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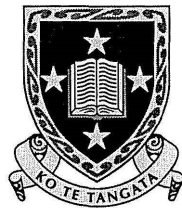
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Stratigraphy and Sedimentology of  
Pliocene Strata in the Forearc Basin  
(Waikoau and Waikari River catchments),  
Northern Hawke's Bay

A thesis  
submitted in partial fulfilment  
of the requirements for the Degree  
of  
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by

Rhys B. Graafhuis



The  
**University  
of Waikato**  
*Te Whare Wānanga  
o Waikato*

2001



**Frontispiece:** Sunrise over the study area, taken from the Maungaharuru Range (Photo: A. Pallentin)

*“Every day in every way it’s getting better and better”*

(John Lennon ‘Beautiful Boy’)

## ABSTRACT

An area of over 250 km<sup>2</sup> in northern Hawke's Bay has been geologically mapped at a scale of 1:50 000, and over 1350 m of Pliocene sedimentary section described and interpreted in the Waikoau and Waikari River catchments. Two new formations and 13 members have been defined, and two formations redefined. The strata show little structural deformation and form a shallow to moderately dipping (5° - 25°) succession on the uplifted limb of the Hawke's Bay Monocline. The rocks are of Pliocene age, ranging from Opoitian to Nukumaruan. The formations show rapid changes in thickness and lithology along strike from the southwest to the northeast, which is oblique to the depositional paleoslope. Coarse-grained lithologies such as conglomerates and limestones typically become finer-grained, less continuous and thinner towards the northeast.

In ascending order the new formations (except where redefined) are: **Titiokura Formation**, **Rangiora Formation**, **Matahorua Formation** (redefined) and **Waipunga Formation** (redefined). Titiokura Formation is dominated by calcareous siliciclastic sandstone and sandy limestone. The Rangiora Formation and Waipunga Formations are siliciclastic sandstone and siltstone dominated. Matahorua Formation is dominated by siliciclastic sandstone and greywacke conglomerate.

Lithofacies analysis has been applied to the strata to establish the deposition paleoenvironments. Four lithofacies associations (siltstone, sandstone, conglomerate and limestone) and 13 lithofacies have been identified. Interpreted bathymetric ranges for the **siltstone association** ranges from inner to outer shelf. The **sandstone association** is characterised by massive to tabular cross-bedded sandstone interpreted to have been deposited on a shoreface to innershelf setting; storm current and tidally emplaced tempestites and tidalities were deposited on the lower-shoreface to mid shelf; massive to horizontally bedded sandstone and silty beds were deposited on the inner-mid shelf. **Conglomerate associations** are characterised by non-marine greywacke conglomerates deposited on a broad braidplain. Sandstone, siltstone and pumice conglomerate all within a calcareous sandy matrix, are interpreted to have been deposited in tidal channels or on a beachface. The **limestone association** is characterised thick successions (10 – 50 m) of sandy coquina that probably formed on the inner shelf possibly on a structural high as carbonate source areas. Thinner correlative units (50 cm – 6 m) of trough cross-bedded sandy coquina accumulated in inner-mid shelf environments, having been reworked across the shelf from the carbonate source areas.

The successions in the four stratigraphic formations have been interpreted within a sequence stratigraphic framework and 25 sequences have been identified. Interpretation of sequence boundaries is based on observed unconformities between lithologies, inferred unconformities between lithologies of differing paleoenvironments, and correlative conformities.

Four typical sequence stratigraphic motifs have been interpreted from these formations. Each motif comprises three or four systems tracts: transgressive (TST), highstand (HST), regressive (RST) and lowstand system tracts (LST). **Motif 1** is representative of the Titiokura Formation, and consists of sandstone and mud drapes (TST and HST), with

sandstone grading up into limestone (RST) having unconformable tops. **Motif 2** is represented by the Rangiora Formation. This formation is comprised of thick successions (100 m +) of interbedded sandstone and siltstone (TST), siltstone (HST), and siltstone coarsening up into sandstone (RST). The boundary on top of the RST sandstone is typically unconformable. **Motif 3** occurs in the Matahorua Formation. Siltstone or sandstone (TST), sandstone (HST), and interbedded siltstone and sandstone (RST) coarsen up into greywacke conglomerate (LST). The sequence boundary usually lies within the top of the conglomerate between the coarse massive part and finer bedded conglomerate commonly having a heterogeneous silty-sand matrix; rarely the sequence boundary is at the very top of the conglomerate unit. **Motif 4** is represented by the Waipunga Formation. It is characterized by thin successions (10 m) of interbedded siltstone and sandstone (TST, HST) coarsening upward into sandstone (HST).

The stratigraphic evolution of each of these motifs has been interpreted within the context of an across shelf profile. Evolution of the motifs during a sea-level transgression, is generally one of limestone deposition near the highstand shoreline. Thinly bedded tidalities, parasequences and massive sandstone with a weak backlap shellbed occur basinward in the TST. Limestone deposition near the highstand shoreline, and siltstone and thickly bedded tidalities basinward, characterise deposition during a sea-level highstand. Erosion and reworking of sediments basinwards during falling sea level conditions result in the formation of erosional sequence boundaries and the accumulation of a regressive sediment wedge (RST). Sea-level lowstands are characterised by the deposition by greywacke conglomerate on a non-marine braidplain.

The Pliocene sedimentary succession on the western limb of the Hawke's Bay Monocline is interpreted as having been deposited in a steadily subsiding seaway (forearc basin) with uplift on its western margin. Strong storm and tidal currents reworked sediment from shallow into deeper water across a shelf. The siliciclastic sediment was sourced from erosion in the hinterland. The compressive component within the plate boundary zone in North Island, increased around 2-3 Ma, resulting in uplift of the Axial Ranges, which became a major sediment source. Sea-level fluctuations throughout the deposition of the sedimentary succession in the study area resulted in the development of cyclothems. The periodicity of the cycles appears to increase from the Opoitian to the Nukumaruan, for which 6<sup>th</sup> order (41 ka) cyclicity is inferred. The bathymetric range of the cyclothems also appears to increase from the Opoitian to Nukumaruan.

# Acknowledgements

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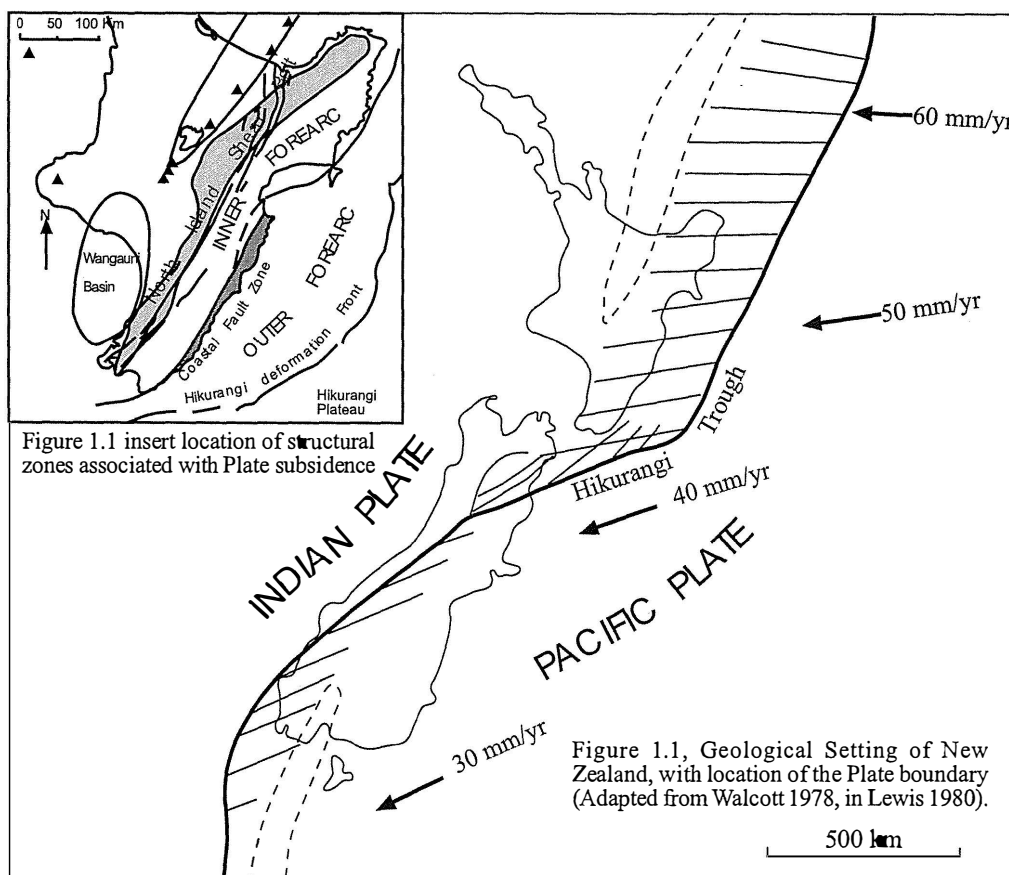


# Chapter 1

# Chapter 1: Introduction

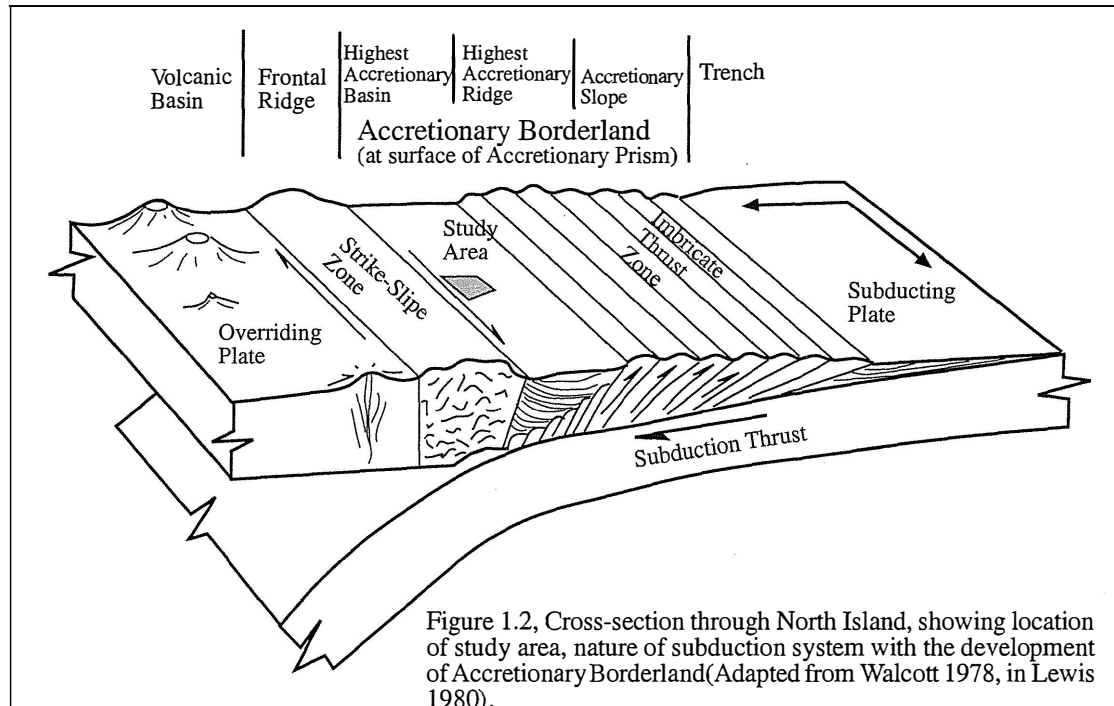
## 1.1 Geological Setting

Currently New Zealand sits astride the active plate boundary between the Australian and Pacific plates. Oceanic crust of the Pacific plate is obliquely subducted beneath oceanic crust of the Australian plate (Fig 1.1). Strike-slip movement along the Alpine Fault in the South Island and subduction and back-arc spreading in central and eastern North Island, take up the relative plate motion through New Zealand. (Field and Uruski 1997). During the last 10 m.y. movement on the plate boundary has become more oblique, and the compressional element has increased in intensity particularly from 2-3 m.y. ago (Lewis 1980). The forearc region is composed of three units, a structural ridge called the North Island Axial Ranges, the principal forearc basin and a subduction complex (Fig 1.1 insert; Kamp 1992).



In the East Coast region the imbricate frontal wedge extends the whole length of the margin. It is comprised of passive margin sediments that have been thrust faulted, structurally kneaded and back-tilted in the last 25 m.y. In the forearc basin of the East Coast region deformation is less marked than in the accretionary prism. Hence in the study area, the region is relatively unfaulted (Field and Uruski 1997).

The Hikurangi Trough represents the seafloor expression of the subduction of the Pacific plate (Figs 1.1 & 1.2; Sporli 1980). Subduction at this margin coupled with sedimentation has resulted in the growth of an accretionary borderland, marked by subparallel accretionary basins and ridges beneath the modern shelf offshore Hawke's Bay and Wairarapa (Lewis 1980). The most inbound basin is referred to here as the forearc basin (see also Haywick 1990). The sedimentary fill is of Neogene age and involves several thousand metres in thickness of sediment. The Pliocene succession occurring in this study was deposited in this main forearc basin and forms part of the Hawke's Bay Monocline that adjoins the actively rising axial ranges to the west (Sporli 1980).



During the formation of the East Coast Region three distinct plate tectonic regimes have occurred during the Mesozoic, Paleogene, and Neogene. During the early Permian to Early Cretaceous rocks of the Torlesse Terrane were accreted to this margin along a

west dipping subduction zone. Regional convergence slowed in the mid-Cretaceous and was followed by crustal extension associated with rifting of NZ from Australia and Antarctica. The Australian and Pacific plate boundary became established during the late Paleogene in the New Zealand region (Late Oligocene), probably as an extensional system of basins through western New Zealand. The present phase of subduction was initiated in the Early Miocene, and resulted in a change from slow carbonate-dominated sedimentation to rapid terrigenous sedimentation and associated deformation. In the late Early Miocene uplift led to erosion of basement and subsidence in the east leading to deposition of thick siliciclastic successions. A change in the Australian-Pacific pole of rotation after 10 Ma caused an increase in compressional deformation across the South Island leading to uplift of the Southern Alps. (Field and Uruski 1997, p111-112). Widespread faulting and folding in the Hawke's Bay area occurred from c. 2.5 Ma onwards, but particularly after 1 Ma (Kelsely *et al.* 1995, in Field and Uruski 1997, p 112), leading to the uplift of the North Island Axial Ranges (e.g. the Ruahine and Kaweka's Ranges).

## 1.2 Structure

The Hawke's Bay – Wairarapa region is divided up into five structural blocks. These are the Woodville, Pongaroa, Coastal, Aorangi, and Tora blocks. They are also divided into two-major NE trending sub-belts, the Western Sub-belt and the Eastern Sub-belt. These divisions are based on changes in facies, structure, and igneous content of Cretaceous to Paleogene strata (Field and Uruski 1997). The study area is located within the Woodville block of the Western Sub-belt of the East Coast Region. This sub-belt is characterised by little complex deformation, deposition of cover rocks unconformably on to Torlesse basement, and comparative absence of igneous cover rocks (Field and Uruski 1997, p 40).

There are three major zones of active faulting related to the East Coast Region. These are the North Island Shear Belt, the Marlborough Fault System and the Coastal Fault Zone (Fig. 1.1 insert). Of these only the North Island Shear Belt is of direct relevance to the study area. It is considered as the 'partitioned, translational component of oblique relative plate motion' (Fitch 1972, in Field and Uruski 1997, p33) and is responsible for the uplift of the axial ranges, with the western strand of the shear belt bounding or traversing the axial ranges. East of the North Island Shear Belt greywacke basement

abuts on to sediment fill of the inner forearc. The Mohaka and Ruahine faults are major dextral structures near the eastern margin of the axial ranges (Field *et al.* 1997, p33).

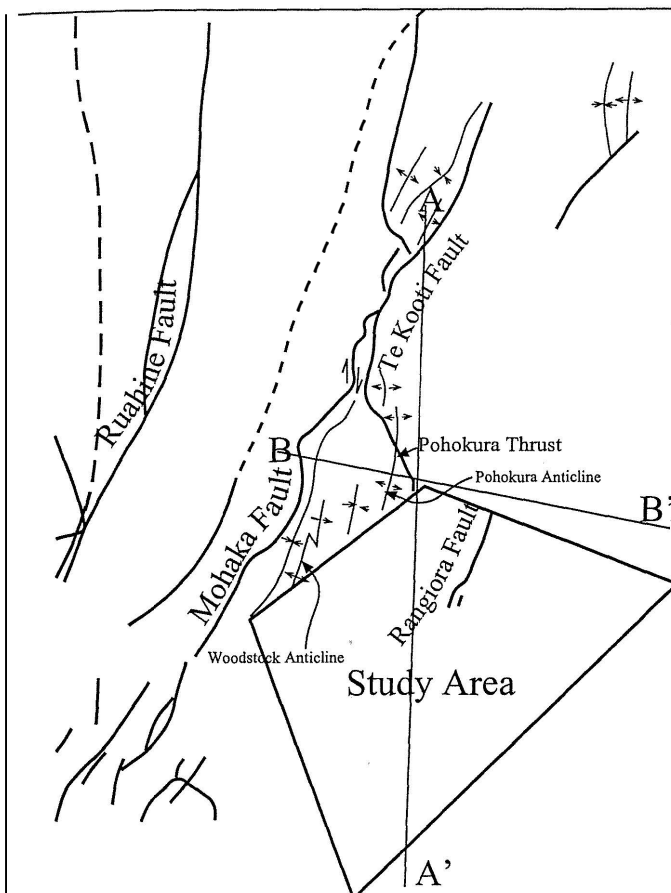
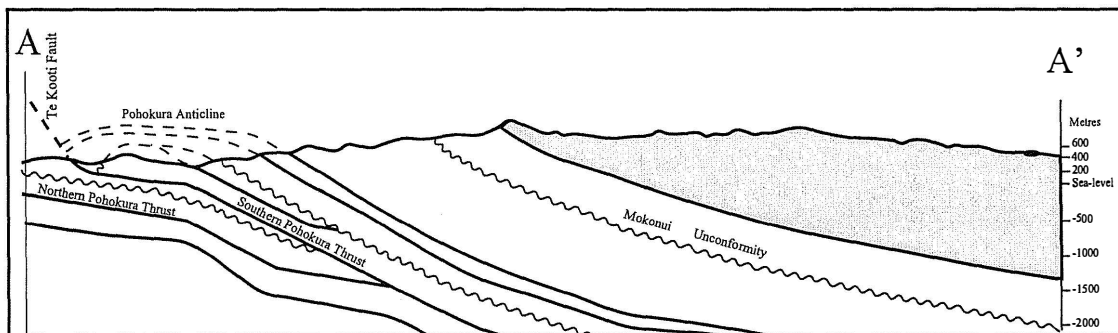
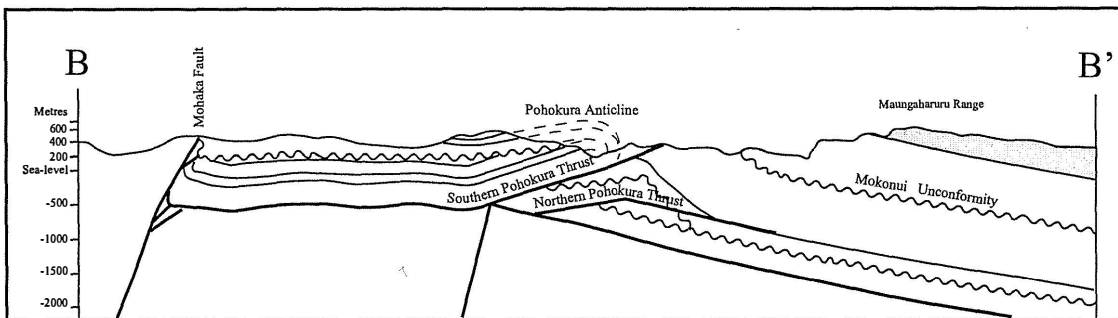


Figure 1.3, location of major faults and folds in proximity to the study area (adapted from Cutten 1994).



The Mohaka Fault is one of few major faults in proximity to the study area. It forms the contact between the Axial Range greywacke and Cretaceous – Neogene aged sediments. It is a reverse dextral fault and trends NNE-SSW, west of the North Island Axial Ranges. It is suggested that as much as 150 km dextral transcurrent movement has occurred on this fault. Movement of the Mohaka fault occurred from 11 to 3 m.y. Other faults in the area include the Te Kooti Fault and the Pohokura Thrust and Anticline. The Te Kooti Fault is described as a dextral strike slip fault, which has splayed off the Mohaka Fault and joined the Pohokura Thrust Fault forming the Pohokura Anticline (Fig. 1.3). The Pohokura Thrust was active from 11 Ma (perhaps as early as 22 Ma) until 6 Ma. Movement on the Te Kooti Fault coincides with movement on the Mohaka Fault, although movement stopped earlier, around 6 Ma (Cutten 1994, p 31,33). In close proximity to the field area the Taraponui Thrust (Francis 1991), Woodstock Anticline and Ngatapa Syncline occur (Francis 1991; Cutten 1994).

Units in the area typically strike NE and dip NW forming on the uplifted limb of the Hawke's Bay Monocline. In Central Hawke's Bay Late Miocene to Nukumaruan beds dip southeastward gently away from the basin margin towards the axis of the Hawke's Bay Syncline (Field and Uruski 1997, p 148).

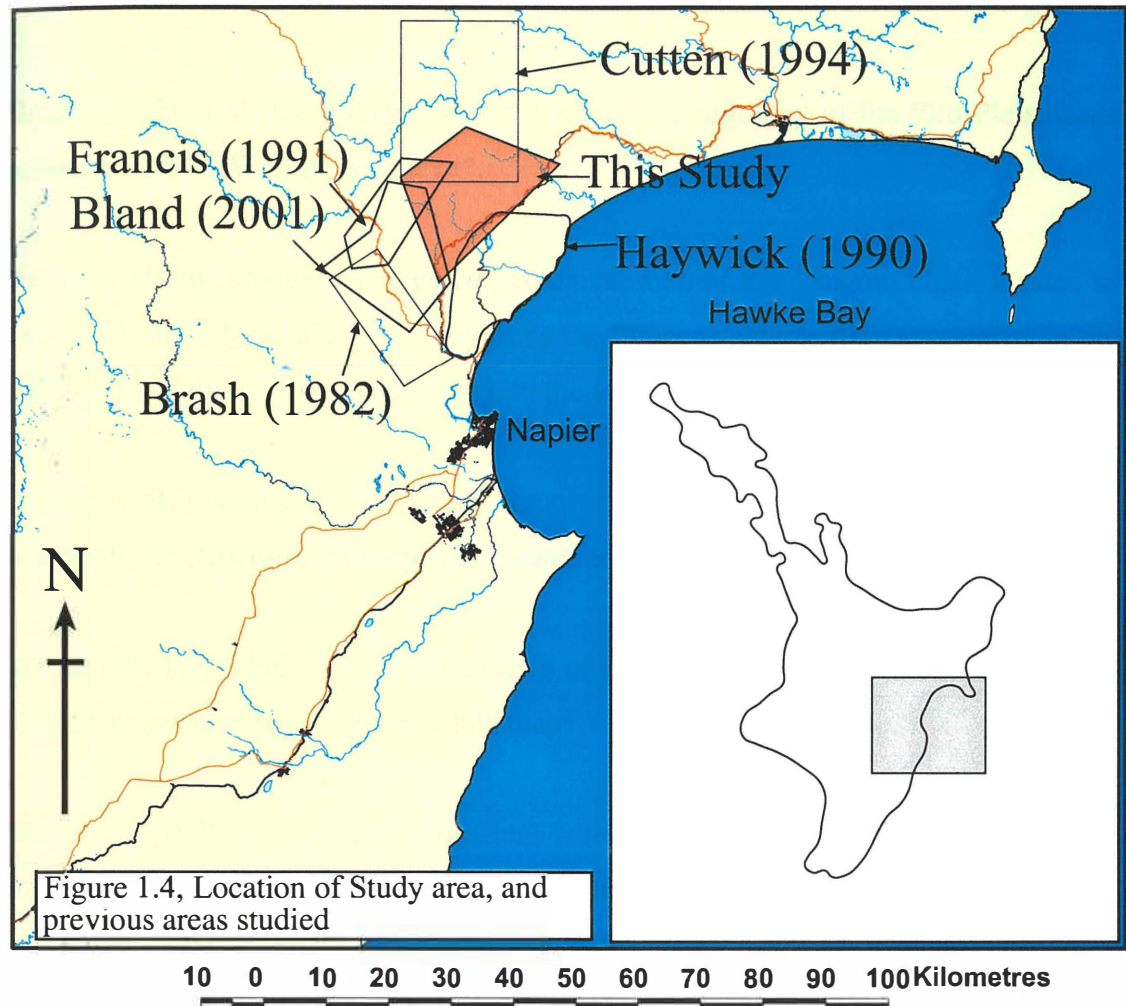
### 1.3 Sedimentary Fill of Basin

Mesozoic, probably Cretaceous beds form the basement to the forearc basin. Late Cretaceous and Paleogene successions are characterised by mudstone and siltstone, with rare flysch sequences. Miocene beds in the forearc basin reach thicknesses of 5 000 m (Grindley 1960). The Miocene succession is mainly bathyal mudstone and flysch with units of conglomerate, sandstone and limestone. Bioclastic limestones, sandstones, siltstone, and conglomerates, characterise the Pliocene succession, which is up to 2000 m thick.

### 1.4 Location of Study Area

The study area is located in northern Hawke's Bay. It is c. 250 km<sup>2</sup> in size comprising an area north of the Esk River northeast to the Waikari River (Fig 1.4). Previous geological mapping in parts of this area has been undertaken by Grindley (1960), Kingma (1965), Haywick (1990), Francis (1991), Cutten (1994), and Beu *et al.* (1995)

(Fig 1.4). However, no detailed mapping, or lithofacies analysis has been undertaken in the study area.



Topography ranges from 200 a.s.l. at the base of the field area near Lake Tutira to over 1300 a.s.l. at the crest of the Maungahuru Range at Taraponui Trig. There is much native forest in the area, particularly at Boundary Stream Reserve (Department of Conservation), and extensive exotic forest plantations exist in the Esk catchment. In these areas exposure of geological units is limited. For the most part the study area is undulating to steep hill-country, with moderate to excellent exposure of the stratigraphic units. The best exposures of beds occur in the lower reaches of rivers in the study area. Rocks are generally exposed in the upper areas of the catchments on steep hillsides.

## 1.5 Previous Geological Work in the Area

- Grindley (1960) produced a 1:250 000 map covering the area from Taupo to Hawke's Bay. The scale of this map is such that it gives a very general outline of the geology.
- Brash (1982) produced a map and described the stratigraphy of the Plio-Pleistocene succession to the SW of the field area\*.
- Haywick (1990) produced a detailed geological map of the Tangoio block located to the south of the field area\*. This study links the Pliocene sedimentary succession in the Waikoau and Waikari river catchments into the succession described by Haywick.
- Francis (1991) produced a Petroleum Report of the Te Pohue area, with emphasis on stratigraphy and structure. This study is located to the northwest of this study area\*.
- Cutten (1994) produced a geological map of the Mohaka River catchment. Some of this study area was incorporated into this map\*.
- Beu *et al.* (1995) produced a geological bulletin, which described the Maungahuru Formation limestones and sandstones from the area (now the Titiokura Formation) and produced a generalised geological map of the area.

\*See figure 1.4 for location of this previous work.

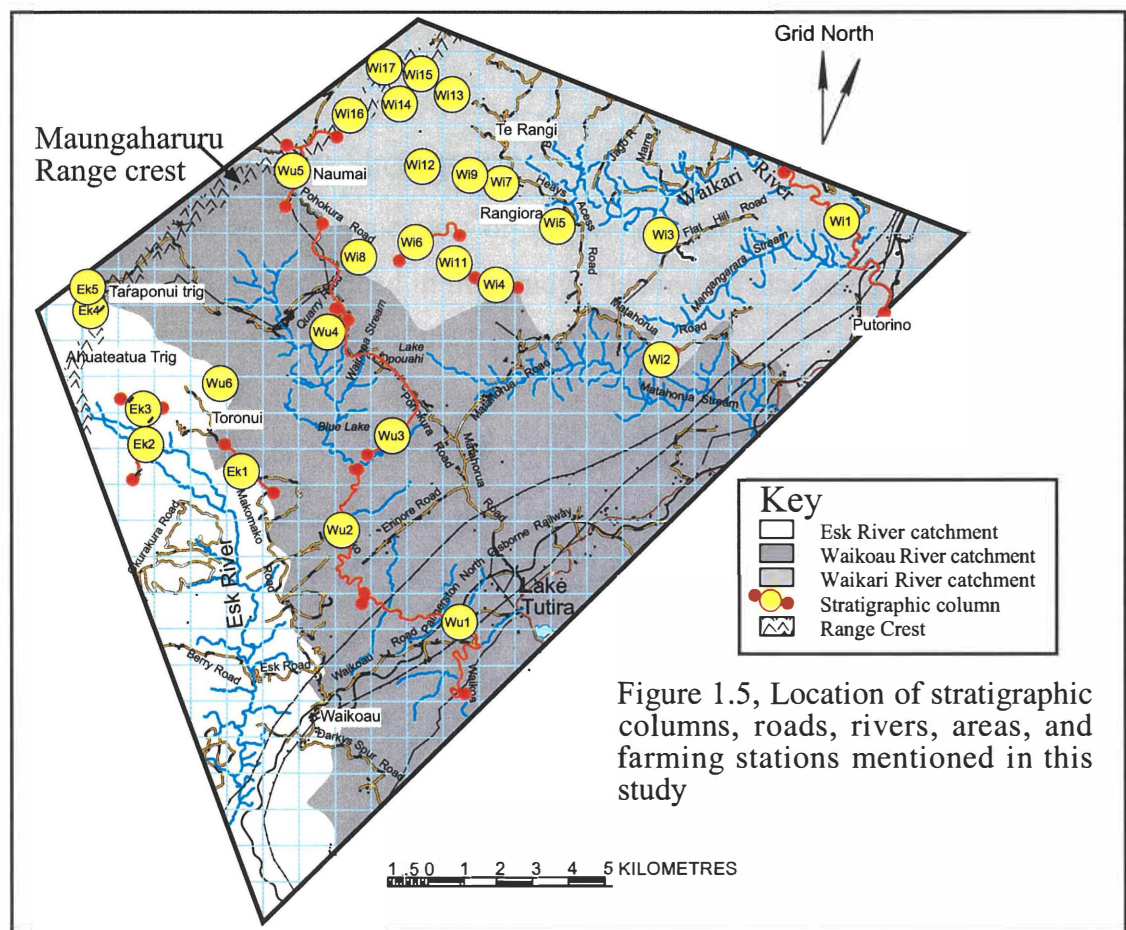
## 1.6 Aims of Study

- Map the Pliocene geology of the Waikoau and Waikari river catchments. The map also includes the geology of parts of the Esk River catchment.
- Describe the stratigraphy of Pliocene sedimentary rocks in the two catchments, and link it to the stratigraphy of the Tangoio block as described by Haywick (1992).
- Interpret the depositional paleo-environments by application of facies analysis.
- Interpret the depositional history in terms of a sequence stratigraphic context.

- Interpret the controls that would have influenced the deposition of the sedimentary succession in the field area.

## 1.7 Research Method

Fieldwork was carried out from November 1999 to March 2000, and involved the description of the sedimentary succession in the study area. Stratigraphic columns (Fig 1.5, Appendix 1), and a geological map (back pocket) were produced for the study area. Stratigraphic columns have been given an alphanumeric code, which corresponds to the catchment they occur in combined with a numerical code that corresponds to the relative stratigraphic age of the sedimentary succession logged (Fig 1.5).



Fossil samples were collected and identified in the lab and used for age and paleobathymetry assessments (Appendices 2,3 and 4). Some siltstone samples containing foraminifera were collected, separated and foraminifera identified. It was hoped that the foraminifera would enable biostratigraphic stages to be identified, but the necessary planktic foraminifera were not present in the samples.

## 1.8 Thesis Content

### Chapter 2: Lithostratigraphy

This chapter describes the lithostratigraphic framework for the field area, including a geological map (back pocket) and columns (appendix 1), and description of lithologic units and their relationship to each other.

### Chapter 3: Lithofacies

The lithofacies chapter describes individual facies occurring within the sedimentary succession and groups them into lithofacies associations based on the dominate lithology. Each of these facies are interpreted as part of a specific depositional environment.

### Chapter 4: Sequence Stratigraphy

This chapter applies the principles of sequence stratigraphy to the sedimentary succession mapped and described in this study. This results in a better understanding of the depositional setting for each of the formations.

### Chapter 5: Controls on Sedimentation – Synthesis

The purpose of this chapter is to address the relative roles of eustasy, tectonism and sediment supply on structural and stratigraphic development of the sedimentary succession within the study area.

### Chapter 6: Summary and Conclusions

This chapter summaries the main conclusions drawn from this study.



# Chapter 2

## Chapter 2: Lithostratigraphy

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### 2.1 Introduction

Four formations have been defined in the Waikoau to Waikari River catchments. The four formations include 13 members, which have been mapped within the field area at a scale of 1:50 000 (refer Geological Map in back pocket). Previously this succession was covered by the Maungaharuru Formation (Francis 1991; Cutten 1994) and to a lesser extent by the Petane Group (Haywick *et al.* 1991). The Maungahuru Formation has been raised in level to the **Maungahuru Group** (new), and comprises three new formations: the **Titiokura Formation** (new), the **Rangiora Formation** (new), and the **Matahorua Formation** (new). The **Petane Group** (redefined) has been redefined to include; **Matahorua Formation** (new). In this study the base of the Esk Formation is mapped and the strata above this level included as undifferentiated Petane Group formations (i.e. only the Matahorua and Waipunga Formations are mapped in this study). Members are named and coded within each of the mapped formations, and constituent facies defined (and also given codes) within these members (Table 2.1).

The four formations mapped in this study span the Pliocene, with the Kapitean-Opoitian boundary occurring within the underlying Mokonui Formation. The top of the Nukumaruan stage is located near the top of the Petane Group according to Haywick *et al.* (1991). With the exception of the Matahorua Gravel Member, which is included in the Matahorua Formation, and the Waipunga Formation, which has been divided into 3 members, all names are new. A vertical stratigraphic section over 1300 m thick is compiled in this area (figure 2.1). The sedimentary succession has moderate to shallow dips (25-5° SE). The units in this area are predominantly siliciclastic in composition, with usually minor carbonate content. All grid references quoted in this thesis are related to the NZMS 260 topographic map series of New Zealand.

Table 2. 1: Lithostratigraphic Nomenclature for the Pliocene Succession in the Waikoau and Waikari River catchments

Group	Formation	Member	Facies (*)	Code	
Petane	Undifferentiated	-	-	-	
	Petane Group sediments	-	-	-	
	Waipunga (wp)	Elston (B) Mahiaruhe (A)	Sandstone (2) Siltstone (1)	wp (A,B) 2 wp (A,B) 1	
Maungaharuru	Matahorua (mt)	Grassy Knoll (D) Papakiri (C) Trelinnoe (B) Deep Stream (A)	Conglomerate (3) Sandstone (2)	mt (A,B,C,D) 3 mt (A,B,C,D) 2	
	Rangiora (rg)	Mokamoka (B) Waikari (A)	Sandstone (2) Siltstone (1)	rg (A,B) 2 rg (A,B) 1	
	Titiokura (tk)	Opuoahi (E) Bellbird Bush (D) Taraponui (C) Te Rangi (B) Naumai (A)	Limestone (4) Sandstone (2) Conglomerate (3)	tk (A,B,C,D,E) 4 tk (A,B,C,D,E) 2 tk (A,B,C) 3	
		Mokonui (mk)		Sandstone (2)	mk 2

\*These facies are found in more than one member of the formation; facies codes 1=siltstone, 2=sandstone, 3=conglomerate; 4=limestone; i.e. code rg-B-2 = Rangiora Formation, Mokamoka Member, sandstone facies.

# Pliocene Geology of the Waikoau and Waikari River Catchments

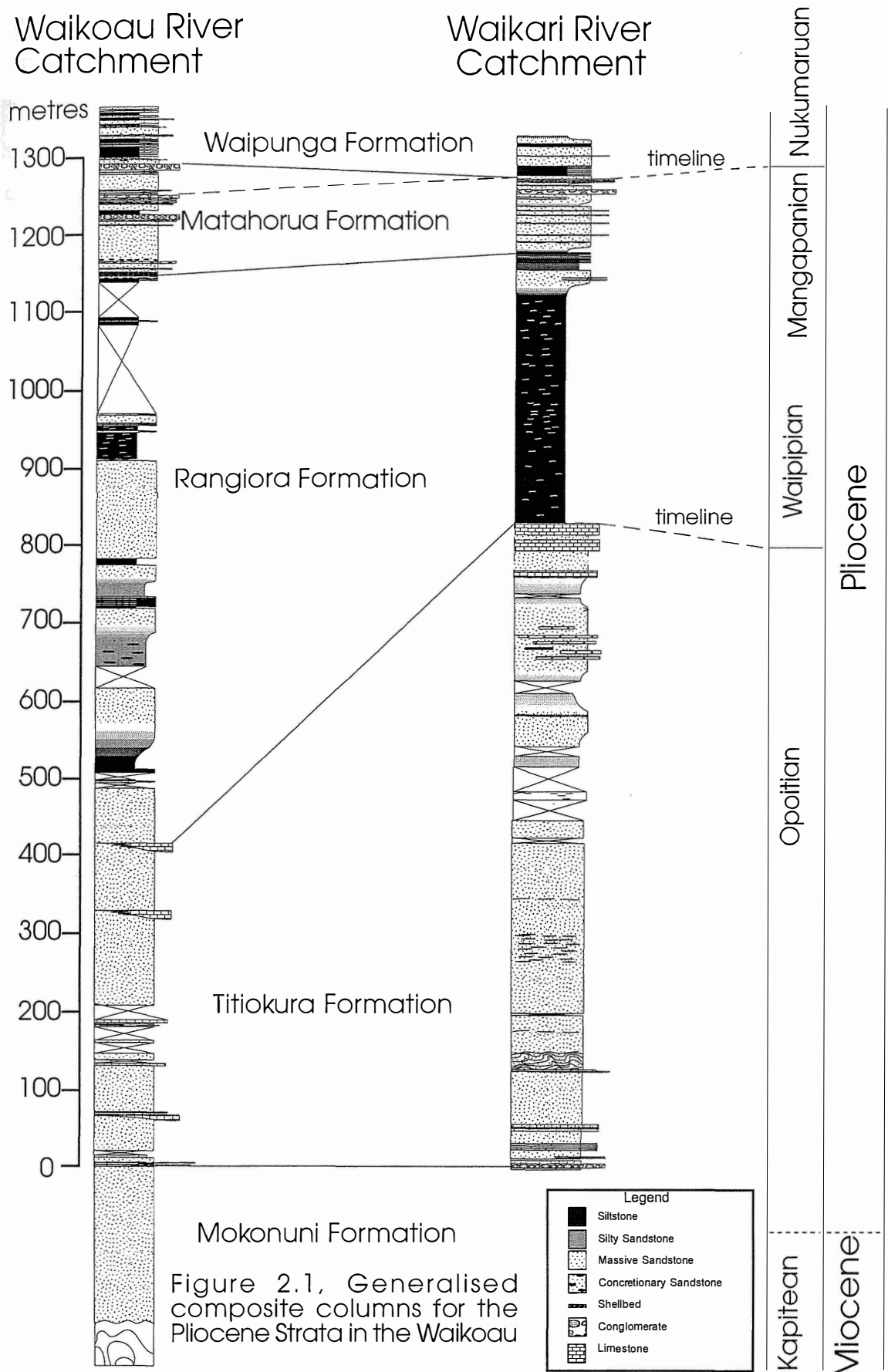


Figure 2.1, Generalised composite columns for the Pliocene Strata in the Waikoau

## 2.2 Maungaharuru Group (new)

Upper and Lower Boundaries: Three formations, the Mokonui Formation, the Titiokura Formation and the Rangiora Formation constitute the Maungaharuru Group. The lower boundary of the group is defined as the base of the Mokonui Formation. Here unfolded sediments lie unconformably on top of folded Miocene siltstone (Cutten 1994). The upper boundary of the group is placed on top of the Opuoahi limestone (tk-E-4) of the Titiokura Formation, although this boundary was not observed directly in the field area.

Distribution: the Maungaharuru Group comprises the lowermost three formations in the field area. This group comprises the majority of the map area. Its thickness is estimated at 1350 m in the Waikoau catchment. Its thickness in the Waikari catchment is not known as the thickness of the Mokonui Sandstone Formation is not known.

Lithology: As a whole the group comprises massive siliciclastic siltstone and massive to cross-bedded siliciclastic sandstone, often including mud drapes, which typically become more calcareous up-section and grade into sandy limestone. Limestones, conglomerates and breccias are common throughout the group, especially in the lower half of the formation. The group is more calcareous in the southwest of the field area, and sandier to the northeast.

### 2.2.1 Mokonui Sandstone Formation (mk)

Upper and Lower Boundaries: Bounded at its base by the Mokonui unconformity, below which folded siltstone of Miocene age occurs (Rakaita Siltstone Member of the Waitere Formation; Cutten 1994). Mokonui Sandstone has an eroded top with up to 6 m relief with the Naumai Member basal conglomerate (tk-A-3) of the Titiokura Formation.

Distribution and Thickness: Cutten (1994) describes the Mokonui Sandstone Formation as 300 m thick in the south of the Mohaka Map (geological map 6) and 1000 m in the north. In the field area the unconformity occurs 200 m below the Titiokura Formation at (V19/376275), making the Mokonui Formation only 200 m thick.

Age: Early Kapitean to Opoitian based on foraminifera (Scott *et al.* 1990, in Cutten 1994) part way up the member.

Lithology: Defined by Cutten (1994) as a blue-grey, weathering to yellow-brown, well bedded, medium sandstone, with calcareous interbeds and micro-fossil fragments, with isolated beds of granule size shell fragments, and bioturbated siltstone beds.

### 2.2.2 Titiokura Formation (new) (tk)

Upper and Lower Boundaries: The lower boundary of the Titiokura Formation is defined at the base of the Naumai Member, where a conglomerate occurs. This conglomerate is recorded in sections Wi17, Wu5 and Ek4 where it lies unconformably upon the underlying Mokonui Formation. Relief of up to 6 m is evident. The upper boundary of the formation is on top of the Opuoahi limestone (tk-E-4), but the contact with the overlying Rangiora Formation was not observed directly in the field area.

Distribution and Thickness: In the southwest of the map area the Titiokura Formation is comprised of 50 m of limestone (Figure 2.2), which is exposed in bluffs south of the Ahuateatua Trig (V19/327200 to 326210). Here neither sandstone nor siltstone beds are found, and because of this the individual members of the formation are unable to be identified. North of Ahuateatua Trig (V19/330220) silty sandstone separates this single thick limestone unit into two units. Identification of the constituent members of the Titiokura Formation at the Taraponui Trig (V19/331228, section Ek4, Figure 2.2) is possible as the limestones (Tk-A,B,C,D,E-4) are separated by silty sandstone beds (plate 2.1). Northeast of Taraponui Trig the thickness of the formation increases across strike, as the thickness of sandstone (tk-A,B,C,D,E-2) between the limestone beds increases. The thickness of the limestone beds (tk-A,B,C,D,E-4) decrease to the northeast of the map area, whereon they also become less calcareous and finer grained. In the northeast of the map area many of these limestones grade into indurated cross-bedded fossiliferous sandstones (sections Wi17, Wi13, Wi12, Wi9, Wi6, Wi4). Here the formation is over 800 m thick (sections Wi17, Wi 13, Wi12, Wi9, Wi6, Wi4; Figure 2.2).

Lithology: The Titiokura Formation consists of ripple bedded to cross-bedded, bioturbated, glauconitic calcareous sandstone, with concretions, scattered fossils,

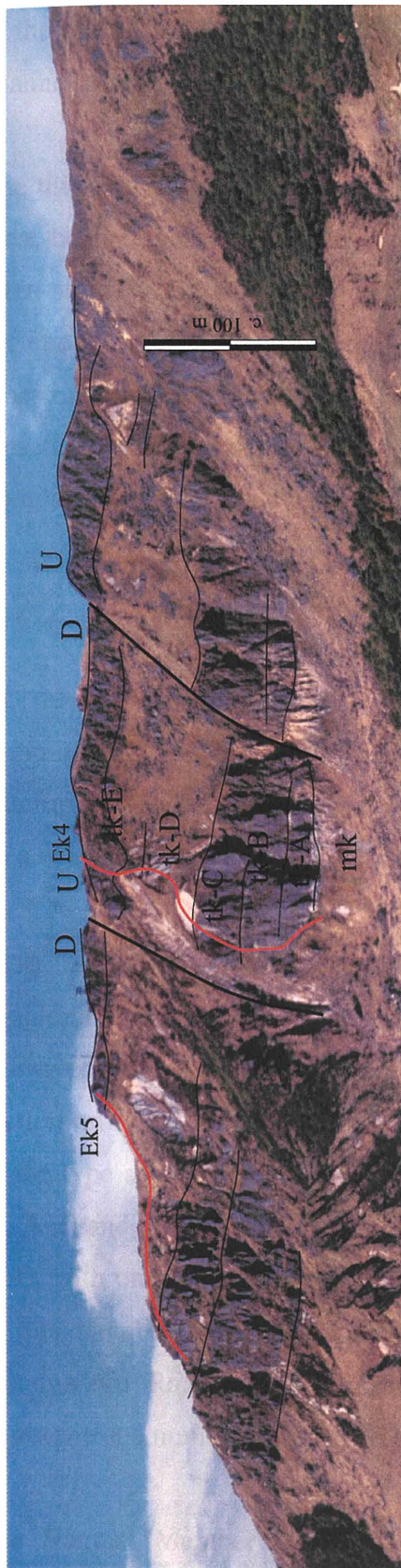


Plate 2.1, Titiokura Formation at Taraponui Trig (V19/331228; sections Ek4 & Ek5 (red line)). The entire Titiokura Formation is contained in this section. At the base of the cliff a conglomerate with imbricated pumice, greywacke pebbles and sandstone clasts and up to 1m relief occurs. The cross-bedded limestone coquina that comprises the majority of the section is divided (generally) in two by a thick sandy-siltstone. However, the constituting Zmembers of the Formation can be identified in this section by thin sandstone beds and unconformities in the thick limestone. Two Normal faults with throws of c. 20 m are highlighted (Photo: A. Pallentin).



