-Levee) Deposits from New Zealand: An Outcrop Analog for Reservoirs in the Gulf of Mexico.* ***IN;*** Gulf Coast Association of Geological Societies Transactions XLVII.

Burgess, P. M. & Hovius, N., 1998; *Rates of delta prrogradation during highstands: consequences for timing of deposition in deep-marine systems.* ***IN;*** Journal of the Geological Society, London, p. 217-222.

Clarke, E. d. C., 1912; *The geology of the New Plymouth Subdivision.* ***IN;*** New Zealand Geological Survey bulletin n.s. 14, p. 59 and maps.

Deramond, J., Souquet, P., Fondecave-Wallez M-J, Specht. M., 1993; *Relationships between thrust tectonics and sequence stratigraphy surfaces in foredeeps: model and examples from the Pyrenees (Cretaceous-Eocene, France, Spain).* ***IN;*** William, G.D., Dobb, A. (eds.) Tectonics and seismic sequence sequence stratigraphy. Geological Society , London, Special Publication 71, p. 193-219.

Gibson, G. W., 1963; *Some Miocene stratigraphy and paleontology - the Tongaporutuan Stage.* ***IN;*** Unpublished PhD thesis lodged in the Library Victoria University of Wellington.

Glennie, K. W., 1958; *The Miocene formations of west Taranaki.* ***IN;*** Shell BP and Todd Oil Services Ltd. GR 16 Institute of Geological and Nuclear Sciences Ltd unpublished open file petroleum report 419, Wellington, New Zealand.

Grange, L. I., 1922; *Ohura Subdivision.* ***IN;*** New Zealand Geological Survey 16th annual report n.s. 7, p. 7-8.

Grange, L. I., 1927; *The geology of the Tongaporutu-Ohura Subdivision, Taranaki Division.* ***IN;*** New Zealand Geological Survey Bulletin n.s 31., p. 63 p. and maps.

Hansen, R. J., 1996; *Stratigraphy, sedimentology and paleomagnetism of a Late Miocene succession, eastern Taranaki Basin margin.* ***IN;*** Unpublished MS thesis, University of Waikato, Hamilton, New Zealand.

Haq, B. U., Hardenbol, J. & Vail, P. R., 1987; *The chronology of fluctuating sea level since the Triassic. IN;* Science 235, p. 1156-1167.

Hay, R. F., 1967; *Sheet 7 - Taranaki (1st edition). Geological map of New Zealand 1:250.000. IN;* Wellington, Department of Scientific and Industrial Research.

Henderson, J. & Ongley, M., 1923; *The geology of the Mokau Subdivision. IN;* New Zealand Geological Survey bulletin n.s. 24, p. 52 and maps.

Holt, W. E. & Stern, T. A., 1994; *Subduction, platform subsidence, and foreland thrust loading: the late Tertiary development of Taranaki Basin, New Zealand. IN;* Tectonics 13, p. 1068-1092.

Jordan, D. W., Schultz, D. J. & Cherng, J. A., 1994; *Facies architecture and reservoir quality of Miocene Mt Messenger deep-water deposits, Taranaki Peninsula, New Zealand. IN;* Weimer, P., Bouma, A.H., Perkins, B. (eds.) Submarine fans and turbidite systems: sequence stratigraphy, reservoir architecture and production characteristics, Gulf of Mexico and international: Gulf Coast Section, Society of Economic Paleontologists and Mineralogists Foundation, Houston, p. 151-166.

King, P. R., Browne, G. H. & Slatt, R. M., 1994; *Sequence architecture of exposed Late Miocene basin floor fan and channel-levee complexes (Mount Messenger Formation), Taranaki Basin, New Zealand. IN ;* Weimer, P.; Bouma, A. H.; Perkins, B. F. (eds.) Submarine fans and turbidite systems: sequence stratigraphy, reservoir architecture and production characteristics Gulf of Mexico and International: Gulf Coast Section, Society of Economic Paleontologists and Mineralogists Foundation, Houston, p. 177-192.