Plate 2.2, Naumai Station (V19/393272; section Wu5 (red line) at the type sections for both Naumai (tk-A) and Te Rangī (tk-B) Members. Here the members outcrop almost continuously and can be traced across the Maungaharuru Range (Photo: A. Pallentin)

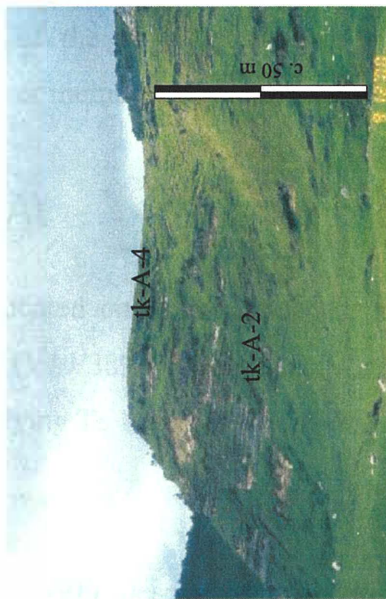


Plate 2.3, Naumai Member (tk-A) at the type section (Wu5) on Naumai Station (V19/393272). The member is comprised of a basal conglomerate (tk-A-3), sandstone facies (tk-B-2) and a capping limestone (tk-B-4).



Plate 2.4, Basal conglomerate (tk-A-3) on Pohokura Road unconformable overlying the Mokonui Sandstone Formation, with up to 6 m erosional relief (V19/389274; section Wu5).

re-activation surfaces, mud drapes and silt laminae. Convolute bedding is present within many of the sandstone beds. Thin lensoidal and channelised conglomerates are common, especially in the lower members of the formation. Cross-bedded calcareous sandstone and limestone beds form the top of members within the formation. The bases of the limestones (tk-A,B,C,D,E-4) often show localised scouring with rip-up clasts and channel fill conglomerates.

The thick limestone found at the Ahuateatua Trig (V19/327200 to 326210) is a tabular cross-bedded, very well sorted, sandy coquina with small shell fragments (1-2 mm), and often slightly iron stained. It contains large barnacle plates, echinoids, bryozoans, and pectens. North of the Ahuateatua Trig (V19/330220) sandstone separates this thick limestone into two units. At the Taraponui Trig (V19/331228, section Ek4) the limestones are coarser grained than at any of the other sections in the field area. Conglomerate lenses and beds occur in the lower members of the formation.

### 2.2.2.1 Naumai Member (tk-A)

Name Derivation: From Naumai Station located on Pohokura Road near the ridge summit crest of the Maungahuru Range (V19/389274, section Wu5). Excellent outcrops of the Naumai Member and the overlying Te Rangi Member are present in this area.

Type and Reference Sections: Cutten (1991) described a section through a conglomerate at V19/342239 that forms the base of the Naumai member (tk-A). However this section is relatively difficult of access, and easier access exists at a section on Pohokura Road (V19/389274, Section Wu5; plate 2.2), which is designated as the type section. Here excellent exposure is present though the basal conglomerate (tk-A-3) and good exposure though the overlying sandstone (tk-A-2) and limestone (tk-A-4), with only a small amount of section not exposed (plate 2.3). The uppermost bed of this member comprises a limestone, which can be traced along the crest of the Maungahuru Range facing northwest, and a basal conglomerate occurs below the limestone at a number of localities.

The Naumai Member is easily accessed to the southwest on Woodstock Station (V19/331228, section Ek4) beneath the Taraponui Trig where a reference section is

described through the basal conglomerate and the overlying facies. This section gives excellent and continuous exposure throughout the Titiokura Formation. A number of other sections located to the northeast expose the limestone at the top of this unit. A reference section is described on Te Rangi Station (V19/413293, section Wi17) where there is complete exposure of the entire member.

**Upper and Lower Boundaries:** The type section on Pohokura Road (section Wu5) displays an erosional lower contact between the underlying Mokonui Formation and Titiokura Formation. The contact has irregular relief of up to 6 m, within as many metres laterally (plate 2.4). The top of this section is capped by sandy limestone, which is sharply, but conformably overlain by clean sandstone with mud drapes. The section to the southwest at Woodstock Station (section Ek4) displays 1 m relief on the lower contact.

**Distribution and Thickness:** The Naumai Member is thickest in the northeast of the map area. In the sections at Te Rangi and Naumai Stations (V19/413293, Section Wi1 and V19/389274, Section Wu5; plates 2.2 and 2.3) it is 50-60 m thick. The thickness of the unit decreases to the southwest, where at Taraponui Trig it is only 15 m thick (figure 2.2; plate 2.1).

Each of the individual facies of the member undergoes thickness changes along strike. The basal conglomerate (tk-A-3) is thickest (10 m) to the southwest at section Ek4. In the northeast of the map area at section Wu5, thickness varies from 3-6 m, while at Te Rangi Station it is 4 m thick.

To the southwest of the field area the sandstone facies (tk-A-2) of this member thins and is only 3 m thick at Taraponui Trig. At the section described at Ahuateatua Trig the sandstone facies (tk-A-2) is not seen (Figure 2.2). The sandstone is thickest in the northeast of the field area where it is around 50 m thick (sections Wi17 and Wu5).

The limestone (tk-A-4) at the top of the member crops out along the northwestern scarp of the Maungharuru Range, and there is a general thickening of the bed towards the southwest. The limestone is thickest (9 m) at Taraponui Trig, and thins to between 4-6 m in the northeastern sections. At the Ahuateatua Trig the limestone amalgamates with

other limestones (tk-A,B,C,D,E-4) within the formation, and a 50 m thick limestone is present, which represents the entire Titiokura Formation (Figure 2.2).

**Age:** The occurrence of *Phialopecten marwicki* in the limestone facies of this member indicates an age of Opoitian to Waipipian. The underlying Mokonui Sandstone is probably Early Opoitian based on the occurrence of *Globorotalia crassaformis*, *G. pliozea* and *G. puncticulata* (Cutten 1994). The Naumai Member is inferred to also be of Opoitian age.

**Constituent Facies:** Basal conglomerate (tk-A-3)

**Lithology:** The conglomerates at the three described sections are coarse grained typically differentially cemented, very poorly sorted, clast supported, massive to crossbedded, separated by a sandstone unit, and capped by a calcareous bed. The unit becomes increasingly fossiliferous and calcareous to the southwest along the Maungahauru Range and has an increased greywacke pebble component in this direction.

At the Pohokura Road cutting (V19/389274; Section Wu5) the conglomerate is made up of 90% well rounded to angular mudstone and siltstone clasts with 10% sandstone clasts, within a 20% shelly sandstone matrix (plate 2.5). The lower conglomerate bed becomes well cemented towards the top before grading into a thin cross-bedded sandy limestone, which is overlain by a moderately cemented, slightly calcareous, fossiliferous sandstone with rare large conglomerate blocks. The sandstone is sharply overlain by a cross-bedded sandy limestone, which grades into another conglomerate. This conglomerate has similar properties to the lower conglomerate bed, however within it blocks of the underlying sandy limestone bed occur. The conglomerate grades up-section into a cross-bedded sandy limestone bed, which is considered to be the top of the conglomerate facies.

To the northeast at section Wi17 (V19/413293) the conglomerate is finer grained than at other described sections and contains a reworked high tephra content. It consists of a single conglomerate bed with large (30 cm) angular mudstone and siltstone blocks. Within the conglomerate is a sandstone bed, which is bi-directionally cross-bedded. In comparison to other described sections (Ek4 and Wu5) the conglomerate at section Wi17 is less calcareous. To the southwest at Taraponui Trig (section Ek4) the

conglomerate is 10 m thick (plate 2.1). The conglomerate at Taraponui Trig is highly calcareous, contains greywacke pebbles, sandstone clasts that are heavily bioturbated, and reworked pumice and charcoal at the base of the conglomerate. The large clasts at the base of the conglomerate show imbrication in a roughly southeast direction.

Constituent Facies: sandstone (tk-A-2)

Lithology: Poorly cemented, bioturbated, poorly bedded to massive, glauconitic slightly calcareous sandstone with concretionary layers, mud drapes and silt laminations. Concretions become more common and continuous up-section. Midway up-section is a carbonaceous mudstone breccia, which grades laterally over 10s of metres into a channel-fill breccia/conglomerate. Blocks range in size from 1-30 cm, are very poorly sorted and rounded to highly angular (plate 2.6). Fossil content increases, with shell-rich zones in the sandstone, and concretionary layers become thicker and more common up-section towards the overlying cross-bedded limestone. Northeast of the type section on Te Rangi Station (section Wi17) the sandstone is massive to poorly bedded sandstone with mud drapes and reworked tephra (5%). The sandstone coarsens up from silty sandstone into sandstone with mud drapes, scattered mud rip-up clasts, mud clast pods, slumped beds, and moderately indurated channelised shellbeds. The sandstone becomes more fossiliferous and calcareous up-section and grades into the overlying calcareous sandstone/sandy limestone (tk-A-4). The equivalent sandstone is not found at Taraponui (section Ek4); there cross-bedded conglomerate grades directly into the above limestone. This sandstone is not present at Ahuateatua Trig.

Constituent Facies: Limestone (tk-A-4)

Lithology: Moderately cemented cross-bedded slightly glauconitic and conglomeratic sandy limestone, with rip-up clasts up to 60 x 30 cm (plate 2.9). The basal bed of the limestone is conglomeratic, and contains large and numerous mudstone rip-up clasts. It also comprises a series of distinct amalgamated beds. Local scouring is present at the base of the limestone, and a thick conglomerate occurs in areas, contains clasts of sandstone and mudstone (plate 2.7). To the northeast of the map area (section Wi17) the limestone is finer grained (greywacke pebbles are absent) and less calcareous than at the type section. Along strike to the southwest at Taraponui Trig (section Ek4) the limestone bed of this member contains large rip-up clasts, a high greywacke pebble content, and larger and greater shell content than at sections Wu5 and Wi17. At



Plate 2.5 (above), Basal conglomerate (tk-A-3) on Pohokura Road (V19/389274), showing angular mudstone and siltstone clasts in a 20% shelly sandstone matrix.

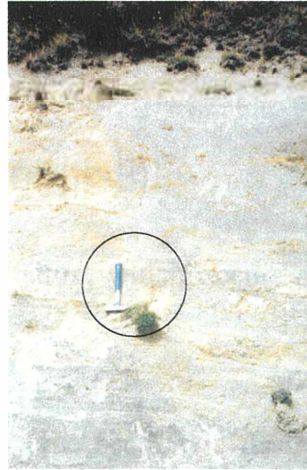


Plate 2.6, Channel fill conglomerate in sandstone (tk-A-2), on Nuamai Station (V19/393272; section Wu5). Mudstone and siltstone blocks occurring in the conglomerate range in size from 1-30 cm, are very poorly sorted, and highly angular.

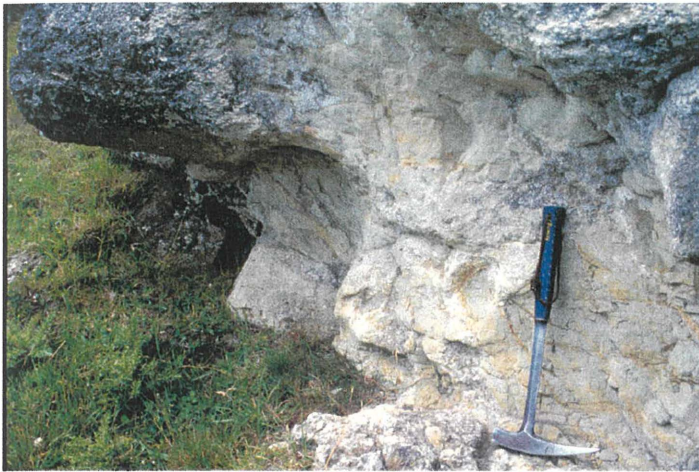


Plate 2.7, Naumai Member limestone (tk-A-4). Well cemented, cross-bedded limestone, with basal scouring and sandstone blocks as large as 1 m<sup>2</sup> occur (Photo: A. Pallentin).

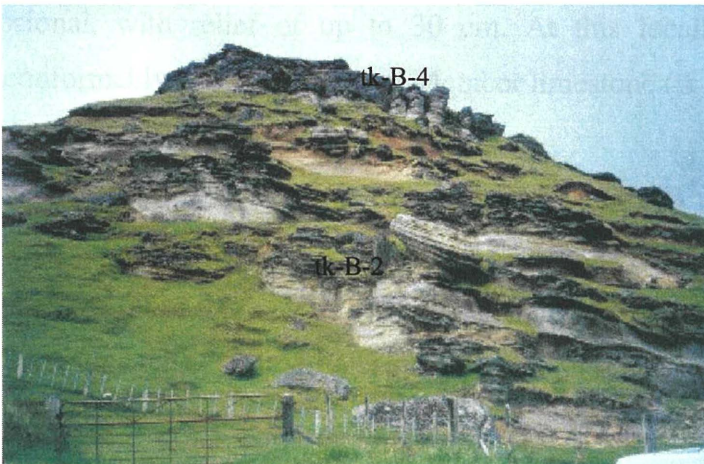


Plate 2.8, Te Rangi Member (tk-B), showing both the sandstone facies (tk-B-2) and the limestone facies (tk-B-4). The sandstone is cross-bedded calcareous sandstone with mud drapes, convolute bedding, reactivation surfaces and coquina lenses and beds. It grades upsection into the top cross-bedded limestone facies (tk-B-4). Naumai Station (V19/393272; section Wu5).



Plate 2.9, Te Rangi Member sandstone (tk-B-2). Uni-directional trough cross-bedded volcaniclastic sandstone, with internal truncations (reactivation surfaces). Naumai Station (V19/393272; section Wu5).

Ahuateatua Trig (section Ek6) the limestone is unable to be discriminated because “everything” is limestone (Figure 2.2).

## Te Rangi Member (tk-B)

Name Derivation: From Te Rangi Station, which occurs at the end of Heays Access Road (V19/446279).

Type and Reference Section: The type section is designated on Naumai Station (V19/392274; section Wu5). A number of reference sections have been logged through this unit, including to the southwest at Taraponui Trig (V19/331228, section Ek4), on Naumai station (V19/392274; section Wu5; plates 2.2 and 2.8; and V19/407287; section Wi16), and to the northeast on Te Rangi Station (sections Wi17, Wi16 and Wi13).

Upper and Lower Boundaries: In all sections described the lower boundary of the member is sharp and erosional. The upper boundary is described at section Wi13, where a sandstone breccia unconformably overlies Te Rangi Member sandstone, with up to 60 cm relief. At section Wi14, contact with the overlying sandy limestone is also erosional, with relief of up to 30 cm. At this locality a calcareous conglomerate unconformably overlies Te Rangi Member limestone (tk-B-4).

Distribution and Thickness: This unit is thickest (70 m) in the northeast of the map area on Te Rangi Station (section Wi13). It thins to the southwest at Naumai Station where it is 60 m thick (V19/392274; section Wu5; plate 2.8). Further to the southwest at Taraponui Trig (section Ek4) the unit is 20 m thick.

In comparison with the type section the sandstone member of this formation becomes more fossiliferous and more highly bioturbated northeast (section Wi16) of the type section. Here the sandstone contains lenses of rounded mudstone clasts. Northeast of section Wi16 (sections Wi17, Wi15, Wi13) on Te Rangi Station the member becomes less cemented and barren of fossils. Calcareous layers and mudstone clasts present elsewhere as pods or rip-up clasts grade out to the northeast and are no longer present in the most northeastern section described (Wi17). Southwest (V19/331 228, section Ek4) of the type section, at Taraponui Trig, the sandstone (tk-B-2) is 2-3 m thick. Further southwest at Ahuateatua Trig this sandstone is absent. The limestone (tk-B-4)

of the Te Rangi Member grades from a 4 m thick calcareous shelly sandstone on Te Rangi and Naumai stations (sections Wi14, Wi13) to a 10 m thick sandy limestone coquina at Taraponui Trig. Further southwest at Ahuateatua Trig, where a 50 m thick limestone occurs, division of this limestone into equivalent members is not possible. The Te Rangi Member limestone can be traced southwest along the Maungaharuru Range into this thick limestone.

**Age:** No macrofossils were extracted from this member. However, based on stratigraphic position, this member is Opoitian in age.

**Constituent Facies:** sandstone (tk-B-2)

**Lithology:** The section described from Pohokura Road on Naumai Station (V19/392274, section Wu5) is a very complex section with reworked volcanoclastic sandstone that helps to highlight the internal structure of the unit. It is a moderately cemented, slightly calcareous, bioturbated, fossiliferous, very well bedded sandstone with concretions and discontinuous mudstone conglomerate lenses (plate 2.8).

Sedimentary structures visible in the unit are many and varied. They include horizontal laminations, ripple cross-laminations, trough and tabular cross-bedding, mud off-shoots, and hummocky cross stratified sandstone is apparent towards the top of the sandstone (tk-B-2) facies of the member. This sandstone contains many thin sandstone beds (50-100 cm), which are bounded by mud drapes or reactivation surfaces (truncation at the top of the bed, plate 2.9). Many of these thin sandstone beds are massive in their lower portions but contain convolute bedding (caused by liquefaction) towards the top of each individual bed (plate 2.8) Unidirectional trough cross-bedding is common in these individual beds, with rare mud off-shoots on the cross-bed foresets (plate 2.10).

The mud drapes have sharp planar bases with rippled or jagged tops, and small (>1 cm) angular rip-up clasts can occur 1-2 cm above the mud drape in the overlying sandstone bed. Small-scale (15-30 cm in amplitude, 0.5-1.5 m wavelength) hummocky cross-beds occur near the top of the sandstone facies immediately underlying the limestone at the top of the member. The individual sandstone beds become more thickly bedded (2-3 m) up-section toward the limestone facies (plate 2.11), and are generally cross and convolute-bedded. To the southwest of the map area, at Taraponui Trig, the sandstone

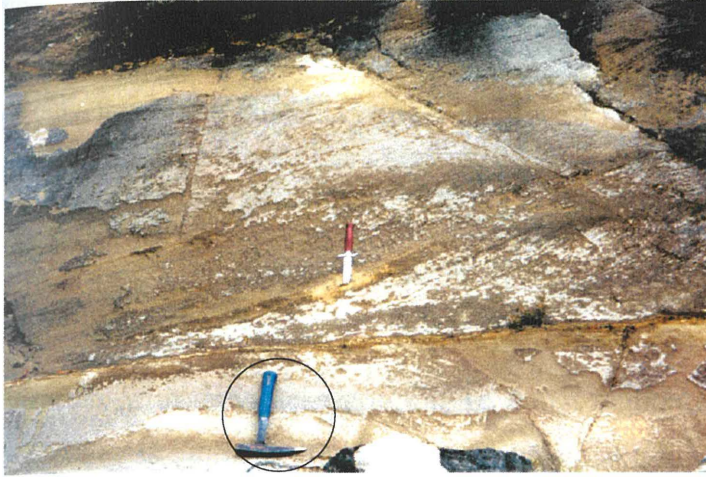


Plate 2.10, Te Rangi Member sandstone (tk-B-2). Uni-directional trough cross-bedded sandstone, with reactivation surfaces and mud offshoots on cross-bed foresets. Naumai Station (V19/393272; section Wu5).

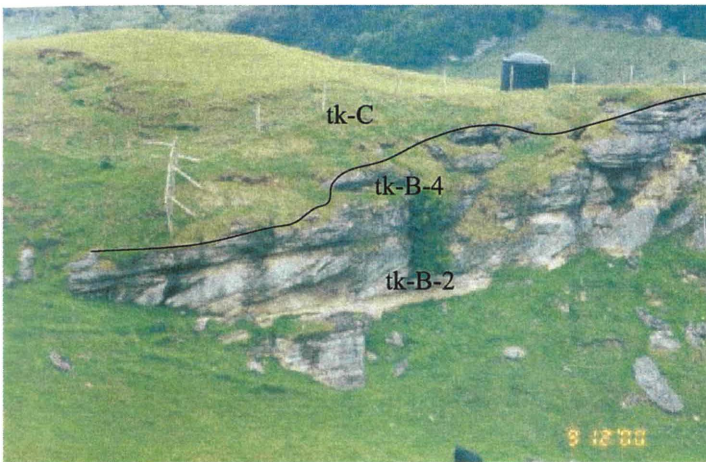


Plate 2.11, Te Rangi Member (tk-B) on Naumai Station (V19/393272; section Wu5), the sandstone (tk-B-2), limestone (tk-B-4) and Taraponui Member (tk-C) overlying the Te Rangi Member. Thick convolute beds and trough bedding occur towards the top of the sandstone, beneath the limestone.



Plate 2.12, Highly calcareous, highly fossiliferous, trough cross-bedded mass-emplaced Taraponui conglomerate (tk-C-3), with large (up to 70 cm) clasts of mudstone, siltstone and greywacke pebbles. This photo is taken at the type section on Te Rangi Station (V19/408284; section Wi14). Here the Taraponui Member (tk-C) unconformably overlies Te Rangi Member (tk-B; Photo: A. Pallentin).



Plate 2.13, Taraponui Member on Te Rangi and Rangiora Stations. The limestone facies of the member (tk-C-4) can be traced across strike into sections Wi12 (V19/422270-423270) and Wi9 (V19/440281-435271). Here it has graded into a fossiliferous cross-bedded and amalgamated sandstone (Photo: A. Pallentin).

facies (tk-A-2) of this member is thinner at, only 3 m. Here it contains a high shell content, conglomerate rip-up clasts and lenses, convolute bedding, and a high greywacke pebble content. Further southwest towards Ahuateatua Trig this sandstone facies is absent.

Constituent Facies: limestone (tk-B-4)

Lithology: Well cemented, poorly sorted, fossiliferous, tabular cross-bedded sandy limestone with greywacke grit. On Te Rangi Station (section Wi14; V19/408284) the limestone is thinner than at the type section. Here a cross-bedded sandy limestone/calcareous sandstone is present and is overlain by a highly cemented, calcareous, highly fossiliferous, mass-emplaced conglomerate with large clasts of mudstone, sandstone and greywacke pebbles. Further northeast (section Wi13; V19/428288) the limestone is absent, and instead the basal facies of the overlying member is found. This is a clast supported sandstone breccia, which lies unconformably on Te Rangi sandstone (tk-B-2). The capping limestone thickens to the southwest and at Taraponui Trig it is almost 10 m thick (plate 2.1). Here the limestone contains large (up to 1 m<sup>2</sup>) rip-up clasts of the underlying sandstone, and contains larger sized and more common greywacke pebbles.

### 2.2.2.3 Taraponui Member (tk-C)

Name Derivation: From Taraponui Trig and radiomast.

Type and Reference Section: Because of the incomplete exposure of the entire member in one continuous section in either the Waikoau or Waikari catchments, a number of described sections define the type section for this member. These include section Wi9 (V19/443267), section Wi12 (V19/423270), section Wi13 (V19/428288), section Wi14 (V19/408284), and section Wu5 (V19/392274), (Figure 2.2). In the Waikoau catchment section Wu5 shows incomplete exposure of this member, but it includes excellent exposure of the top limestone facies (tk-C-4) of the member, and is therefore considered a good reference section.

Upper and Lower Boundaries: Both sections Wi14 and Wi13 show good exposure between the underlying Te Rangi Member and the Taraponui Member. At section Wi14 the Te Rangi Member limestone (tk-B-4) is overlain by a mass-emplaced highly

calcareous conglomerate (tk-C-3; plate 2.12). At section Wi13 non-calcareous sandstone conglomerate unconformably overlies Te Rangi Member sandstone (tk-B-2). This conglomerate is overlain by thick (20 m) contemporaneously slumped sandstone with convolute bedding. The upper boundary between this member and the Bellbird Bush Member is observed in sections Wu5, and Wi9. In section Wu5 the upper limestone bed of this member is sharply overlain by sandstone. At section Wi9 cross-bedded sandstone (lateral equivalent to Taraponui Member limestone) is conformably overlain by massive sandstone (Figure 2.2; plate 2.13).

**Thickness and Distribution:** The Taraponui Member (tk-C) to the northeast at Te Rangi Station is a minimum of 70-80 m thick, at Naumai Station it is approximately 50 m. A conglomerate is found at the base of the member in both sections Wi14 and Wi13. In the most northeastern section (Wi13) a 20 m thick contemporaneous slump sandstone bed (plate 2.14), with convolute bedding, occurs above this conglomerate. The conglomerate is not found any further southwest than section Wi14 (figure 2.2). The limestone described at Taraponui Trig (section Ek4) is 10 m thick and thin sandstone lenses are included at the base of the limestone (tk-C-4). The same limestone at Naumai Station (section Wu5) is only 3 m thick and is finer grained than at Taraponui Trig. Here the limestone is less calcareous and has a lower shell content. The limestone continues to become less calcareous and fossiliferous to the northeast of the map area and grades into the sparsely fossiliferous, cross-bedded and amalgamated sandstone, which occurs at section Wi12. These cross-beds can be traced into the cross-bedded sandstone beds at the Boundary Stream Walkway section (Wi9; Figure 2.2; plate 2.13).

**Age:** No age diagnostic fossils have been found in this member. It is considered to be Opoitian in age based on stratigraphic position.

**Constituent Facies:** conglomerate ((breccia) tk-C-3)

**Lithology:** At the type section Wi13 on Te Rangi Station a clast-supported sandstone breccia (tk-C-3) unconformably overlies Naumai Member sandstone (tk-A-2; plate 2.12). This breccia has erosional relief of 60 cm at its base, contains 45% sub-angular sandstone clasts averaging 3 cm size (maximum of 7 x 70 cm) in a sandstone matrix. The other conglomerate bed found along strike at section Wi14 (V19/408284) is highly fossiliferous (predominantly oysters and pectens), calcareous, contains greywacke pebbles and large rip-up clasts throughout (15 x 20 cm average, 30 x 70 cm

maximum). At this locality the conglomerate is found above Te Rangi Member limestone (tk-B-4). A highly fossiliferous 50 cm thick shellbed (also predominantly oysters and pectens) is found above the conglomerate, rip-up clasts and flame structures are found at the base of this shellbed.

Constituent Facies: sandstone (tk-C-2)

Lithology: At section Wi13 above the lower conglomerate facies (tk-C-3) the member grades up-section into clean sandstone with low angle crossbeds, which passes sharply upwards into a 20 m thick slump unit with convolute bedding (plate 2.14; V19/433288). The degree of deformation decreases up-section as the convolute beds grade into a slightly cemented, massive to ripple bedded sandstone with mud drapes and calcareous layers. This massive section of sandstone grades up into differentially cemented, horizontally laminated, rippled and low-angle cross-bedded, sandstone with mud drapes. The mud drapes become rarer up-section and the sandstone is more massive. It is this massive sandstone that occurs at the base of the Boundary Stream Walkway (section Wi9). From a distance the high bluffs appear outwardly massive (plate 2.15). However, it is only the lower and very uppermost section of this outcrop that is massive. Close inspection of these outwardly massive bluffs shows the presence of mud drapes, reactivation surfaces and other small-scale sedimentary structures (plate 2.16). The reactivation surfaces are 20 cm to 3 m apart, the mud drapes are rippled at the base with an amplitude of up to 1 cm, and are generally 1-5 cm thick, and yellow-brown jarosite staining is common towards the base of many of the mud drapes. The mud drapes are bioturbated and the burrows are commonly in-filled by sandstone. In some cases mud drapes are barely evident as they have been completely burrowed away, and only rare mud clasts are remnants of the once present mud drape. The sandstone beds are rippled towards the base and in some beds the wavelength of the ripples increases up-section into small-scale cross-bedded units up the individual beds. The ripples and cross-beds stand out because of separation of light coloured quartz and feldspar minerals from the heavier and darker coloured minerals. The top 10-20 cm of the beds may contain convolute bedding caused by liquefaction. Bioturbation is common throughout the sandstone beds with large slightly better cemented oval burrows (10 x 7 cm) common in the lower portion of the beds and tubeworm flecks throughout the beds. Concretionary layers and pods stand out from outcrop and give the sandstone a poorly horizontally laminated appearance (plate 2.17); some of these may be secondary concretions formed by the movement of water through the unit.

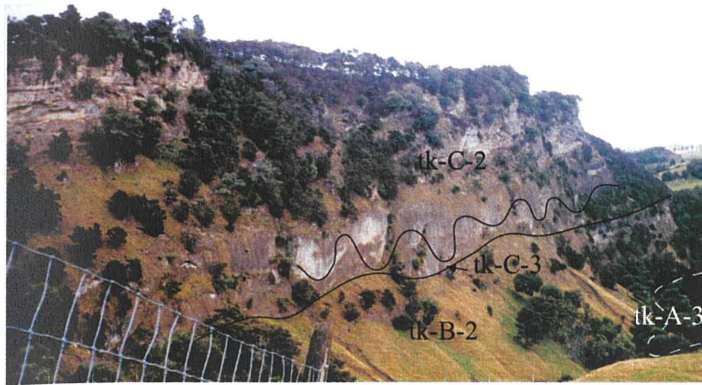


Plate 2.14, Twenty metre thick slump bed in Taraponui Member sandstone (tk-C-2). Below this slump bed is a basal breccia (tk-C-3) that unconformably overlies the Te Rangi Member. The Te Rangi Member is underlain by Naumai Member limestone (tk-A-4), which is obscured by bush in this photo. On Te Rangi Station (V19/433288; section Wi13).



Plate 2.15 (far left), Taraponui Member sandstone appears outwardly massive in the high sandstone bluffs at boundary stream walkway (V19/443267; section Wi9). Plate 2.16 (left), However, close inspection of these bluffs shows the presence of mud drapes, reactivation surfaces, and small scale ripples.



Plate 2.18 (above), Bellbird Bush limestone (tk-D-4) as outcropping in a tributary of the Waikoau River (V19/396213).

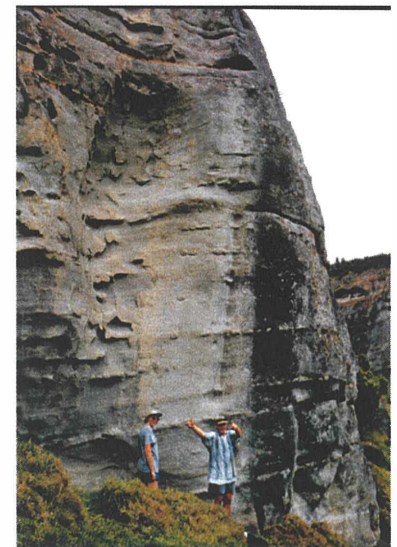


Plate 2.17 (below), Taraponui Member sandstone (tk-C-2) appearing poorly horizontally laminated as a result of bioturbation and concretion layers, which stand out from outcrop at Boundary Stream Walkway (V19/445280).

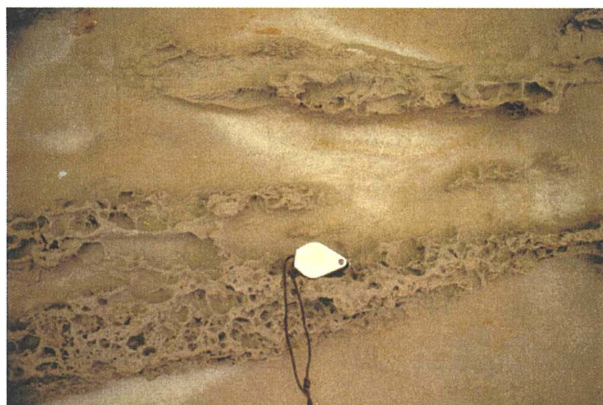


Plate 2.19 (left), Bioturbation (*skolithos*) in the Bellbird Bush Member sandstone (tk-D-2), bioturbated areas form large concretions (V19/438277; section Wi9; Photo: A. Pallentin).

Reasonable exposure of the Taraponui Member sandstone (tk-C-2) is present at section Wi12 (V19/423270). Here the sandstone is poorly cemented, well sorted, massive to very low-angle cross-bedded, fine sandstone with mud drapes. The sandstone grades up into a moderately cemented well sorted, massive, bioturbated (which form hard concretions) fine sandstone with siltstone stringers (mud drapes coarsening up-section into 'silt drapes'). The top beds in this section are uncemented, amalgamated, cross-bedded, moderately fossiliferous sandstone, and are considered to be a lateral equivalent of Taraponui Limestone. Many of the individual and also the top cross-beds are sharply truncated. This cross-bedded unit can be traced northeast across the map area into the Boundary Stream section (Wi9; Figure 2.2). Here the Taraponui Member limestone (tk-C-4) equivalent is a differentially cemented, low-angle cross-bedded, small-scale cross- and ripple-bedded, bioturbated, volcanoclastic sandstone, with mud drapes. At section Ek4 this facies is less than 1 m thick; further southwest at Ahuateatua Trig this sandstone unit is absent.

Constituent Facies: limestone (tk-C-4)

Lithology: Moderately cemented, cross-bedded glauconitic sandy limestone, with mudstone rip-up clasts, rare volcanoclastic clasts, and greywacke pebbles. Contains barnacle plates (which increase in size towards Taraponui Trig), and echinoderm, bryozoan and pecten remains. This unit thickens from 3 m at Pohokura Road to 10 m in the southwest at Taraponui Trig (plate 2.1). Its thickness is not known at Ahuateatua Trig as the limestone found there is unable to be sub-divided into individual beds or members.

#### 2.2.2.4 Bellbird Bush Member (tk-D)

Name Derivation: From the name of the DoC (Department of Conservation) reserve the limestone facies of this member occurs in.

Type and Reference Sections: The type section is located on Pohokura Road (section Wu4; V19/403227 to 402225) it does not show complete exposure of the member but it is easily accessed and displays good exposure of the upper limestone bed of this member. This member is not exposed in its entirety anywhere within the map area and because of this a number of reference sections are logged. Reference sections include section Wi9 (V19/423270), section Wi6 (V19/330220), section Wi7

to 434250), section Wi8 (V19/404244 to 406245), section Wu3 (V19/405210 to 395255) and section Wi4 (V19/438237 to 449235). With the exception of section Wu3, which occurs on Pohokura Road, all of these references sections occur on Rangiora Stud. Here outcrop is discontinuous and each column is compiled from the tracing of distinctive marker beds across the field area. A reference section is described at Taraponui Trig (V19/331228, section Ek4), where good exposure occurs through the limestone bed (tk-D-4) of the member. Thick outcrop of the limestone in the member occurs at Bellbird Bush Reserve (section Wu3; V19/390240) and in a tributary of the Waikoau River (plate 2.18; V19/396213).

**Upper and Lower Boundaries:** The lower boundary of the Bellbird Bush Member occurs on Rangiora Stud (section Wi4). Here a series of channelised indurated cross-bedded shellbeds form the upper boundary of the Taraponui Member (tk-C). In this section the shellbeds get thicker and more continuous up-section, and the upper boundary is considered to be located at the top of the thickest and most continuous shellbed. The contact with the overlying Opuoahi Member is gradational, as the shellbeds thin and become less continuous above this upper boundary. The lower boundary also occurs at the very top of the section described on Naumai Station (section Wu5). Here sandstone (tk-D-2) sharply overlies Taraponui Member limestone (tk-C-4).

The upper boundary is found on top of the Bellbird Bush limestone (tk-D-4 in the reference section (Wu4) on Quarry Road. The thin (1-2 m) trough cross-bedded gravelly limestone beds grade into overlying sandstone. This exposure represents the pinching and inter-fingering of the Bellbird Bush limestone with sandstone.

**Distribution and Thickness:** Poor and discontinuous exposure means that estimates of the thickness of this unit are difficult; it is probably about 200 m thick in the Waikari River catchment. The member is approximately 70 m thick in the Waikoau River catchment. The member is 30 m thick at Taraponui Trig (Figure 2.2).

**Age:** According to Beu (1995), the unit named here the Bellbird Bush Member limestone is Waipipian to Opoitian in age.

**Constituent Facies:** sandstone (tk-D-2)

**Lithology:** The Bellbird Bush Member sandstone grades out of the cross-bedded tephra-rich sandstone of the Taraponui Member sandstone. The lower parts of this facies are massive to horizontally laminated sandstone with rare silt laminations. Above the massive sandstone zone is a heavily bioturbated sandstone 25 m thick. The heavily bioturbated zone contains *Skolithos* burrows which form large concretions (25 x 100 cm; plate 2.19). The bioturbated zone is overlain by steeply cross-bedded sandstone, 1.5 m thick. The cross-bedded sandstone has a high shell, heavy mineral and mud clast content. The cross-bedded sandstone is overlain by bioturbated, convolute bedded, concretionary sandstone with mud and silt drapes. The mud drapes coarsen upwards into horizontally laminated to massive sandstone with rare silt laminations. Massive sandstone with a number of fossiliferous cross-beds are described in the section (section Wi6) found above the Boundary Stream Walkway (section Wi 9 (figure 2.2)). In the upper part of this unit is bioturbated, and rippled mud drapes are present. The mud drapes differ from elsewhere within the member, as they are substantially thicker (10 – 25 cm) and cross-bedded (plate 2.20).

**Constituent Facies:** limestone (tk-D-4)

**Lithology:** Highly indurated trough cross-bedded, flaggy limestone, consisting of amalgamated, shell and greywacke grit-rich, thin (5-10 cm) beds. The thin limestone bed on Quarry Road (section Wu4) is heavily bioturbated with large trace fossil burrows and escape structures. The limestone bed here is separated, by thick (20 cm) bioturbated mudstone, with sandstone in-fills. The mudstone bed shows horizontal to rippled cleavage. The limestone bed is 10 m thick at Bellbird Bush (V19/393242) and thins to 50 cm at the section described on Quarry Road (section Wu4). Across strike the limestone grades into section Wi4 where it no longer constitutes a limestone, but a series of channelised shellbeds. The limestone bed grades to the south from section Wu4 (down dip) into undifferentiated sandstone, which forms the large bluffs dipping down from Lake Opouahi, along the Waipapa Stream, into the Waikoau River.



Plate 2.20, Thick (10-25 cm) cross-bedded mud drapes in Bellbird Bush Member sandstone on Maori Gully track (tk-D-2; section Wi8; V19/405246)

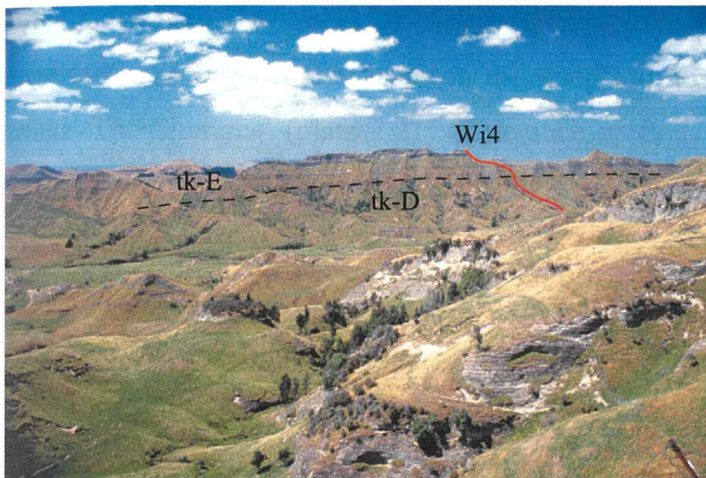
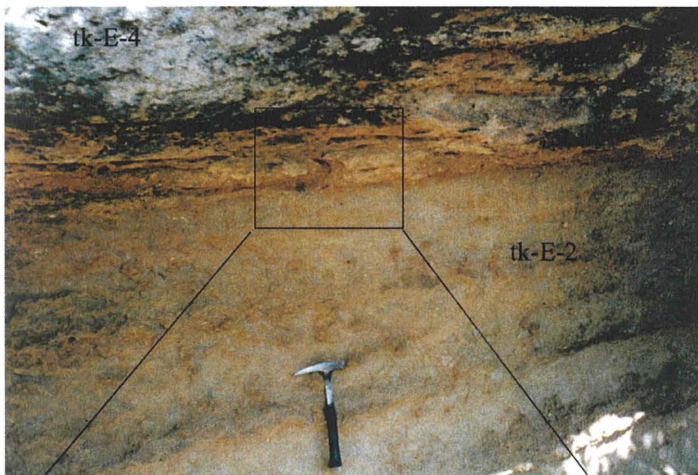


Plate 2.21, The boundary between Bellbird Bush Member (tk-D) and the Opuoahi Member (tk-E) occurs in the steep hill known as 'the Sharkies' on Rangiora Stud. Section Wi4 (V19/439235-449235) is shown. At the top of this section a cross-bedded calcareous sandstone occurs, which is the lateral equivalent to Opuoahi limestone (tk-E-4; Photo: A. Pallentin).



Plates 2.22, and 2.23, show the base of Opuoahi Member limestone on Pohokura Road (tk-E-4) where a carbonaceous mudstone layer has been 'ripped-up' into the the overlying limestone. (section Wu4; V19/401228-403227).



### .2.2.5 Opouahi Member (tk-E)

Name Derivation: From Lake Opouahi (V19/415215) and Opouahi Station

Type and Reference Sections: The type section, section Wu 4 is located on Quarry Road, off Pohokura Road from V19/403227 to 402225. The reference section Wi4, from V19/438237 to 449235, where the uppermost bed of this member is the topographically highest unit found in the steep hill north of Matahorua Road, which is named 'The Sharkies' (plate 2.21). Reference sections are described at Taraponui Trig (section Ek4, V19/331228) and Ahuateatua Trig (section Ek6, V19/330220).

Upper and Lower Boundaries: The lower boundary of this unit grades out of the upper part of the Bellbird Bush Member channelised shelly sandstone. The upper boundary is not observed because the upper cross-bedded sandstone is the highest unit exposed in the section logged. To the northeast, looking down into the Waikari River gorge, siltstone is sighted 20-30 m above the sandstone, inferring that the top of this unit occurs between these two units.

Distribution and Thickness: The member is 100 m thick on Rangiora Stud (section Wi4; plate 2.21). It is inferred that this unit grades laterally into the high sandstone bluffs that outcrop in the Waikoau River. Here the member contains some sandy siltstone units, which coarsen up-section into massive sandstone. To the northeast the basal member occurs and the silty sandstone which occurs at the type section, grades laterally into siltstone (section Wi5; Figure 2.2).

Age: Beu (1995) states that the presence of *Mesopeplum crawfordi* in the limestone on Opouahi Station indicates an Opoitian age.

Constituent Facies: sandstone (tk-E-2)

Lithology: The lower unit contains channelised sandy shell lenses, which become less continuous up-section. It grades into a heavily bioturbated, massive to poorly bedded silty sandstone with discontinuous mud drapes. This silty sandstone grades up into fossiliferous, bi-directionally cross-bedded calcareous sandstone with clean sand lenses and greywacke grit. The lower portion of the calcareous sandstone is finer grained than

Further up-section and is also ripple-bedded. Sharply overlying this unit is a calcareous silty sandstone with rare heavily bioturbated siltstone drapes. Again this unit coarsens up into thick fossiliferous (gastropods and bivalves) bi-directionally crossbedded calcareous sandstone with clean sand lenses and greywacke grit. The cross-bedded calcareous sandstone beds at the top of section Wi4 are a lateral equivalent of Opouahi Member limestone (tk-E-4).

Constituent Facies: limestone (tk-E-4)

Lithology: Low-angle cross-bedded limestone with sand lenses. The carbonaceous mudstone layer at the base of the member is heavily bioturbated and is 'ripped-up' into the overlying limestone (plates 2.22 and 2.23). The limestone contains 5% greywacke pebbles, up to a maximum size of 1.5 cm. Sand lenses are largest and most common towards the base and become smaller and increasingly rare up-section.

### 2.2.3 Rangiora Formation (new) (rg)

The Rangiora Formation is a new formation identified in the study area. It was previously included in the Maungaharuru Formation as described by Cutten (1991). It differs from the Titiokura Formation as mud drapes are generally absent from the sandstone facies and the carbonate content is much lower, and there are no limestones present within any of the constituent members. The Rangiora Formation is dominated by siltstone that coarsens up-section into thick (50 m +) sandstone. The Rangiora Formation consists of two members, the Waikari Member (rg-A) and the Mokamoka Member (rg-B)

Name Derivation: From Rangiora Stud on Heays Access Road (V19/450261).

Thickness and Distribution: In the Waikoau River (section Wu2) the Rangiora Formation is approximately 800 m thick. The formation is approximately 350 m thick in the Waikari River.

Age: The Waipipian-Mangapanian boundary occurs within the Rangiora Formation, based on the presence of *Pratulium puchellum*, *Semicassis fibrata* (section Wi3), and *Mesopeplum crawfordi* (section Wi1).

**Lithology:** The Rangiora Formation is characterised by inter-bedded siltstone and sandstone that occurs at the base of thick sections of siltstone and sandstone units. Fine-grained sediments coarsen and inter-finger up-section into coarser grained sediment. The siltstone facies are typically fossiliferous and contain concretions and bioturbation. Sandstone is usually very thick, calcareous, with concretion nodules, silty beds and rare scattered fossils. The formation becomes finer-grained to the northeast of the map area as the Mokamoka Member grades into the Waikari Member, which is found in the Waikari River (W19/540254 to V1/477255, section Wi1; plate 2.24).

### 2.2.3.1 Waikari Member (rg-A)

**Name Derivation:** From the Waikari River, where the type section for this member is located.

**Type and Reference Sections:** The type section is designated in the Waikari River (section Wi1), from W19/540254 to V19/477255. Small outcrops of sandy siltstone and siltstone are found on Heays Access Road, and Matahorua Road where siltstone coarsens up-section into a well sorted fossiliferous sandstone. A reference section (section Wi3) is described in outcrop off Flat Hill Road (W19/486243 (Figure 2.4)).

**Upper and Lower Boundaries:** The lower boundary of the Waikari Member is only described from a distance in bluffs above the Waikari River gorge (V19/477255). Here Waikari siltstone (rg-A-1) sharply overlies cross-bedded calcareous sandstone (Opuoahi Member limestone equivalent, tk-E-4). The upper boundary of this member is found in the Waikari River (section Wi1, W19/545249 section Wi1). Here Waikari Member sandstone (rg-A-2) is sharply overlain by Mokamoka Member sandstone (rg-B-2).

**Distribution and Thickness:** This Waikari Member is estimated to be at least 250 m thick, calculated from measured dips and strikes in the Waikari River. The Waikari Member grades to the southwest into the Mokamoka Member, which crops out in the Waikoau River.