King, P. R., Scott G.H. & Robinson, P. H., 1993; *Description, Correlation and Depositional History of Miocene Sediments Outcropping along North Taranaki Coast. IN;* Institute of Geological and Nuclear Sciences Monograph 5.

King, P. R. & Thrasher, G. P., 1992; *Post-Eocene development of the Taranaki Basin, New Zealand; convergent overprint of passive margin. IN;* Watkins, J. S; Zhiqiang, F; McMillen, K. J. (eds.) Geology and Geophysics of Continental Margins, American Association of Petroleum Geologists memoir 53.

King, P. R. & Thrasher, G. P., 1996; *Cretaceous-Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. IN;* Institute of Geological & Nuclear Sciences Limited Monograph 13.

Kneller, B.C.; Branney, J.M., 1995; Sustained high-density turbidity currents and the deposition of thick massive sands *IN; Sedimentology 42,* p.607-616.

Komar, P. D., 1973; *Continuity of turbidity current flow and systematic variations in deep-sea channel morphology. IN;* Bulletin of the Geological Society of America 84, p. 3329-3338.

Lindsay, S. C., 1996; *Sedimentology of Late Miocene siltstone beds and sequence stratigraphic significance, eastern margin Taranaki Basin. IN;* Unpublished MS thesis, University of Waikato, Hamilton.

McKee, E. D. & Weir, G. W., 1953; *Terminology for stratification and cross-stratification in sedimentary rocks. IN;* Geol. Soc. America Bull. 64, p. 381-390.

Menard, H. W., 1964; *Marine Geology of the Pacific, McGraw-Hill.;* p. 271.

Miall, A. D., 1997; *The geology of stratigraphic sequences. IN;* Springer-Verlag. New York, p. 433.

Middleton, H. V., 1970; *Experimental studies related to problems of flysch sedimentation. IN;* J. Lajoie (ed.), Flysch Sedimentology in North America, Geological Association of Canada Special Paper 7 , p. 253-272.

Morgan, P. G. & Gibson, W., 1927; *The geology of the Egmont Subdivision, Taranaki. IN;* New Zealand

Geological survey bulletin n.s. 29, p. 99 p. and maps.

Mutti, E., 1979; *Turbidites et cones sous-margins profonds.* ***IN;*** Sedimentation Detritique (Fluvatile, littorale et Marine). Institute Geologie Universite de Friborg, Friborg, p. 353-419.

Mutti, E., 1985; *Turbidite systems and their relation to depositional sequences.* ***IN;*** Zuffa, G.G. (ed.), Provenance of Arenites, NATO-ASI Series, Reidel Publishing Company, p. 65-93.

Mutti, E. & Normark, R. W., 1987; *Comparing examples of modern and ancient turbidite systems: problems and concepts.* ***IN;*** Marine Clastic Sedimentology, p. 1-38.

Nodder, S. D., Nelson, C. S. & Kamp, P. J. J., 1990b; *Mass-emplaced siliciclastic-volcaniclastic-carbonate sediments in Middle Miocene shelf-to-slope environments at Waikawau, northern Taranaki, and some implications for Taranaki Basin development.* ***IN;*** New Zealand journal of geology and geophysics 33, p. 599-615.

Normark, W. R., 1978**;** *Fan Valleys, Channels, and Depositional Lobes on Modern Submarine Fans: Characters for Recognition of Sandsy Turbidite Environments.* ***IN*;** The American Association of Petroleum Geologists Bulletin V. 62, No. 6 p. 912-931.

North American Commission on Stratigraphic Nomenclature [NACSN], 1983; North American stratigraphic Code: American Association of Petroleum Geologists, Bulletin 67, p. 841-875.

Posamentier, H. W., Erskine, R. D. & Mitchum, R. M. Jr., 1991; *Models for submarine-fan deposition within a sequence-stratigraphic framework.* ***IN;*** Weimer, P., Link, M.H. (eds.): Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Sytems. Springer, Heidelberg, p. 127-136.