Age: The Waipipian-Mangapanian boundary occurs within the Waikari Member. This is based on the presence of *Galeodea* sp, *Pratulium puchellum*, *Semicassis fibrata* (section Wi3), and *Mesopeplum crawfordi* (section Wi 1)

Constitute Facies: siltstone (rg-A-1)

Lithology: Massive, calcareous, blue-grey, moderately fossiliferous siltstone, with concretions and bioturbation zones (plates 2.24 and 2.25). The member coarsens up-section into a dull blue-grey silty sandstone with scattered fossils and shell lenses, which is sharply overlain by a 10 m thick massive micaceous sandstone.

Constitute Facies: sandstone (rg-A-2)

Well sorted massive micaceous sandstone, lies sharply and conformably on top of the sandy siltstone lithology of the Waikari Member siltstone (rg-A-1). The sandstone is 10 m thick and is in turn sharply overlain by the sandy siltstone of the Mokamoka Member siltstone (rg-B-1).

### 2.2.3.2 Mokamoka Member (rg-B)

Name Derivation: From Mokamoka Road, which is located in the Esk River catchment. A reference section (section Ek1) is described of this member on Mokamoka Road.

Type and Reference Section: The type section for this formation is defined in the Waikoau River from V20/397192 to 405152 (section Wu2). This section is difficult to access and exposure of many of the units within the member is poor. A reference section is described in the Waikari River from W19/545249 to 554228 (section Wi1; plate 2.2.6).

Distribution and Thickness: In the Waikoau River the member (rg-B) is approximately 800 m thick. The upper units of the Mokamoka Member (rg-B) grade across strike into the Waikari Member (rg A) in the northeast of the map area, as seen in the Waikari river section (Wi1). The Mokamoka Member is 60 m thick in the Waikari River (Figure 2.4; plate 2.26).



Plate 2.24, Massive, calcareous, moderately fossiliferous Waikari Member siltstone (rg-A-1). Concretions and bioturbation zones (Plate 2.25), in the Waikari River (section Wil; W19/525265)



Plate 2.25 (above), Bioturbation tubes forming concretions in the Waikari Member siltstone (rg-A-1; section Wil; W19/534258).

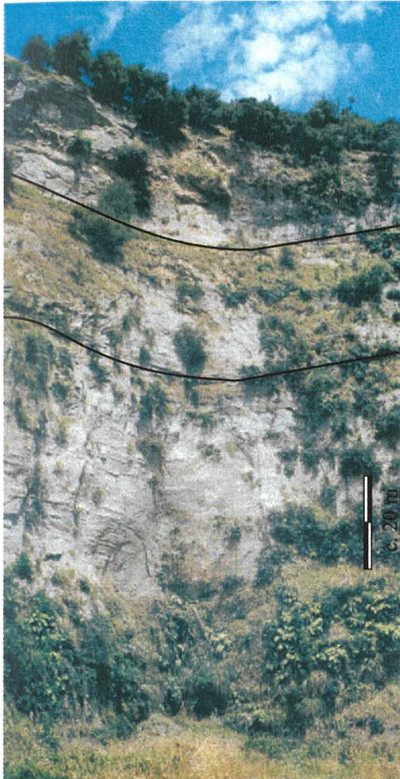


Plate 2.26 (left), High bluffs of the Mokamoka Member (rg-B) in the Waikari River (section Wil). This member is comprised of thick successions of sandstone with minor siltstone. Three sequences of siltstone coarsening upwards into sandstone are shown in this photo.



Plate 2.27 (above), Sharp planar contact between sandstone (rg-B-2) and siltstone facies (rg-B-1) of the Mokamoka Member in the Waikoau River (section Wu2, V20/401163).

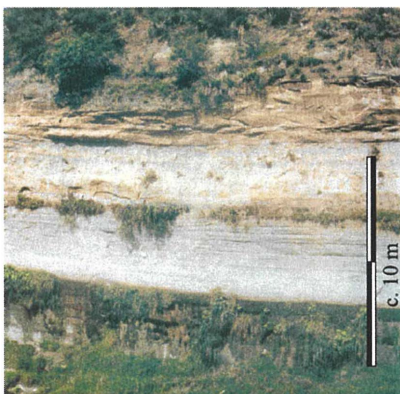


Plate 2.28, Parasequences within the Mokamoka Member (rg-B), in the Waikoau River (section Wu2; V20/408149).



Plate 2.29, Massive to poorly bedded Mokamoka Member sandstone (rg-B-2; V19/465225).

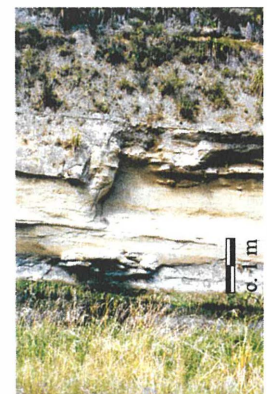


Plate 2.30, Amalgamated, Mokamoka Member sandstone (rg-B-2) with shellbeds and hummocky cross stratification, in the Waikari River (section Wil, W19/545250)

**Upper and Lower Boundaries:** The lower boundary of the Mokamoka Member is located above the Opuoahi Member limestone (tk-E-4), but has not been sighted in outcrop in the field area. The upper boundary of the Mokamoka Member in the type section (Wu2) is planar and conformable. Here concretionary sandstone sharply overlies siltstone. In the Waikari River section (Wi1) the lower boundary of the Mokamoka Member is located on top of the Waikari Member sandstone (rg-A-2). Here the boundary is sharp and planar. The upper boundary in the Waikari River is a concretionary bed located below a fossiliferous shellbed.

**Age:** This member is considered to be Mangapanian in age based on fossils sampled from the Waikari and Waikoau Rivers. Diagnostic fossils from the Waikari River (section Wi1 (stop 136)) are *Polinicies waipipiensis*, *Austrofusius pagoda*, *Amalda oraria*, and *Splendrillia kingmai*, while from the Waikoau River (section Wu1 (V20/412147)) *Austrofusius pagoda*, *Zethalia coronata*, *Polinicies waipipiensis*, *Myadora stephaniae* and *Patro undatus* (V20/406151, section Wu2) have been collected.

**Constitute Facies:** siltstone (rg-B-1)

**Lithology:** There are seven siltstone units within the member in the Waikoau River section (Wu2), but only two siltstone units in the Waikari River section (Wi1) (Figure 2.3). In the Waikoau River section (Wu2) contact between the siltstone and the underlying sandstone was only exposed in outcrop in one site. This is also the case in the Waikari River section (Wi1). Here the contact was planar without distinguishable irregularities (plate 2.27). The base of three of the siltstone units are characterised by thin parasequences of siltstone coarsening upwards into sandstone (plate 2.28). This siltstone facies varies from blue-grey frittered siltstone to silty sandstone, commonly containing concretions and sometimes fossiliferous. This siltstone coarsens up-section into concretionary sandstone, and in some cases is gradationally overlain with a series of parasequences coarsening up into the sandstone facies (rg-B-2).

**Constitute Facies:** sandstone (rg-B-2)

**Lithology:** Massive to poorly bedded, sparsely fossiliferous sandstone with occasional shellbeds and lenses, and silty laminae and beds, and occasionally amalgamated sandstone with hummocky cross stratification (plates 2.29 and 2.30). In the Waikoau

River catchment seven sandstone units occur within this member. In reference sections in the Waikari River two sandstone units occur within the member.

## Petane Group

The Petane Group comprises one new formation, the Matahorua Formation, which is dominated by greywacke gravel and siliciclastic sandstone and siltstone. The group includes the 11 formations formally defined by Haywick *et al.* (1991). The Petane Group therefore now comprises 12 formations. In ascending order these are: **Matahorua Formation** (new), Waipunga Formation, Esk Formation, Tutira Formation, Aropaoanui Formation, Darkys Spur Formation, Mairau Formation, Tangoio Formation, Te Ngaru Formation, Waipatiki Formation, Devils Elbow Formation, and Kaiwaka Formation. The Matahorua Formation is included in the Petane Group because of the lithological similarities it shares with the currently defined Petane Group, especially with the lower formations (e.g. Waipunga, Esk, Aropaoanui, Tutira and Darkys Spur formations). These similarities are siltstone and sandstone coarsening up-section into greywacke conglomerates. Only the Matahorua and Waipunga Formations are mapped in this study. The stratigraphy above the Waipunga Formation was not examined or mapped in detail in this study.

**Lithology:** The Petane Group is dominated by greywacke gravels, sandstone and minor siltstone in the Matahorua Formation. Bedded siltstone and sandstone characterise the Waipunga Formation. Haywick (1990) described the Petane Group in the Tangoio block (Esk Formation, Tutira Formation, Aropaoanui Formation, Darkys Spur Formation, Mairau Formation, Tangoio Formation, Te Ngaru Formation, Waipatiki Formation, Devils Elbow Formation, and Kaiwaka Formation) as comprising greywacke conglomerate, siliciclastic sandstone and siltstone, calcareous sandstone, and bioclastic limestone.

### 2.3.1 Matahorua Formation (new) (mt)

**Name Derivation:** Previously from Cutten (1994) who defined the Matahorua Gravel Member (now this member is defined within the Trelinnoe Member of the Matahorua

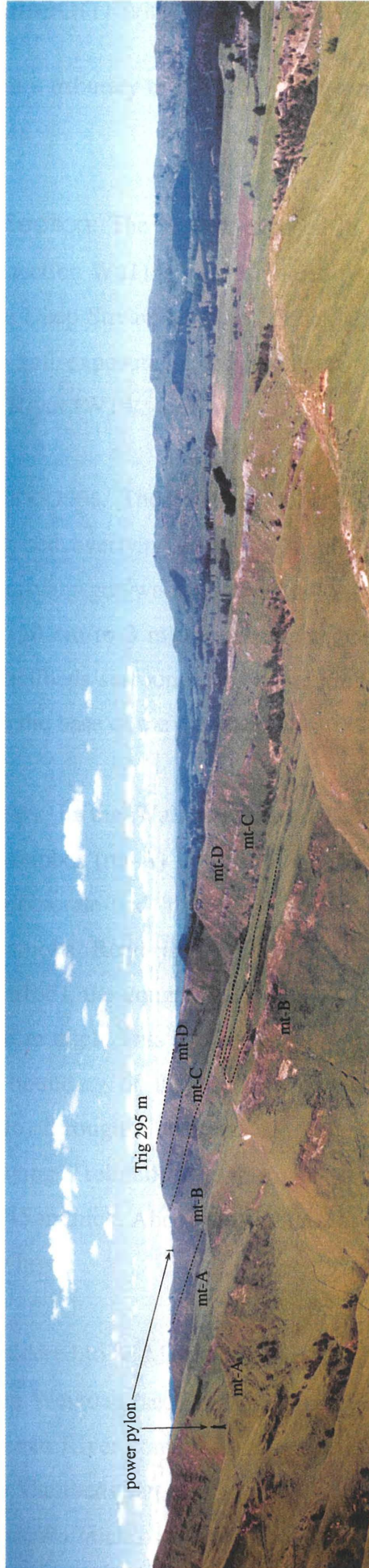
Formation). The name was derived from Matahorua Road (V19/490217) where the type section is located.

**Upper and Lower Boundaries:** The lower boundary of the Matahorua Formation is defined as the sharp contact (V19/414146, section Wu1) at the base of a concretionary layer overlying Mokamoka Member siltstone (rg-B-1).

**Thickness and Distribution:** The Matahorua Formation is 150 m thick in the Waikoau River catchment, and decreases in thickness towards the Waikari River catchment where it is 100 m thick. In the Waikari River only two of the four conglomerates are present. The formation is estimated to be 160 m thick in the Esk River, where all four of the conglomerates are found (plates 2.31, 2.32 and 2.32).

**Age:** This formation is Mangapanian to Nukumaruan in age based on the presence of fossils such as *Phialopecten triphooki* (Bland pers. comm. 2000), *Zethalia coronata*, *Basina parva*, *Mactra mula*, *Nucula nitidula*, *Splendrillia kingmai*, *Crassostrea ingens*, *Polincies waipipiensis*, *Amalda oraria*, *Dosinia greyi*, *Panopea zelandica*, *Maorimactra chrydea*, *Aenator (Aenator) sp.*, *Zenatia acinaces*, *Gari sp.*, *Bassina yatei*, and *Xymene sp.*

**Lithology:** Commonly inter-bedded siltstone and sandstone at the base of members with reworked gravel lenses, overlain by thick, massive, micaceous sandstones. Sandstones directly below the greywacke conglomerates are typified by fossiliferous layers and cross-bedded intervals, with minor siltstone beds and laminations which may be normal or reversely graded. Members are capped by poorly sorted greywacke-dominated conglomerates which are inter-bedded with sandstone and siltstone lenses, beds, rip-up clasts and tumble blocks.



Plates 2.31, 2.32 and 2.33 (top to bottom), The Matahorua Formation (mt) forming moderate dip slopes ( $9^{\circ}$  to  $18^{\circ}$ ) in the Waikoau to Waikari catchments. In plate 2.30 taken from atop the Grassy Knoll Member conglomerate (tk-D-3; V20/423154) above the Waikoau River looking SW towards the Esk River. Plate 2.31 faces NE towards the 295 m trig (V20/438168). In both plates 2.30 and 2.31 all of the constituent members of the Matahorua Formation are identifiable. However, in plate 2.32 looking SW from Matahorua Road in the Waikari catchment, only two conglomerates are identifiable.

### 2.3.1.1 Deep Stream Member (mt-A)

Name Derivation: From a tributary of the Esk River, named Deep Stream (enters the Esk River at V20/376072).

Reference and Type Section: The section exposed in the Waikoau River between V20 414146 to 412147 (section Wu1) is the designated type section. This section gives complete exposure of the Deep Stream Member. Other sections are present in the map area although none give full exposure of this member. A reference section (Wi1) is described in the Waikari River (W19/543252).

Upper and Lower Boundaries: The lower boundary of this unit is sharp with a continuous concretionary bed overlying siltstone (plate 2.34). The upper boundary is sharp with sandstone overlying greywacke gravel; no relief is seen on the contact. In the Waikari River thick (50 cm to 3 m) concretionary horizons mark both upper and lower boundaries, with shellbeds surrounded by concretionary layers above (part of the overlying member) and at the base of the member.

Distribution and Thickness: In the Waikoau River (V20/406152 to 415145, section Wu1) the Deep Stream Member (mt-A) is 40 m thick. The conglomerate bed here is only 1 m thick. The conglomerate bed (mt-A-3) of this member only crops out in the map area between Mokamoka Road and Pohokura Road. In the hill parallel to Matahorua Road (V20/436168), the conglomerate (mt-A-3) is 6 m thick and the Deep Stream Member (mt-A) 50 m thick. This is the furthest northeast the conglomerate (mt-A-3) occurs. The upper boundary of the member is traced into the Waikari River (section Wi1, W19/544246) through a shellbed and concretionary layer, which is the lower facies of the overlying Trelinnoe Member (mt-B). In the Waikari River this member is approximately 45 m thick. Above the shellbed at the base of this member is a thin (20 cm) concretionary layer.

Age: This member is considered to be Mangapanian in age, based on the faunal content of shellbeds sampled in the Waikoau (section Wu1) and Waikari Rivers (section Wi1). The shellbeds in the Waikoau River contain *Zethalia coronata*, *Basina parva*, *Mactra mula* and *Nucula nitidula*. Shellbeds sampled in the Waikari River contain *Splendrillia kingmai*, *Crassostrea ingens*, *Polinicies waipipiensis*, and *Amalda oraria*.

## Chapter Two: Lithostratigraphy

Plate 2.34, Thick (4 m) concretionary bed in the Waikoau River (section Wul; V20/412147), marking the base of the Matahorua Formation.



Plate 2.35, Trelinnoe Member (mt-B). Reworked greywacke gravel lenses in cross-bedded sandstone (tk-B-2) underlying conglomerate (tk-B-3) near to Matahorua Road (section Wi2; W19/492216).

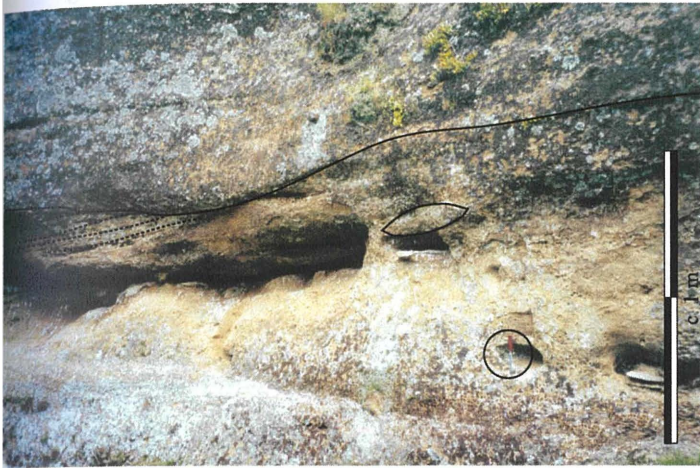


Plate 2.36 (left), Trelinnoe Member conglomerate (mt-B-3), well to poorly sorted, horizontal laminated to cross-bedded greywacke conglomerate (section Wi2; W19/492216).

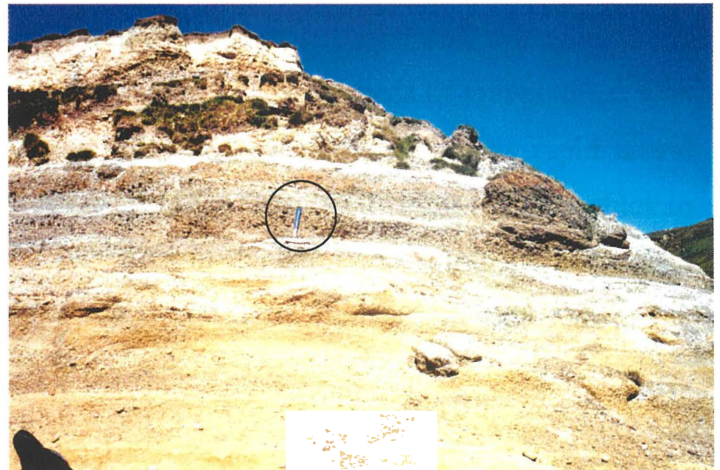
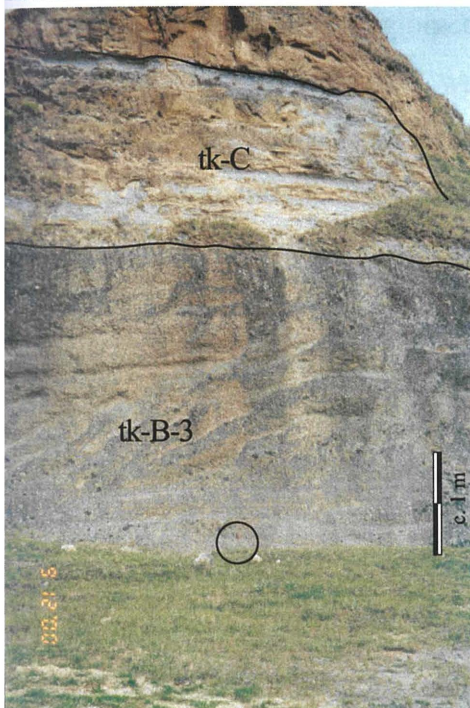


Plate 2.37 (above), Reworked tephra in the Trelinnoe Member conglomerate (tk-B-3), which is prominent in all sections described of this conglomerate (V20/422154)



Plate 2.38 (left), Papakiri Member in the Waikoau River. Micaceous, slightly calcareous sandstone (mt-C-2) grades upsection into greywacke conglomerate (mt-C-3). The conglomerate shows trough cross-bedding in the thin beds below the main conglomerate bed which is massive (section Wul; V20/429144).

Constituent Facies: sandstone (mt-A-2)

Lithology: At the base of the sandstone, nodular concretions form semi-horizontal to rippled layers, which sits sharply on top of the underlying siltstone (rg-B-1). Up-section the concretionary layers become amalgamated and the concretionary layers form a 4 m thick nodular concretionary bed (plate 2.34). The upper surface of this concretionary bed is sharp and planar. Above the concretionary bed is a poorly cemented, massive, slightly calcareous, micaceous, concretionary sandstone. Part way up this sandstone facies are three lensoidal highly fossiliferous shellbeds, which are surrounded by large *Ophiomorpha* burrows, many of which form hard concretions. The three highly fossiliferous shellbeds contain shoreface fossil assemblages including *Bassina yatei*, *Zethalia coronata*, *Xymene* sp., and *Bassina parva* in the lower shellbed, *Zethalia coronata*, *Dosinia greyi*, *Panopea zelandica*, *Maorimactra chrydea*, *Aenator* (*Aenator*) sp., *Zenatia acinaces*, *Gari* sp., and *Mactra mula* are found in the upper shellbed.

Constituent Facies: conglomerate (mt-A-3)

Lithology: Poorly cemented, wavy lenticular to cross-bedded, well rounded, moderately sorted, greywacke conglomerate with a maximum clast size of 7 cm, averaging 2 cm. The conglomerate is made up of thin (decimetre) lenses and beds of gravel, often with cross-bedded sandstone between gravel beds. The conglomerate shows rapid lateral facies changes from the Waikoau River (V20/415145) where it is less than 2 m thick to the northeast (V20/426166) where it increases in thickness to 6 m at the Matahorua Road outcrop (V20/436168). This outcrop is the most northeastern exposure of the conglomerate in the map area.

### 2.3.1.2 Trelinnoe Member (mt-B)

Name Derivation: From Trelinnoe Gardens on Old Taupo Road (V20/340070), where excellent exposure of the conglomerate (mt-B-3) in this member is found.

Reference and Type Sections: The type section is defined in the Waikoau River, where there is excellent exposure (V20/415145 to 426143, section Wu1). Reference sections logged through this member are located in the Waikari River (W19/544246 to 549243, section Wi1) and on Pohokura Road (V19/490217, section Wi2), which Cutten (1994) previously defined as the type section. The reference section on Pohokura Road section gives excellent exposure of the conglomerate facies of the member, but not of

the rest of the member. However, access to the Pohokura Road is easier than access to the type section in the Waikoau River section (Wi1), although the area of land has recently been planted in forestry and outcrop may be poor in the future.

**Upper and Lower Boundaries:** The upper and lower boundaries of this member are sharp and erosional. Relief locally is typically sinuous with about 15 cm amplitude. The basal beds of the sandstone facies contain reworked greywacke gravel from the underlying gravel member.

**Distribution and Thickness:** This member can be accurately mapped across the entire study area, and occurs in all three river catchments. Both the conglomerate and the member become thinner in the northeast of the map area. The member is 70 m thick in the Waikoau River, and thins to the northeast into the Waikari River where it is 45 m thick. The conglomerate facies is 10 m thick in the Waikoau River (section Wu1), it is 9 m thick at the section on Pohokura Road (section Wi2), and thins to 5 m in the Waikari River (Wi1). The sandstone facies of the member becomes increasingly fossiliferous in the northeastern sections of the map area (section Wi1), where channelised indurated sandy shellbeds occur.

**Age:** Molluscs such as *Struthiolarian* sp. suggest a Mangapanian age (Cutten 1994).

**Constituent Facies:** sandstone (mt-B-2)

**Lithology:** Poorly cemented, massive, sparsely fossiliferous, slightly calcareous, micaceous, concretionary sandstone. This facies contains thin lenticular siltstone stringers that often inter-finger with the sandstone and lense out. Towards the base of the sandstone, siltstone stringers occur that coarsen upward into ripple bedded sandstone with rare greywacke pebbles. Concretions are more common at the base of the sandstone than further up-section. Reworked greywacke gravel in cross-bedded sandstone is found directly above the underlying conglomerate (plate 2.35); further up-section moderately fossiliferous sandstone (1 m) occurs 4-5 m below the conglomerate.

**Constituent Facies:** conglomerate (mt-B-3)

**Lithology:** Uncemented, well to poorly sorted, horizontal laminated, cross-bedded greywacke conglomerate. Greywacke clasts in the main conglomerate bed range from coarse sand in size to large cobbles up to 25 cm in length, from sub-angular to rounded,

commonly spherical and sometimes oblate in shape, well to poorly sorted and typically clast-supported (plate 2.36). Distinct beds can be identified within the conglomerate on the basis of differing clast size and sorting. Distinctive tephra beds and lenses are prominent throughout all sections described of this conglomerate (plate 2.37), although the location of the tephra beds within the conglomerate varies along strike. The tephra may be concentrated within the upper, middle or lower units of the conglomerate, as lenses, beds or evenly distributed throughout the conglomerate. In the thicker (1-3 m) tephra beds convolute bedding is common, caused by volcaniclastic dykes and soft sediment slumping. The tephra beds are commonly massive, horizontally bedded or ripple-bedded to cross-bedded.

Thin (5-25 cm) greywacke conglomerate lenses are common under the main conglomerate bed. These lenses often coarsen up-section towards the main conglomerate bed. The gravel lenses are often found within cross-bedded or wavy laminated fine to coarse sandstone. The thicker lenses and beds (<15 cm) typically contain localised scouring at their base. The conglomerate lenses contain well-rounded, spherical greywacke pebbles, averaging 2 cm in size, with a maximum clast measured as 10 cm diameter. The main conglomerate unit consists of many individual beds whose structures range from massive, horizontal laminated to cross-bedded greywacke. Sandstone lenses are common throughout the main conglomerate bed.

### 2.3.1.3 Papakiri Member (mt-C)

Name Derivation: From Papakiri Stream which flows parallel to Matahorua Road and into Lake Tutira. Excellent exposures of the conglomerate found within the member are located in close proximity to this stream.

Type and Reference Sections: The type section for this unit is designated in the Waikoau River section at V20/426143 to 430143 (section Wu1; plate 2.28). Reference sections are described in the Waikari River (W19/549243 to 551239, section Wi1) and on Pohokura Road (V19/492216, section Wi2). In both these reference sections the conglomerate facies are simply a series of thin gravel beds and lenses which become increasingly difficult to map across the field area in the northeastern direction. Rare outcrops of the conglomerate occur across the interfluves in the Waikari catchment area.

**Upper and Lower Boundaries:** In all cases upper and lower boundaries are sharp and erosional, with relief locally up to about 15 cm.

**Distribution and Thickness:** While this unit has been described in all three river sections, it is only consistently prominent in outcrop in the Esk and Waikoau River catchments. This member, along with the three other Matahorua Formation members form long dip slopes in steep hill sides in these catchments (plates 2.31, 2.32 and 2.33). The member is 25 m thick in the Waikoau River (plate 2.28) and thins to the northeast in the Waikari River, where it is 12 m thick.

**Age:** Mangapanian to Nukumaruan based on stratigraphic position with respect to the overlying unit, which contains *Phialopecten triphooki*, which occurs in the Esk River catchment (Bland 2001).

**Constituent Facies:** sandstone (mt-C-2)

**Lithology:** Moderately cemented, massive, slightly calcareous, micaceous, sparsely fossiliferous concretionary sandstone. At the base of this member interbedded (0.5-1 m) siltstone and sandstone occur. This section is overlain by massive sparsely fossiliferous concretionary sandstone, which becomes increasingly cross-bedded up-section. The sandstone is horizontally laminated below the first conglomerate bed, and low-angle cross-bedded between the two lower conglomerate beds. In reference sections described in the map area tabular cross-bedding is described below the main conglomerate bed (plate 2.28), with small-scale ripple bedding found immediately below the main conglomerate bed.

**Constituent Facies:** conglomerate (mt-C-3)

**Lithology:** Uncemented, moderately sorted, well rounded, clast-supported, greywacke conglomerate (plate 2.28). Greywacke clasts range from medium to large pebbles (5 cm maximum, 3 cm average), and are supported in a 20% silty sand matrix. The upper boundary is sharp and erosional with relief of up to 4 cm, and is overlain by a lignite bed (plate 2.38). The member coarsens upwards from the underlying sandstone, and a number of gravel beds and lenses are found below the main conglomerate bed. The gravel lenses are found within tabular cross-bedded to horizontally laminated sandstone that contains thin siltstone laminae. Thick (0.5 - 1 m +) conglomerate beds are found

Below the main conglomerate bed; these beds are trough cross-bedded and have local relief at the base and top. Small greywacke pebble lenses outline cross-beds within the sandstone. The main conglomerate bed appears massive. At the reference section (V19/490217, section Wi2) on Matahorua Road, numerous thin (10-20 cm) greywacke conglomerate lenses occur (plate 2.39).

#### 2.3.1.4 Grassy Knoll Member (mt-D)

Name Derivation: From a small hillock in the Esk River catchment (V20/338053).

Type and Reference Sections: The type section (Wu1) is described in the Waikoau River V20/430143 to 435148. The conglomerate facies of this member do not occur in the Waikari River and while there are probably equivalent facies in this section, they were not located. Exposure through the greywacke conglomerate can be found in the Esk and Waikoau catchments. Exposure occurs at the gravel pit on Esk Road (V20/395127; Berry Road north of the Esk River), and in frequent outcrop in hillsides. However, it is only in the Waikoau and Esk Rivers where exposure of the complete member is found, and for this reason there are no described reference sections.

Upper and Lower Boundaries: The type section in the Waikoau River displays erosional upper and lower boundaries. The lower boundary is found on top of the Papakiri Member conglomerate, where a thin lignite bed has been located (section Wu1; plate 2.38). Up to 4 cm of relief occurs on top of this bed. The upper boundary is found atop the Grassy Knoll Member conglomerate (mt-D-3), where relief of up to 50 cm is described.

Distribution and Thickness: The top of the member forms the stratigraphically highest dip-slope in the Waikoau catchment area (plates 2.31 and 2.32). The conglomerate bed is not found in the Waikari catchment area and is thought to thin (plate 2.39) to the northeast and eventually disappear (plate 2.33). The member is 40 m thick in the Waikoau River where it comprises thin siltstone, sandstone, and gravel beds and lenses. Southwest of the Waikoau River individual beds of sandstone and siltstone are not present and the conglomerate is wholly made up of clast-supported greywacke gravel



Plate 2.38 (above), Lignite bed occurring atop the Papakiri Member conglomerate (mt-C-3; section Wul; V20/429144) in the Waikou River (Photo: K. Bland).

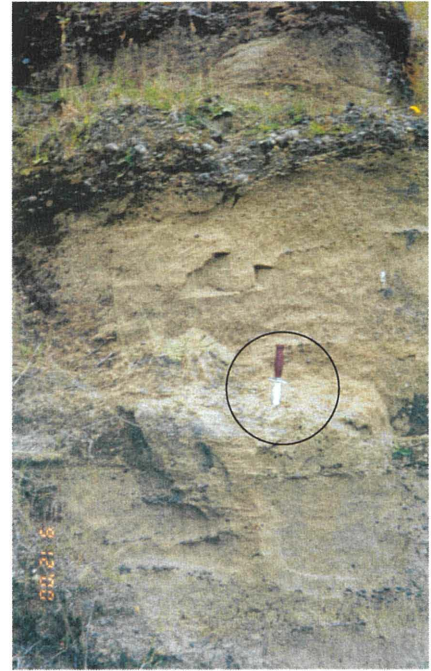


Plate 2.39 (above), Thin greywacke conglomerate beds of the Papakiri Member conglomerate (mt-C-3) on Pohokura Road (section Wu2; W19/493216).



Plate 2.40 (above), Sparsely fossiliferous shellbeds with mud and pumice clasts in tabular cross-bedded Mahiaruhe Member sandstone (wp-A-2; section Wul; V20/435143).



Plate 2.41 (left), Siltstone showing cleavage on top of Mahiaruhe Member sandstone (wp-A-2; section Wul; V20/435143), with large burrows down from the siltstone in the sandstone.

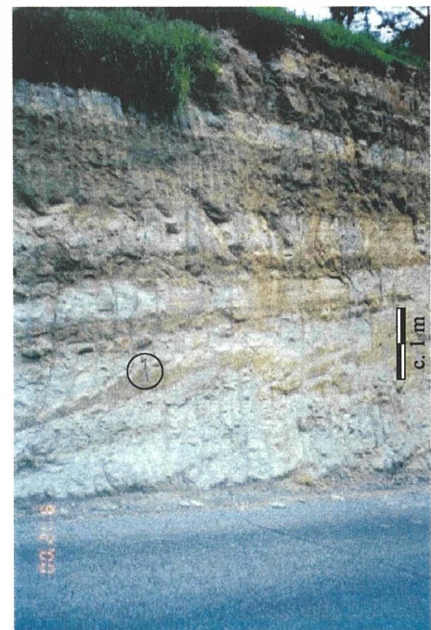


Plate 2.42 (right), Elston Member (wp-b) on Waikou Road, here a series of siltstone and sandstone beds (wp-B-1) coarsening upwards into sandstone (wp-B-2; section Wul; V20/439138).

with rare silt intra-clasts. Gravel lenses and beds below the main gravel member coarsen upwards of the fining upward beds of siltstone and sandstone.

AGE: Nukumaruan, based on the presence of *Phialopecten triphooki* (Bland 2001) in the conglomerate facies in the Esk River.

Constituent Facies: sandstone (mt-D-2)

Lithology: Uncemented, well sorted, massive, micaceous sandstone. At the type section in the Waikoau River (section Wu1) the base of this member is marked by a laterally discontinuous lignite bed (part of the underlying member, mt-C-3 (20cm thick)), which is overlain by two 1.5 m thick siltstone beds. The lowest siltstone bed is overlain by a 1 m thick coarse greywacke sandstone bed, with scouring at its base (up to 7 cm relief). The second siltstone bed coarsens up-section into sandstone, which contains reworked gravel lenses. The beds are overlain by 20 m of massive, micaceous sandstone (plate 2.41). Conformably overlying the massive sandstone are fining upward beds of siltstone and sandstone, the silty sandstone beds become less common up-section towards the conglomerate bed (mt-D-3), and sandstone is sharply overlain by the conglomerate bed. The sandstone immediately below the conglomerate bed is highly bedded with small trough beds to low-angle tabular cross-beds.

Constituent Facies: conglomerate (mt-D-3)

Lithology: Partially cemented (iron stained), moderately to poorly sorted, parallel laminated to cross-bedded, greywacke conglomerate. Greywacke clasts range from large cobbles to coarse sand-sized greywacke grit, spherical to oblate in shape, and show no imbrication. The conglomerate is horizontally bedded, with individual beds varying from coarse sand to large pebbles; these beds may be well to poorly sorted, are often channelised and scour into the underlying conglomerate bed. Sub-angular, deformed siltstone clasts (soft sediment deformation, clasts deformed/wrapped around another clast), sandstone rip-up clasts and tumble blocks are found within some of the individual conglomerate beds, and some individual beds are predominantly composed of these siltstone and sandstone clasts. At the type section in the Waikoau River, the conglomerate contains sandstone and siltstone beds and lenses. The siltstone and sandstone beds are typically trough to tabular cross-bedded or wavy laminated.

### 2.3.2 Waipunga Formation (redefined) (wp)

Name Derivation: From Haywick (1991), named after the Waipunga Railway Station (V20/385015). This formation has been extended to include previously undefined sediments from the Waikoau River section (section Wu1, V20/438138 to 435126).

Type and Reference Section: This member is found in all three river catchments, but is only able to be divided into its two constitute members in the Waikoau River section (V20/438138 to 435124, section Wu1).

Distribution and Thickness: The Waipunga Formation is 70 m thick in the Waikoau River section. In the Waikari River the formation is 50 m thick; the two constitute members are able to be identified.

Age: Based on stratigraphic position this formation is Nukumaruan in age.

Lithology: Inter-bedded fossiliferous massive siltstone and cross-bedded to massive micaceous sandstone, with common reworked tephra and organic material.

#### 2.3.2.1 Mahiaruhe Member (wp-A)

Name Derivation: From the Mahiaruhe Stream, which flows into the Waikoau River (V20/441135).

Type and Reference Sections: The type section is defined in the Waikoau River (section Wu1) from V20/436138 to 435144. Outcrop here is poor but it is the only area where this member occurs. No reference sections are defined for the member.

Upper and Lower Boundaries: Relief of 4 cm is described at both the upper and lower boundaries. The lower boundary in section Wu1 is an undulating erosional surface between the Grassy Knoll Member conglomerate (mt-D-3) and overlying Mahiaruhe Member sandstone (wp-A-2). The upper boundary is identified by a sparse shellbed with greywacke pebbles and grit unconformably overlain by siltstone (wp-B-1). This upper boundary is found at two localities in the Waikoau catchment, one on Waikoau

Road (section Wu1, V20/439137), the other in the Waikoau River (also section Wu1, V20/434126).

**Distribution and Thickness:** The Mahiaruhe Member is only identified in the Waikoau River catchment. It is 50 m thick in the Waikoau River. The upper sandstone unit of this member is logged in the Waikoau River (V20/436138) and in a tributary (V20/418126), where the sandstone unit contains tabular cross-bedded to horizontally laminated volcanoclastic sandstone over a 1.5 m interval, with thin siltstone laminae. Volcanoclastic sediment is also found in section Wu 1, although there it is only 30 cm thick.

**Age:** Based on stratigraphic position this member is of Nukumaruan age.

**Constituent Facies:** sandstone (wp-A-2)

**Lithology:** This sandstone unit (wp-A-2) is separated by the siltstone facies (wp-A-1), which constitutes the middle facies of the member. The lower sandstone unit sits unconformably on top of the underlying conglomerate (mt-D-3). This lower sandstone unit is massive micaceous sandstone, which is unconformably overlain by Mahiaruhe Member siltstone (wp-A-1). The sandstone and siltstone are bounded by a moderately fossiliferous shellbed (V20/439138) with 15% greywacke grit and concretions; the greywacke grit is found 15 cm either side of this boundary. The erosional boundary shows relief of up to 3 cm. This boundary occurs in a tributary of the Waikoau River (V20/432127). Here the erosional relief is up to 10 cm, and greywacke grit is found 40 cm up from the boundary into the overlying siltstone (mt-A-1); this boundary is very sparsely fossiliferous.

The upper sandstone facies (wp-A-2) occurs conformably on top of the middle siltstone facies (wp-A-1). The upper sandstone facies is massive to cross-bedded micaceous sandstone and contains a number of lensoidal shellbeds. An erosional boundary is found in the lower portion of this upper unit; below this boundary the sandstone is tabular cross-bedded and there are two sparsely fossiliferous shellbeds (plate 2.40). The shellbeds contain small (1-4 mm) reworked rounded mudstone and tephra clasts, which outline cross-beds in the sandstone. The sandstone is heavily bioturbated below the shellbeds, with small worm tubes (1-2 mm) and also larger burrows (1-2 cm in width and up to 50 cm long). On top of these shellbeds is 50 cm of interbedded siltstone and

sandstone with small-scale ripples. The siltstone shows cleavage caused by very thin (<1 mm) wavy sandstone laminations (plate 2.41). Several lensoidal shellbeds are found in the above massive, well sorted, micaceous sandstone. This upper sandstone is unconformably overlain by siltstone (wp-B-1) of the overlying Elston Member.

Constituent Facies: siltstone (wp-A-1)

The middle facies of this member is an uncemented non-calcareous blue-grey massive siltstone with tabular cross-bedded micaceous sparsely fossiliferous sandstone interbeds (plate 2.44). The sandstone interbeds are described here as part of the siltstone facies (mt-A-1). Rapid gradation is present between the silt and sand beds (< 5 mm); the sand beds thicken towards the middle of the unit (mt-A-1) and are very thin and rare towards the base. Towards the top of this inter-bedded unit sandstone beds become thinner but more closely spaced. Rare (~ 1%) scattered pumice granules, 1-2 mm in size, are found throughout both sandstone and siltstone beds. The siltstone is underlain by an erosional surface with 20 cm relief, and two sparsely fossiliferous shellbeds with ~15% greywacke grit are situated either side of this erosional boundary.

### 2.3.2.2 Elston Member (wp-B)

Name Derivation: From Elston Station on Waikoau Road (V20/428137).

Type and Reference Sections: The type section for this unit is defined in the Waikoau River from V20/436142 to 434126 (section Wu1).

Upper and Lower Boundaries: At the type section this member has an irregular erosional lower boundary with 10-15 cm relief, and is slightly fossiliferous either side of this boundary. The upper boundary coarsens up-section into the Esk Formation (Ek1).

Thickness and Distribution: This unit is only found in the Waikoau River catchment, where it is 20 m thick.

Constituent Facies: siltstone (wp-B-1)

Lithology: Moderately cemented, massive, barren siltstone. At the base of this member (wp-B) above the lower erosional boundary the siltstone contains plant fossil remains, greywacke grit and a thin very sparsely fossiliferous shellbed. A thin (40 cm) massive

sandstone bed is found in the middle of this siltstone, with sharp boundaries above and below. The siltstone coarsens upwards into the overlying sandstone (wp-B-2). Two other siltstone beds are found within the Elston Member and are also separated by sandstone beds within the member. The middle bed fines upwards out of sandstone, which also inter-fingers with the siltstone. The upper siltstone bed fines up-section out of sandstone and then coarsens upward with a series of interbeds into the uppermost sandstone bed of this member.

Constituent Facies: sandstone (wp-B-2)

Lithology: Uncemented, massive, micaceous sandstone, with scattered fossils and shell lenses. A fossiliferous uncemented shellbed occurs near the top of this unit. It contains a high degree of bioturbation at the base of the shellbed. Above this shellbed the sandstone grades into a sandy siltstone.

The Elston sandstone is composed of thick (10 m) beds of sandstone grading (plate 2.42), either via interbeds or coarsening into siltstone and *vice versa*. Sandstone (wp-B-1) typically is massive, micaceous, moderately fossiliferous with lensoidal shellbed throughout, occasional low angle cross-beds occur in the upper parts of sandstone beds, and are commonly fossiliferous with reworked pumice clasts, and *Ophiomorpha* burrows Haywick *et al.* (1991).

## 2.4 Structure within the Area

Few faults exist within the field area. The most significant is the Rangiora Fault, which extends from 453276 to 440252, striking 030°. A fault scarp is visible on the southern bank of the Waikari River (V19/452273) at this exposure three faulting events of between 4-6 m are indicated. At an exposure on Heays Access Road (V19/449267) four faulting events are indicated. Movement on these faults is aged at between 3280 B.P. and 1850 B.P (Cutten *et al.* 1988; Cutten 1994). At the base of Taraponui Trig two normal faults with throws of 15 m occur (plate 2.1). One 2 m section in the southern fault displays four steps representing at least four movements on the fault. Based on stratigraphic position this fault is interpreted as younger than Waipipian. A small normal fault occurs in the Trelinnoe Member of the Titiokura Formation, with a throw of c. 10 m, in the Waikaou River at V20/417136 to 421141 (plate 2.31). Two normal

faults are inferred along the back of the Maungahuru Range within the Titiokura Formation, both striking SE-NW. One with a throw of c. 50 m from V19/328223 to 340215, the other with a throw of c. 30 m from V19/326203 to 333201. The Taraponui Thrust (Francis 1991) protrudes into the most northeast corner of the map area, from V19/215323 to 330237 on the western side of the Maungharuru Range. Francis (1991) suggests that the hanging wall has overridden the footwall from NE – SW. A plunging syncline is inferred on Toronui Station trending NNE – SSW from V19/348197 to 357241.

Limestone beds found at Ahuateatua Trig strike at c. 43°, and dip 25° SE, in comparison to time equivalent facies, which strike at 46°, and dip 15° SE on Naumai Station. This either indicates an anticline running NE-SW, or is indicative of thin limestone beds (as occurring at section), which trail off thicker limestone successions and consequently dip at different angles. Members strike 45° to 22° NE in the Titiokura Formation and dips range from 10° to 30° SE. Strike of the beds in the Rangiora Formation range from 50° NE in the Waikoau catchment to 38° NE in the Waikari catchment, and dip from 18°-20° SE. Matahorua Formation members strike at 50° in the Waikoau catchment and 34° in the Waikari catchment. Dips shallow upsection from 20° SE in the Deep Stream Member (mt-A) to 9° SE in the Grassy Knoll Member (mt-D). Few dips and strikes were able to be measured on the Waipunga Formation. Generally the formation strikes at 32° NE and dips 9°-5° SE. Dip and strikes measured on limestone beds on Toronui Station (V19/366196) are typically much steeper than elsewhere (25°-30° SE). This may be due to the fact that they are not in situ, or simply deposited at angles trailing off thick limestone successions.

## 2.5 Stratigraphic Synthesis

Titiokura Formation; While limestones within the formation are traced continuously across the field area, many are lensoidal, or form thick successions in limited areas (e.g. Bellbird Bush, Opouahi Members). However channelised or thin beds may be traced across the field area. Figure 2.2 displays a selection of sections from the Titiokura Formation. A single 50 m thick limestone at Ahuateatua Trig (section Ek6), divides across the field area into 5 members constituting the Titiokura Formation. The limestone beds become thinner more lensoidal and less calcareous to the northeast, and siltstone beds occur in the most northeastern section (Wi4).



Figure 2.3 displays sections for the Rangiroa Formation. Correlation of beds within this formation is not possible, but it appears that siltstone dominates the succession in the NE, with the thick siltstone dominated Waikari Member occurring here. The Rangiroa Formation is comprised of sandstone and siltstone beds comprising the Mokamoka Member in the Waikoau and Esk catchments. The Mokamoka Member is found in the Waikari River. However, there the Rangiroa Formation is comprised largely of the Waikari Member.

The Matahorua Formation is comprised of four members in the Waikoau and Esk catchments, however only three of these members occur in the Waikari catchment (the lower member is inferred). Two members occur within the Waipunga Formation in the Waikoau River, and only one occurs in the Waikari River.

Figure 2.4 shows the spatial lithostratigraphic relationship amongst the Maungaharuru and Petane Group strata. This diagram shows the Titiokura Formation dividing up into five members from a single limestone comprising the entire Formation at Ahuateatua Trig. The Rangiroa Formation can be seen comprising two members. The Waikari Member occurs (rg-A) in the NE constituting the majority of the formation. The Mokamoka Member in the centre and SW of the study area. The Formation increases in thickness from the NE to the SW of the study area. The Matahorua Formation is shown decreasing in thickness to the NE. There only three of the constituting members occur. The Waipunga Formation is found in all three catchments, but the two members can only be identified in the Waikoau Catchment where it is the thickest.

# Lateral Changes within the Rangiora Formation

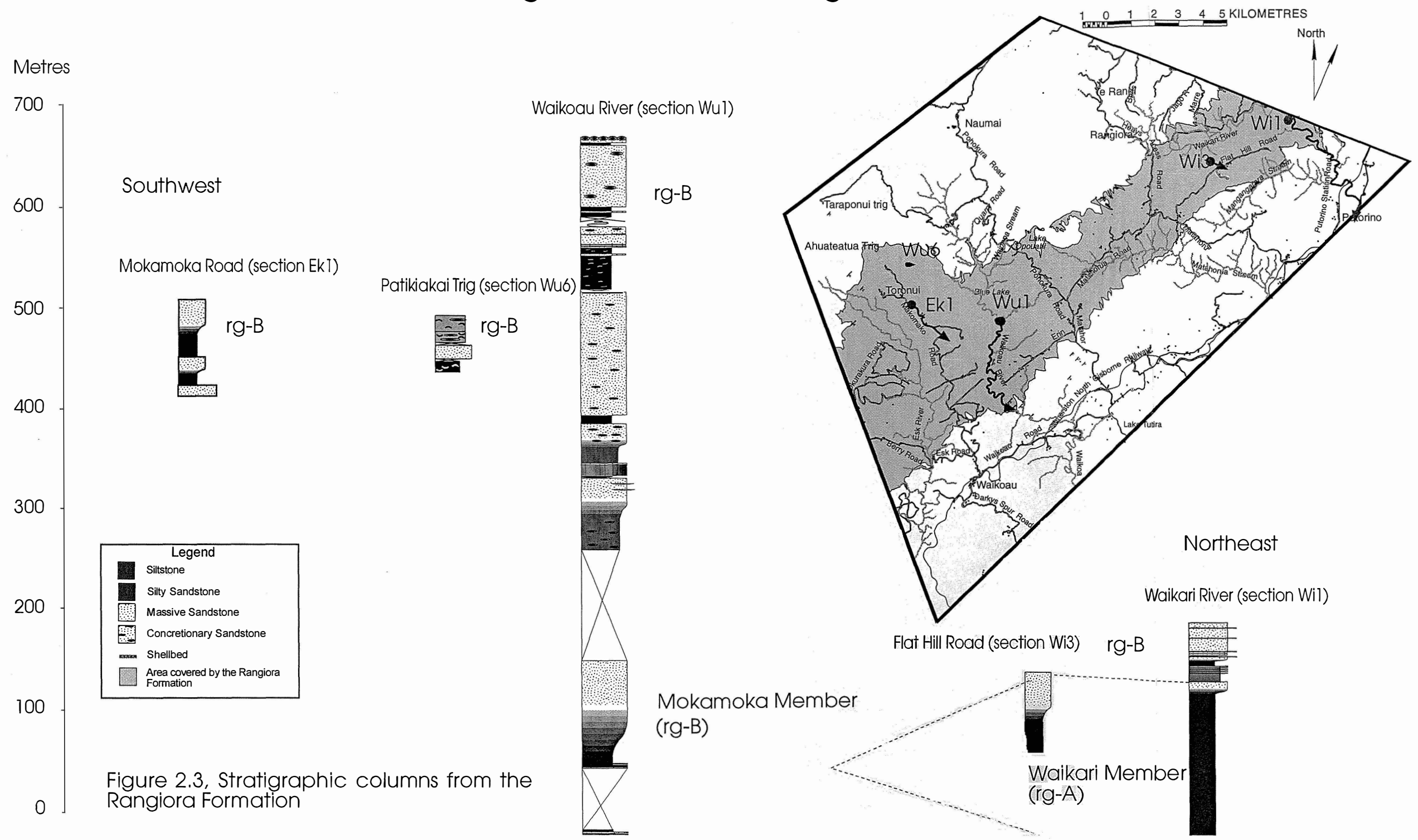
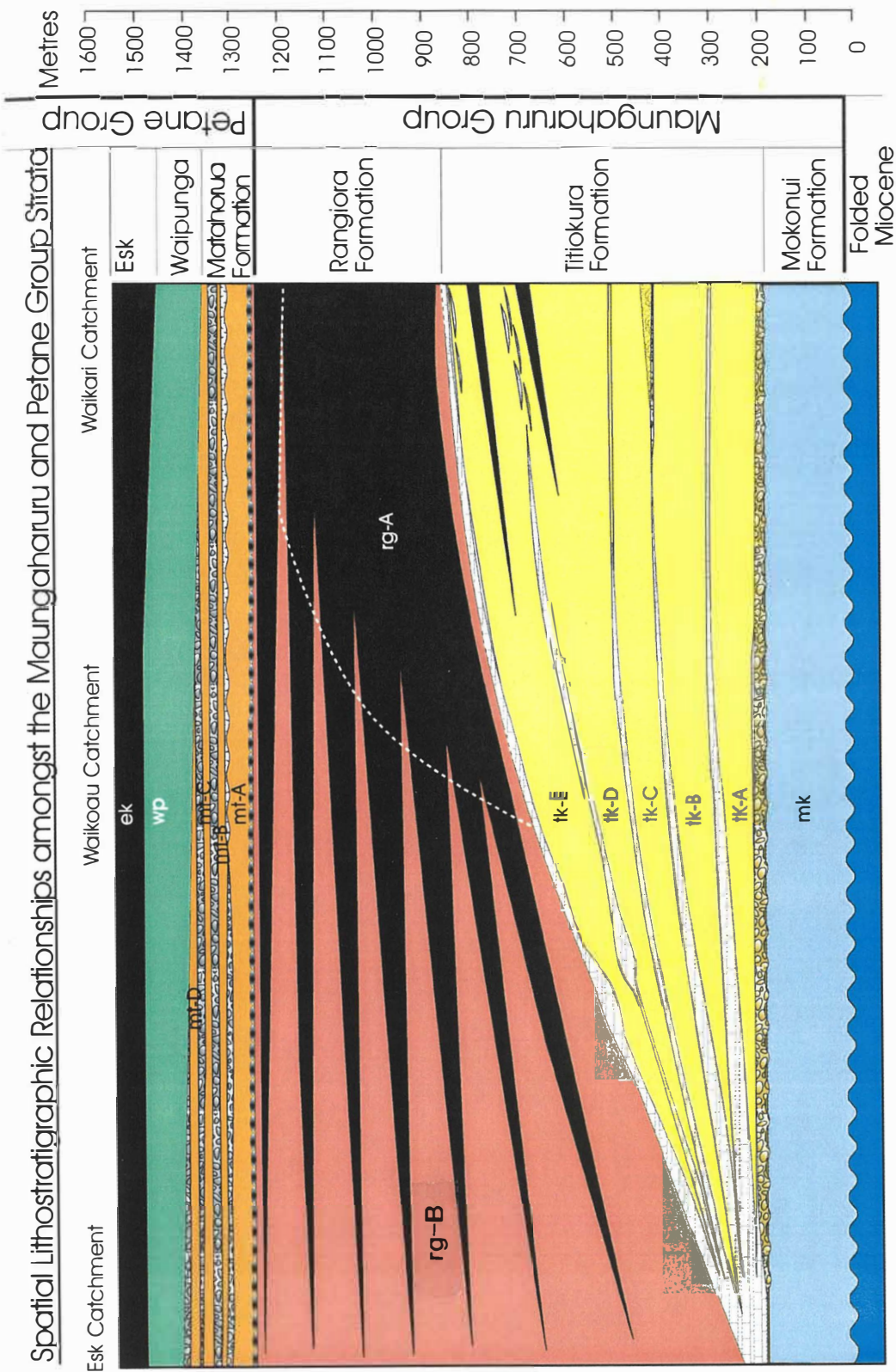


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Spatial Lithostratigraphic Relationships amongst the Maungaharuru and Petane Group Strata

Ahuateatua Trig Taraponui Trig Naumai Station Te Rangi and Rangiora Stations

Figure 2.4



# Chapter 3

## *Chapter 3: Lithofacies*

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### 3.1 Introduction

Distinctive bodies of rocks are termed facies, which refers to depositional units that are distinguished by lithological, structural, and organic characteristics. Lithofacies are characterised by physical characteristics such as colour, lithology, texture, and sedimentary structures. Biofacies are defined on the basis of paleontologic characteristics, but in this study are incorporated as a defining property of lithofacies (Boggs 1995, p290). The law of correlation of facies states that facies that occur in conformable vertical successions of strata occur in laterally adjacent environments (Walther 1894, in Boggs 1995, p 501). Because of this fact lithofacies are best studied in association with one another, so those with gradational contacts are inferred to have been laterally equivalent environments (Boggs 1995, p290).

### 3.2 Sedimentary Facies Associations

Thirteen sedimentary facies have been identified in the study area. The facies associations are grouped according to their dominant lithology, and then subdivided according to distinctive sedimentary structures and fossil content. Some of the facies have been classified into variants of the facies where environment or processes of deposition are considered to be similar. In facies where macro-fossils are common, a palaeontology heading is used to list common macro-fossils (for full faunal list and interpretation refer Appendices 2 and 3). The dominant features of each facies are described and an interpretation of depositional environment is made. This is summarised in Table 3.1. The generalised stratigraphic distribution of lithofacies is shown in Figure 3.1. All sedimentary lithofacies are shown as codes on relevant stratigraphic columns in Appendix 1.

Table 3.1 Lithofacies Summary

Code	Description	Interpretation
Z1	Massive Siltstone	Mid to outer shelf, with reworking of inner shelf sediments.
Z2	Silty Sandstone or sandy siltstone	Mid to Inner Shelf, with high energy currents resulting in sediment by-passing.
Z3	Interbedded siltstone and sandstone	Offshore inner shelf between fair-weather wave base and storm wave base.
C1	Greywacke conglomerate	Braided river system in a broad alluvial fan.
C2	Locally sourced/tidal channel/intraformational conglomerate	Tidal channels, forming during a sea-level rise.
S1	Planar cross-bedded to massive sandstone	Beach to shoreface sandstone
S2	Massive sandstone	Shoreface to innermost shelf sandstone
S3	Sandstone with mud drapes trough-hummocky-swaley cross-bedding, mud off-shoots, and limestone lenses.	Inner shelf to lower shoreface sandstone, storm and tidal current emplaced sandstone.
S4	Sandstone with thin mud drapes, current ripples, rare cross-beds, bioturbation and concretions.	Inner-mid shelf sandstone with strong tidal currents.
S5	Massive to poorly bedded with silty sandstone beds with mud drapes	Inner shelf sandstone, with reworking of shoreface taxa or some sediment bypassing.
S6	Massive to poorly bedded with silty sandstone beds without mud drapes.	Inner-mid shelf sandstone with small amount of interdigitation of siltstone and sandstone
L1	Cross-bedded Limestone coquina to calcareous sandstone, with common basal scouring.	Inner-shelf, with current swept sea-floor.
L2	Trough cross-bedded Limestone.	Inner-mid shelf, rapidly emplaced limestone beds, eroded off limestone mounds.

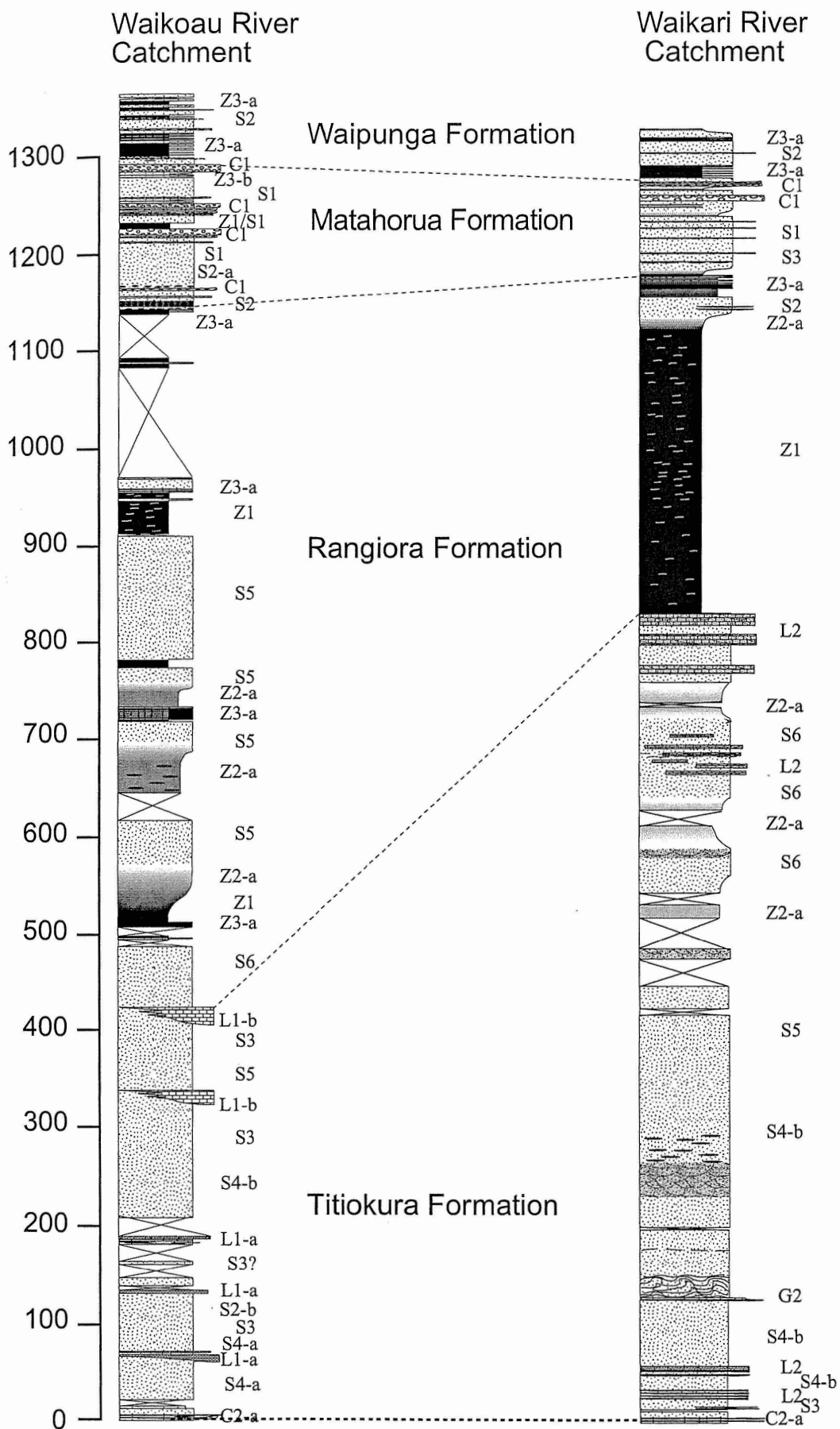


Figure 3.1, Generalised stratigraphic distribution of litho-facies in the Waikoau and Waikari River catchments.

### 3.2.1.1 Siliciclastic Siltstone Association

#### Facies Z1

**Description:** Massive, slightly calcareous, micaceous, barren to moderately fossiliferous siltstone with concretions and bioturbation zones, which occasionally form concretions. This facies occurs commonly within the Rangiora Formation, as siltstone grading into sandstone in the Makomako Member and as thick (350 m+) siltstone in the Waikari Member, and in the Waipunga Formation (plate 3.1).

**Stratigraphic Occurrence:** This facies occurs within the Rangiora Formation, and comprises most of the Waikari Member. Thin beds occur in the Titiokura, Matahorua and Waipunga Formations.

**Interpretation:** Outer shelf macro-fossils such as *Patro undatus* and the occurrence of foraminifera *Notorotalia* sp., *Nonionella flemingi*, *Cibicides marboroughensis* indicate a mid to outer shelf paleo-environment, with periods of sediment by-passing due to strong currents. The presence of estuarine or shallow water foraminifera such as *Zeaflorilus pari*, *Lagena* sp., *Elpehidium* sp. and carbonaceous material in samples along with deep-water foraminifera indicate transportation of shallow-water faunas into deeper-water (angular nature of some sediments indicate short distance of travel). The high portion of planktics in a sample from the Mokamoka siltstone (rg-B-1) in the Waikoau River, indicates slightly deeper water, probably outer shelf to upper bathyal (Hayward 1999, Lewis 1979). The occurrence of *Mesopeplem crawfordi* indicates a current-swept hardground (Beu and Maxwell 1990).

#### Facies Z2

**Description:** Z2-a: Silty sandstone, sometimes slightly calcareous, with scattered fossils rarely shellbeds, absent to moderate bioturbation (plate 3.2). Common macro-fossils include *Ostrea chiliensis*, *Amalda mucronata*, and *Pratulam puchelluam*, which occur in shellbeds.

Z2-b: horizontally laminated, sandy siltstone. Where fossils occur they are very finely ground up, and occur stratigraphically below limestone facies L1-b.

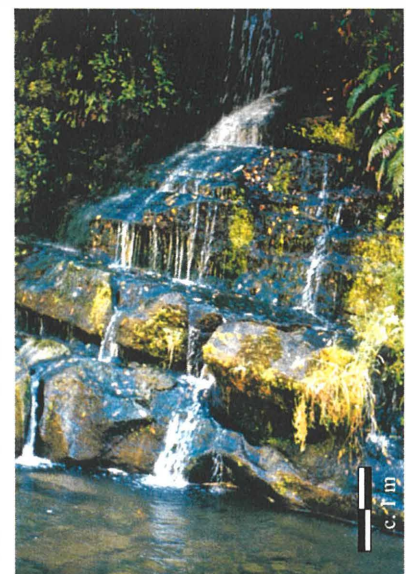


Plate 3.1, Lithofacies Z1 (Rangiora Formation, Mokamoka Member, section Wu2, V20/401163). Massive slightly calcareous siltstone with concretions and bioturbation zones, deposited in a mid-outer shelf paleo-environment, with periods of sediment bypassing and transportation of shallow water fauna into deeper water.



Plate 3.2, Lithofacies Z2-a, Rangiora Formation, Mokamoka Member, Waikari Member, section W11 (W19/543262). Slightly calcareous silty sandstone with rare shellbeds. This photo shows an *Ostrea chilensis* dominated shellbed. This facies was deposited in an inner-mid shelf paleo-environment, with relatively high energy currents resulting in sediment bypassing.

Plate 3.3 (below left) and Plate 3.4 (below right), Lithofacies Z3-a, thinly (plate 3.3, Rangiora Formation, Mokamoka Member, section W11, W19/545260) to thickly (plate 3.4, Waipunga Formation, Mahiaruhe Member, section Wu1, V19/436140) inter-bedded sandstone and siltstone beds. Depositional environment is interpreted as offshore shelf between fairweather wave base and stormwave base. Siltstone represents fairweather deposition with storm emplaced sandstone causing inter-digitation on the shelf.



**Stratigraphic Occurrence:** This facies is common within the Rangiora Formation (Z2-a) often as an intermediate facies in a shoaling upward succession. Here it is typically associated with facies S2, S5, S6, and Z1. Facies Z2-b occurs within the Titikura Formation in association with carbonate facies L1-a/b.

**Interpretation:** Z2-a: Fossil assemblages indicate a mid to inner shelf environment with relatively high energy. Shellbeds containing *Ostrea chiliensis* indicate a high-energy environment with sediment bypassing allowing stratigraphic condensation and increased carbonate formation.

Z2-b: Small grain-size of the terrigenous fraction of Z2-b indicates a low energy environment; Association of this facies to inner-shelf limestone facies L2-b indicates an inner to inner-most shelf sheltered environment. Shelter may be due to the close proximity to large limestone 'banks', which shelter areas from strong currents. Horizontally laminated sedimentary structures may represent tidal laminations, and indicate an estuarine setting with tidal currents.

**Facies Z3:** (Interbedded Siltstone and Sandstone)

**Description:** Z3-a: Thinly to thickly (decimetre to metre scale) inter-bedded sandstone siltstone beds. Typically there is rapid gradation between beds and planar contacts between beds (plates 3.3 and 3.4).

Z3-b: associated with C1 and S1-b of the Matahorua Formation, beds commonly fine upward, contains micaceous siltstone and sandstone with rare tephra clasts.

**Stratigraphic Occurrence:** This facies is common in the Rangiora, Matahorua and Waipunga formations where it is associated with facies S1, S2, and Z1.

**Interpretation:** Z3-a: Offshore shelf between fairweather wave base and storm wave base. Siltstone represents fair-weather deposition with storm emplaced sheet sandstone causing inter-digitation of the sand and silt beds (Johnson and Baldwin 1996). This probably represents an inner-mid shelf paleo-environment. More thinly (millimetre

scale) bedded sandstone and sandy siltstone, represents a slightly deeper setting. The coarser nature of siltstone here probably represents a constant input of fine sandstone. Fine sandstone laminae represent tails of storm emplaced sand sheets in more distal environments.

Z3-b: The relative amount of siltstone or sandstone occurring stratigraphically below this facies is not able to be used to interpret paleo-depth, as it may be simply a function of occurrence in relation to sandstone lobes, i.e. if deposition occurs in an inter-lobe area, silt content will be higher than if occurrence is on a sandstone lobe (figure 3.4). Because of this, the facies interpreted as inner-most shelf to lower beachface, in proximity to a coarse grained delta. Fining upwards beds are considered down-stream flood deposits.

### 3.2.1.2 Conglomerate Association

#### Facies C1

Description: C1 Greywacke Conglomerate, well to very poorly sorted, coarse sand to cobble sized well rounded greywacke clasts, bedding ranges from massive through poorly stratified to planar and trough cross-bedded (plate 3.5). Typically the conglomerate may be divided up into distinctive beds on the basis of bedding, sorting, and clast size. Some of these beds may contain angular and deformed siltstone and sandstone clasts. In some outcrops within and on top of the conglomerate, thin (millimetre to centimetre) ripple and parallel laminations of sandstone and siltstone are present. Thicker (decimetre) massive lensoidal and tabular beds of sandstone and siltstone are also present. Rare carbonaceous mudstone layers are observed at the top of some of these conglomerates.

Stratigraphic Occurrence: Occurs exclusively in the Matahorua Formation in association with facies S1-b, S2, and Z3-b.

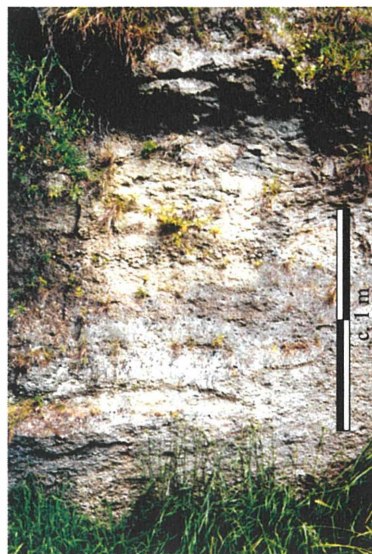


Plate 3.5 (above left), Lithofacies C1, Matahorua Formation, Trelinnoe Member, section Wi2, W19/492216). Well to poorly sorted greywacke conglomerate, massive through stratified and trough cross-bedded. Non-marine deposition in rivers on a braid plain. Plate 3.6 (above right), Matahorua Formation, Trelinnoe Member, (W19/542240), Conglomerate lenses beneath the conglomerate bed. Knife is 7 cm long.

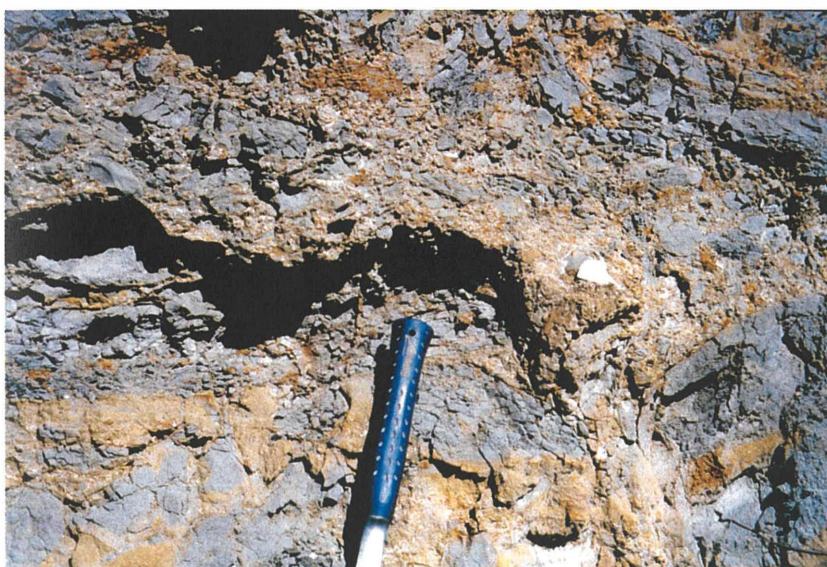


Plate 3.7, Lithofacies C2-a, Titiokura Formation, Naumai member, section Wu5, (V19/389274). Very poorly sorted, clast supported, fossiliferous angular conglomerate. Deposition occurred in a high-energy shoreline setting, probably close to steep paleo-relief, such as a channel close to a coastal cliff, or seaward portions of a sandy tidal flat. This facies is associated with tidally laminated facies S4-a.

Plates 3.8 and 3.9 (below left and right respectively), Lithofacies C2-b, Titiokura Formation, section Ek4 (V19/331228). Highly calcareous conglomerate, with reworked pumice, charcoal and greywacke grit, showing imbrication of these clasts. Imbrication of clasts indicates intertidal beach deposition.



**Interpretation:** Deposition in a braided river system in a broad braid plain. Non-marine deposition is inferred on a gravel laden braided river system, sourced from uplifted ranges nearby, forming a large delta system upon entering the sea.

A lack of any imbrication or fossil content indicates a non-marine setting. Roundness of individual clasts indicate a high-energy setting and transportation. The thin rippled and parallel laminated silts and sands represent deposition in abandoned braidchannels. Thin lignites formed on the braid plain margins. Large angular silt and sand blocks represent localised erosion bar top or abandoned channel deposits.

The gravel in braided river systems are deposited by one of two mechanisms: traction currents or by gravity flows when large amounts of loose sediment move in one mass movement event. This is generally caused by catastrophic runoff events, which cause liquefaction. Deposits from gravity flows are generally massive, poorly sorted and matrix supported (Miall 1992).

Massive sands and silts found within the conglomerate facies of the Matahorua Formation, of tabular geometry represent rapid deposition from suspension during floods (Collinson 1996). Thin lensoidal beds result from rapidly shifting and entrenching braided channels, whereas thicker strata infer deeper channelised flow. Conglomerates can become matrix filled during low stage infiltration (Nemec and Steel 1984). Reversely graded siltstone sandstone beds beneath the main gravel unit, probably represent downstream flood deposits in early stages of the alluvial plain.

Thin gravel lenses and beds found within sandstone below the main conglomerate units represent shoreface to inner-shelf sheets and lenses of gravel (plate 3.6).

### Facies C2:

**Description:** C2-a: Very poorly sorted, clast supported, differentially cemented, fossiliferous, massive to cross-bedded (both uni-directional and bi-directional), highly angular, conglomerate/breccia, with sandstone, siltstone, mudstone clasts, and in places tephra and pumice clasts (plate 3.7).

C2-b: highly calcareous conglomerate, with reworked pumice and charcoal greywacke and sandstone clasts that are heavily bioturbated and show imbrication (plates 3.8 and

**Stratigraphic Occurrence:** Occurs exclusively within the Titiokura Formation, in association with facies S4-a, and L1-a/b.

**Interpretation:** C2-a: The calcareous and fossiliferous nature of these conglomerates indicates a high-energy shoreline marine setting. The erosive bases indicate that the conglomerates are most likely channelised. Angular clasts are locally sourced, and rapidly buried. Probably close to steep paleo-relief, such as a coastal cliff, channel close to the paleo-shoreline or on seaward portions of a sandy tidal flat, caused by storm driven geostrophic current. Sediment deformation is common under some of the conglomerates as the clasts drop down into soft sediment.

The seaward area of a sandy tidal flat, in tidal gullies contain shell lags and mud clasts (Dalrymple 1991). In an excellent example of an intra-formational conglomerate in the Titiokura Formation at the Naumai Station (V19/392274), mudstone and siltstone clasts from the surrounding mud drapes are interpreted as dropping down into a channel cut into the sandstone (plate 3.10). The clasts are rounded to highly angular, and transportation is minimal as the source mud drape can be identified. Sediment deformation below the larger clasts is common, and sedimentation differs from one side of the clast to the other, inferring ongoing sedimentation during the erosion of these clasts creating obstacles for flow once deposited in the channel. Smaller clasts are eroded of the larger clasts and 'tail off' channel-wards into the surrounding sediment. Figure 3.2 shows the interpreted development of an intra-formational conglomerate in the tidally laminated sandstone facies (S4-a).

C2-b: Conglomerate that shows imbrication and heavily bioturbated clasts indicates inter-tidal beach deposition, where the high-energy swash zone aligns clasts in one direction and bioturbation is by shoreface organisms.

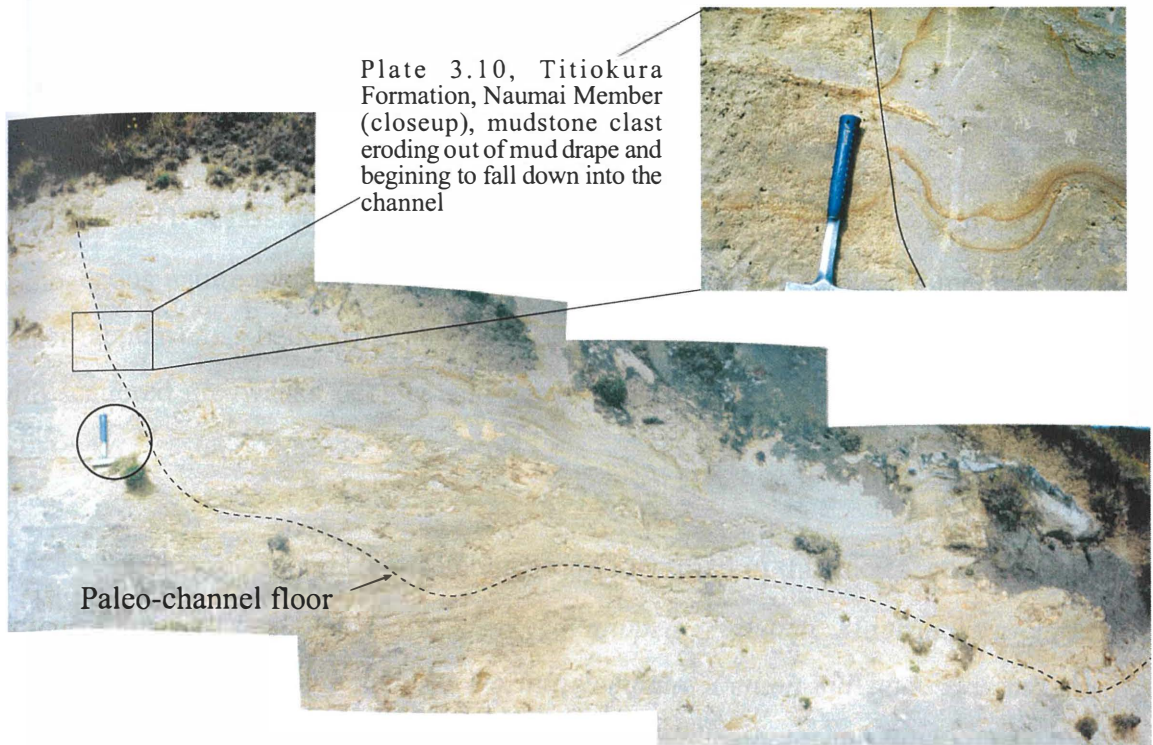
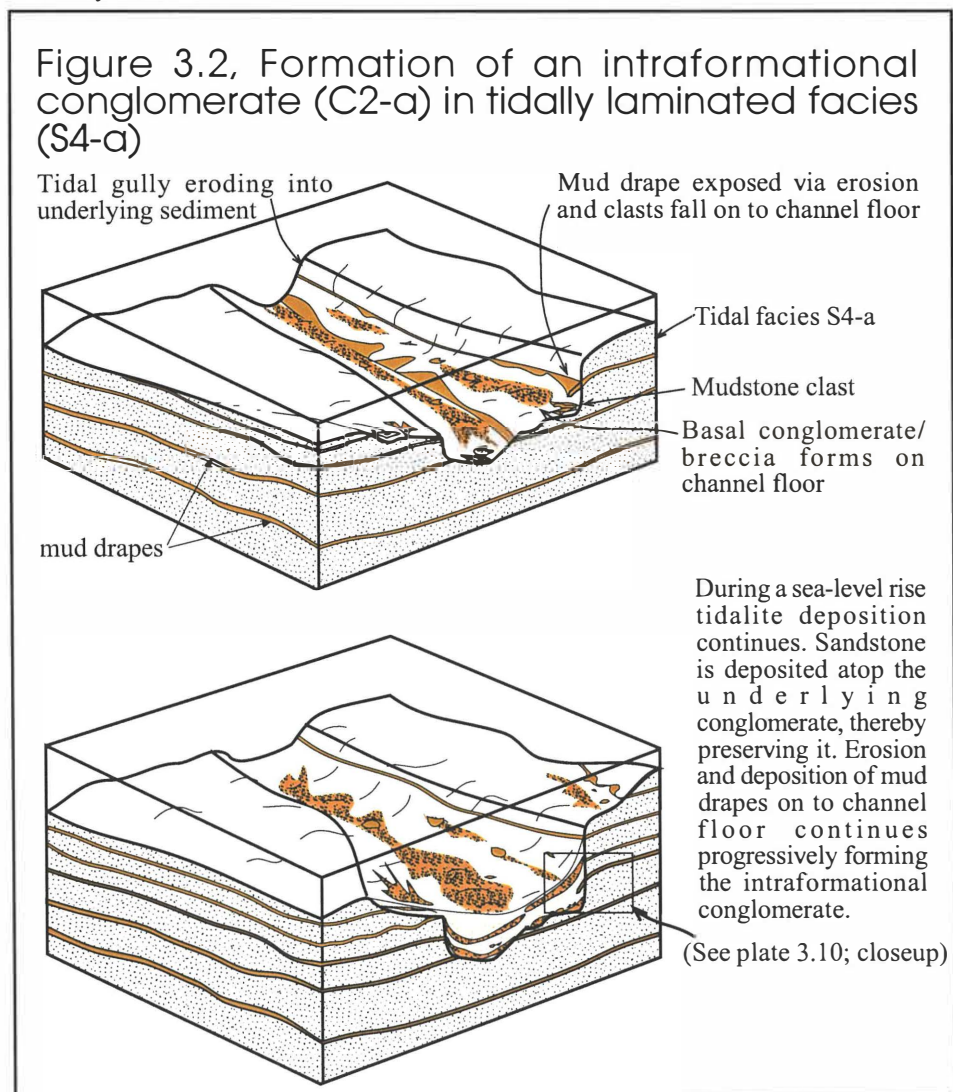


Plate 3.10, Lithofacies C2-a, Titiokura Formation, Naumai Member, section Wu5 (V19/393272). Intraformational conglomerate occurring at Naumai Station. Mudstone and siltstone clasts are interpreted to drop down into a channel cut (closeup) into a tidally laminated sandstone (S4-a). Interpreted as deposition in the seaward portions of a sandy tidal flat.



### 3.2.1.3 Siliciclastic Sandstone Association

#### Facies S1

**Description:** Massive well sorted barren micaceous sandstone; well-sorted and homogenous nature of sandstone obstructs visibility of any possible sedimentary (rarely planar/tabular cross-bedded) structures. Tabular cross-bedded fine to coarse sandstone, with scattered greywacke pebbles and lenses, typically found beneath facies C1 (plate 3.11).

**Palaeontology:** Shoreface assemblages are identified in this facies, common fossils include *Eumarcia benhami*, *Dosinia greyi*, *Panopea zelandica*, *Maorimactra chrydea*, *Nucula nitidula*, *Zenatia acinaces*, *Dosinia lambata*, *Penion sulcatus*, *Bassina yatei*, *Zethalia coronata*, *Xymere*, *Dosinia subrosea*, *Dosinia lambata*, and *Bassina parva*.

**Stratigraphic Occurrence:** This facies occurs within the Rangiora and Waipunga Formations, in association with facies S2, S5, S6, Z1, Z2, and Z3.

**Interpretation:** The massive to tabular cross-bedded sedimentary structures indicate shoreface deposition, i.e. wave reworking in the swash zone. This washes away fine sands and causes the breakdown of many fossils. Shallow water fossil assemblages are found in this facies.

#### Facies S2

**S2-a:** Massive well sorted barren micaceous sandstone. Well sorted and homogenous nature of sandstone obstructs visibility of any possible sedimentary (probably would be planar/ tabular cross bedded) structures. These indicate shoreface deposition. With wave reworking in the swash zone, washing away of fine sands and the breakdown of any fossils. Some fossils are found in rare shell-beds in this facies (plate 3.12).

**S2-b:** Swaley cross-stratified sandstone with mud drape remnants, wave ripples and convolute bedding. Each bed is truncated with up to 30 cm of relief by subsequent beds. Beds/lense out laterally and are 10-40 cm thick. No fossils are found in this facies (plate 3.13).



Plate 3.11 (left), Lithofacies S1, Matahura Formation, Grassy Knoll Member (V20/407132). Tabular cross-bedded sandstone with scattered greywacke pebbles and lenses occurring beneath lithofacies C1.



Plate 3.12 (left), Lithofacies S2-a, Waipunga Formation, Elston Member (V20/425143), massive, micaceous, well sorted sandstone. Inner-most shelf to shoreface deposition, with wave reworking in the swash zone, washing away of fine sands and breakdown of fossils.

Plate 3.13 (below), Lithofacies S2-b, Titiokura Formation, Te Rangi Member, section Wi5 (V19/393272). Swaley cross-stratified sandstone with mud drape remnants, wave ripples, and convolute bedding. Deposition occurred in a high energy shallow marine environment where mud drapes are eroded away. This facies occurs above storm emplace facies S3. knife is 7 cm long



Plate 3.14 (below), Lithofacies S3, Titiokura Formation, Te Rangi Member, section Wi5 (V19/393272). Calcareous sandstone with mud drapes and reactivation surfaces. Sandy coquina beds are common throughout this facies. Deposition by storm and tidal currents, below fair-weather wave base. Knife is 7 cm long.

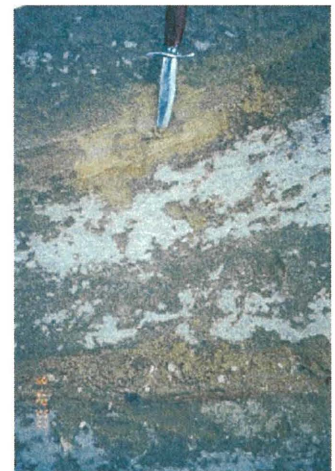


Plate 3.15 (left) Titiokura Formation, Te Rangi Member, section Wi5 (V19/393272). Rare hummocky cross stratification occurring in lithofacies S3, indicating storm reworking of sediment. knife is 7 cm long.

Plate 3.16 (above), Lithofacies S3, Titiokura Formation, Te Rangi Member, section Wi5 (V19/393272). Large scale trough/ tangentially bedded sandstone with mud off-shoots. Indicating deposition from unidirectional traction currents, probably formed from shore parallel geostrophic currents. Knife is 7 cm long.

## Palaeontology

Common macro-fossils in (S2-a) facies include *Ostrea chiliensis*, *Mactra* aff. *discors*, *Mactra murchisoni*, *Zentatia acinaces*, *Gari* sp., *Dosina creba*, *Gari linoleata*, *Dosina zelandica*, *Dosinia* (*Austrodosinia*) *anus*, *Dosinia* (*Phacosoma*) *subrosea*, *Myadora* sp., *Zethalia coronata*, *Calliostoma* sp., *Amalda* (*Barryspira*) *depressa*, *Fellaster zelandiae*, *Pervicacia tristis*, and *Fellaster zelandiae*. These fossils infer an inner-most shelf to shoreface paleo-environment.

**Stratigraphic Occurrence:** Facies S2-a occurs in the Waipunga Formation in association with facies S1. Facies S2-b occurs in the Te Rangi Member of the Titiokura Formation, in association with facies L2, S4, and S3.

## Interpretation

S2-a: The fossils assemblages are interpreted as originating in shoreface to inner-most shelf environments. Some infer strong by-passing currents, others occur in mixed assemblages.

S2-b occurs exclusively within the Titiokura Formation, interpreted as a high-energy, shallow marine environment above storm wave base close to fair-weather wave transition, in the middle to upper shoreface (Rossetti 1997). This facies occurs above facies S3. Reactivation surfaces and the eroded nature of the mud drapes indicates a high-energy environment where mud drapes are eroded away or not deposited. Wave ripples indicate deposition above fair weather wave base.

## Facies S3

**Description:** Calcareous sandstone with mud drapes and reactivation surfaces. Mud drapes either have sharp lower boundaries or are symmetrically rippled, commonly have uneven surfaces on top with mud clasts occurring in the overlying sandstone bed (plate 3.14). Mud drapes in this facies are typically thicker than in facies S4-a/b, and are up to 25 cm thick. Heavily bioturbated, shell rich zones with fragmented shells, mudstone clasts, discontinuous thin conglomerates are common, and rare hummocky cross-stratification occurs (plate 3.15). Associated sandstone has large scale trough cross-

bedding with rare mud off-shoots (plate 3.16). Massive sandstone beds are common. Convolute bedding is common at the top of both cross-bedded and massive sandstone beds. Sandy coquina lenses and beds are common throughout this facies and occur either above or below mud drapes. Mud drapes become rarer up-section, and this facies grades into facies S2-b.

Often sedimentary structures are not observed in this facies due to poor outcrop, or lack of variation of grain size or delineating minerals (glauconite, tephra, or heavy black minerals). However concretionary layers usually occur in this facies, with rare hummocky cross stratification. Sandstone may show trough cross-bedding. A variation on this facies occurs in the Rangiora Formation, where mud drapes are absent, but hummocky cross stratification is present. Sandstone is amalgamated with shell lenses and beds.

**Stratigraphic Occurrence:** Common within the Titiokura Formation, where it is associated with facies S4, L1-a and L2. This facies occurs rarely in the Rangiora Formation, in association with S6.

**Interpretation:** This facies is interpreted to have been emplaced by both storm and tidal processes, with storm emplaced sandstone and tidal current reworking, followed by fair-weather (storm induced) mud deposition. The facies is deposited below fair-weather wave base and above storm wave base, probably within a sheltered embayment, which amplified tidal currents (Sztano and De Boer 1995;).

Trough/tangentially bedded sandstone (plate 3.16) is deposited from shore parallel geostrophic currents or from storm and wave reworked tidal sand waves. Sandstone is deposited during waning storm conditions from uni-directional traction currents, which form sub-parallel to the paleo-shoreline, during the falling flow stages of a storm set-up geostrophic current (Rossetti 1997, Dalrymple 1992, Winn 1991, Vera *et al.* 1998). During storm conditions, erosion of the underlying bed occurs. Absence of sole marks or gutter clasts indicate that this flow was highly liquefied at the time of deposition.

Hummocky cross-stratification occurs in storm-reworked sandstone, but is commonly overprinted by subsequent events (Reading and Collinson 1996) and accounts for the rarity of hummocky cross stratification in this facies. Depending on the environment of deposition during waning storm conditions either trough cross-beds or wave ripples are formed (Symmetrical ripples indicate combined flow, where they represent diminishing wave orbital velocities during the waning stages of a storm (Walker and Pint 1992)). A multiplicity of processes account for storm induced deposition (tempestite); geostrophic currents, wave oscillations, and density induced flow. Each of these processes is considered to be part of the spectrum of processes acting at any stage within a storm. These varied processes account for the wide spectrum of sedimentary structures occurring in the facies (Myrow and Southard 1996). Symmetrical ripples and parallel lamination are also attributed to storms inducing shore-normal geostrophic currents, often with subsequent overprint by wave ripples.

Mud drapes are interpreted as post storm/fair weather deposition. As with the modern day Hawke Bay where mud is carried in suspension in the breaker zone and carried by tidal and coastal currents and deposited in the offshore, low energy environment (Lewis 1973). Mud drapes may be deposited after storm conditions, as high winds stir up fine sediment and then deposition of this sediment may occur during the dominant tidal current during the following fair-weather conditions (Bartholdy and Anthony 1998). Mud drapes commonly infer tidal current deposition, the thickness (up to 20 cm) and lack of rhythmic bedding in this facies dismisses this facies as tidal rhythmites. However association of this facies to the inner-shelf tidal facies (S4-a) indicates this facies does have some tidal influence, (also dismisses deeper water setting as many of these sedimentary structures are able to be formed in outer shelf and slope settings (Shanmugan 2000)).

Common soft sediment deformation (plate 3.13) in this facies forms after deposition, probably during a subsequent storm, caused by changes in the interstitial pore-pressure. This can result from a number of mechanisms. The most likely is a residual increase in pore pressure due to storm waves. This deformation is thought to occur some time after deposition and is preserved only if the liquefaction occurs at a certain depth below the sediment water interface (Molina *et al.*, 1998). Liquefaction structures are further

encouraged in some facies with high volcanoclastic content, where the hydrophilic nature of the tephra increases the pore-water content thereby increasing deformation.

The carbonate lenses and nodules occur in this facies due to reworking/transportation of shoreface shells offshore during tempestite events. This is inferred to be due to the absence of whole body fossils in this facies. Fossils in this facies are broken up and not *in situ*, inferring transportation and reworking.

## Facies S4

**Description:** Massive to horizontally laminated, to ripple bedded sandstone with mud drapes and reactivation surfaces, bioturbation, and intra-formational conglomerates. Mud drapes normally contain bioturbation, sometimes down into the underlying sandstone. Remnant mud drapes commonly occur as horizontally aligned mudstone clasts (plates 3.17, 3.18, 3.19, and 3.20).

Bioturbation commonly forms large concretionary nodules and commonly destroys mud drapes leaving remnants behind (plate 3.18). Mud drapes in this facies are typically no thicker than 2 cm and where horizontally laminated, reactivation surfaces can be made out. These commonly lack mud drapes and occasionally stand out due to liesegang iron staining. These are reactivation surfaces and mud drapes on them delineate the tidal bundles.

This facies contains two variants; Variation A (S4-a): thinly bedded sandstone and mud drapes (5-20 cm sandstone beds; plate 3.19) examples being at Namai Station (V19/392274), Variation B (S4-b): thickly bedded sandstone and mud drapes (thick 20-200 cm) sandstone and thin (>2 cm mud drapes) in Boundary Stream sections (plate 3.20).