Posamentier, H. W. & James, D. P., 1993; *An overview of sequence stratigraphic concepts: uses and abuses.* ***IN;*** Posamentier, H.W, Summerhayes, C.P., Haq, B.U., & Allen, G.P. (eds.), Sequence Stratigraphy and Facies Associations, International Association of Sedimentologists Special Publication 18, p. 3-18.

Posamentier, H. W. & Vail, P. R., 1988; *Eustatic controls on clastic deposition II-sequence and systems tract model.* ***IN;*** Wilgus, C.K., Hastings, B.S., Kendell, C.G. St. C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C., (eds.) Sea-Level Change- An Intergrated Approach: Society of Economic and Mineralogists Special Publication 42, p. 125-154.

Quennel, A. M., 1938; *Geological report on the area between Waitara, Taranaki and Awakino River basin.* ***IN;*** NZ Oil Exploration Co. Ltd. Intitute of Geological & Nuclear Sciences Ltd unpublished open file petroleum report number 14, Wellington, New Zealand.

Reading, H. G. & Richards, M. T., 1994; *The classification of deep-water siliciclastic depositional systems by grain size and feeder systems.* ***IN;*** American Association of Petroleum Geologists 78, p. 792-822.

Richards, M., Bowman, M. & Reading, H., 1998; *Submarine-fan systems I: characterization and stratigraphic prediction.* ***IN;*** Marine and Petroleum Geology 15, p. 689-717.

Sanders, J. E., 1963; *Concepts of fluid mechanics provided by primary sedimentary structures.* ***IN;*** Journal of Sedimentary Petrology 33, p. 173-179.

Sanders, J. E., 1965; *Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms.* ***IN;*** Middelton, G. V. (ed.), Primary Sedimentary Structures and their Hydrodynamic Interpretation. Society of Economic Paleontologists and Mineralogists Foundation, Special Publication 12, p. 192-219.

Shanmugam, G., 2000; *Fifty years of the turbidite paradigm: Deep water processes and facies models - a critical perspective.* ***IN;*** Marine & Petroleum Geology 17, p. 285-342.

Stockmal, G. S., Cant, D. J. & Bell, J. S., 1992; *Relationship of the stratigraphy of the Western Canada* *forland basin to Cordilleran tectonics: insights from geodynamic models.* ***IN;*** Maqueen, R.W., Leckie, D.A. (eds.) Foreland basins and fold belts. American Association of Petroleum Geologists Memoir 55, p. 107-1124.

Van Wagoner, J. C., Mitchum, R. M., Campion, K. M. & Rahmanian, V. D., 1990; *Siliciclastic sequence stratigraphy in well logs, cores, and outcrop: concepts for high-resolution correlation of time and facies.* ***IN;*** American Association of Petroleum Geologists Methods in Exploration Series 7, p. 1-55.

Van Wagoner, J. C., Posamentier, H. W., Mitchum, R. M., Vail, P. R., Sarg, J. F., Loutit, T. S. & Hardenbol, J., 1988; *An overview of the fundamentals of sequence stratigraphy and key definitions .* ***IN;*** Wligus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H.W., Van Wagoner, J.C., & Kendall, C.G.St.C (eds.):Sea-level changes: An integrated Approach. Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 39-45.

Viana, A. R., Faugeres, J. C. & Stow, D. A. V., 1997; *Bottom-current controlled sand deposits - a review of modern shallow- to deep-water environments.* ***IN;*** Sedimentary Geology 115, p. 53-80.

Walker, R. G., 1978; *Deep water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps.* ***IN;*** American Association of Petroleum Geologists Bulletin 62, p. 932-966.

Waschbusch, P. J. & Royden, L. H., 1992; *Episodicity in foredeep basins.* ***IN;*** Geology 20, p. 915-918.