Features within S4-b facies include the thick penecontemporaneous slump occurring within the Taraponui Member (tk-C-2) of the Titiokura Formation. This facies typically always shows signs of bioturbation, but is occasionally very heavily bioturbated. These burrows form concretions and sedimentary structures within the sandstone are

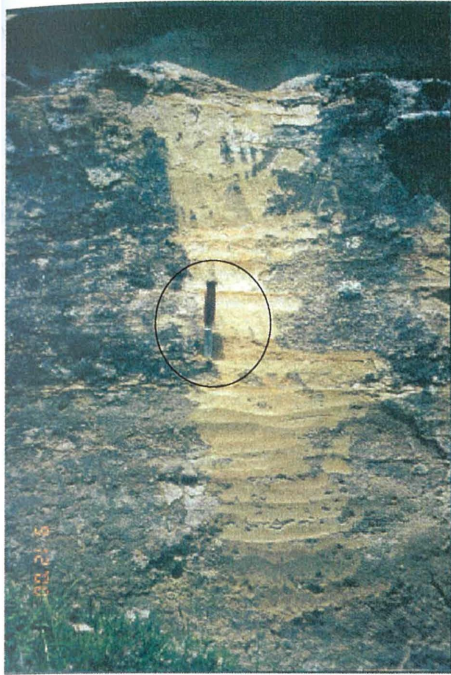


Plate 3.17 (left), Lithofacies S4-a, Titiokura Formation, Naumai Member, section Wi5 (V19/393272), massive to ripple bedded sandstone with mud drapes and reactivation surfaces. Interpreted as tidally emplaced sediments. knife is 7 cm long.



Plate 3.18 (above) Titiokura Formation, Te rangi Member, section Wi5 (V19/393272), Remnant mud clasts in lithofacies S4. Knife is 7 cm long.

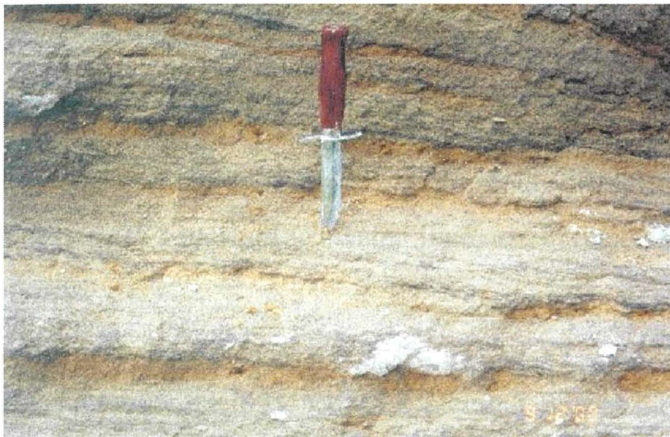


Plate 3.19 (left), Lithofacies S4-a, Titiokura Formation, Naumai Member, section Wi5 (V19/393272). Thinly bedded sandstone and mud drapes. Deposited in inner-shelf, and may represent diurnal to neap-spring tidal cycles in outcrop. Knife is 7 cm long.

Plate 3.20 (below), Lithofacies S4-b, Titiokura Formation, Taraponui Member, section Wi9 (V19/445268). Thickly bedded sandstone with thin mud drapes. Interpreted as deposited in a deeper water setting than S4-a, with deposition occurring on the inner-outer shelf.



Plate 3.21 (below), Lithofacies S6, Rangiora Formation. Massive to poorly bedded sparsely fossiliferous, poorly sorted, micaceous sandstone to silty sandstone, with common silty-sandstone interbeds. Interpreted as inner-mid shelf deposition.



obliterated. In S4-a intraformational conglomerate or channel lag deposit (lithofacies C2-a) is common (plates 3.7 and 3.10).

**Stratigraphic Occurrence:** This facies is extensive throughout the Titikura Formation. It is associated with facies S3, L2, L1, and C2.

**Interpretation:** Absence of indicator fossils in this facies means that the paleo-environmental interpretation is dependent solely on sedimentary structures observed in outcrop.

Mud drapes, reactivation surfaces, current ripples, and channel scour conglomerates are diagnostic of tidal sedimentation. Changes in tidal current speed and direction characterise tidal deposition. The deposition of a single tidal cycle is called a tidal bundle, and may be bounded by mud drapes or reactivation surfaces (Dalrymple 1991).

The two sub-facies probably represents differing paleo-environments but similar processes; (S4-a) shallow water inner-shelf deposits; and (S4-b) inner to outer shelf deposits.

S4-a: Outcrops such as found at Naumai Station are considered shallow water inner-shelf, perhaps even tidal flat deposits. In this facies rhythmic bedding is displayed, with reactivation surfaces often less than 5 cm apart (plate 3.20). These are considered to represent diurnal to neap-spring tidal cycles in outcrop, however for this to occur accommodation space on the shelf must be present to allow complete expression of each tidal cycle (Dalrymple 1991, Greb and Archer, 1998) and so such rhythmic bedding only occurs when adequate accommodation space occurs, i.e. during rising sea-level.

S4-b: The depositional environment is interpreted as mid-outer shelf. Thick stratigraphic successions such as at the Boundary Stream section (Wi9; plate 3.21) form this facies. These may show excellent tidal expression. This facies is thought to have occurred on a shallow sheltered shelf with abundant accommodation space, (Note; tidal deposits may occur in a wide spectrum of depths. Cross-ripple bedded sandstone with mud drapes observed at depths down to upper slope to bathyal depths (Shanmugam *et*

*al.* 1993)). These deposits may represent a continuum between storm emplaced sandstone, or tempestites, and tidally reworked sandstone. Storms may play a role in remobilising and transporting sediment over the shelf, but any evidence has been subsequently over-printed by latter process, such as tidal currents.

Depositional rates for rythmites range from 20 cm to 100 cm per neap-spring cycle, but may exceed this (Adkins and Eriksson 1998). These thickness are similar to the rhythmic bedding found in the thick sections of sandstone with mud drapes. An example of this is at Boundary Stream Walkway, which may represent neap-spring cycles, although diurnal cycles may be expressed in some outcrops. Convolute bedding at the top of sandstone beds probably occurs due to post-deposition loading and an increase in pore pressure between sand grains resulting in liquefaction (Molina *et al.* 1998).

Rare cross-bedding in this facies indicates an exposed shoreface-innershelf setting for this facies. Planar cross-bedding may represent event deposits caused by storm generated bottom currents (Yagishita 1994), or shoreface swash zone.

Not all tidal currents express tidal cyclicity. They may represent or be superimposed by strong seasonal activity or sediment flux (Dalrymple 1991). Mud drapes may be deposited in fair-weather conditions post windy events, which stir fine sediments allowing transportation out on to the shelf on the dominant tidal current, with deposition during the following fair-weather conditions (Bartholdy and Anthony 1998).

Thick sections where sedimentary structures are obliterated by bioturbation, represent slightly deeper water settings where increased pelagic sedimentation of fine grained sediments and a less energised environment allows for the increased growth of organisms, and subsequent bioturbation. Other features in this facies such as the penecontemperanous slump unit, probably was also formed in deeper water settings, perhaps outer shelf to upper slope, triggered by some event such as a large storm or earthquake, or from sea-level transgression.

## Facies S5

**Description:** Massive to poorly bedded sparsely fossiliferous poorly sorted micaceous and occasionally glauconitic sandstone to silty sandstone with occasional shellbeds and lenses, occasional siltstone laminae, and mud drapes. This facies typically forms very thick stratigraphic sections. This facies differs from S4 in that silty-sandstone beds are present, often associated with facies L2 and mud drapes are less common.

**Stratigraphic Occurrence:** This facies occurs in the Titiokura and Rangiroa formations, where it is associated with facies Z1, Z2, S3, S4 and S6.

**Intrepretation:** Dominated by *Dosinia (Asa) lambata*, *Fissidentalium zelandicum*, *Austrofusus pagoda*, *Splendillia aequistrata*, *Ostrea chiliensis* and *Atrina pectinata zelandica*. These fauna indicate inner shelf deposition. The presence of shoreface and inner-most shelf fossils in these sediments indicates some reworking of shallow water assemblages off-shore. Fossils such as *Ostrea chiliensis* indicate sediment by-passing on a current swept shelf (Beu and Maxwell 1991). Mud drape and silt laminae indicate tidal influence, as with facies S4-b, where fine-grained sediments are deposited offshore during fair-weather conditions. Deposition occurred on a current swept inner shelf, at 20-60 m water depth.

## Facies S6

**Description:** Massive to poorly bedded sparsely fossiliferous poorly sorted micaceous and occasionally glauconitic bioturbated sandstone to silty sandstone with occasional shell beds and lenses (plate 3.21). This facies is very similar to the above facies but mud drapes are absent, silty-sandstone beds are commonly inter-bedded with sandstone (plate 3.21). The fauna are dominated by *Atrina pectinata zelandica*, *Pratulium pulchellum*, *Austrofusus pagoda*, *Splendrillia* sp., and *Fissidentalium zelandicum*.

**Stratigraphic Occurrence:** Occurs within the Rangiora Formation, where it is associated with facies S5, Z1, Z2, and Z3.

**Interpretation:** Inter-bedded siltstone and sandstone normally represents inter-digitation of storm remobilised/emplaced sandstone with fair-weather siltstone deposition (Johnson and Baldwin 1996). Common shallower water fossils represent constant offshore reworking of sediment. Absence of mud drapes is explained by the absence or lack of influence of tidal currents. Deposition is interpreted to have occurred on the inner-mid shelf.

### 3.2.1.4 Carbonate Association

#### Facies L1

**Description:** L1-a: Moderately to well cemented slightly glauconitic tabular cross-bedded limestone coquina, with greywacke grit, sandstone lenses and beds. Basal beds of limestone units are typically conglomeratic (basal scour), often with mudstone, sandstone and rare limestone blocks, with clasts as large as 1 m<sup>2</sup>. The facies is commonly composed of distinctive amalgamated limestone and sandstone beds. Skeletal content comprises, Byrozoan, Barnacle, Echinoderms, and Pectens with *Phialopecten marwicki* the only macro-fossil identified in this facies. Beds are typically less than 6 m thick (plate 3.22).

L1-b: Planar/Trough to hummocky cross-bedded sandy coquina. Very well sorted, small shell fragments (1-2 mm) form thick outcrops (10-50 m; plate 3.23). This is the only real difference between L1-a and L1-b. Outcrops of this facies at Bellbird Bush and Opoauhi are flaggy in outcrop. This is probably a secondary cemented 'skin'.

**Stratigraphic Occurrence:** Occurs exclusively within the Titiokura Formation, where it is associated with facies C2, S3, S4, and S5.

**Interpretation:** L1-a: Basal scouring indicates a high-energy environment of deposition (lag deposit considered unlikely as clasts are found up into the limestone) and probably some channelling. The presence of fossils such as *Phialopecten marwicki* indicates a shallow, high-energy environment (Beu and Maxwell 1990). Other skeletal components indicate a current swept sea-floor as barnacles and pectens are filter feeders



Plate 3.22, Lithofacies L1-a, Titiokura Formation, Naumai Member, section Wu5 (V19/393272). Cross-bedded limestone coquina, with greywacke grit, and basal scour with large blocks of sandstone and siltstone 'ripped-up' into the bed. Skeletal content of limestone comprises byrozoans, barnacle plates, enchinoderms, and pectins. Interpreted as deposited in a high-energy environment, probably inner shelf (Photo: A. Pallentin).



Plate 3.23, Lithofacies L1-b, Titiokura Formation, Bellbird Bush Member (V19/384233). Crossbedded limestone that forms thick outcrops (10-50 m). Typical content of lithofacies is of byrozoans, barnacles, enchinoderms, pectins and common greywacke grit. Probably formed on structural highs that are intermittently reworked by storm and tidal currents. Sedimentary structures in this facies indicate an inner-innermost shelf depth.

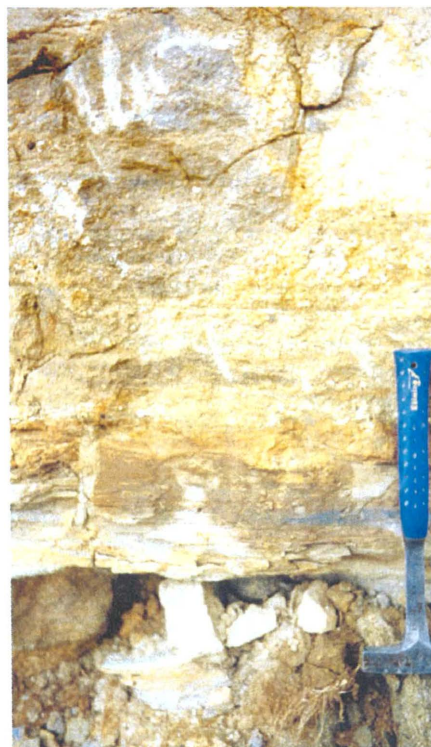


Plate 3.24, Lithofacies L2, Titiokura Formation, Bellbird Bush Member, section Wu4, (V19/401228). Thin trough cross-bedded limestone, with greywacke pebbles delimiting cross-bed foresets. Trough cross-bedding indicates rapid grain-by-grain emplacement by traction currents in the inner-mid shelf, probably reworked from nearby limestone factories.

and require strong current swept conditions (Beu *et al.* 1980, p 21). Barnacles live in the sub-tidal zone attached to hard substrates (Kamp *et al.* 1988). Uni-directional cross-bedding indicates one dominating current direction. This is because storm currents are considered to be too infrequent to keep the sea-floor free of terrigenous sediment to enable growth of these faunas, although large rip-up clasts indicate reworking of these sediments/fauna. The size of intact barnacle plates may be considered a rough measure of distance of transportation of skeletal material, as barnacle plates are highly porous and therefore fragile and don't survive transport from a living site to deposition more than a few tens of metres (Beu 1995).

L1-b: Probably formed on structural highs that are intermittently reworked by storm/tidal currents transporting material forming facies L2 (trough cross-bedded limestone). Sedimentary structures in this facies, such as planar cross-bedding, indicate an innermost shelf depth (not necessary occurrence) with reworking by storms and/or tidal currents. Ubiquitous greywacke pebbles and silt clasts indicate a high-energy environment, probably close to the uplifted North Island Axial ranges.

## Facies L2

**Description:** Thin (< 50 cm) trough/tangentially (concave up) cross-bedded limestone with fossil escape structures and flame structures up through limestone beds (plate 3.24). Limestone may coarsen up out of sandstone, or fine up into sandstone beds. Small greywacke pebbles occur on limestone/sandstone trough cross-bed foresets. Thin sand lenses are common. Thick (15 cm) rippled mud drape occurs within concretionary sandstone, along with other thin mud drapes. Fossils found within this facies include *Mesopeplem crawfordi*, and *Atrina pectinata zelandica*. Some sub-facies of this facies do not show bedding, probably because of their fine grained nature and lack of greywacke pebbles. The skeletal content appears to be similar to other limestone facies but shells are highly fragmented and identification of individual clasts is often not possible.

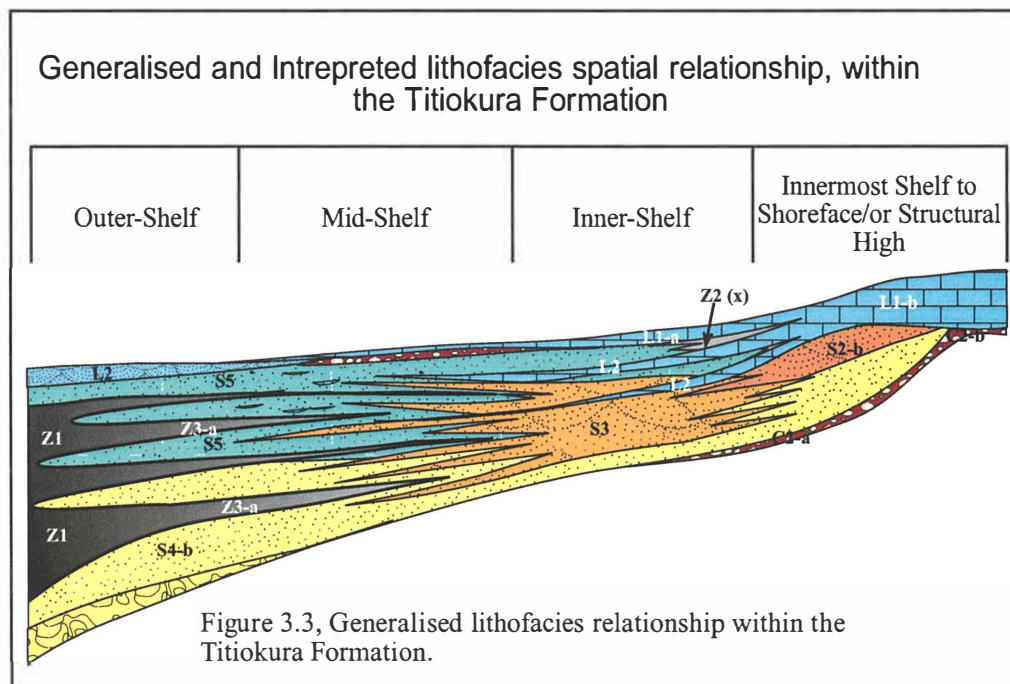
**Stratigraphic Occurrence:** Again this facies occurs exclusively within the Titiokura Formation, where it is associated with facies C2, S3, S4, and S5.

**Interpretation:** Trough cross-beds indicate rapid grain-by-grain emplacement by traction currents. Flame structures and escape burrows through beds indicate rapid emplacement, which along with fining-upwards beds, indicate storm or 'tempestite' deposition where finer grained sediment is deposited during waning stages of a storm. Composition of this facies is similar in all aspects except grain-size, which is smaller. This indicates that these rapidly emplaced beds are probably reworked from near-by limestone factories, such as is presently occurring on the 3 Kings Shelf (Nelson *et al.* 1982), which sporadically have material eroded and re-deposited from them. This facies occurs as a lateral equivalent to facies L1-b. It should be noted that dips measured on this facies are typically steeper than those found on other facies in the study area, inferring progradation from carbonate 'highs'.

### 3.3 Summary of Facies Associations

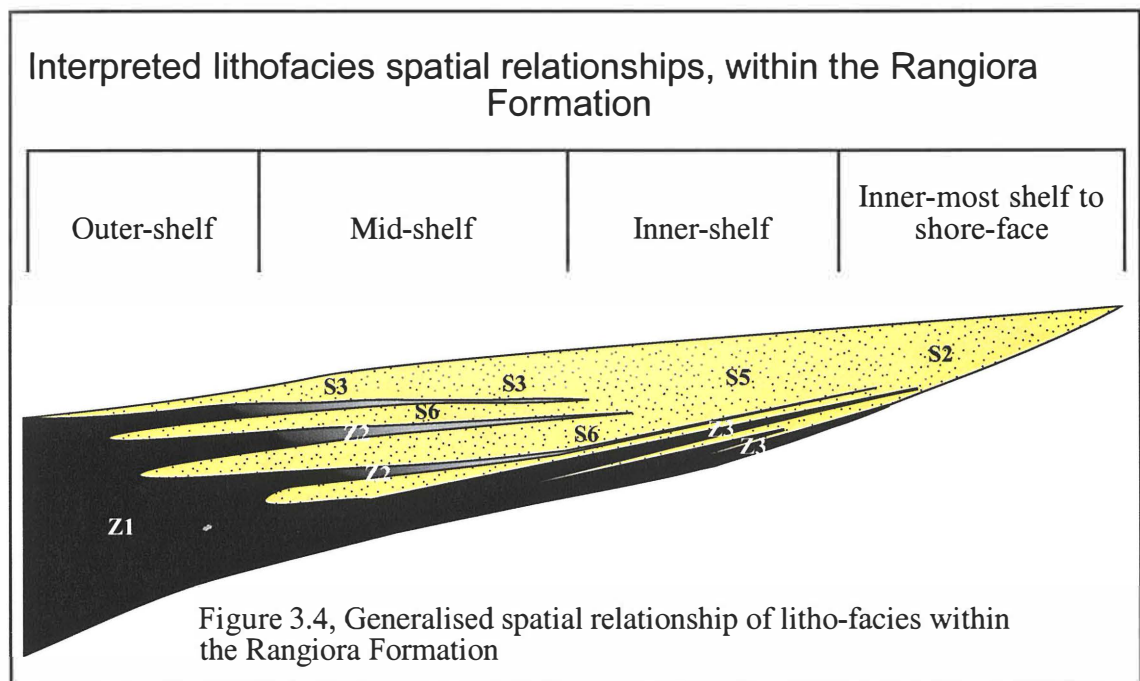
#### 3.3.1.1 Summary of Facies associations within the Titiokura Formation

Figure 3.2 summarises the interpreted lithofacies associations. It attempts to show that in the inner-most shelf, limestone facies L1-b and conglomerate facies C2-b occur. In places this may be separated by a siliciclastic wedge of sandstone (facies S4-a and S2-b). Some storm reworking occurs in the inner shelf environment, but this is generally overprinted by tidal and wave action. During times of increasing accommodation space tidally laminated deposits (S4-a) are common. During time of decreasing accommodation space, wave reworked deposits prevail. Inner shelf facies are typically tidally and storm emplaced deposits (S4, S3, and L2). Some siltstone is interpreted to form in sheltered areas in close proximity to limestone factories. In the mid-outer shelf environment, storm and tidal currents rework sediment, which inter-digits with deeper water facies, such as S4-b, S5, S6. Sediments inferred to have been mass-emplaced are classified in S4-b and and is associated with siltstone Z1-2-3. Limestone (L2) is interpreted as reworked into the mid-outer shelf environment although in this setting bioclasts are finely ground up and sandstone content is higher. Occasionally this reworked limestone is interpreted to have been emplaced by very high energy currents and local scours occur with conglomerate found at the base.



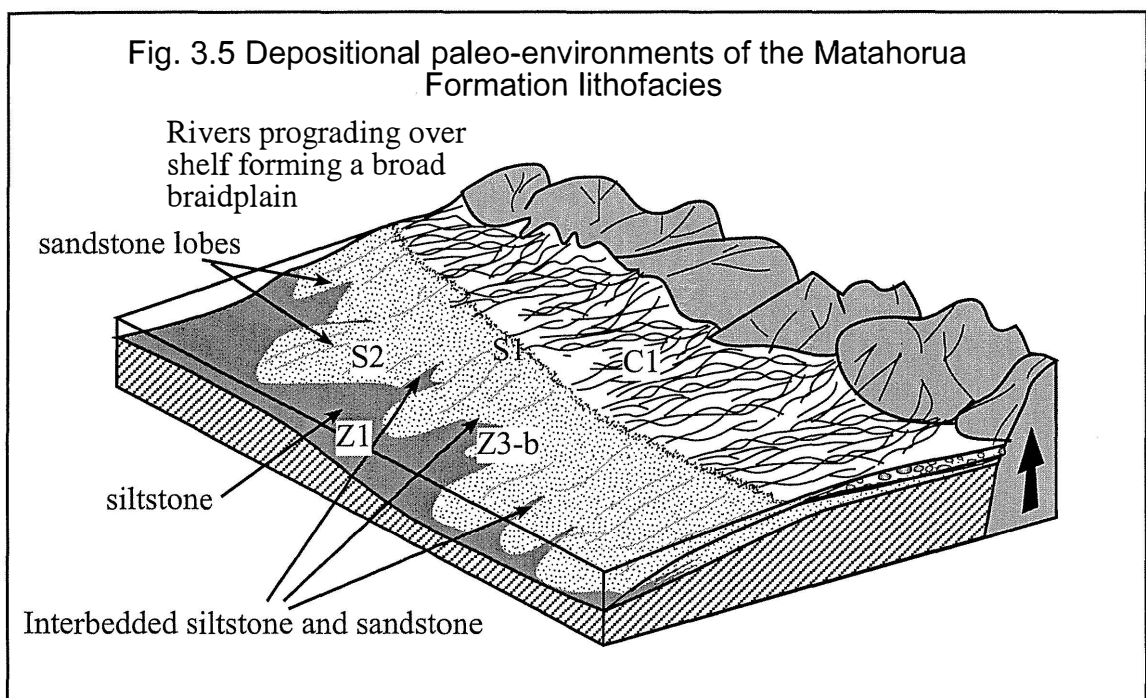
### 3.3.1.2 Summary of Facies associations within the Rangiora Formation

Figure 3.3 summaries lithofacies associations within the Rangiora Formation. Inner shelf facies assemblages are dominated by sandstone. Facies S2 accumulated in the inner-most shelf, and facies S5 to S6 with some Z3 in the inner shelf. Tidal currents are less prominent in the Rangiora Formation and mud drape are not transported as far basinwards as in the Titiokura Formation, leading to the gradation from facies S5 to S6. Some evidence for storm reworking is inferred for the inner-mid shelf with facies S3-b occurring. In the mid to outer shelf, siltstone occurs with sandstone S6 and S3-b interdigitating, although there are some examples of siltstone comprising entire successions in the mid-outer shelf environment (e.g. Waikari Member siltstone).



### 3.3.1.3 Summary of Facies associations within the Matahorua Formation

Figure 3.4 gives a summary of the lithofacies association in the Matahorua Formation. The Matahorua Formation is dominated by siliciclastic sandstone (facies S1, S2) and conglomerate (C1) with minor siltstone (Z2, Z3). Siltstone facies typically occur on top of or beneath thick conglomerate beds. This siltstone probably represents areas between sand lobes of the encroaching delta. Sandstone facies occur underneath and above the conglomerate of the underlying member. The sandstone accumulated within an inner shelf to shoreface environment. The conglomerate facies represents subaerially exposed, fluvial deposition from rivers, which forms a broad braidplain.



### 3.3.1.4 Summary of Facies associations within the Waipunga Formation

The Waipunga Formation is deposited in a similar setting to the Rangiora Formation with siltstone inter-bedded with sandstone (facies Z3, and Z1) on the innershelf, and sandstone dominating the innermost and shoreface environments (facies S1, and S2).



# Chapter 4

## Chapter 4: Sequence Stratigraphy

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### 4.1 Introduction

“Sequence stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities”(Van Wagoner *et al.* 1988, p 39). A sequence is a conformable succession of genetically related strata bounded at its top and base by unconformities and their correlative conformities (Vail *et al.* 1977 in Posamentier and Vail 1988, p 125). Sequences are divided into systems tracts, which are linkages of depositional systems (Van Wagoner *et al.* 1988, p 39). A depositional system is a three dimensional assemblage of litho-facies (Fisher and McGowan 1977 in Posamentier *et al.* 1988, p 110).

Four systems tracts are identified in this study. 1) Transgressive Systems Tract (TST), which corresponds to a time of rapid relative sea-level rise. It is bounded by a transgressive surface of erosion (TSE) at its base and a downlap surface at the top. 2) Highstand Systems Tract (HST), which includes the late part of the relative rise in sea-level, still-stand, and early part of sea-level fall (Van Wagoner *et al.* 1988, p 44). 3) Regressive Systems Tract (RST), includes all deposits which form during the falling limb of a relative sea-level cycle (Naish and Kamp 1997), and 4) Lowstand Systems Tract (LST), which forms when sea-level falls below the shelf edge and exposes the shelf to subaerial erosion and related sedimentation.

Bathymetry changes in sedimentary cycles are controlled by three variables: eustatic sea-level change, rate of subsidence, and rate of sediment accumulation. These variables combine to control accommodation space, which is the space made available on the shelf for potential sediment accumulation (Jervey 1988, p 47). Where accommodation space is less than the sediment influx, sediment bypassing and erosion of older sediment occurs, resulting in progradation of sediments basinward. Where excessive

accommodation space occurs, shallow water facies are not observed and sedimentary cycles are dominated by deep-water facies. The former situation occurs in the Rangiora Formation, and both in the Titiokura Formation.

Vella (1963) identified the occurrence of Pliocene cyclothems in the East Coast Region of New Zealand, which were interpreted as resulting from sea-level fluctuations. Closer to the study area of this thesis, Haywick (1990) identified cyclicity resulting from sea-level fluctuations in Plio-Pleistocene strata of the Tangoio Block, north of Napier. These cyclothems are interpreted as 41 ky sea-level cycles with estimated amplitudes of 50 to 100+ m (Haywick and Henderson 1991; Haywick *et al.* 1991). During the Plio-Pleistocene (last 2.6 m.y.) eustatic sea-level changes are considered the dominant control on shelf and near-shore sedimentation.

An attempt has been made in this chapter to apply the principles of sequence stratigraphy to the sedimentary successions mapped and described in this study. Sequence stratigraphy emphasises the classification of systems tracts between key surfaces. It is different therefore to lithofacies analysis, but very conveniently integrates with it. Fig 4.1 gives a generalised interpretation for selected sequences within each formation of the interpretation of the sequence stratigraphy. It shows the inferred extents of systems within particular cycles to illustrate the type of variability that exists. This variability is addressed in this chapter. Importantly, the extent of systems tracts and the location of key surfaces are shown on the stratigraphic logs in Appendix 1. Fig 4.2 summarises the stratigraphic distribution of the numbered cyclothems (sequences) identified in the succession exposed in the study area.

### 4.1.1 Sequence Boundaries

A sequence boundary is a regional surface, which is characterised by subaerial exposure and erosion. It may be bounded by unconformities or correlative conformities, which are “a surface of erosion or nondeposition that separate younger strata from older rocks and represents a significant hiatus” (Mitchum 1977 in Van Wagoner *et al.* 1988, p 39). A conformity is defined as a surface which separates older from younger strata on which there is no evidence of erosion and no significant hiatus is inferred (Van Wagoner *et al.* 1988, p 41). Sequence boundaries in the study area vary considerably depending on the formation or facies they are associated with. In the Titiokura

Generalised Cycle Motifs for formations in the Waikari and Waikoau River Catchments

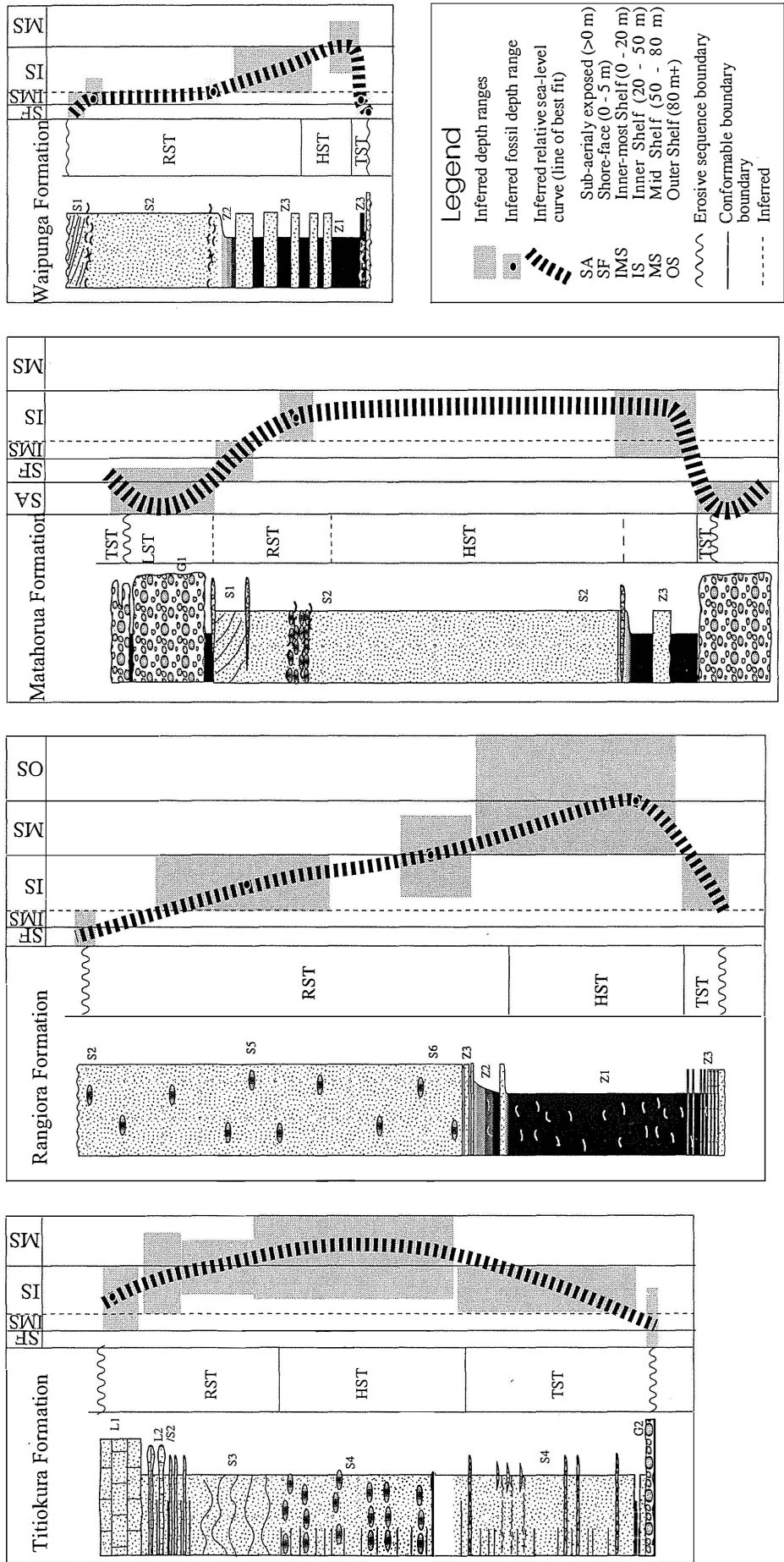


Figure 4.1, Generalised cycle motifs for each formation.

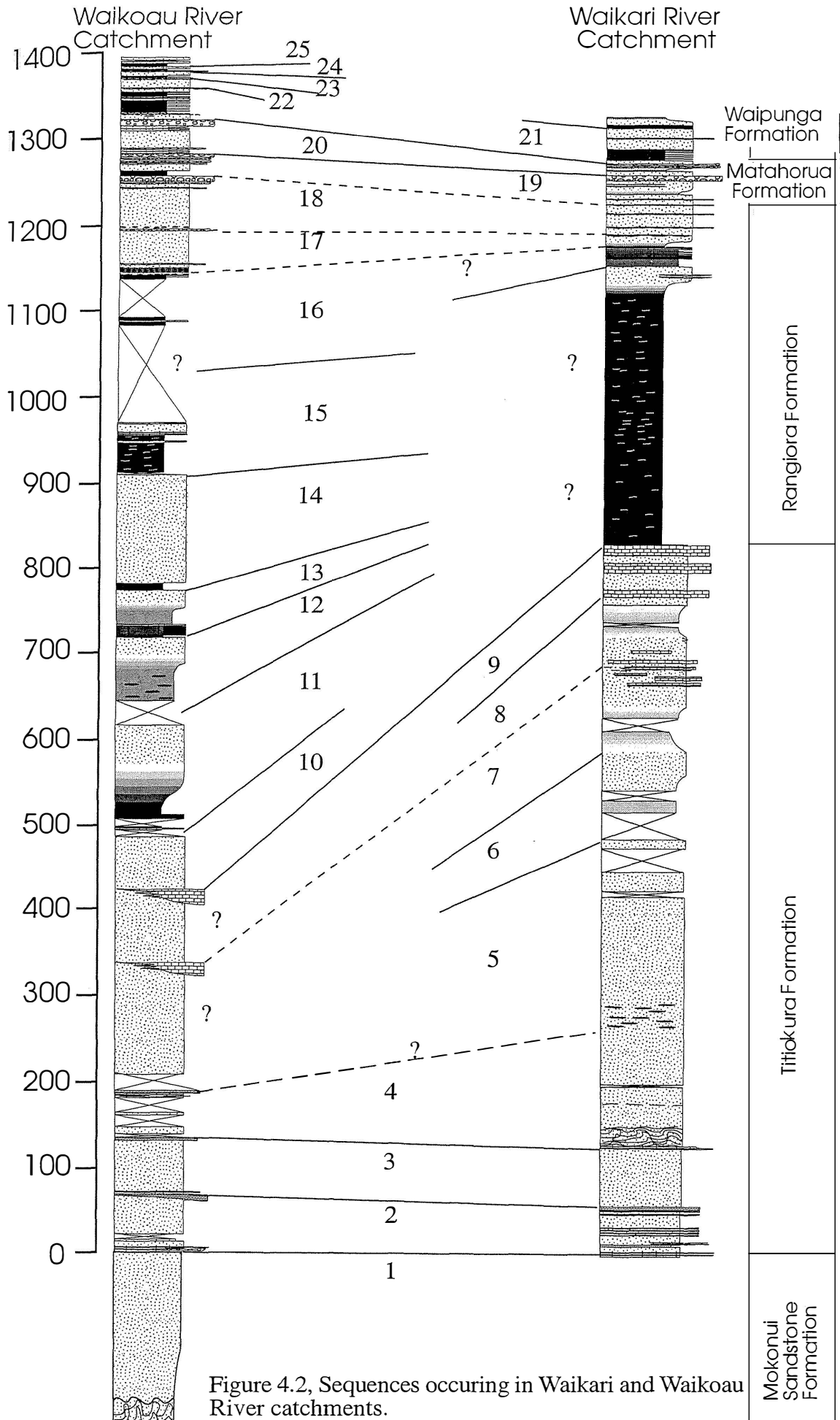


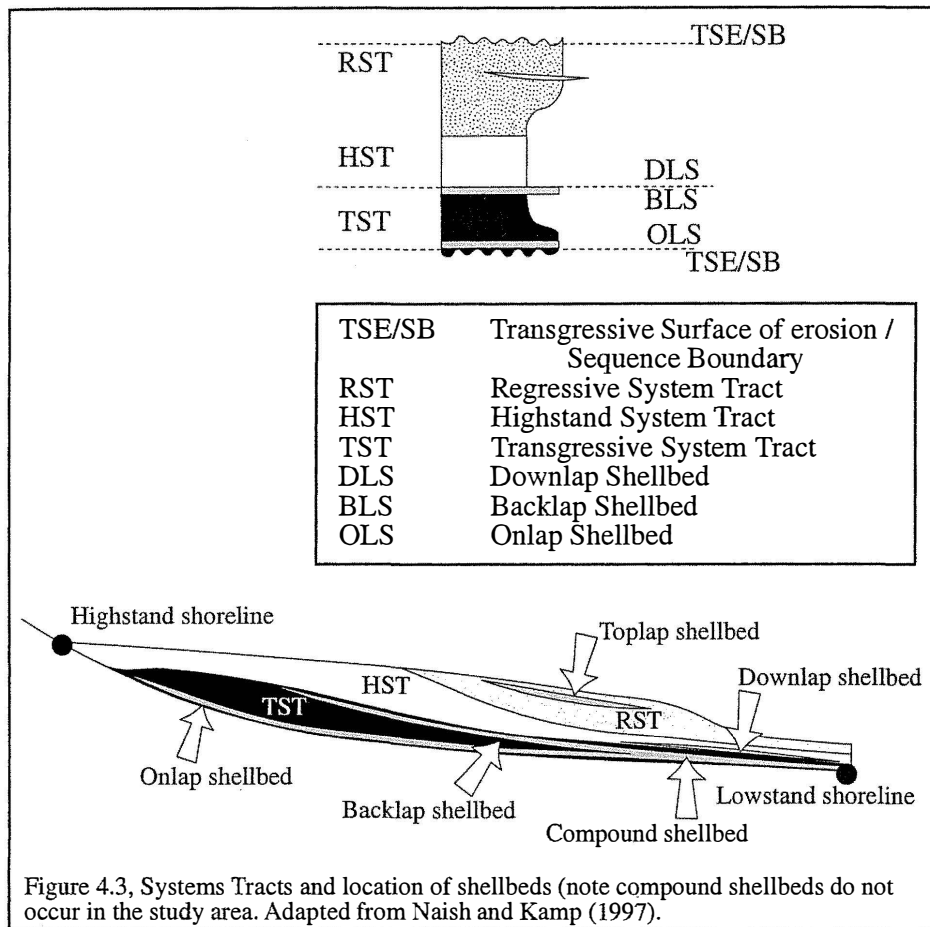
Figure 4.2, Sequences occurring in Waikari and Waikoau River catchments.

Formation, where they are associated with shallow water facies, such as conglomerates and limestones, boundaries are highly erosive, with local relief of up to 10 m occurring. Near the highstand shoreline, where erosion is greatest during lowstands, some sequences are almost completely eroded and an unknown amount of sediment is missing. Where sequence boundaries are associated with siliciclastic sandstone and coquina, sharp planar conformable boundaries occur. In the Rangiora Formation sharp planar boundaries occur as well as erosional surfaces with 10-30 cm local relief. Sequence boundaries are conformable in the Matahorua Formation. Thin shellbeds and wave cut erosional surfaces mark sequence boundaries in the Waipunga Formation.

#### 4.1.2 Shellbeds

Shellbeds are rare in the lower Pliocene succession (Titikura Formation and lower Rangiora Formation) in the study area, but increase in number up the succession. Where they do occur they provide important information for sequence stratigraphic analysis. Shellbeds typically infer sedimentary condensation, omission or erosion, which sometimes infers sequence boundaries and downlap surfaces (Kidwell 1989;1991). Shellbeds are important in discrimination of TST from HST/RST deposits. Shellbeds also provide important paleo-bathymetric information, which is critical for inferring relative sea-level history. However, they do not outcrop regularly or continuously and therefore are not always useful in mapping. Shellbeds in this area are considered to have formed through stratigraphic condensation, which occurs by sediment bypassing or sediment starvation, or are reworked. Condensed shellbeds may form at any stage of sea-level, i.e. rising, falling, or stillstand conditions (Kidwell 1991).

In describing shellbeds in this study, nomenclature used by Naish and Kamp (1997), which was developed from Kidwell (1989 and 1991) is used. There are four main types of shellbeds that occur in this study area; onlap, backlap, downlap, and toplap shellbeds (Fig 4.3).



Onlap refers to the landward termination of strata and applies to the termination pattern on top of a sequence boundary. High sedimentation rates often stop shellbeds forming in the nearshore environment (Kidwell 1991). Onlap shellbeds often sit directly on the transgressive surface of erosion (TSE) or ravinement surface in the study area and indicate the base of a sequence (Naish and Kamp 1997). Onlap shellbeds are shell accumulations, which form at the base of sequences on the TSE. They form through sediment bypassing and winnowing as rising sea-level traps sediment in a shore-connected wedge.

Onlap shellbeds occur in all of the formations within the study area, but each is highly individualised. An erosional sequence boundary does not always occur at the base of a sequence, and is sometimes characterised by a conformity. Typically onlap shellbeds

are: heavily fossiliferous shell-hash with cross-beds; very weakly fossiliferous over 1-2 m or 1-2 cm; or cross-bedded limestone lenses within a calcareous succession. Onlap shell-beds are typified by siliciclastic reworking. Occasional siliciclastic conglomerates occur within the Titiokura Formation, siltstone and sandstone parasequences in the Rangiora and Waipunga formations, and reworked greywacke conglomerate in the Matahorua Formation.

Backlap shellbeds are shell accumulations that form on the shelf within the upper parts of TST's. Backlap shellbeds form through terrigenous sediment starvation and record transition from deposition to starvation (Kidwell 1991, p687). The lower boundary is diachronous across the shelf as a result of sea-level rise and shoreline migration.

Downlap shellbeds are rarely true condensed deposits and rest on an omission surface above the downlap surface and record the start of sea-level lowering. Downlap shellbeds record transition from starvation to deposition (Kidwell 1991, p687). Downlap shellbeds lie within the highstand systems tract (Naish and Kamp 1997). Both backlap and downlap shellbeds are very rare in the field area and form only in the Waipunga Formation, where they are very weakly fossiliferous.

Toplap shellbeds record progressive bypassing of sediment during shallowing upward conditions. Toplap shellbeds have a low preservation potential, and are commonly eroded by subaerial and marine erosion, or reworked into transgressive lags (Kidwell 1991, p688). Kidwell describes toplap shellbeds with low-diversity fossil assemblages, however Kondo *et al.* (1998) states they often contain reworked fauna and are storm reworked. This may explain the high species diversity of toplap shellbeds occurring in this study area, as storms and other currents rework fauna, resulting in an increased species diversity.

## 4.2 Facies Architecture and Cyclicity

Four generalised cycle motifs have been identified from this field area, one for each formation (Fig 4.1). The generalised motifs are considered representative of the entire formation (and may or may not represent actual sequences). Individual sequences for each formation are discussed and placed in an interpreted proximal, distal or margin setting of a depositional environment.

As many as 25 cycles are identified within the study area (Fig 4.2), 22 in the Waikoau River catchment and 16 in the Waikari River catchment. Correlating these sequences across the field area infers the presence of 25 cycles. Thirty cycles are inferred when including the total Pliocene record within the Tangoio block (Haywick 1990) and this study. Note that not all sequence boundaries can be traced across the field area. Often sections that appear to consist of 1 cycle, when followed across the area, are comprised of a number of cycles. An example of this is the Opouahi limestone and the Waikari siltstone.

### 4.2.1 Titiokura Formation Sequence Architecture

A generalised cycle motif for the Titiokura Formation is shown in Fig. 4.1. Selected sequences that comprise the generalised cycle are shown in Fig 4.4. Tectonics and basin subsidence are considered to play a large role in the generation of accommodation space. The Titiokura Formation succession in the Waikari River catchment displays a general upwards deepening, indicating accelerating subsidence of the basin. Each member displays slightly deeper water facies than the previous one, with overprinted eustatic sea-level fluctuations resulting in facies shoaling. Because of this, paleo-bathymetry curves reflect the interplay of basin subsidence, sediment accumulation, compaction, and eustasy. Sea-level curves shown for the Titiokura Formation reflect relative sea-level changes.

The generalised motif (Fig 4.1) for the Titiokura Formation consists of a basal conglomerate or sometimes limestone, which onlaps the underlying sequence. A wedge of siliciclastic sandstone commonly divides the conglomerate into two parts, the top bed is commonly calcareous. The lower conglomerate (facies C2-b) probably represents shoreface deposition with sandstone accumulating in the lower shoreface, and the top calcareous conglomerate (facies C2-a) accumulating in the inner-most shelf. The conglomerate is conformably overlain by tidally laminated sandstone (facies S4-a) with intraformational conglomerates or transgressive lags, with common shell lenses. Both the conglomerate (facies C2-a/b) and the tidal facies (facies S4-a) are considered to accumulate during the TST. Highstand System Tracts are difficult to identify in this motif. They may be represented by thick tidally laminated sandstone (facies S4-b), which accumulates in abundant accommodation space, or extensively bioturbated sandstone units that form in a low energy environment, allowing bioturbation by organisms. HST's grade up into regressive successions, which are typically storm and

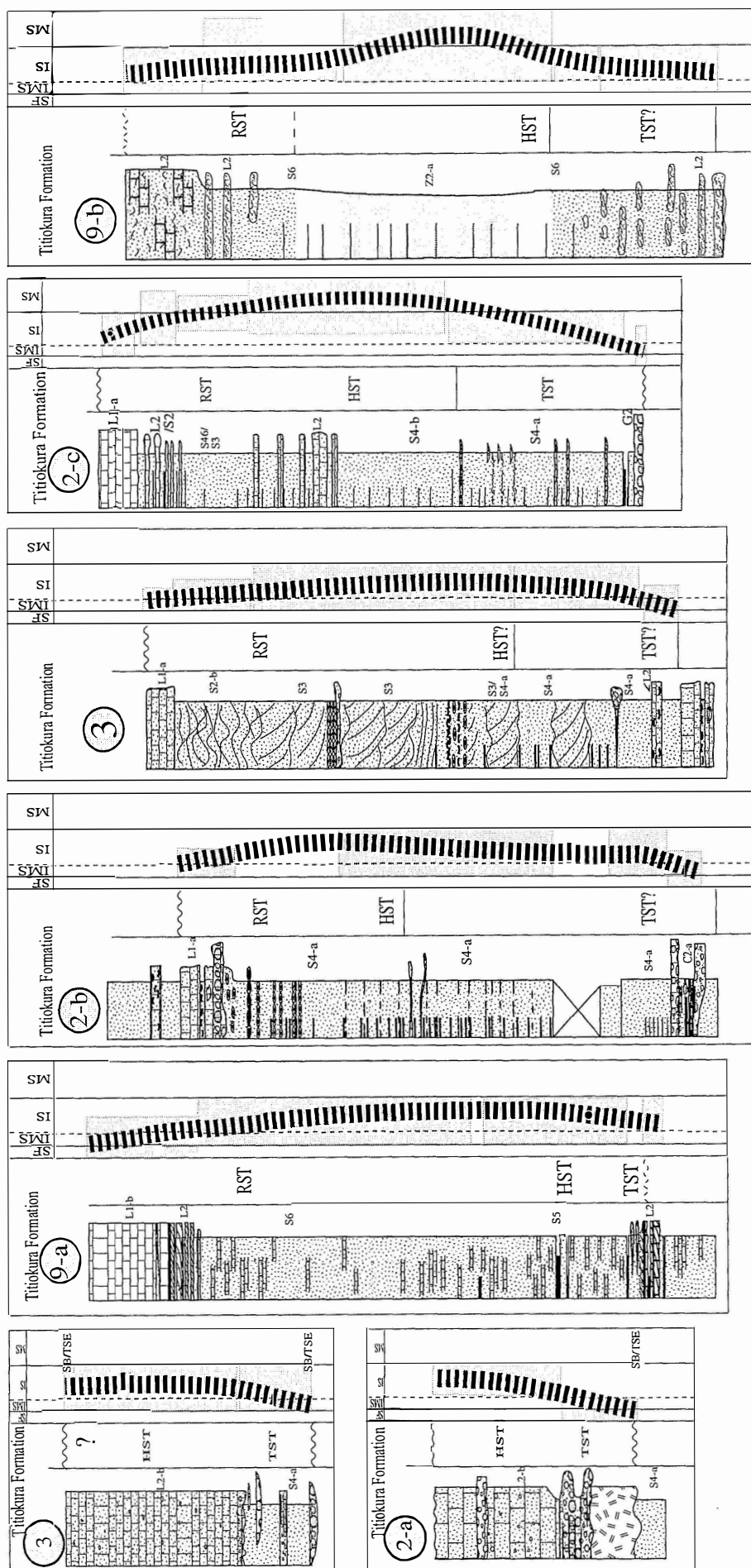
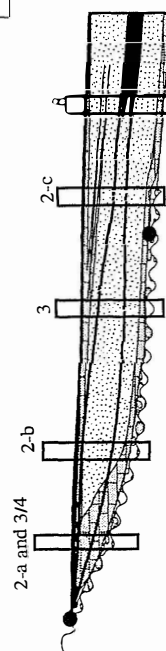


Fig 4.4, Sequences occurring within the Titokura Formation. Sequences 2-a and 3 represent deposition shoreward of the lowstand shoreline, sequence 3 represents deposition near the Highstand shoreline. Sequence 2-c represents deposition basinward of the Lowstand shoreline. Sequences occurring in this figure can be found in Appendix 1. Both sequence 3 and 2-a occur in column Ek4, sequence 9-a occurs in column Wu4, sequence 2-b and 3 occur in column Wu5, sequence 2-c occurs in column W17, and sequence 9-b occurs in column W14.



tidally reworked sandstone with some wave reworking towards the top of the succession and grading into limestone coquina at the very top of the sequence.

#### 4.2.1.1 Sequences in the Titiokura Formation

Figure 4.4 displays seven sequences occurring in the Titiokura Formation, which are considered to correspond to sea-level cycles. Numbers on each column in the figure correspond to sequences that are numbered in Fig 4.2, codes of stratigraphic logs occurring in appendix 1 are shown on this figure and in the text. Lateral variation is a recurring feature of the Titiokura Formation and variations on the generalised cycle motif will be discussed here.

Sequence 2-a (sequence 2 is described in 3 places and so must be differentiated; section Ek4) contains a basal conglomerate, which onlaps on to the underlying sequence. The conglomerate (facies C2-b) accumulated in a shore face environment and is conformably overlain by limestone coquina with thin conglomerate lenses. It is worth noting that the two conglomerate beds, which occur in the generalised motif do not occur here. The conglomerate is considered a TST deposit (probably late) and the limestone a HST deposit. No RST deposits occur in this sequence.

Sequence 2-b (section Wu5) consists of a basal conglomerate, which is composed of a lower bed and an upper calcareous bed, separated by a siliciclastic sandstone wedge. The conglomerate is conformably overlain by tidally laminated sandstone with channelised conglomerates (facies S4-a). This facies occurs in the lower half of the sequence. The conglomerate and tidally laminated sandstone (S4-a) are considered to have formed during a transgression. As sea-level rises the conglomerates are stranded on the shelf and buried by sediment (preserving them). The HST is considered to lie at the top of the facies containing the conglomerates but is not represented by any deep-water facies, but is inferred below the transition to a shallowing upward facies succession. The HST grades into the RST, which is tidally laminated sandstone (facies S4-b) grading up into cross-bedded limestone with localised scouring and sandstone lenses.

Sequence 3 (section Wu5) is composed of reworked limestone, tidally laminated sandstone with occasional lag conglomerates, which occur as a TST. Highstand systems tracts are not identifiable, and are again inferred from the start of the shallowing upward

succession. Regressive deposits are reworked storm, tidal, wave reworked sandstone, grading up into limestone.

Sequence 2-c (section Wi17) also consists of a basal conglomerate comprised of 2 beds, which is conformably overlain by tidal facies S4-a. This facies grades into tidal facies S4-b, which is the deeper water tidal facies. This facies is considered to represent the HST. The beginning of regression is marked by reworking of bioclastic and terrigenous sediment basinwards, resulting in channelised shellbeds and storm reworked sandstone, which grade up into the top calcareous sandstone.

Sequence 8 (section Wi4) does not contain a basal conglomerate, instead reworked/channelised shellbeds in sandstone occur during the TST. This facies fines upwards into a tidally laminated sandy siltstone (facies Z2-a) representing the HST. This coarsens upwards into channelised shellbeds that are conformably overlain by calcareous sandstone, representing the RST.

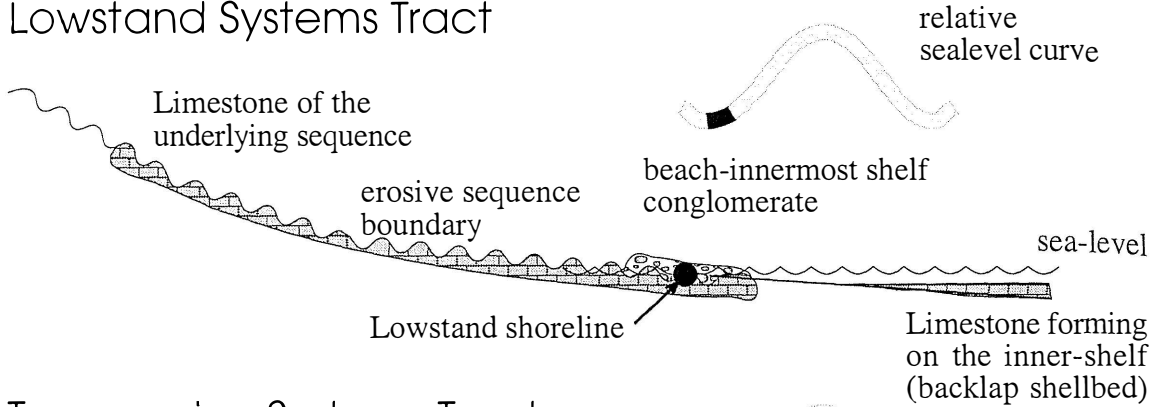
Sequence 9 (section Wi4) lies conformably atop trough cross-bedded sandstone of the lower sequence. Reworked limestone with greywacke pebbles occur during the sea-level transgression. This grades up into sandstone with silty beds (probably representing the HST), which become less common up section as sea-level falls. The sandstone grades into limestone and a series of trough cross-bedded limestone lenses occur below the thick limestone.

#### 4.2.1.2 Interpreted cross shelf profile

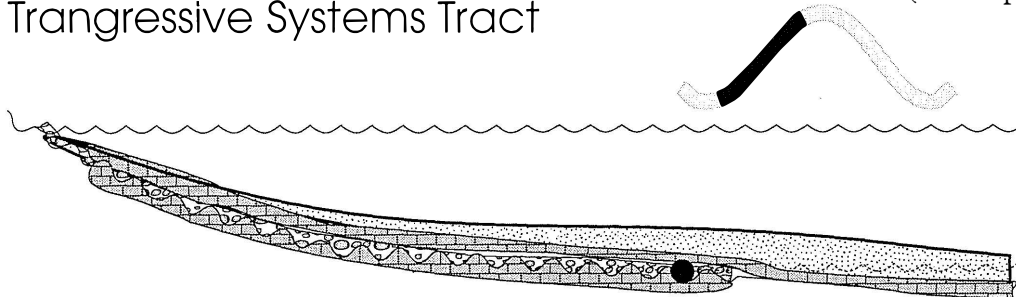
The lateral variations that occur within the Titiokura Formation are considered to occur because of deposition within a spectrum of environments, from near the highstand shoreline to basinwards of the lowstand shoreline. Fig 4.4 shows Titiokura formation sequences, placed in an interpreted position in an across shelf profile.

Sequence 2-a and 3/4, are interpreted to form near the highstand shoreline. Beachface conglomerates occur at the base of both sequences, and deep-water facies are absent. The upper conglomerate bed does not occur in this location as it is indistinguishable from limestone, which forms throughout. Regressive systems tracts (RST) do not occur in this location, because as sea-level falls the inner shelf near the highstand shoreline is

Fig. 4.5: Titiokura Formation.  
Sequence Motif and Systems Tract evolution  
Lowstand Systems Tract

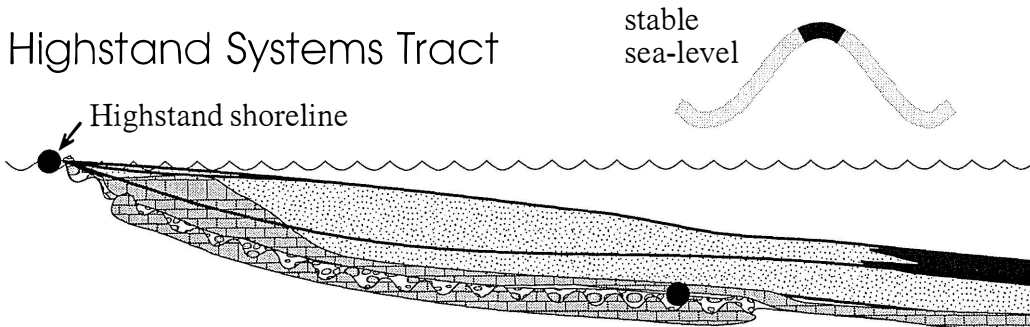


Trangressive Systems Tract



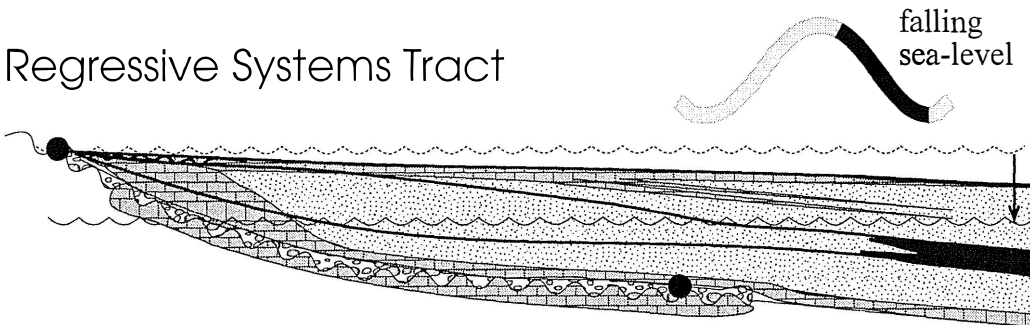
As sealevel rises from the previous lowstand, beach-innermost shelf conglomerate transgresses over the sequence boundary, sandstone is winnowed seaward of the conglomerate and forms a thin bed between the lower conglomerate and the overlying late transgressive limestone conglomerate. Elsewhere thin tidally laminated sandstone with intraformational or channel fill and lag conglomerates form.

Highstand Systems Tract



During the sea-level stillstand of the HST, limestone formation continues near the shoreline. Basinward tidally laminated sandstone and siltstone occur, which are typically very thick.

Regressive Systems Tract



During the lowering of sealevel, much sediment which was deposited during the HST is exposed and reworked basinward. This occurs by strong tidal, storm and wave currents, causing tempestites and wave rippled sandstone. Limestone is reworked basinwards and progrades across the shelf.

exposed, the sediments eroded and reworked basinward. Terrigenous sediment deposition is minimal here and limestone deposition occurs throughout the sequence/cycle. Sediment bypassing and erosion dominates in this location. Sequence 2-b is interpreted to form basinward of the highstand shoreline and landward of the lowstand shoreline. Terrigenous sediment accumulates here during both the transgression and highstand. Thin reworked limestone sheets prograde over the shelf on lowering of sea-level. Sequence 3 and 2-c are interpreted as deeper and more basinwards as storm and tidally reworked sediments dominant during regressions. Sequence 2-c is considered to represent a more basinward setting than sequence 3, as wave induced sedimentary structures do not occur, inferring deposition below wave base. Sequence 8 is interpreted as having been deposited basinward of the lowstand shoreline, as no unconformity occurs at the base of the sequence. Limestone is reworked basinwards during the transgression, resulting in thin limestone beds and lenses. Siltstone is deposited during the highstand, which grades into calcareous sandstone.

Sequence 9 is interpreted that it has accumulated close to a structural high with a carbonate 'factory' on, with limestone sheets (facies L2) periodically reworked off it.

### 4.2.1.3 Interpreted Evolution of the Titiokura Formation

Figure 4.5 displays for the Titiokura Formation the interpreted development of a relative sea-level cycle and associated system tracts. During an LST the shelf is exposed to subaerial erosion, and erosion of the underlying sequence occurs. A basal conglomerate forms on the shoreface and inner-most shelf, with tidal facies forming in the inner shelf. During the sea-level rise the conglomerate onlaps the underlying sequence. The transgression also allows the formation of tidal facies S4-a. Intraformational conglomerates are only expected to be preserved during a rising sea-level. This facies does not occur far basinwards of the lowstand shoreline as a relatively high-energy environment is required to form conglomerates. Instead tidal facies S4-b occurs. As the shoreline reaches its maximum transgression, limestone deposition occurs near the highstand shoreline. Abundant accommodation space results in thick tidal laminations (facies S4-b, in sequences 2-b, 3, and 2-c), and basinward of the lowstand shoreline siltstone (Z2-a) is deposited (sequence 8). As sea-level falls, deposits near the highstand shoreline are exposed, eroded, and reworked basinwards. This results in the progradation of reworked limestone (facies L2) basinward of the highstand shoreline

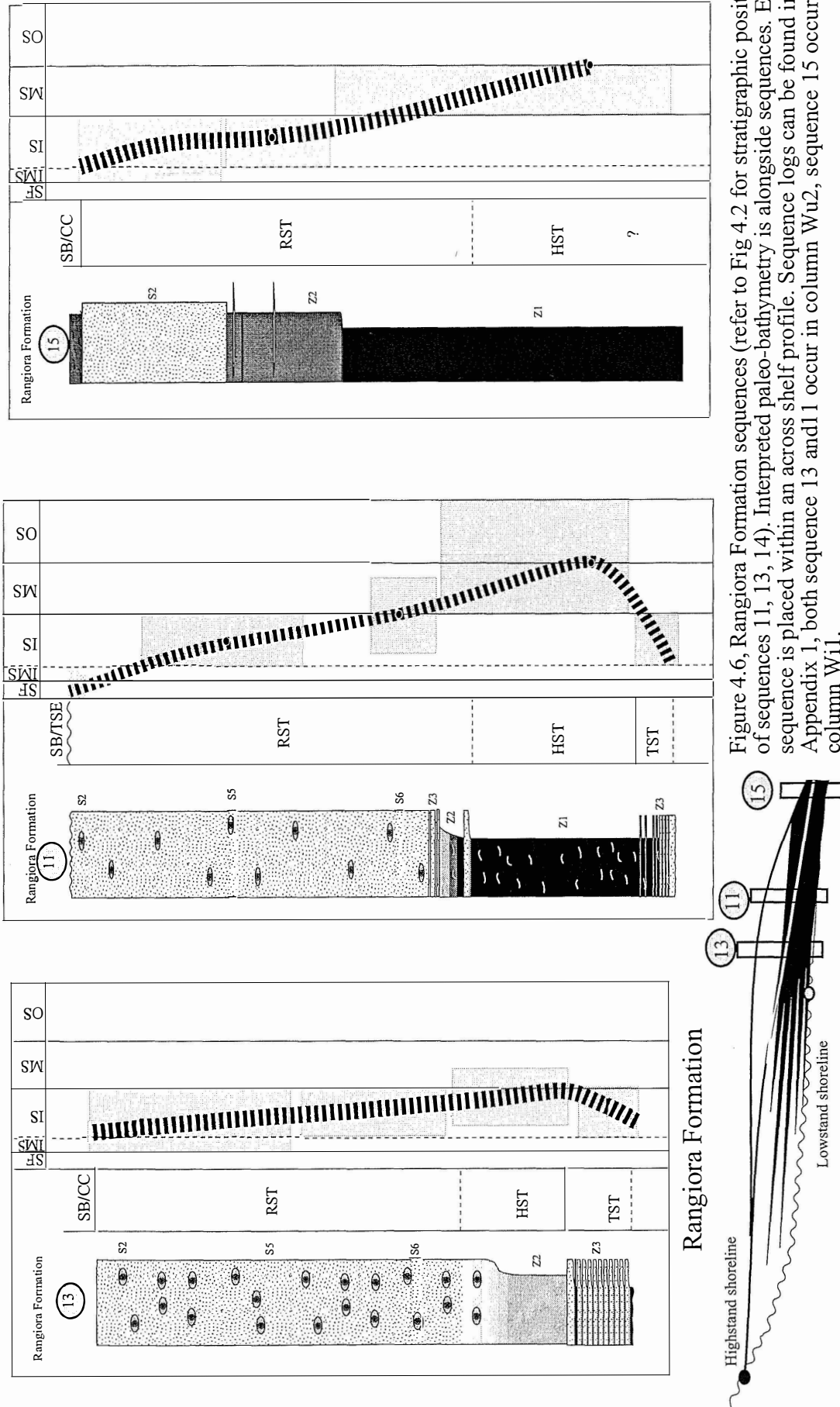


Figure 4.6, Rangiora Formation sequences (refer to Fig 4.2 for stratigraphic position of sequences 11, 13, 14). Interpreted paleo-bathymetry is alongside sequences. Each sequence is placed within an across shelf profile. Sequence logs can be found in Appendix 1, both sequence 13 and 1 occur in column Wu2, sequence 15 occurs in column W11.

(sequences 2-b, 3, 2-c, and 8). No regressive deposits occur near the highstand shoreline as the regression involves sea-level lowering. This interpretation is analogous to a model put forward by Nelson *et al.* (1982) for the Three Kings, in which limestone in a tidally dominated shelf environment are reworked across the shelf, during periods of sea-level lowering.

## 4.2.2 Rangiora Formation Sequence Architecture

A generalised motif for the Rangiora Formation is shown in Fig 4.1. Selected sequences from within the Rangiora Formation are shown in Fig 4.6.

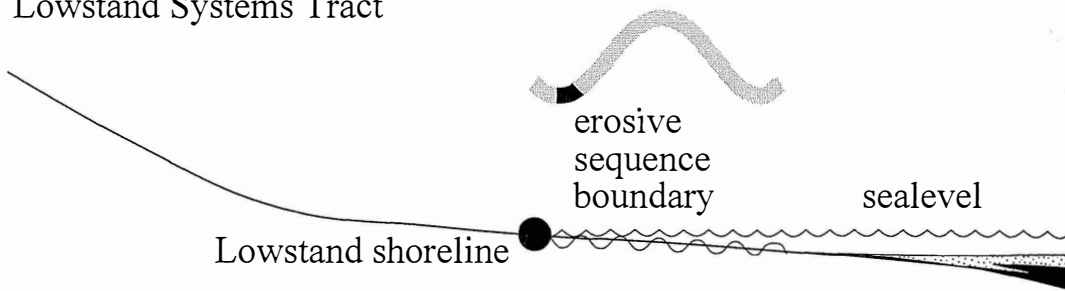
The generalised motif (Fig 4.1) for the Rangiora Formation is comprised of parasequences of siltstone and sandstone, typically 5-10 m thick, which onlap conformably or unconformably on to the lower sequence boundary. The parasequences are probably caused by high sediment influx during a relatively slow sea-level rise (Naish and Kamp 1997). The siltstone to sandstone ratio increases basinward and siltstone becomes more dominant as sandstone is trapped landward by the rising sea-level. The parasequences are conformably overlain by siltstone to silty-sandstone (sandier facies representing more sediment influx, probably due to shallower water or differing tectonic regime). Siltstone is formed during the highstand systems tract. This is gradationally overlain by the RST (regressive system tract) as sea-level begins to fall, resulting in sandstone deposition, reaching 100 m thickness. The sandstone shows little variation upwards, although rare toplap shellbeds and amalgamated sandstone occur.

### 4.2.2.1 Sequences in the Rangiora Formation

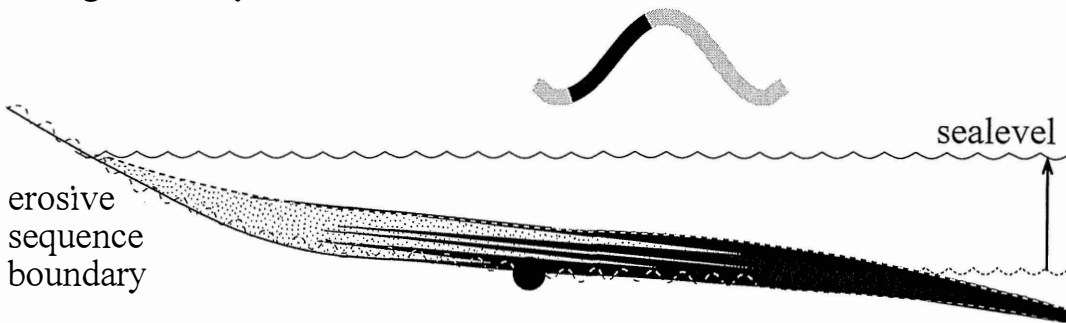
Three sequences from the Rangiora Formation are shown in Fig 4.6, with interpreted paleo-bathymetry alongside. Sequence 13 (section Wu2) is very similar to the generalised model, except the sandstone-siltstone parasequences are thicker (the lower sequence boundary is obscured), and sandy siltstone occurs instead of siltstone. Sequence 11 (section Wu2) is also very similar to the generalised model. Parasequences onlap conformably onto sandstone of the underlying sequence. These occur during a rising sea-level where sediment supply is large. The parasequences are conformably overlain by siltstone representing the sea-level highstand. The HST siltstone grades upsection into the overlying RST sandstone, which is typically very thick. Sequences in this formation are 70 – 150 m thick.

Fig. 4.7; Rangiora and Waipunga Formations. Sequence Motif and Systems Tract development

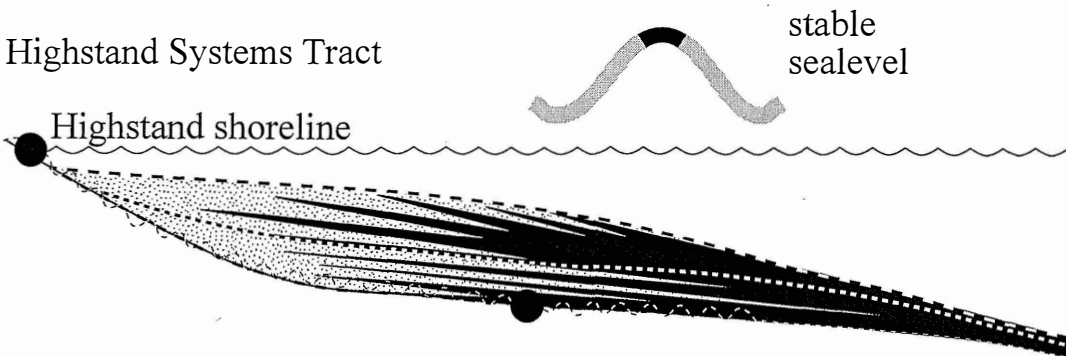
Lowstand Systems Tract



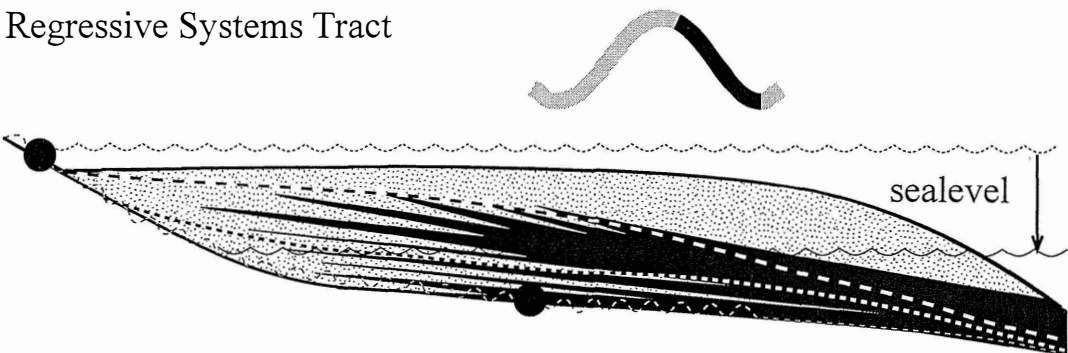
Transgressive Systems Tract



Highstand Systems Tract



Regressive Systems Tract



In sequence 15 (section Wi1) no basal sequence boundary occurs, as the bathymetry is considered to be deep for any sandstone or other lithology change to occur. There is considered a correlative conformity to the underlying sequence. The siltstone shoals up into sandy siltstone, which is sharply overlain by massive sandstone, representing a RST.

#### 4.2.2.2 Interpreted cross shelf profile

In Fig 4.6 an across-shelf profile is drawn, with an interpreted position of the sequences. Sequence 13 is deposited landward of the lowstand shoreline, and onlaps the underlying sequence described above. Sequence 11 is interpreted as having been deposited basinward of sequence 13, due to thinner parasequences and a finer grained HST deposit. It is not possible to infer whether it is deposited landward or basinward of the lowstand shoreline as the bounding sequence boundary is not observed. Sequence 15 is deposited basinward of the lowstand shoreline at the start of the sequence. The sequence boundary occurs with undifferentiated siltstone. The massive sandstone on top of the sandy-siltstone is interpreted as a thin wedge of regressive sandstone, which has prograded basinward.

#### 4.2.2.3 Interpreted Evolution of the Rangiora Formation

Figure 4.7 displays the interpreted systems tract evolution of the Rangiora Formation. During sea-level lowstand a wavecut surface is formed across the exposed shelf down to fair-weather wave base at the lowstand. Siltstone is deposited on the inner-mid shelf. During the transgression the wave cut surface retrogrades across the shelf, resulting in a TSE. A slow sea-level rise coupled with adequate sediment supply results in the accumulation of retrogradational parasequences (Naish and Kamp 1997), which grade into the HST deposit. During the sea-level highstand siliciclastic sandstone starvation may occur and siltstone is deposited. As the sea-level begins to fall wedges of sandstone prograde across the shelf, and the highstand siltstone grades up into sandstone. During the regression sandstone is reworked from near the highstand shoreline basinwards and thick RST deposits occur. In distal settings (sequence 15) only thin sand sheets prograde this far and are probably rapidly emplaced. Thin sandstone laminae may be the only indicator of the regression in such distal settings (see sequence 16 in column Wi1, in Appendix 1).

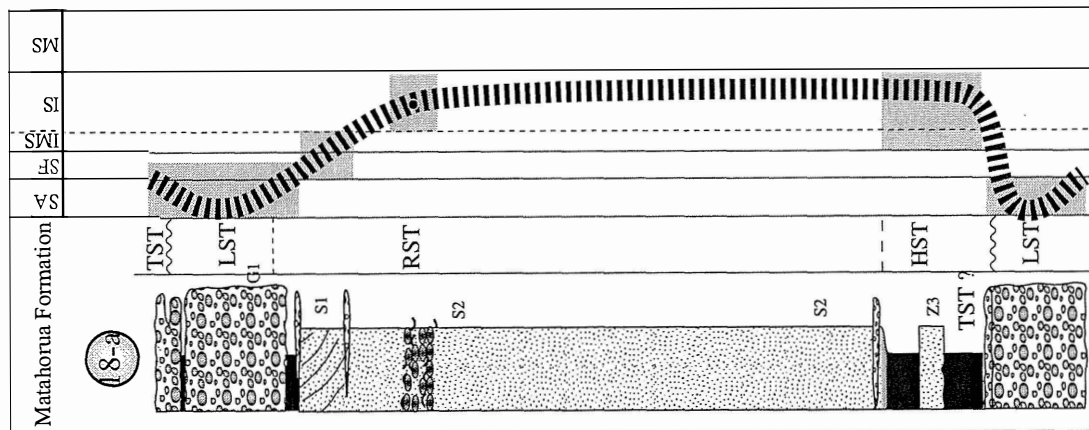
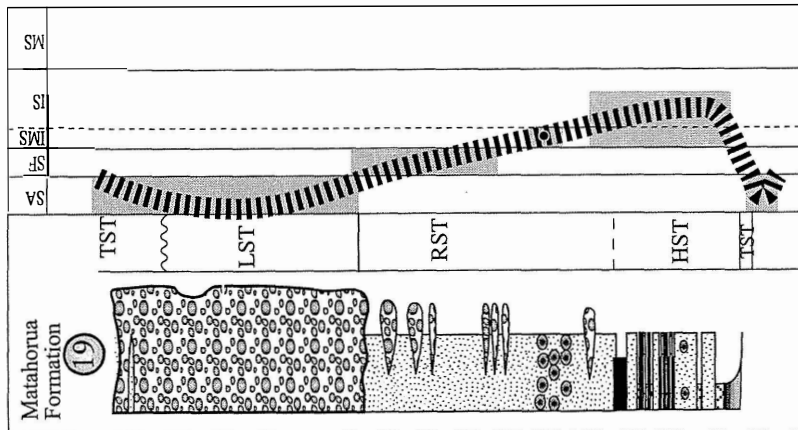
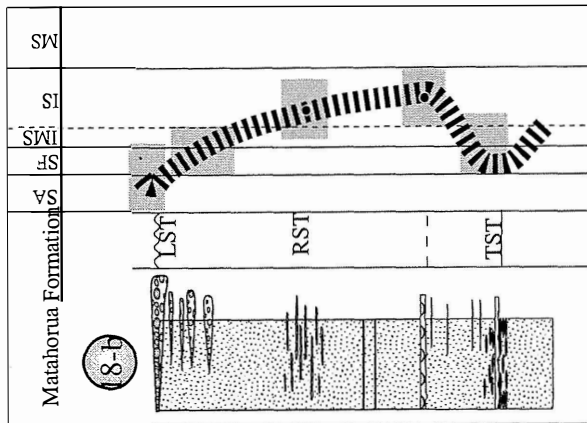
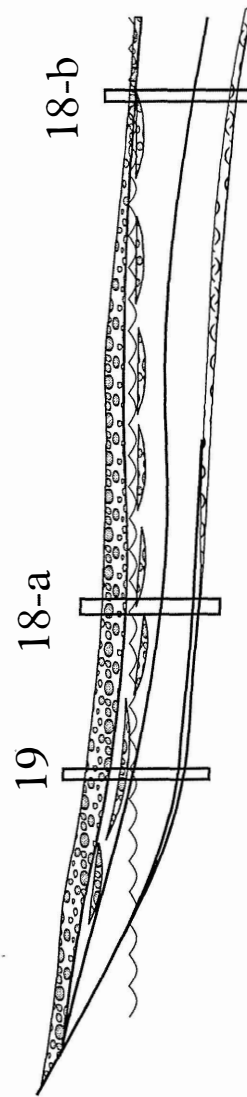


Figure 4.8; Matahorua Formation sequences, and interpreted paleo-bathymetry. Sequences 18-a and 19 are deposited in a more proximal setting to the braid plain while sequence 18-b is more distal.



### 4.2.3 Matahorua Formation Sequence Architecture

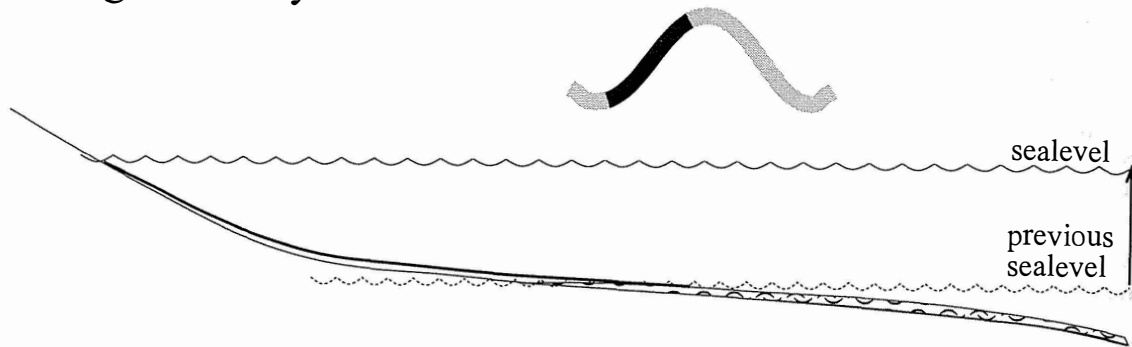
The generalised Matahorua Formation motif (Fig. 4.1) consists of greywacke conglomerate and siliciclastic sandstone. It is characterised by a basal unconformity, which is placed towards the top of the conglomerate, below reworked transgressive gravels. Transgressive deposits in this facies are interpreted as very thin and grade rapidly upward into overlying highstand deposits. Occasional transgressive deposits can be identified at the top of the conglomerate as reworked conglomerate material. This accumulates as sea-level rises over the conglomerate reworking the underlying material. During the sea-level highstand, siltstone and sandstone interbedding occurs. This probably represents siltstone between sand lobes on the pro-delta. The sandstone and siltstone coarsens upwards into the regressive systems tract, which is typically comprised of massive sandstone with gravel lenses, which are reworked basinwards as relative sea-level falls. As sea-level falls, toplap shellbeds occur and the regressive system tract is commonly topped with shoreface facies assemblages. Further lowering exposes the shelf, upon which rivers then prograde resulting in a broad braid plain. Greywacke conglomerates conformably but with some basal scouring overlie shoreface facies. The conglomerates are considered lowstand deposits because they accumulated in a sub-aerial environment. Rare lignite beds also indicate sub-aerial exposure.

#### 4.2.3.1 Sequences in the Matahorua Formation

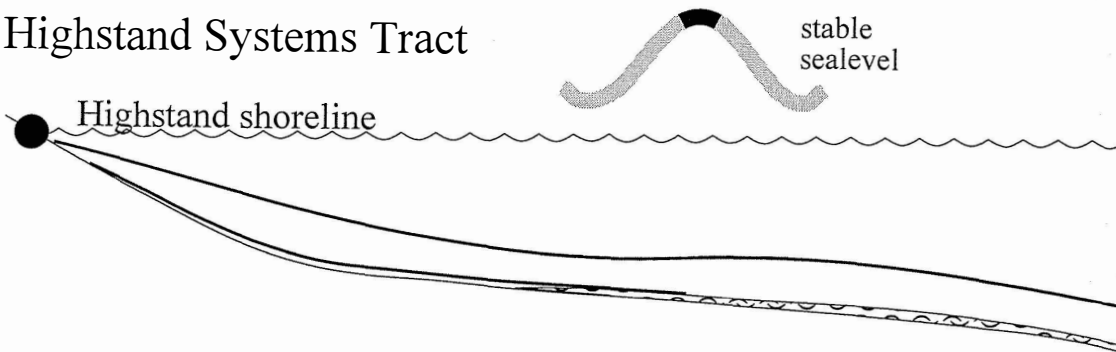
Actual sequences for the Matahorua Formation are shown in Fig 4.8. The generalised motif (from Fig 4.1) represents an actual sequence (19) and is considered representative enough of the majority of Matahorua Formation sequences. Sequence 18 is the only other sequence, which varies enough to be discussed. It is comprised of an onlap shellbed indicating the lower unconformable sequence boundary, and TST. This sequence is composed almost entirely of massive to cross-bedded sandstone throughout. No distinct sedimentary facies forms during the HST, although faunal information does indicate a maximum transgression on the relative sea-level curve. This may infer a downlap shellbed, although it is more likely a toplap shellbed. This is overlain by regressive sandstone with shell lenses and grades into sandstone with thin conglomerate lenses topped by thin (<1 m) conglomerate bed indicating subaerial exposure and thereby a LST.

Fig. 4.9: Matahorua Formation.  
Sequence Motif and Systems Tract development

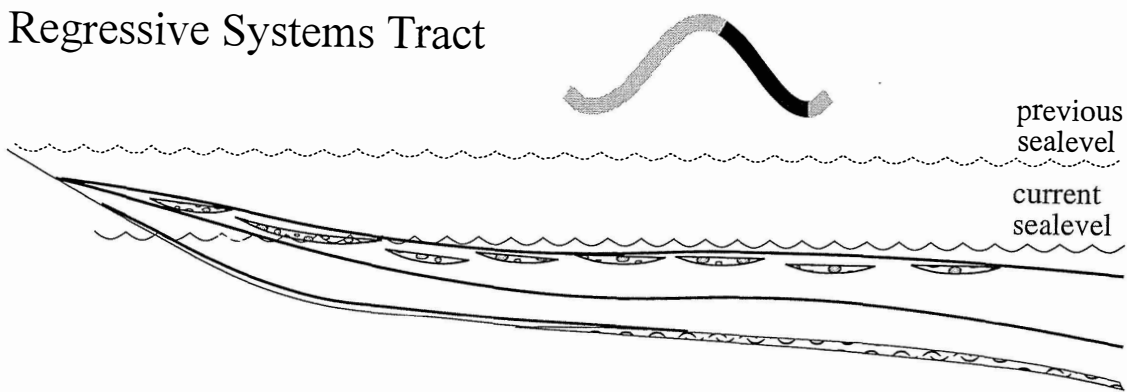
Transgressive Systems Tract



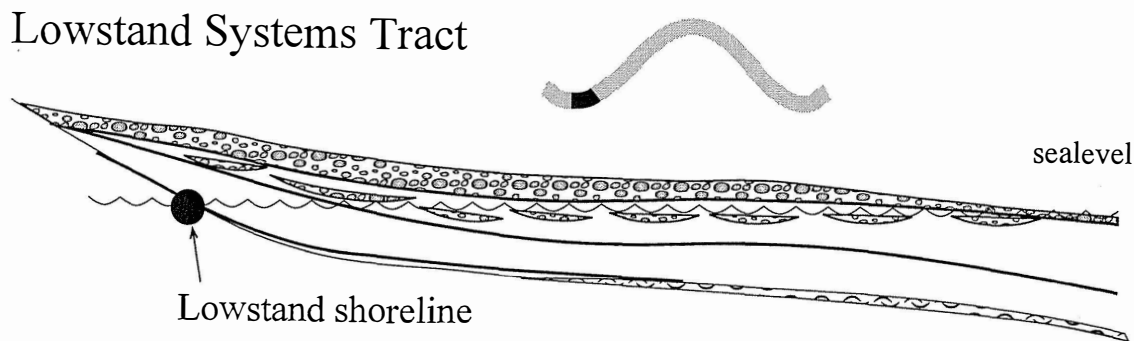
Highstand Systems Tract



Regressive Systems Tract



Lowstand Systems Tract



#### 4.2.3.2 Interpreted cross shelf profile

Sequences from the Matahorua Formation are shown in Fig 4.8, along with an interpreted position in an across shelf profile. The generalised motif (sequence 19) is deposited landward of sequence 18. Sequence 18 is dominated by siliclastic sandstone and toplap shellbeds, thin conglomerate beds indicate less time of subaerially exposure. This indicates sequence 18 was deposited basinward of sequence 19 or at the edges of the large braid plain, with siliclastic sandstone deposition dominating.

#### 4.2.3.3 Interpreted Evolution of the Matahorua Formation

Fig 4.9 displays an interpreted system tract development of the Matahorua Formation. The thin onlap shellbed forms during a relative sea-level rise as sediments are trapped shoreward. Some siltstone is deposited in varying areas during the sea-level highstand, probably representing areas between sand lobes. On sea-level lowering the shelf near the highstand shoreline is exposed and sediment is reworked basinwards. Toplap shellbeds and conglomerates with mixed water assemblages occur. Initial subaerial exposure is characterised by thin lensoidal conglomerates, which represent beach fluvial channels. Brief sub-aerial exposure limits conglomerate deposition to thin beds in distal areas to the braid plain, while in proximal settings thick conglomerate successions accumulate.

#### 4.2.4 Waipunga Formation Sequence Architecture

The generalised cycle motif for the Waipunga Formation is shown in Fig 4.1. It is represented by a thin (> 1 cm) erosionally based onlap shellbed, which occurs due to rapid sea-level rise and low terrigenous sediment input. An alternative expression is one of thin sandstone and siltstone interbeds, which occurs where sediment supply is high and sea-level rise is relatively slow (Naish and Kamp 1997). Both types of TST occur at the base of thin (2-3 m) highstand siltstone beds, which coarsen upsection, typically with a series of progradational parasequences into massive micaceous sandstone with occasional toplap shellbed, and tabular crossbeds occurring at the top of sequences.

Fig 4.10, Waipunga Formation sequences.

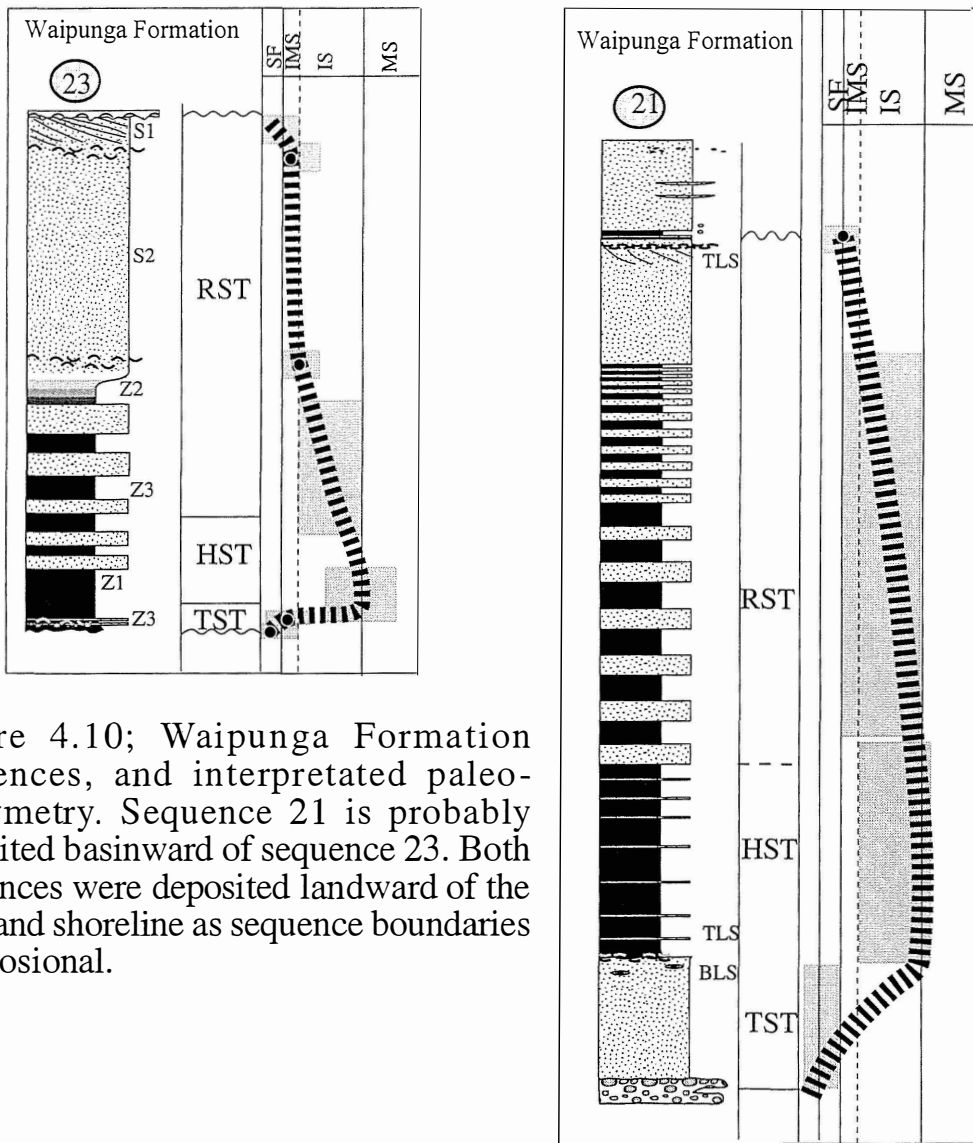
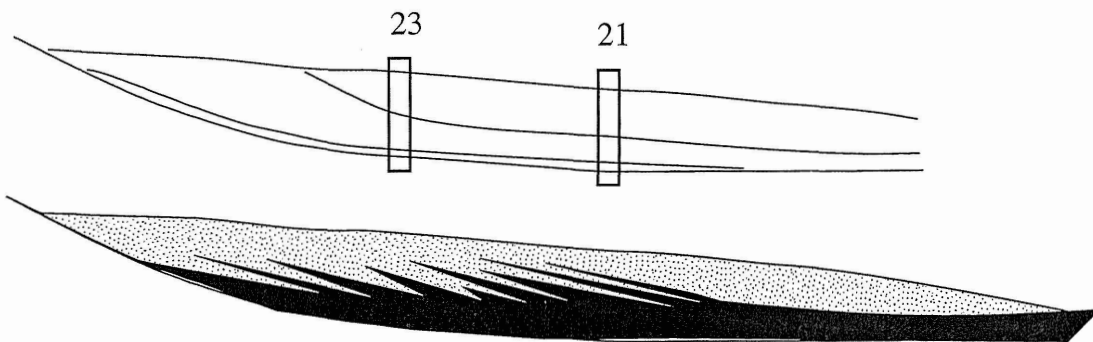


Figure 4.10; Waipunga Formation sequences, and interpreted paleobathymetry. Sequence 21 is probably deposited basinward of sequence 23. Both sequences were deposited landward of the lowstand shoreline as sequence boundaries are erosional.

### Waipunga Formation



#### 4.2.4.1 Sequences in the Waipunga Formation

Two sequences are shown in Fig 4.10 of Waipunga Formation sequences. Sequence 23 is the generalised motif and is representative of the Formation. Sequence 21 is considerably thicker (35 m) than sequence 23. This sequence grades out of the underlying sequence of the Matahorua Formation with a basal correlative conformity. Conglomerate at the base of the sequence is overlain by barren sandstone, which contains a weak backlap shell at the top. This formed due to sediment starvation on the shelf during the sea-level rise. This is topped by a downlap surface with a weakly fossiliferous downlap shellbed, which formed during late sea-level rise (HST). The HST is composed of siltstone with thin sandstone laminae, which occurs because of high sediment flux even during highstand conditions. With the start of relative sea-level fall sandstone is reworked basinward, and grades from the HST to regressive sandstone beds (which are thicker than those deposited during the HST). The siltstone-sandstone interbeds are overlain by massive sandstone with heavily burrowed toplap shellbeds, with a wave cut surface above forming the sequence boundary.

#### 4.2.4.2 Interpreted across-shelf profile

Both described sequences are placed in an interpreted across shelf setting in Fig 4.10. Sequence 21 is probably deposited basinward of sequence 23, as siltstone is more prominent in this sequence. Both are deposited landward of the lowstand shoreline, as sequence boundaries indicate either a wave cut surface or subaerial exposure, and shoreface facies (S1) occur at the top of both sequences.

#### 4.2.4.3 Interpreted Evolution of the Waipunga Formation

Development of the Waipunga Formation system tracts is considered very similar, if not the same as the Rangiora Formation (both are dominated by siliciclastic sandstone and siltstone) and is interpreted in Fig 4.7. The essential difference is that all sequences within the Waipunga Formation are considered deposited land-ward of the lowstand shore line and therefore have basal unconformities.

## 4.3 Discussion

### 4.3.1.1 Sequence Boundaries

Sequence boundaries occur as erosional surfaces, or as conformable surfaces. Within the Titiokura Formation sequence boundaries occur as erosional surfaces at the base of conglomerates or as sharp-based surfaces on top of limestone or calcareous sandstone. In the Rangiora Formation, sequence boundaries are sharp and planar, with siltstone sharply overlying sandstone. Sequence boundaries within the Matahorua Formations are interpreted as unconformities within and occasionally on top of greywacke conglomerates. Basin-ward, cycles often have thin shell-beds with shell hash marking the sequence boundary, or sparsely fossiliferous shellbeds with tabular cross-bedding, greywacke pebbles, and sandstone siltstone interbeds, particularly in the Waipunga Formation.

### 4.3.1.2 Transgressive Systems Tract

A high rate of sea-level rise and low terrigenous sediment supply results in sediment-starved deposits such as shellbeds. Low rates of sea-level rise and adequate sediment supply results in retrogradational para-sequences (Naish and Kamp 1997).

Transgressive Systems Tracts in the study seem to be associated with rapid sea-level rise. They are characterised by: 1) thinly bedded tidalities with channelised transgressive lag conglomerates; 2) aggradational and retrogradational parasequences, reworked conglomerate beds, which are typically less homogenous than the underlying conglomerate and smaller in grain size; 3) and massive sandstone topped by a weak backlap shellbed. Near the highstand shoreline transgressions are characterised by onlapping shoreface to innermost shelf conglomerates, which are commonly overlain by a late transgressive sediment starved limestone. Onlap shellbeds and occasionally weakly developed backlap shellbeds occur on the inner shelf caused by terrigenous sediment starvation during rising sea-level. Tidally laminated sandstone with intraformational conglomerates occurs where limited accommodation space means that erosion of underlying sediment occurs, resulting in channel lags. Where accommodation space is plentiful the thick tidally laminated facies (S4-b) occur.

### 4.3.1.3 Highstand Systems Tract

Highstand systems tracts correspond to the late rise and early fall of a relative sea-level cycle (Van Wagoner *et al.* 1988), the HST occurs above the downlap surface with the Maximum Flooding Surface (MFS) defining the upper boundary (interpreted as the point of maximum transgression) (Mail 1997). The HST is characterised as follows. In the Titiokura Formation placement of this systems tract is difficult to locate. It is placed above the tidally laminated facies S4-a, which occur during transgression, or at the base of finer grained packets of sediment, which infer a deeper water environment.

Highstand Systems Tracts in both the Rangiora and Waipunga Formations are characterised by siltstone, occasionally silty sandstone, typically with some thin sandstone inter-beds. In the Titokura Formation HST deposits are interpreted as thick sections of cyclic sandstone, or silty sandstone with mud drapes, where abundant accommodation space allowed for the deposition of cyclic beds. The boundary between HST's and RST's is difficult to identify in the field. Within the Matahorua Formation HST's are difficult to recognise because of the dominance of sandstone.

### 4.3.1.4 Regressive Systems Tract

Regressive systems tracts form during falling sea-level. They differ from Hunt and Tucker's (1992) forced regressive systems tract or Hart and Long's (1996) forced regression, as no basal surface of erosion or regressive surface of erosion occurs and instead grade upwards from the underlying highstand systems tract (Naish and Kamp 1997). Because no regressive surfaces of erosion occur in the field area, highstands are interpreted to grade into regressions.

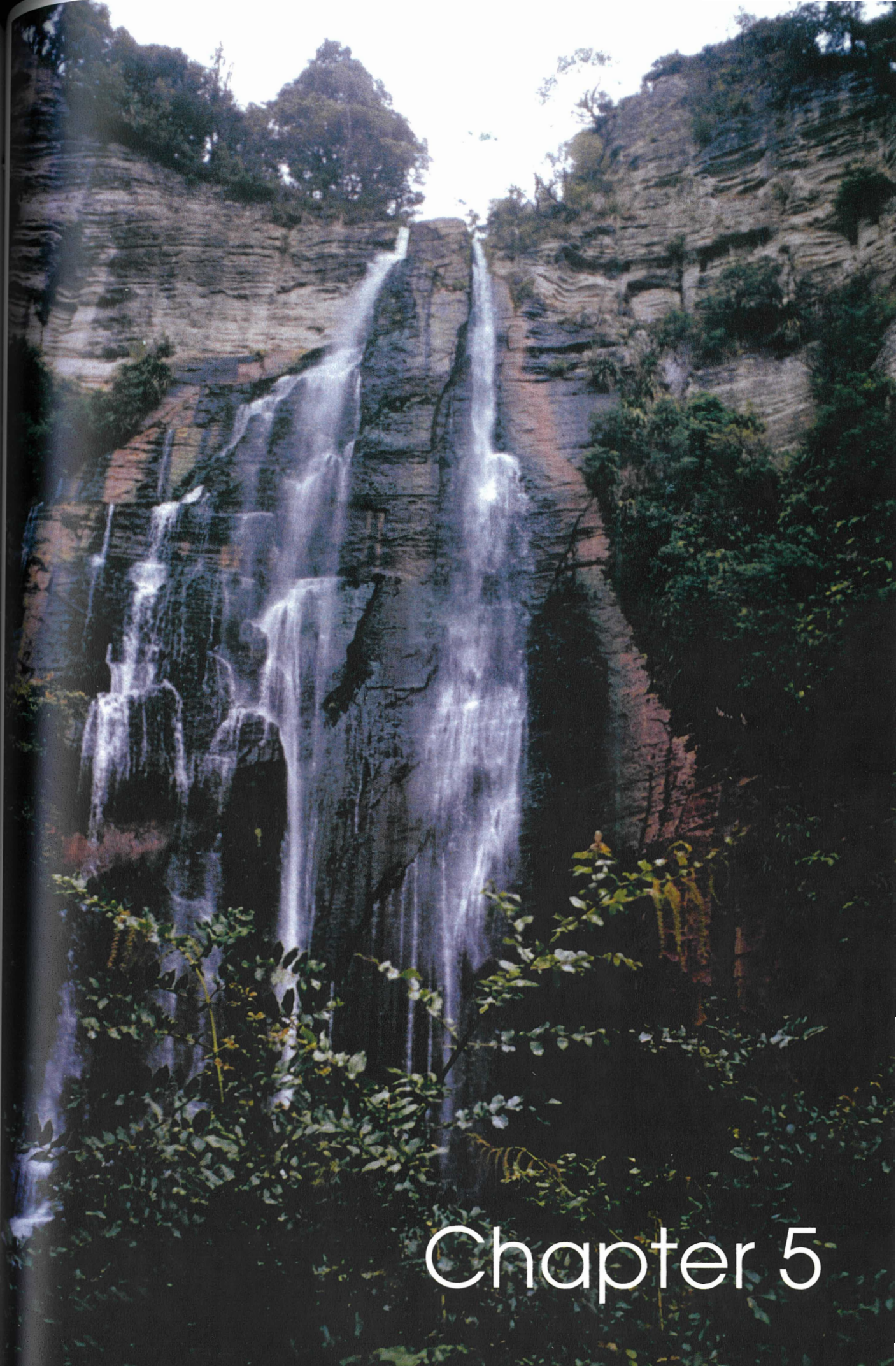
Regressive systems tracts in the Titiokura Formation are characterised by storm and wave reworked sediments. Mud drapes present in deeper water sediments are commonly eroded away due to the shallower more highly energised environment. Carbonate sediments are transported basinward as sea level falls exposing limestone near the highstand shoreline. This means that sequences near the highstand shoreline are commonly incomplete due to erosion, and basinward sequences are very thick.

In the Matahorua Formation regressions are characterised by shoaling upwards from inner shelf massive sandstone to shoreface sands and gravels, then sub-aerial exposure where braided river deposits prograde across the shelf and conglomerates are deposited.

The regressions within the Waipunga Formation are characterised by siltstone coarsening upward into sandstone, some times via interbedded siltstone and sandstone. The RST's may contain toplap shellbeds, and associated sandstone may have tabular crossbeds and or tube burrows, indicating shoreface deposition.

#### 4.3.1.5 Lowstand Systems Tract

Lowstand Systems Tracts (LST) form when the shelf is exposed to subaerial erosion; this type of systems tract is only found in the Matahorua Formation where a broad braid plain forms once sea level has dropped sufficiently to expose the shelf. After which rivers prograde across the shelf depositing greywacke conglomerates.



# Chapter 5

## *Chapter 5: Controls on Sedimentation and Synthesis*

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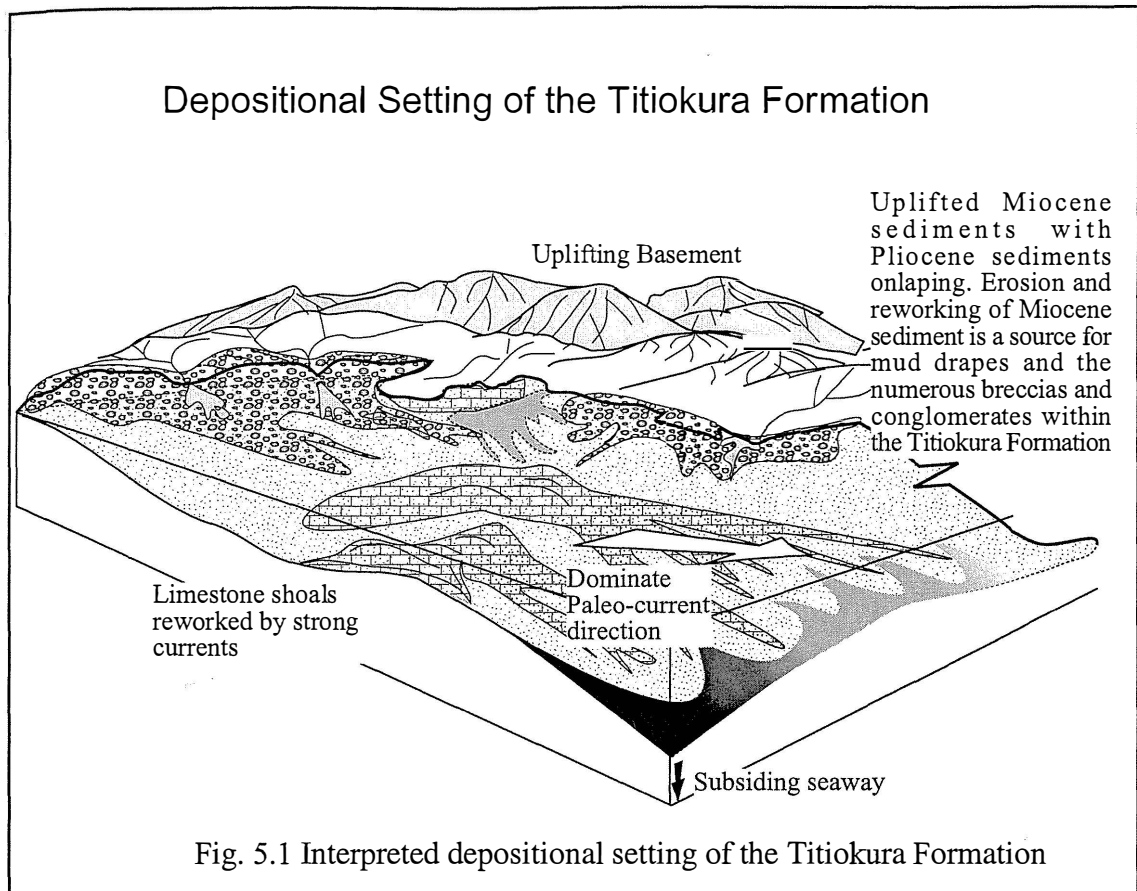
### 5.1 Introduction

The purpose of this chapter is to address the relative roles of eustasy, tectonism and sediment supply on structural and stratigraphic development of the sedimentary succession within the study area. Tectonism, eustatic sea-level changes, and sediment supply are considered to be the three major variables controlling stratigraphic development. In the forearc setting of Hawke's Bay tectonism expressed as basin subsidence and uplift and erosion in the hinterland thereby generating the sediment flux, is the dominant control on the nature of the succession.

#### 5.1.1 Formation Characteristics and their Significance

##### 5.1.1.1 Titiokura Formation

The Titiokura Formation is early Opoitian to early Waipipian in age. It is comprised of barnacle rich coquina, and siliciclastic sandstone with tidal laminations. It is considered to have been deposited in inner-most to inner shelf (and rarely to mid-shelf) paleo-environments. The limestone coquina sourced must have been derived from extensive barnacle 'banks' on the shallow margins of the seaway. These sediments were periodically reworked into deeper water possibly during falling sea-level conditions, forming storm and tidally emplaced coquina sheets (Fig. 5.1).



Ubiquitous greywacke pebbles occurring in coquina within the formation, indicate some uplift and erosion of basement rocks in the hinterland. However, despite this slow uplift in the west, sedimentary successions in both the Waikoau and Waikari catchments display an overall deepening upsection. This overall fining and deepening upwards is accompanied by a decrease in carbonate percentage, indicating a paleo-environment that became progressively more distal from the source carbonate. Decreasing evidence of tidal current activity upsection indicates a less restricted seaway developed with time in the basin.

A recurring feature of all successions in the study area is rapid lateral changes in thickness and lithology. The Titiokura Formation shows a gradation from a single limestone in the southwest of the study area, to a thick succession of siliciclastic siltstone, sandstone and calcareous sandstone in the northeast of the study area. This indicates that more accommodation space was generated in the basin in a northeastern direction into which the sediments prograded.

Although an overall deepening succession is interpreted in this formation, repetitive shoaling occurs due to eustatic sea-level fluctuations. Evidence for cyclothems becomes

less obvious in the southwest of the study area due to the thinner limestone-calcareous sandstone succession as a whole, which was associated with sediment bypassing and erosion of the seafloor.

Exceptions to this pattern occur at the Bellbird Bush and Opouahi limestone outcrops in the Waikoau catchment. There thick limestone blocks occur, although they do show signs of reworking. They are interpreted to form on structural highs, possibly antiforms, or other features, or a period of sudden shallowing. Common thin beds of reworked limestone 'finger out' laterally from these outcrops, and are considered to represent proximity to carbonate 'factories', with thin beds reworked basinwards upon sea-level lowering.

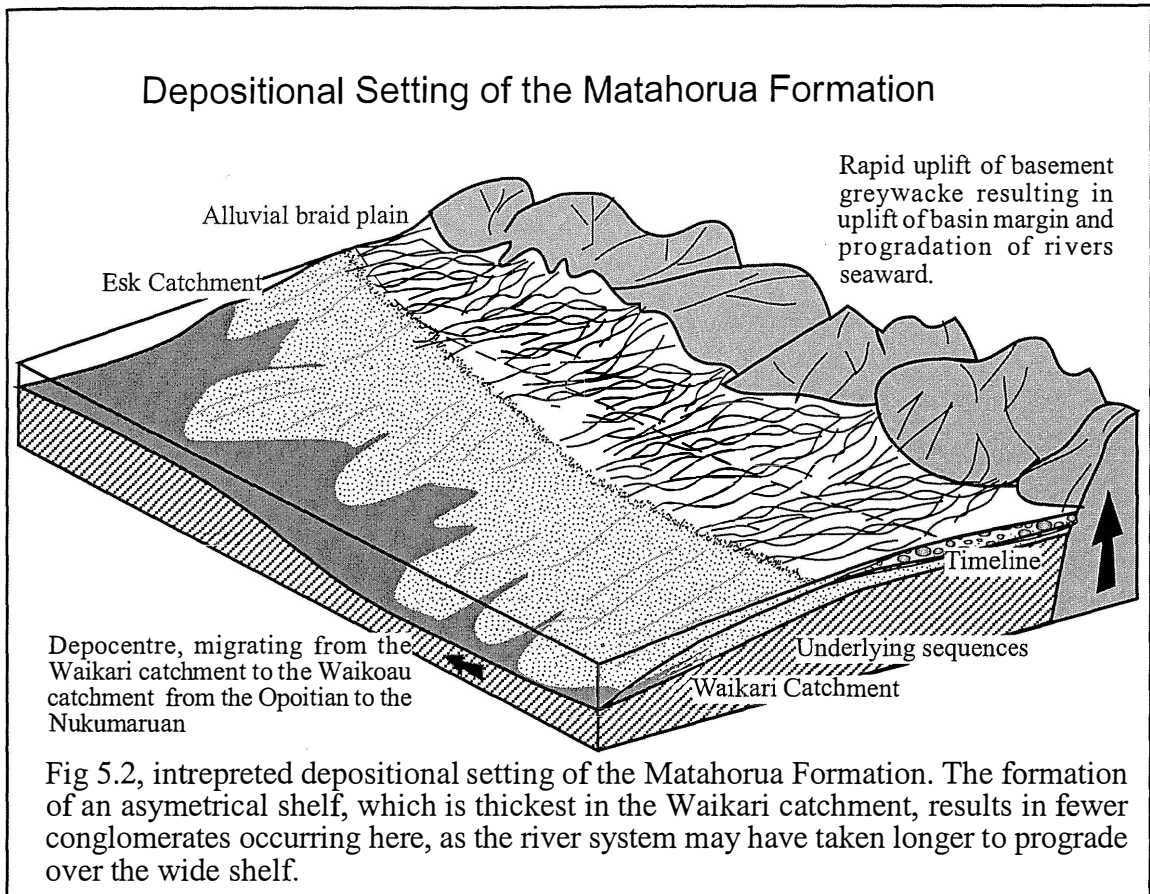
### 5.1.1.2 Rangiora Formation

The Titiokura Formation in effect grades into the Rangiora Formation, which is early Waipipian to late Mangapanian in age. It is dominated by sandstone in the Esk catchment, siltstone and sandstone cycles in the Waikoau catchment, and siltstone in the Waikari catchment. It was deposited in an inner to outer shelf paleo-environment. Only in the Waikoau River catchment is sedimentary cyclicity consistently observed. Very thick cycles occur in this formation (100 m+). The succession in the Waikari Catchment is considered too deep for any sandstone to have been deposited. The depositional paleo-environment in the Esk catchment at that time was too shallow for siltstone deposition. In the upper parts in the Waikari catchment the formation begins to coarsen upsection. This shoaling indicates the beginning of uplift within the basin during the Mangapanian.

### 5.1.1.3 Matahorua Formation

The Matahorua Formation is late Mangapanian to early Nukumaruan in age. It developed as a result of tectonic uplift and erosion of the axial ranges (Fig. 5.2) coupled with eustatic sea-level fluctuations in the basin, which intermittently exposed the shelf and allowed deposition in non-marine environments. The base of the formation is marked by concretionary horizons and fossiliferous shellbeds, which are otherwise rare in the Pliocene succession in the study area. This may mark a period of transgression, resulting in a degree of terrigenous sediment starvation, and hence accumulation of

carbonates. Lateral changes in lithology occur in the formation. The formation is finer grained in the northeast than the southwest of the basin.



The progradation of the Matahorua Formation conglomerates into the basin marks the initiation of uplift and erosion of the axial ranges (Fig. 5.2). Dips measured on the conglomerates increase with stratigraphic age, indicating steady tilting within the basin during and after their deposition.

In the Waikari catchment because the progradation of sequences was more rapid in Opoitian to early Mangapanian times, the resulting paleo-shelf in the Waikari catchment is wider than in the Esk and Waikoau catchments (Fig 5.2). The result is that more time is required for rivers to prograde over the shelf in the Waikari catchment, and therefore not all of the conglomerate units occur in this catchment. The conglomerates 'pinch out' to the north representing the northward progradation of the braid plain with time and an overall regression in the basin during this time.

#### 5.1.1.4 Waipunga Formation

The Waipunga Formation is characterised by thinly bedded sandstone and siltstone. It is of Nukumaruan age and is overlain by the Esk Formation and other younger Petane Group sediments as described by Haywick (1991). Sedimentology of this formation indicates a nearby-enclosed embayment with continued subsidence, a high siliciclastic influx and sea-level oscillations occurring during the emplacement of this formation.

## 5.2 Controls on Stratigraphic Development

Bathymetric changes in a sedimentary cycle are controlled by three variables, eustatic sea-level change, rate of subsidence, and rate of sediment supply. However, interpreting which variable dominates the controls on sedimentation is difficult. This is particularly so given the forearc basin setting of the basin and its location within a plate boundary zone. However, rapid rates of subsidence can be advantageous in producing thick sequences that may carry a sea-level signature.

### 5.2.1 Tectonic Controls

Since 10 Ma an increasingly compressive component of strain between the Australian and Pacific plates and associated crustal shortening, has result in uplift in the basement axial ranges in the west, and subsidence in Hawke's Bay basin. It is this subsidence coupled with periodic uplift in the west, which leads to the development of the Waunganui-Hawke's Bay paleo-seaway and deposition within it (Fig. 5.3). Sustained subsidence in the basin coupled with tilting of the basin margin characterise the tectonic effects during the Pliocene, with tilting gradually increasing from the latest Miocene into the Pleistocene. In the field area uplift of the Axial Ranges coincides with movement on local faults, such as the Mohaka, Te Kooti, and the Pohokura Thrust faults. The development of the Hikurangi Margin during the Miocene is a result of plate convergence and is the main factor instigating sustained subsidence of Hawke's Bay basin, particularly since the Late Miocene. Imbricate faulting and scraping of sediments on to the overriding crust, loads the crust and initiates subsidence, but this mainly affects the coastal hill country south of Cape Kidnappers and offshore beneath the modern shelf and slope. The origin of the subsidence in the forearc basin of Hawke's Bay is not really known.

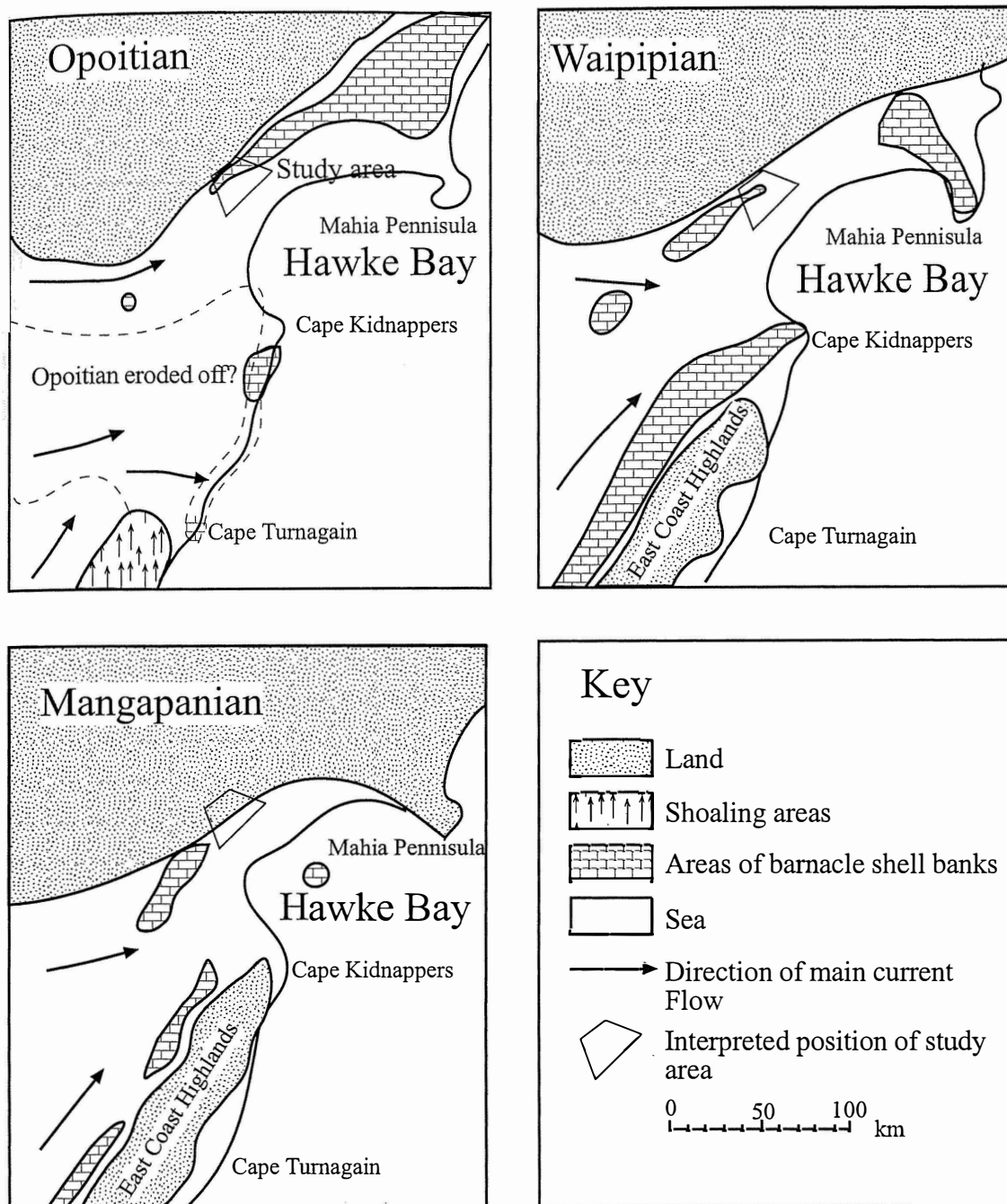


Figure 5.3, Development of the Wanganui-Hawke's Bay seaway during the Pliocene (Adapted from Beu *et al.* 1980).

The Mokonui Formation reflects shelf development across underlying bathyal mudstone. The Titiokura Formation is characterised by sediment bypassing, reworking and overall deepening. Subsidence in the seaway continues well into the Waipipian, with sediments derived from the axial ranges forming further to the east. The Rangiora Formation was deposited during this period of prolonged basin subsidence. It continued into the late Waipipian to early Mangapanian when subsidence slowed and shoaling occurred in the basin.

A widespread period of folding and reverse faulting occurred from c. 2.5 Ma, but particularly after 1 Ma (Kelsely *et al.* 1995, in Field and Uruski 1997, p 112). This corresponds to an increase in the compressional component on the plate boundary during this time. This is manifested by formation of the Ruahine and Kaweka Ranges. This uplift extended into the basin allowing a wide river braid plain and delta to form. This corresponds to deposition of the Matahorua Formation. Dips in this formation shallow from 18° to 9° indicating tilting of the margins of the basin, thereby promoting the progradation of conglomerates. Progressive tilting continued into the Waipunga Formation, with dips as low as 5° occurring within it.

## 5.2.2 Eustatic Controls

During the Plio-Pleistocene (from about 2.75 Ma), eustatic sea-level changes caused by the repeated accumulation and melting of the ice on the Northern Hemisphere continents have been a feature of Earth history. However, sea-level cycles are evident in the sedimentary succession from the early Opoitian (c. 5 Ma) onwards, suggesting that prior to 2.75 Ma ice was fluctuating on Antarctica. Cyclothems, the stratigraphic expression of relative sea-level changes are only expressed when paleo-bathymetric conditions are right for their preservation or deposition. In many parts of the succession in the area cyclothems are not distinguishable. The periodicity of the cycles that are evident are difficult to establish without the absolute dating of horizons in the succession. However, there appears to be a general trend of increasing order of cyclicity, and also an increase in amount of paleo-bathymetric change within cyclothems from the Opoitian to the Nukumaruan.

While sequences in older successions (Titiokura Formation) in the field area show successions of sedimentary facies, inferred to result from sea-level fluctuations, the over-riding control in these successions is most likely the rate of subsidence.

Eustatic sea-level changes may be explained by cyclic changes in the Earth's tilt and orbit, known as Milankovitch cycles. These changes in the Earth's orbit affects the amount of growth and melting of Northern Hemisphere ice caps particularly since 2.75 My. There are three orbital rhythms 1) change in the Earth's orbit (eccentricity) around the sun (400 000 – 100 000 year periodicity), 2) tilt of the Earth's axis (41 000 year periodicity) also termed obliquity or 6<sup>th</sup> order cyclicity, and 3) wobble (or precession)

due to the tilt axis sweeping out a cone (21 000 year periodicity) (Plint *et al.* 1992, p 20).

Nine cycles are identified in the Opoitian sedimentary succession in the field area, corresponding to c. 190 ka per sequence. Cycles during the Opoitian are typically c. 60 – 80 m thick, with sea-level fluctuations of less than 50 m. During the Waipipian-Mangapanian cyclothems are thicker, at around 100-150 m, and appear to comprise a slightly broader paleo-bathymetric range, c. 60 –80 m. Ten cycles are identified during the Waipipian-Mangapanian amounting to 135 000 ka each. Late Mangapanian cycles are almost certainly 41 ka cycles (6<sup>th</sup> order). The Nukumaruan cyclothem record is considered an excellent 6<sup>th</sup> order cyclicity record with 13 cycles occurring (= 650 000 years / 13 = 50 000 Ky ~ 41 ky cycles).

### 5.2.3 Sedimentation Rate

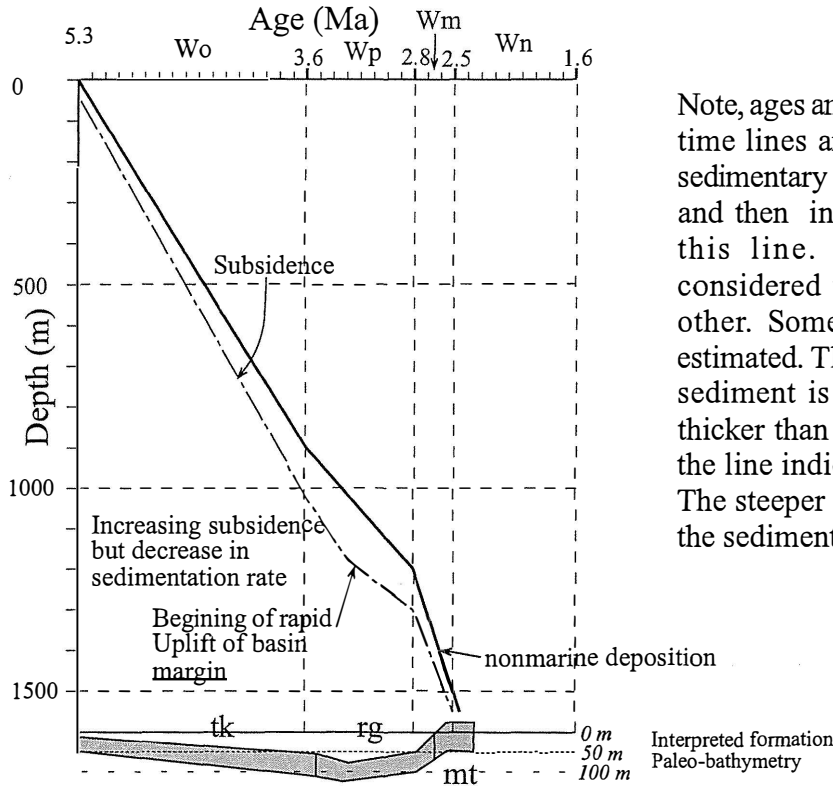
Table 5.1 Sediment Accumulation Rates

Age (NZ Stages)	River catchment and sedimentary thickness	Sediment Accumulation Rate
Opoitian 5.3 – 3.6 = 1.7 million years	Taraponui = 80 m Naumai = 500 m Waikari Catchment = 900 m	<u>0.05 m/ky</u> <u>0.3 m/ky</u> <u>0.5 m/ky</u>
Waipipian 3.6 – 2.8 = 800 000 years	Waikoau catchment = 600m Waikari catchment = 300	<u>0.8 m/ky</u> <u>0.4 m/ky</u>
Mangapanian 2.8 – 2.5 = 550 000 years	Waikoau/Waikari catchment = 300m	<u>0.5 m/ky</u>
Nukumaruan 2.5 – 1.6 = 650 000 years	Waikoau catchment = 500 m	<u>0.8 m/ky</u>

Table 5.1. Sediment Accumulation Rates for the Pliocene in the Esk, Waikoau and Waikari river catchments.

Figure 5.4 displays Pliocene sediment thickness versus age. The gradient of this line represents sedimentation rate. The steeper the gradient of the line the greater the sedimentation rate (actual sedimentation rates are shown in table 5.1), and *vice versa*. The shaded area indicates the interpreted paleo-bathymetric range of the formation/member. When the interpreted shaded area is added to the line representing sedimentary thickness versus age, this represents the subsidence required for deposition of the Pliocene succession (minus compaction, as it is not taken into account). A number of assumptions are made for this, assuming vertical stacking of sediments rather than basinward prograding stacking of sequences, estimation of the ages of some stage boundaries for this propose, and estimation of some thicknesses where exposure is incomplete. From this graph, four sedimentation rates could be inferred, but it should be considered that only four divisions occur within this graph and therefore that observation is misleading. It also should be pointed out that the inferred thickness of the sedimentary succession in the Waikari catchment for the Waipipian is an estimate. It does however show an increase in the sedimentation rate over time (with an exception in the Waikari catchment where the sedimentary succession thickness is an estimate). Changes in environment of deposition may be coupled with increases in sedimentation rate, especially when tectonic activity is high.

Waikari catchment sedimentary succession



Note, ages and depths are traced along time lines and depth lines until the sedimentary succession thickness line and then interpreted at an angle to this line. All successions are considered to stack on top of each other. Some stage boundaries are estimated. The thickness of Wp aged sediment is estimated and may be thicker than estimated. Gradients of the line indicate sedimentation rate. The steeper the gradient, the greater the sedimentation rate.

Waikoau catchment sedimentary succession

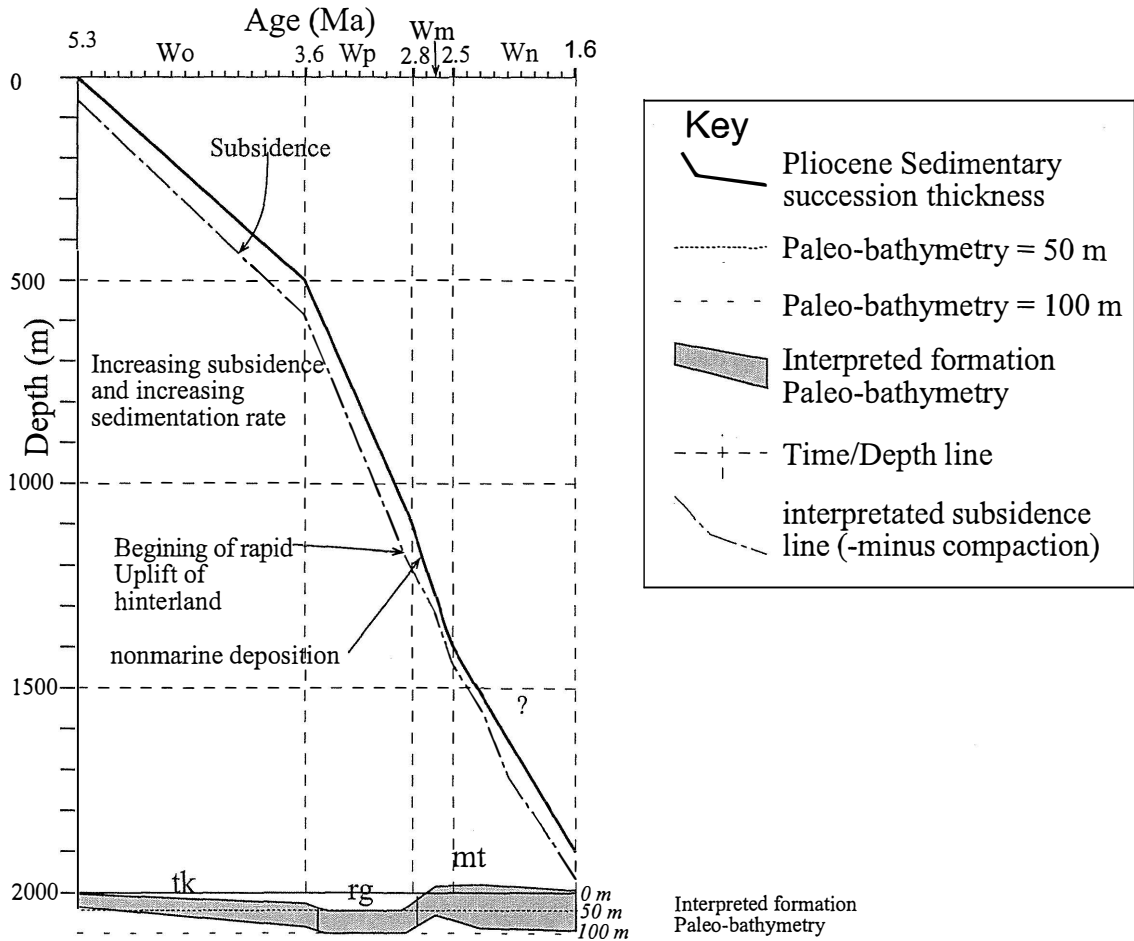


Figure 5.4, Sedimentation rate and paleo-bathymetry for the Waikari and Waikoau catchments.

In the study area where the terrigenous sedimentation rate is less than 0.1 m/ky carbonate sediment dominates. Between 0.1 m/ky and 0.5 m/ky the sediments are calcareous sandstone in lithology. Above 0.8 m/ky sedimentation is dominated by sand and gravel. When these values are compared to values found on the contemporary New Zealand shelf, where it is considered that when terrigenous sediment accumulation is less than 1 m/ky, 5% carbonates will occur (Kamp and Nelson 1987). From this it appears that terrigenous accumulation values in the study area need to be lower than contemporary values before carbonate sedimentation occurred, as carbonates don't occur in the study area where sediment accumulation rates exceed 0.5 m/ky. This may be because constant reworking of sediments occurs in this area meaning that even when sedimentation rates are low, sediment is constantly reworked precluding carbonates from forming.

Changes in paleo-bathymetry over time are also illustrated in figure 5.4. This is partly due to sea-level changes. Before the Mangapanian tectonic controls are considered to dominate with minor influence of sea-level changes. This can be used to infer overall subsidence of the basin during the Pliocene, minus compaction of sediments.

### 5.2.3.1 Possible sources of sediment supply

Limestones distal from the paleo-shoreline are interpreted to be reworked from proximal settings during relative sea-level lowering. Sites close to limestone 'factories' receive limestone deposition during all stages of a sea-level cycle.

Glauconite grains in the calcareous sediments may have been sourced from older sediments containing glauconite, or may have formed authigenically in the basin.

Heavy minerals and tephra that occur throughout the formation are probably sourced from the Coromandel Volcanic Arc, which was active during this time. Reworked ignimbrite deposits occur within the Titiokura Formation, indicating considerable distances of transport.

Mica flakes are ubiquitous throughout the Mangapanian - Nukumaruan sedimentary record. They may have several sources: 1) erosion of small amounts of schist in the axial

ranges, 2) mica from Alpine Schist, sourced through the paleo-seaway, 3) mica from reworked ground up greywacke conglomerates of the Matahorua Formation, or 4) reworking of older uplifted sediments.

Uplifted Miocene mudstone and sandstone, onlapping on to the basement ranges, is a possible supply of siliciclastic sediment clasts for breccias and conglomerates within the Titiokura Formation. These clasts were not transported far as indicated by their angular nature. The uplifted Miocene succession is also interpreted as a source of mud for the common mud drapes in the Titiokura Formation.

Common greywacke pebbles occurring in Titiokura Formation coquina are probably sourced from greywacke basement exposed during the early Opoitian. A significant distance of travel, and relative low levels of uplift at this time means that the pebbles are typically small and always well-rounded. Greywacke clasts in the Matahorua Formation are likely to have been sourced from the uplifting axial ranges.

## 5.3 Geological History

### 5.3.1.1 Opoitian

During the early Opoitian, the Mokonui Formation accumulated in an innershelf environment. It marked the rapid infilling of a basin during the Tongoportuan. The base of the Titiokura Formation was deposited on Mokonui Sandstone at the contemporary basin margins (Fig 5.1). Much of the carbonate sediment was sourced from barnacle banks on the shallow margins of the seaway. In the centre of the seaway mud was deposited (Beu *et al.* 1980). Subsidence in parts of the seaway coupled with eustatic sea-level changes resulted in cyclic sedimentation, consisting of sandstone coarsening upwards to limestone. Continued subsidence in the centre of the seaway results in a broad upward fining succession in the study area. Areas proximal to the seaway margins, or on structural highs are dominated by limestone formation. These limestones are frequently reworked to distal areas, which are characterised by erosive surfaces and internal truncation. Siltstone forming close to such outcrops is thought to be the result of deposition in areas not affected by strong currents. High-energy storm and tidal currents dominated this seaway during the Opoitian, sweeping the seaway clean of siliciclastics. Sediment during this time was sourced through the seaway and from older sediments on

the uplifted margins of the seaway. During the Opoitian the main depocentre (in the field area) is located in the Waikari catchment. Sequences prograde further into the centre of the seaway, causing increased loading and associated subsidence, and possibly the development of an asymmetrical paleo-shelf, that is wider in the Waikari region.

### 5.3.1.2 Waipipian – Mangapanian

Deposition of the Titiokura Formation continued into the early Waipipian. Although siliciclastic sandstone began to dominate during this time, carbonate sedimentation is restricted to structural highs and reworked beds. A period of subsidence in the seaway, resulted in slackening tidal currents and decreasing carbonate content. The rapid change from a carbonate-dominated succession to the siliciclastic-dominated succession of the Rangiora Formation is initiated by continued subsidence. This deeper and less energised environment, with less current activity, no longer swept the sea-floor clean of terrigenous sediment, so carbonate sedimentation is choked, and subsequently halts. Increasing sedimentation occurs during this time, especially in the Waipipian. At some time in the late Waipipian or early Mangapanian uplift and erosion of the North Island axial ranges starts. This uplift is recognised in the Waikari catchment where thick siltstone shoals into sandstone. The shelf is subaerially exposed during the Mangapanian allowing non-marine conglomerate to accumulate. This results in the progradation of rivers across the exposed shelf forming an expansive braid-plain. Exposure of the shelf and associated erosion results in a marked increase in the sedimentation rate.

During the Waipipian the depocentre is still centred in the Waikari catchment but migrating towards the Waikoau. This is because siltstone is being deposited in the Waikari catchment at this time and subsequently sedimentation rates have decreased. Because of this, more subsidence associated with sediment loading occurs in the Waikoau catchment and the depocentre 'switches' from the Waikari to the Waikoau catchment from the Opoitian to Mangapanian.

Typically transgressions during the Waipipian-Mangapanian are marked by retrogradational parasequences in the Waikoau catchment. In the Esk catchment these are absent (Bland 2001). This may indicate a steeper paleo-shelf in the Waikoau region,

resulting in relatively slow transgressions in comparison with the setting in the Esk catchment.

If the paleo-shelf was wider in the Waikari region as postulated above, upon uplift of the axial ranges during the Waipipian to early Mangapanian, rivers would have taken longer to prograde across this wider shelf in the Waikari region than across the narrower shelf in the Esk-Waikoau catchments. Thereby relatively more uplift is required for subaerial exposure to occur and because of this fewer conglomerates appear in the Waikari catchment, and they are thinner.

### 5.3.1.3 Nukumaruan

Matahorua Formation deposition continued into the early Nukumaruan. Following this and during the early Nukumaruan, the Waipunga Formation is deposited. Carbonaceous material occurring in some sediment within the formation indicates partial closure (or closure) of the seaway and development of an estuary to source organic material. Subsidence coupled with sea-level fluctuations resulted in deeper water facies combined with shallow water facies. Haywick (1990) concluded that large sea-level changes (c. 75 –100 m) occurred during this time. The range of paleo-bathymetry during the Nukumaruan is considered larger than during the other Pliocene stages. This is due to larger sea-level cycles, and sea-level cyclicity becoming the dominant control on sedimentation during this period.



# Chapter 6

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## *Chapter 6: Summary and Conclusions*

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### 6.1 Summary

#### 6.1.1 Lithostratigraphy

Over 1300 m of the Pliocene sedimentary succession has been described in both the Waikoau and Waikari River catchments. This succession dates from the early Opoitian to mid Nukumaruan. The succession has been divided on the basis of lithology and sedimentary character into two groups comprising four formations and 12 members.

Rapid lateral changes in lithology within formations are a recurring feature within the sedimentary succession in the study area.

The Titiokura Formation is dominated by calcareous sandstone and limestone. The formation is Opoitian to early Waipipian in age, and comprised of five members. The formation increases in thickness across the field area toward the NE. In this formation a thick limestone occurring in the SE region of the study area passes to the NE into thick calcareous sandstone with thin limestone beds.

The Rangiora Formation is comprised of two members characterised by fossiliferous siltstone and sandstone with concretions. Sandstone dominates the sedimentary succession in the SW in the Esk and Waikoau catchments, and siltstone dominates in the NE in the Waikari catchment.

The Matahorua Formation is comprised of greywacke conglomerate with siliciclastic sandstone and minor siltstone beds. The Formation includes four members, however as the conglomerates pinch-out across the study area only three members are identified in the Waikari catchment.

The Waipunga Formation includes two members (which are only identifiable in the Waikoau catchment) comprised of fossiliferous interbedded siltstone and sandstone. The formation thins from the Waikoau catchment in the centre of the map area to the NE in the Waikari catchment.

### 6.1.2 Lithofacies

Four sedimentary facies associations have been identified in the study area, with 13 lithofacies groups. Each lithofacies is interpreted to form in a differing paleo-environment.

The lithofacies are grouped into associations on the basis of lithology, thereby there are associations for siltstone, sandstone, conglomerate and limestone. There are three siltstone association lithofacies, which occur in all four formations. Paleo-bathymetry of this association ranges from inner-shelf to outer-shelf. The conglomerate association has been divided into two lithofacies. Depositional environment ranges from tidal flat to subaerial deposition in a braided river system. Conglomerate facies occur in both the Titiokura and Matahorua Formations. Sandstone is the most common sedimentary association occurring in the study area. Six lithofacies occur within this association. Lithofacies range from shoreface cross-bedded sandstone to storm and tidal current emplaced sandstone beds, and occur in inner-mid shelf environments. Limestone occurs within the Titiokura Formation, and two lithofacies occur within this association. It occurred in inner-shelf environments as limestone banks, and as reworked channelised beds on the inner to mid shelf.

### 6.1.3 Sequence Stratigraphy

Four differing sequence stratigraphic motifs have been put forward in chapter 4, one for each of the formations identified in the study area. Twenty-five sedimentary cycles are identified in the study area, 22 in the Waikoau River catchment, and 16 in the Waikari River catchment. The whole of the Pliocene record contains 30 cycles. Sequences in the Titiokura Formation are characterised by reworking and erosion.

Within the Titiokura Formation **sequence boundaries** occur as erosional surfaces at the base of conglomerates or as sharp-based surfaces on top of limestone or calcareous

sandstone. In the Rangiora Formation sequence boundaries are sharp and planar, with siltstone sharply overlying sandstone. Sequence boundaries within the Matahorua Formations are interpreted as unconformities placed within and occasionally on top of the greywacke conglomerates. Basinward cycles often have either thin shell-beds with shell hash marking the sequence boundary, or sparsely fossiliferous shellbeds with tabular cross-bedding, greywacke pebbles, and sandstone siltstone interbeds, particularly in the Waipunga Formation.

**Transgressive Systems Tracts** in the study seem to be associated with rapid sea-level rise. They are characterised by: 1) thinly bedded tidalities with channelised transgressive lag conglomerates; 2) late transgressive sediment starved limestone, 3) aggradational and retrogradational parasequences, reworked conglomerate beds, which are typically less homogenous than the underlying conglomerate and smaller in grain size; 4) and massive sandstone topped by a weak backlap shellbed.

Placement of the **Highstand Systems Tract** in the Titiokura Formation is difficult as siltstone, which is normally associated with this systems tract is uncommon. In this case the HST is placed above the tidally laminated facies, which occur during a sea-level transgression, or at the base of rare finer grained packets of sediment. Highstand Systems Tracts in both the Rangiora and Waipunga Formations are characterised by siltstone, occasionally silty sandstone, typically with some thin sandstone inter-beds. In the Titokura Formation HST deposits are interpreted as thick sections of cyclic sandstone, or silty sandstone with mud drapes, where abundant accommodation space allowed for the deposition of cyclic beds. Within the Matahorua Formation HST's are difficult to recognise because of the dominance of sandstone.

**Regressive Systems Tracts** in the Titiokura Formation are characterised by storm and wave reworked sediments. Carbonate sediments are transported basinward as sea level falls exposing limestone near the highstand shoreline. This means that sequences near the highstand shoreline are commonly incomplete due to erosion, and basinward sequences are very thick. In the Matahorua Formation regressions are characterised by shoaling upwards from inner shelf massive sandstone to shoreface sands and gravels, then sub-aerial exposure where braided river deposits prograde across the shelf and conglomerates are deposited. Regressions within the Waipunga Formation are characterised by siltstone coarsening upward into sandstone.

**Lowstand System Tracts** are only found in the Matahorua Formation where a broad braidplain forms once sea-level has dropped sufficiently to expose the shelf, after which rivers prograde depositing greywacke conglomerates.

#### 6.1.4 Controls on Sedimentation and Synthesis

Tectonism, eustatic sea-level changes, and sediment supply are considered to be the three major variables controlling stratigraphic development. Subduction of the Pacific plate under the Australian plate leads to subduction in the west and uplift in the east of the study area. This leads to the development of the Wanganui-Hawke's Bay paleo-seaway and sediment supply from the uplifting hinterland.

Sea-level fluctuations resulting from the melting of ice caps on the Northern Hemisphere continents overprint the slow tectonic subsidence, resulting in the deposition of cyclothems. Cyclicity appears to increase from the Opoitian to the Nukumaruan with the deposition of 6<sup>th</sup> order cyclothems in the Nukumaruan. The bathymetric range of the cycles through the succession appears to increase over this time as well.

Sediment is sourced through and from the margins of the uplifted seaway. Sedimentation rates appear to increase from the Opoitian to the Nukumaruan. Where the sedimentation rate exceeds 0.5 m/ky carbonate sedimentation is absent.

## 6.2 Conclusions

- The Maungahuru Group was deposited in a steadily subsiding seaway, with uplift occurring on the margins. Strong tidal and storm currents resulted in reworking and erosion of sediments and carbonate accumulation in sediment bypass environments.
- A rapid change from the carbonate-dominated succession of the Titiokura Formation to the siliciclastic-dominated succession of the Rangiora Formation occurs as a result of continued subsidence and an increase in sediment supplied from the hinterland.

- Rapid uplift of the North Island Axial ranges during the late Waipipian or early Mangapanian in association with the increasing compressional component on the plate boundary, resulted in subaerial exposure of the study area. Resulting in the formation of a wide braidplain and siliciclastic dominated delta.
- Sea-level oscillations throughout the Pliocene result in the deposition of cyclothem occurring in all four formations.

### 6.3 Recommendations for further research

- Dating of tephras occurring in the Titiokura and Matahorua Formations.
- Dating and foraminiferal work on the Waikari Member siltstone, the establishment of New Zealand Stage boundaries and paleo-bathymetry of the member.

Both these above recommendations may lead to better age control and subsequently the ability to 'link' the stratigraphic succession in the area to the global oxygen isotope curve.

- Limestone diagenesis of Titiokura Formation limestones (currently beginning undertaken).
- Extend mapping of the Titiokura Formation to the northeast of the study area.
- Detailed paleo-current analysis of the Titiokura Formation, especially of the Te Rangi Member.

These recommendations could lead to a better understanding of the processes involved in the deposition of the Titiokura Formation.



# References

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## References

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- Adkins, R.M., and Eriksson, K.A., 1998: Rhythmic sedimentation in a mid-Pennsylvanian delta-front succession, Magoffin Member (Four Corners Formation, Breathitt Group), Eastern Kentucky: A near complete record of daily, semi-monthly, and monthly tidal periodicities. In Alexander, C.R., Davis, R.A., and Henry, V.J. (Eds), *Tidalites: Processes and Products*. SEPM Special Publication # 61: 85-94.
- Balance, P.F., 1993: The New Zealand Neogene Forearc Basins. In Hsu, K.J., and Ballance, P.F., (Eds). *South Pacific Sedimentary Basins*, Elsevier: 229-236.
- Batholdy, J., and Anthony, D., 1998: Tidal Dynamics and Seasonal Dependent Import and Export of fine-grained sediment through a Back Barrier Tidal Channel of the Danish Wadden Sea. In Alexander, C.R., Davis, R.A., and Henry, V.J. (Eds), *Tidalites: Processes and Products*. SEPM Special Publication # 61: 43-52.
- Bland, K.J., 2001: Analysis of the Pliocene forearc basin succession, Esk River catchment, Hawke's Bay. Unpublished M.Sc. thesis, University of Waikato.
- Beu, A.G., Grant-taylor, T.L., Hornibrook, N.de B. 1980: The Aute Limestone facies, Poverty Bay to Northern Wairarapa. 1:250 00. New Zealand Geological Survey Miscellaneous Series 13 (2 sheets) and notes. New Zealand Department of Scientific and Industrial Research, Wellington.
- Beu, A.G., Maxwell, P.A. 1990: Cenozoic Mollusa of New Zealand. New Zealand Geological Survey Paleontological Bulletin 58.
- Beu, A.G., 1995: Pliocene limestones and their scallops: lithostratigraphy, pectinid biostratigraphy and paleogeophy of eastern North Island, Late Neogene limestone. Institutue of Geological and Nuclear Sciences Limited, Monograph 10.
- Boggs, jr., S., 1995: *Principles of Sedimentolgy and Stratigraphy* 2<sup>nd</sup> Edition.

- Brash, R.A. 1982: The Plio-Pleistocene Geology of the Te Pohue-Esk Regions, Hawke's Bay, New Zealand. University of Auckland.
- Collinson, J.D. 1996: Alluvial sediments. In Reading, H.G. (Ed.), *Sedimentary Environments: processes, Facies and Stratigraphy* 3<sup>rd</sup> Edition, Blackwell Science. p 37-82
- Colquhoun, G.P., 1995: Siliciclastic sedimentation on a storm- and tide-influenced shelf and shoreline: the Early Devonian Roxburgh Formation, NE Lachlan Fold Belt, southeastern Australia. *Sedimentary Geology*, 97: 69-98
- Cutten, H.N.C., 1994: Geology of the middle reaches of the Mohaka River. Institute of Geological and Nuclear Sciences Limited, Geological Map 6.
- Dalrymple, R.W., 1992: Tidal Depositional Systems. In Walker, R. G., James, N.P. (Eds.) *Facies Models: Response to Sea Level Change*. Geological Association of Canada, Ontario,
- Field, B.D., Uruski, C.I., and others, 1997: Cretaceous – Cenozoic Geology and Petroleum Systems of the East Coast Region, New Zealand. Institute of Geological and Nuclear Sciences Limited, Geological Monograph 19.
- Francis, D.A., Petroleum Corporation of NZ (Exploration) Ltd; 1991; Report on the Geology of the Te Pohue area, Western Hawkes Bay (PPL 38316) with emphasis on stratigraphy and structure. Ministry of Commerce New Zealand Unpublished Petroleum Report PR 1750.
- Greb, S.F., and Archer, A.W., 1998: Annual sedimentation cycles in Rhythmites of Carboniferous tidal channels. In Alexander, C.R., Davis, R.A., and Henry, V.J. (Eds), *Tidalites: Processes and Products*. SEPM Special Publication # 61, p 75-84.
- Grindley, G.W., 1960: Geological Map of New Zealand, 1:250 000, Sheet 8 – Taupo. New Zealand Geological Survey.
- Hart, B.S., Long, B.F., 1996: Forced regressions and lowstand deltas: Holocene Canadian examples. *Journal of Sedimentary Research, Section B: Stratigraphy and Global Studies*. Vol 66, No. 4: 820 – 829.
- Hayward, B. W., Grenfell, H. R., Reid, C. M., Hayward, K. A., 1999: Recent New Zealand shallow-water benthic foraminifera: Taxonomy, ecological distribution, biogeography, and use in paleoenvironmental assessment. Institute of Geological and Nuclear Sciences Limited, Monograph 21.

- Haywick, D.W., 1990: Stratigraphy, Sedimentology, Palaeoecology and Diagenesis of the Petane Group (Plio-Pleistocene) in the Tangoio Block, Central Hawke's Bay, New Zealand. PhD thesis, James Cook University of North Queensland.
- Haywick, D.W., A.G. Henderson, 1991: Foraminiferal Paleobathymetry of Plio-Pleistocene Cyclothem Sequences, Petane Group, New Zealand. *Palaios*, vol 6: 586-599.
- Haywick, D.W., Lowe, D.A., Beu, A.G. Henderson, R.A., Carter, R. M. 1991: Pliocene-Pleistocene (Nukumaruan) lithostratigraphy of the Tangoio block, and origin of sedimentary cyclicity, central Hawke's Bay, New Zealand. *New Zealand Journal of Geology and Geophysics*, 34: 213-225.
- Hunt, D., Tucker, M.E., 1992: Stranded parasequences and the force regressive wedge systems tract: deposition during base-fall. *Sedimentary Geology*, 81: 1-9.
- Jervey, M.T. 1998: Quantitative geological modeling of siliciclastic rock sequences and their seismic expression. In: Wilgus, C.K., Hastings, B.S., Posamentier, H.W., Van Wagoner, J.C., Ross, C.A., Kendall, G.C.St.C. (Eds.), Seal Level Changes: An integrated Approach. Soc. Econ. Paleotol. Mineral. Spec. Publ. 42: 39-40.
- Johnson, H.D., and Baldwin, C.T., 1996: Shallow clastic seas. In Reading, H.G. (Ed.), *Sedimentary Environments: processes, Facies and Stratigraphy* 3<sup>rd</sup> Edition, Blackwell Science.
- Kamp, P.J.J., Nelson, C.S., 1987: Tectonic and sea-level controls on non-tropical Neogene limestones in New Zealand. *Geology*, 15: 610-613.
- Kamp P.J.J., Harmsen, F.J., Nelson, C.S., Boyle, S.F., 1988: Barnacle-dominated limestone with giant cross-beds in a non-tropical, tideswept, Pliocene forearc seaway, Hawke's Bay, New Zealand. *Sedimentary Geology*, 60: 173-195.
- Kamp, P.J.J., 1992: Tectonic Architecture of New Zealand. In Soons, J.M., Selby, M.J. (Eds), *Landforms of New Zealand* 2<sup>nd</sup> Edition:
- Kidwell, S.M., 1989: Stratigraphic condensation of Marine Transgressive records: Origin of major shell deposits in the Miocene of Maryland. *The Journal of Geology*, vol 97, No. 1: 1-24.

- Kidwell, S.M. 1991: Condensed Deposits in Siliciclastic Sequences. Expected and Observed Features. In Einsele, G., Ricken, W., Seilacher, A., (Eds) Cycles and Events in Stratigraphy. Heidelberg, Springer-Verlag: 682-695.
- Kondo, Y., Abbot, S.T., Kitamura, A., Kamp, P.J.J., Naish, T. R., Kamataki. T., Saul, G.S. 1998: The relationship between shellbed type and sequence architecture: examples from Japan and New Zealand. *Sedimentary Geology*, 122: 109-127.
- Lewis, K.B., 1979: Foraminifera on the Continental Shelf and Slope off Southern Hawke's Bay, New Zealand. New Zealand Oceanographic Institute Memoir 84.
- Lewis, K.B., 1980: Quaternary sedimentary on the Hikurangi oblique-subduction and transformation margin, New Zealand. In Ballance, P.F. and Reading, H.G., Sedimentation in Oblique-slip Mobile Zones. Spec. Pub. of Sedimentary Geologists (1980) 4: 171-189.
- Miall, A.D., 1992: Alluvial Deposits. In Walker, R. G., James, N.P. (Eds.) Facies Models: Response to Sea Level Change. Geological Association of Canada, Ontario.
- Maill, A.D. 1996: The geology of Fluvial Deposits. Sedimentary Facies, Basin Analysis and Petroleum Geology. Springer.
- Maill, A.D. 1997: The geology of Stratigraphic Sequences. Springer.
- Molina, J.M., Ruiz-Ortiz, P.A., Vera, J.B., 1997: Calcareous tempestites in pelagic facies (Jurassic, Betic Cordilleras, Southern Spain). *Sedimentary Geology*, 109: 95-109
- Molina, J.M., Alfaro, P., Moretti, M., and Soria, J.M. 1998: Soft-sediment deformation structures induced by cyclic stress of storm waves in tempestites (Miocene, Guadalquivir Basin, Spain). *Terra Nova*, 10, No. 3: 145-150.
- Myrow, P.M. and Southard, J.B., 1996: Tempestite Deposition. *Journal of Sedimentary Research*, 66, No. 5: 875 – 887.
- Naish, T., Kamp, P.J.J., 1997: Sequence stratigraphy of six-order (41 k.y.) Pliocene-Pleistocene cyclothems, Wanganui basin, New Zealand: A case for the regressive systems tract. *Geological Society of America*, 109: 978-999.

- Nelson, C.S., Hancock, G.E., and Kamp, P.J.J., 1982: Shelf to Basin, Temperate skeletal carbonate sediments, Three Kings Plateau, New Zealand. *Journal of Sedimentary Petrology*, 52, No. 3: 712-732.
- Nemec, W., and Steel, R.J., 1984: Alluvial and Coastal conglomerates: Their significant features and some comments on gravelly mass-flow deposits. In Koster, E.H., and Steel, R.J. (Eds), *Sedimentology of Gravels and Conglomerates*. Canadian Society of Petroleum Geologists, Memoir 10: 1-31.
- Pettinga, J.R., 1982: Upper Cenozoic structural history, coastal Southern Hawke's Bay, New Zealand. *New Zealand Journal of Geology and Geophysics*, v 25, 145-191.
- Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988: eustatic controls on clastic deposition I – Conceptual Framework. In: Wilgus, C.K., Hastings, B.S., Posamentier, H.W., Van Wagoner, J.C., Ross, C.A., Kendall, G.C.St.C. (Eds.), *Sea Level Changes: An integrated Approach*. Soc. Econ. Paleontol. Mineral. Spec. Publ. 42: 39-40.
- Posamentier, H.W., Vail, P.R., 1988: eustatic controls on clastic deposition II – Sequence and Systems Tract models. In: Wilgus, C.K., Hastings, B.S., Posamentier, H.W., Van Wagoner, J.C., Ross, C.A., Kendall, G.C.St.C. (Eds.), *Sea Level Changes: An integrated Approach*. Soc. Econ. Paleontol. Mineral. Spec. Publ. 42: 39-40.
- Reading, H.G., Collinson, J.D. 1996: Clastic coasts. In Reading, H.G. (Ed.), *Sedimentary Environments: processes, Facies and Stratigraphy* 3<sup>rd</sup> Edition, Blackwell Science: 154-231.
- Rossetti, D. F., 1997: Internal architecture of mixed tide- and storm-influenced deposits: and example from the Alcantara Formation, northern Brazil. *Sedimentary Geology*, 114, 163-188.
- Sporli, K.B., 1980: New Zealand and oblique-slip margins: tectonic development up to and during the Cainozoic. In Ballance, P.F. and Reading, H.G., *Sedimentation in Oblique-slip Mobile Zones*. Spec. Pub. of Sedimentary Geologists (1980) 4: 147-170.
- Shanmugan, G., Spalding, T.D., Rofheart, D.H., 1993: Traction structures in deep-marine, bottom-current-reworked sands in the Pliocene and Pleistocene Gulf of Mexico, *Geology*, vol 21: 929-932.

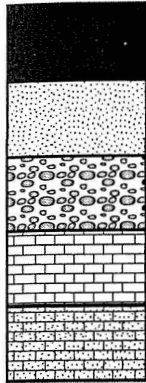
- Shanmugan, G., 2000: 50 years of the turbidite paradigm (1950s\_\_1990s): deep-water processes and facies models\_\_a critical perspective. *Marine and Petroleum Geology*, 17, 2: 285-242.
- Sztano, O., and De Boer, P. L., 1995: Basin dimensions and morphology as controls on amplification of tidal motions (the Early Miocene North Hungarian Bay). *Sedimentology*, 42, 665-682.
- Vera, J.A., and Molina, J.M., 1998: Shallowing-upward cycles in pelagic troughs (Upper Jurassic, Subbetic, Southern Spain). *Sedimentary Geology*, 119: 103-121
- Walker, R.G., Pint, A.G., 1992: Tidal Depositional Systems. In Walker, R. G., James, N.P. (eds.) *Facies Models: Response to Sea Level Change*. Geological Association of Canada, Ontario: 219-238.
- Winn, R.D., 1991: Storm Deposition in Marine Sand Sheets: Wall Creek Member Frontier Formation, Powder River Basin, Wyoming. *Journal of Sedimentary Petrology*, Vol 61, No. 1, 86-101
- Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., and Hardenbol, J., 1988: An overview of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Posamentier, H.W., Van Wagoner, J.C., Ross, C.A., Kendall, G.C.St.C. (Eds.), *Sea Level Changes: An integrated Approach*. Soc. Econ. Paleotol. Mineral. Spec. Publ. 42, 39-40.
- Vella, P., 1963: Plio-Pleistocene Cyclothems, Wairarapa, New Zealand. *Transactions of the Royal Society of New Zealand, Geology*, vol. 2, no. 2.
- Yagishita, K., 1994: Planar cross-bedding associated with rip currents of Upper Cretaceous formations, northeast Japan. *Sedimentary Geology*, 93: 155-163



# Appendices

## Legend for Stratigraphic Columns

### Lithology



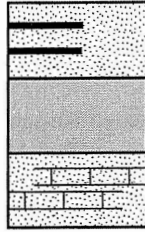
Siltstone

Sandstone

Conglomerate

Limestone

Sandy Limestone (coquina)



Sandstone with mud drapes

Silty sandstone

Calcareous sandstone

### Physical Structures



Horizontally bedded



Tabular cross-bedded



Bi-directionally cross-bedded



Trough cross-bedded



Internal truncation



Truncation of trough cross-bed



Ripple bedded



Convolute bedded



Wavy laminated

### Miscellaneous



Plant material



Bioturbation



Bioturbation down into bed



Escape structure



Scattered fossils



Shell bed



Concretion



Conformable sequence boundary



Erosional sequence boundary inferred



Erosional sequence boundary



Sequence number

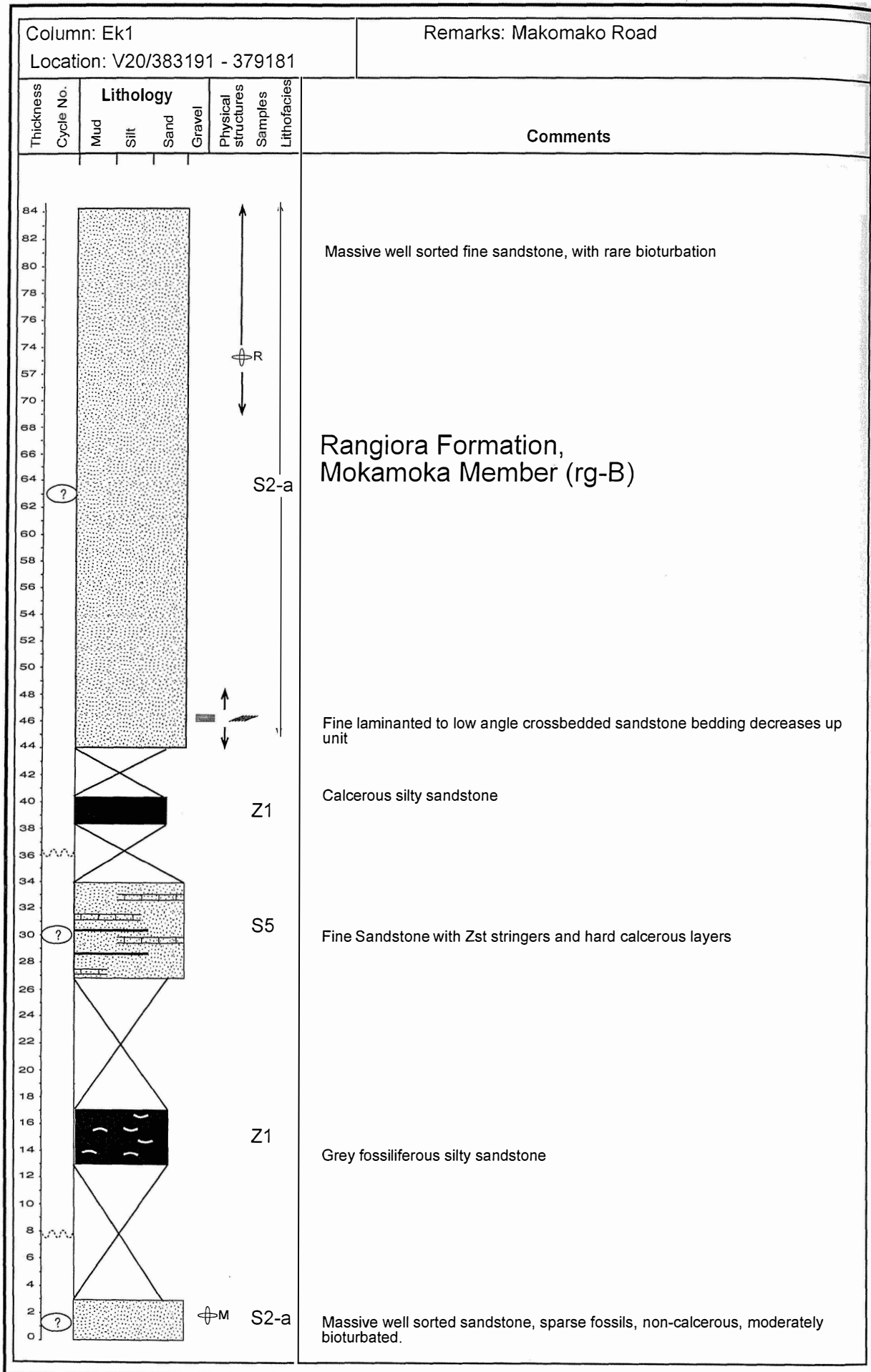


Grainsize sample

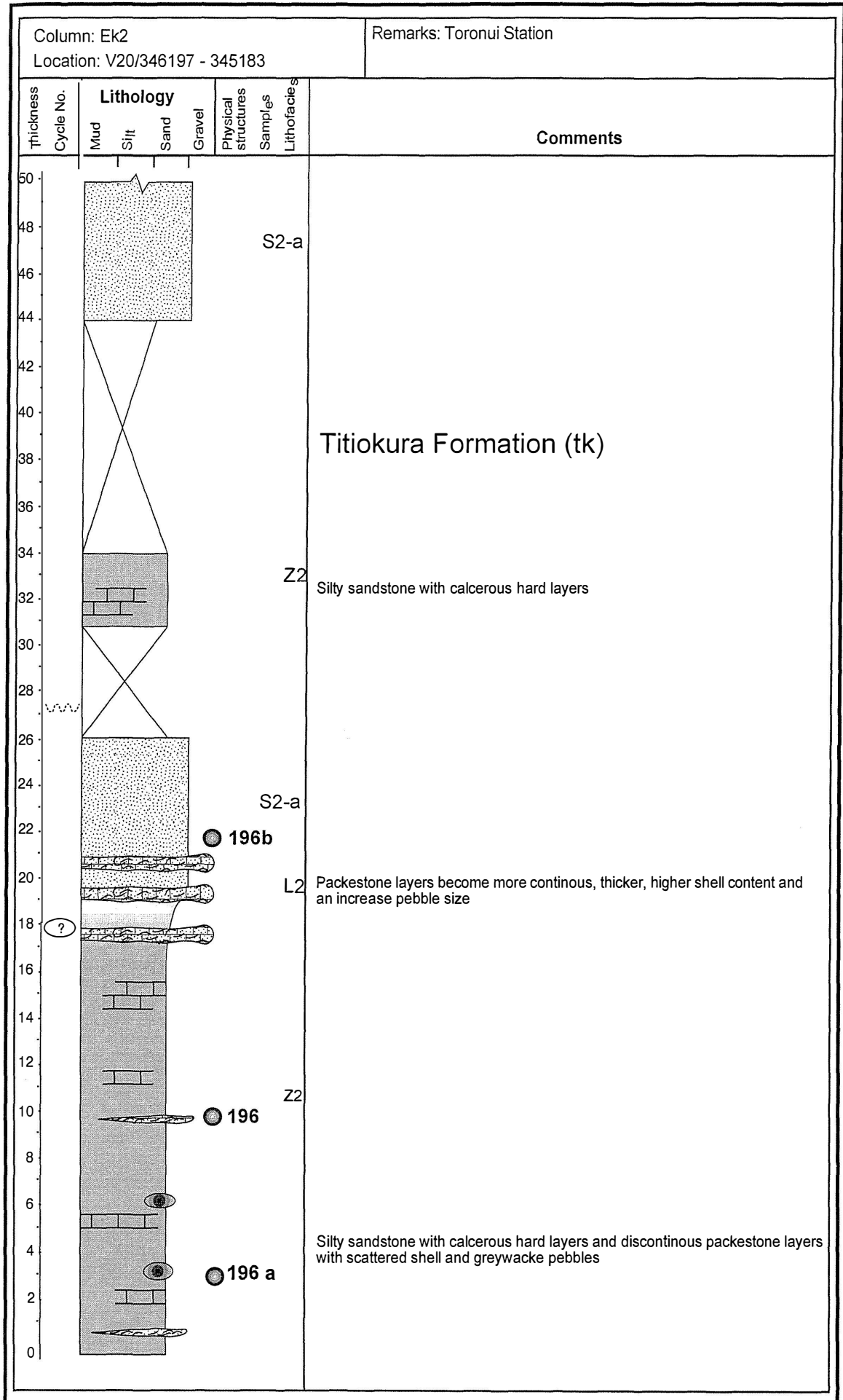


Sample locality

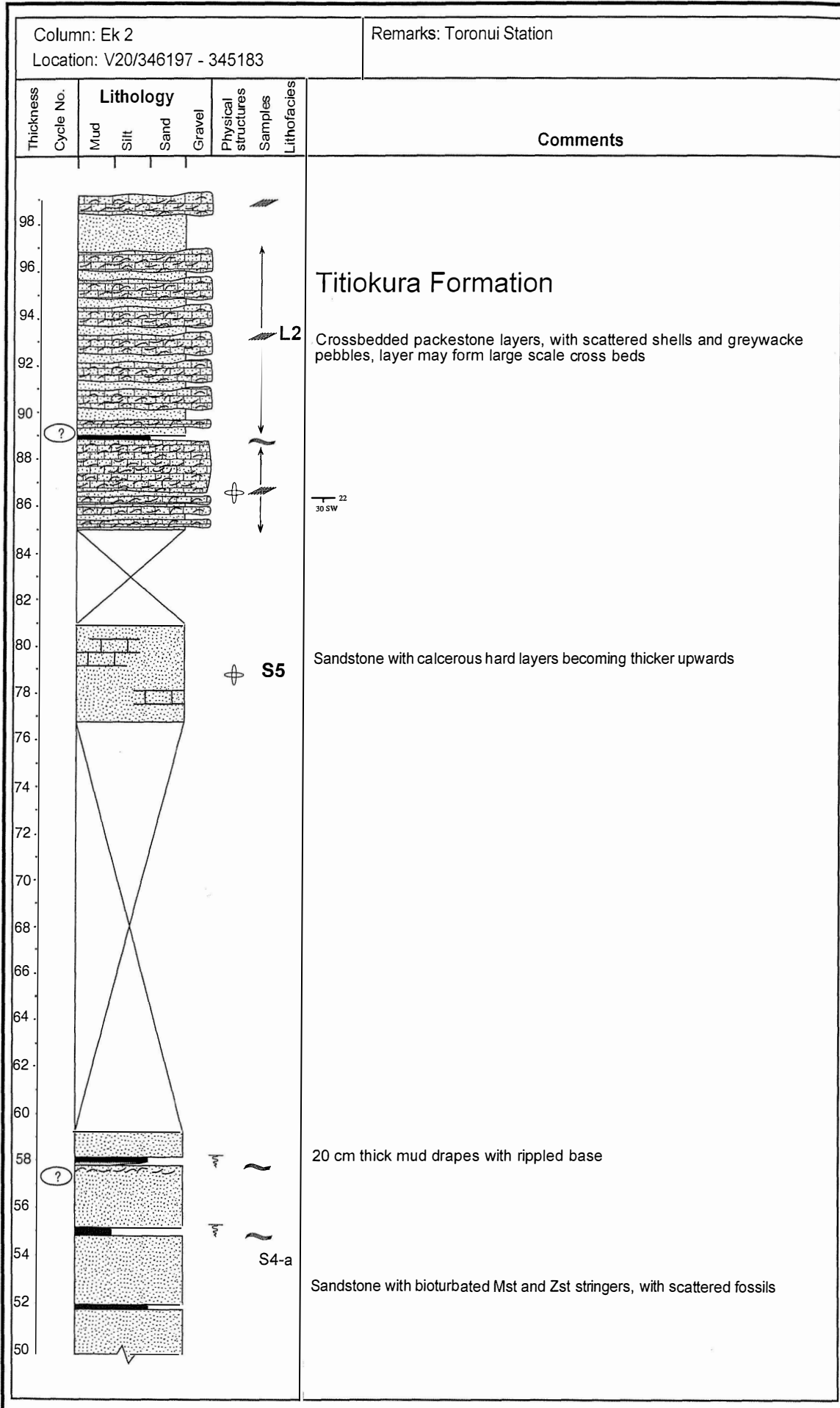
Appendix 1: Stratigraphic Columns



Appendix 1: Stratigraphic Columns

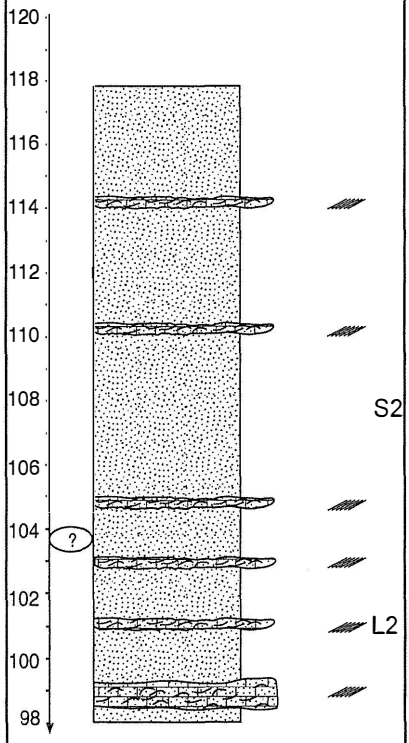


# Appendix 1: Stratigraphic Columns



Appendix 1: Stratigraphic Columns

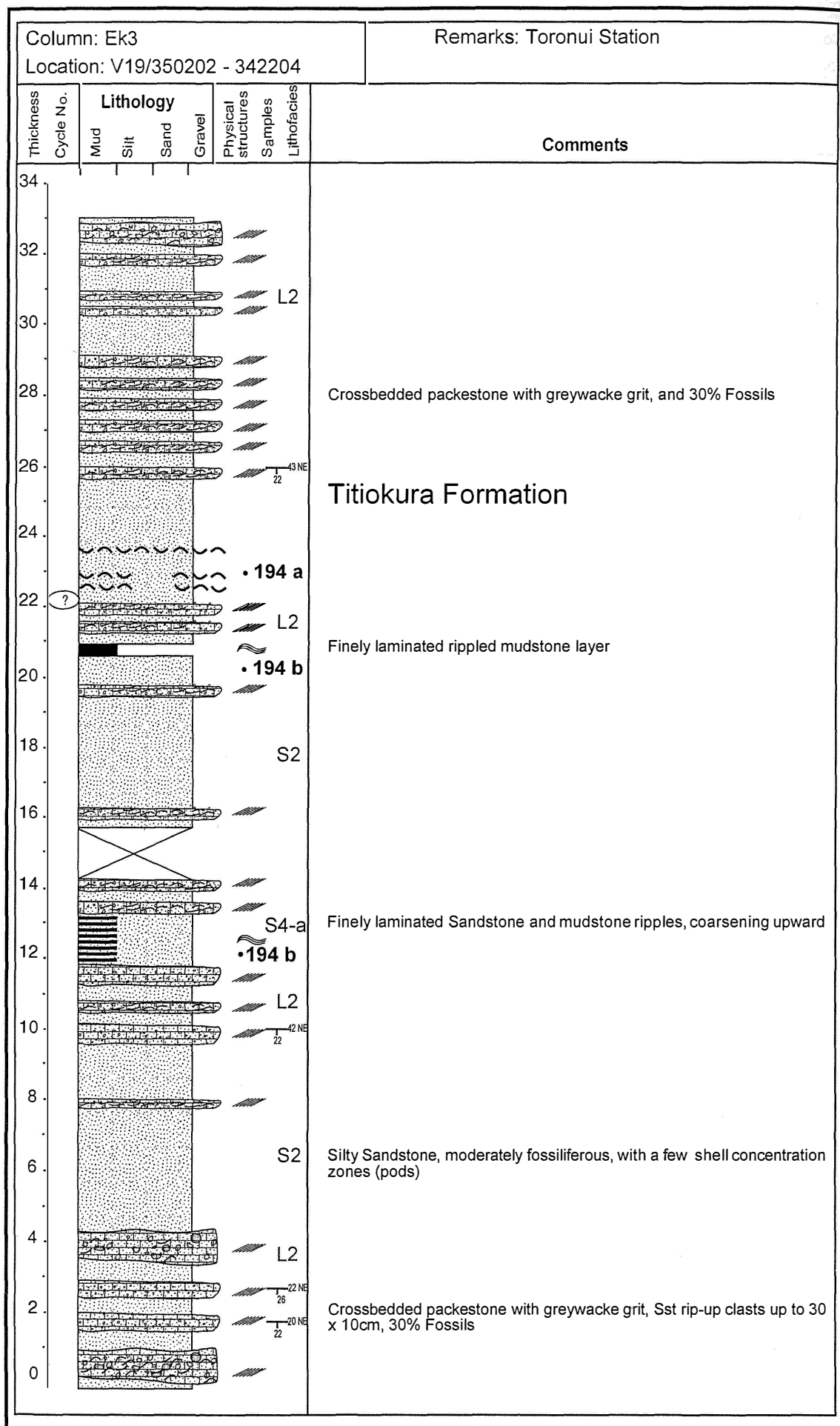
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Location: V20/346197 - 345183									
Thickness	Cycle No.	Lithology				Physical structures	Samples	Lithofacies	Comments
		Mud	Silt	Sand	Gravel				
120									
118									
116									
114									
112									
110									
108									
106									
104									
102									
100									
98									



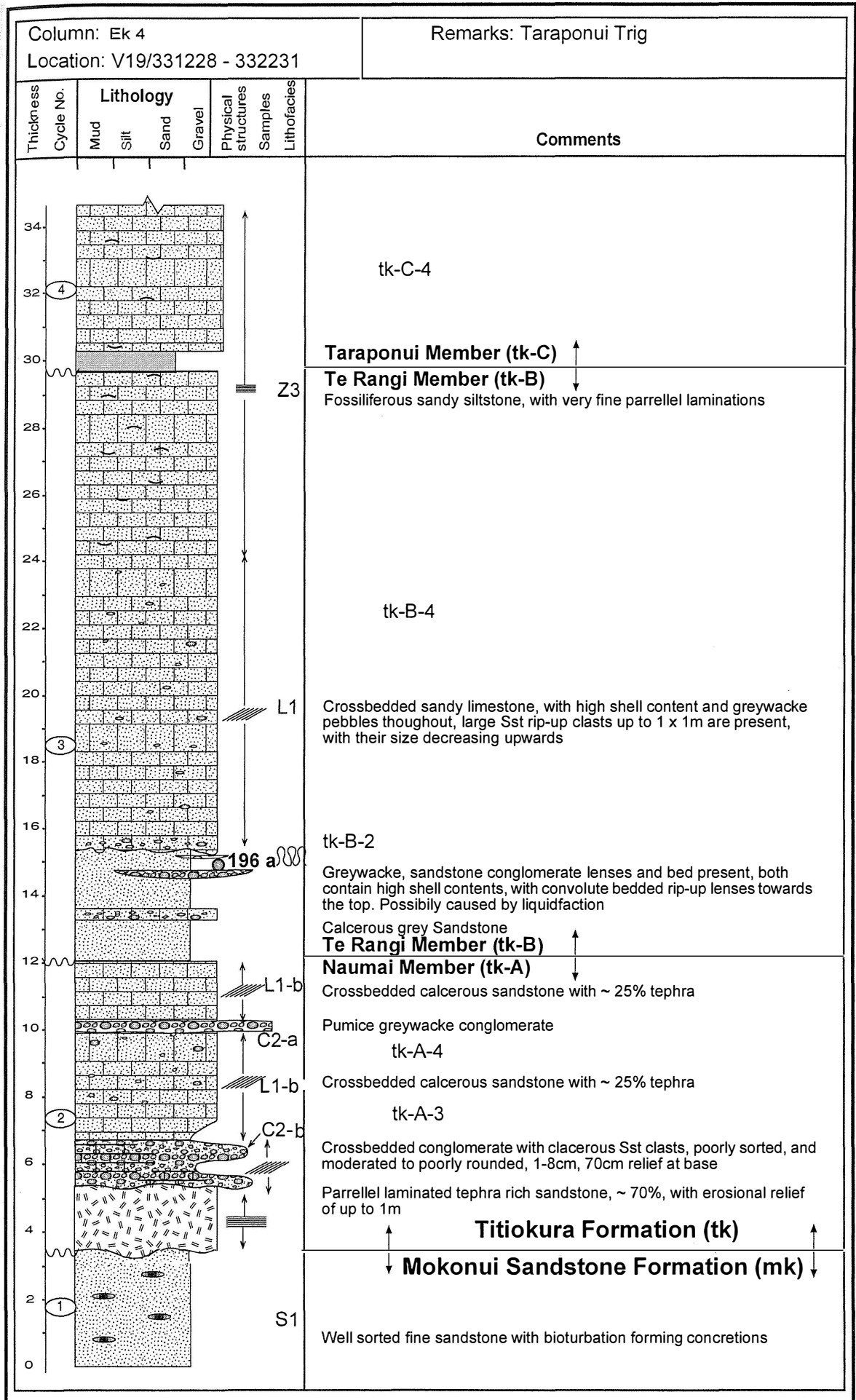
Titiokura Formation

Packstone layers becoming thinner and further apart, sand content increasing

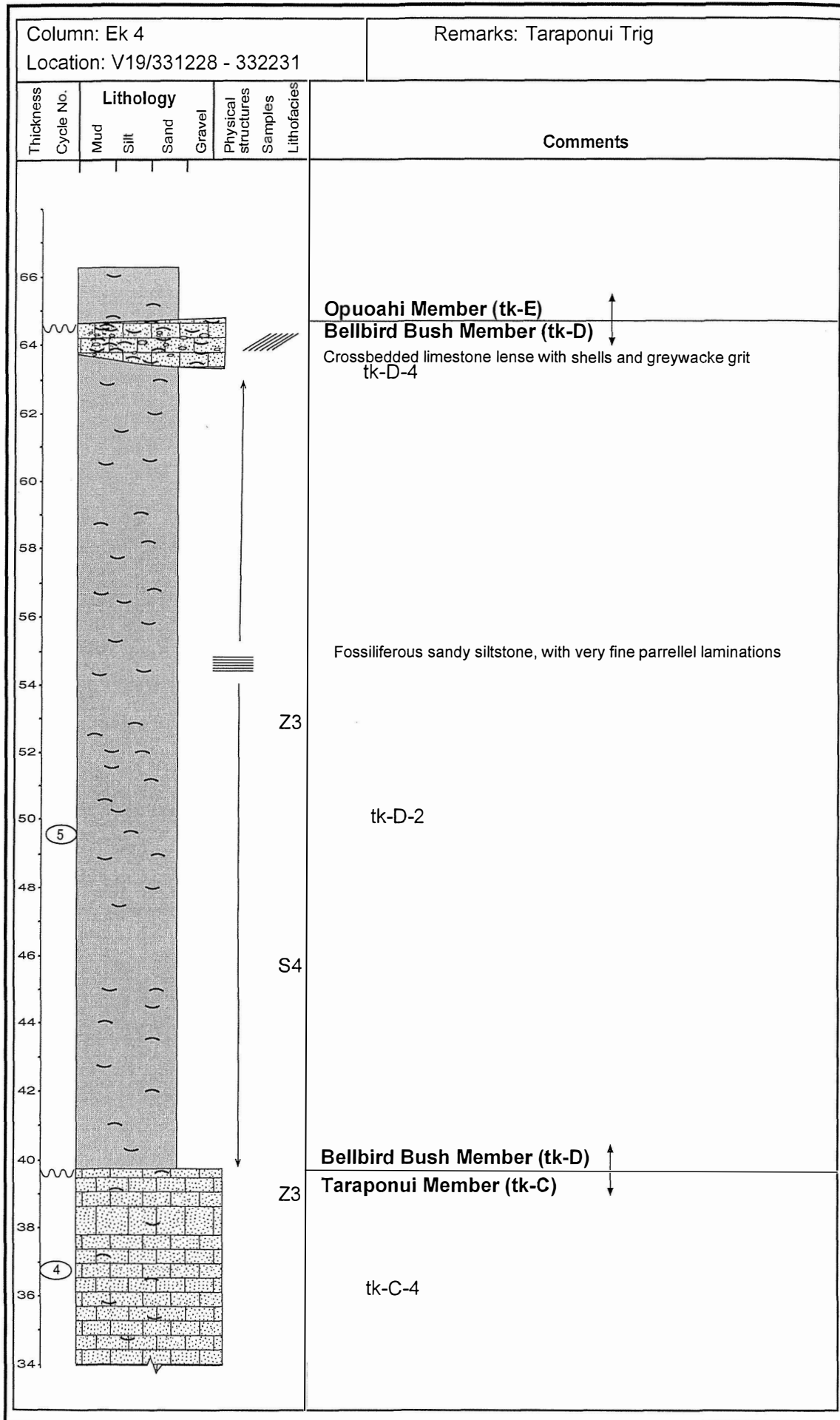
Appendix 1: Stratigraphic Columns



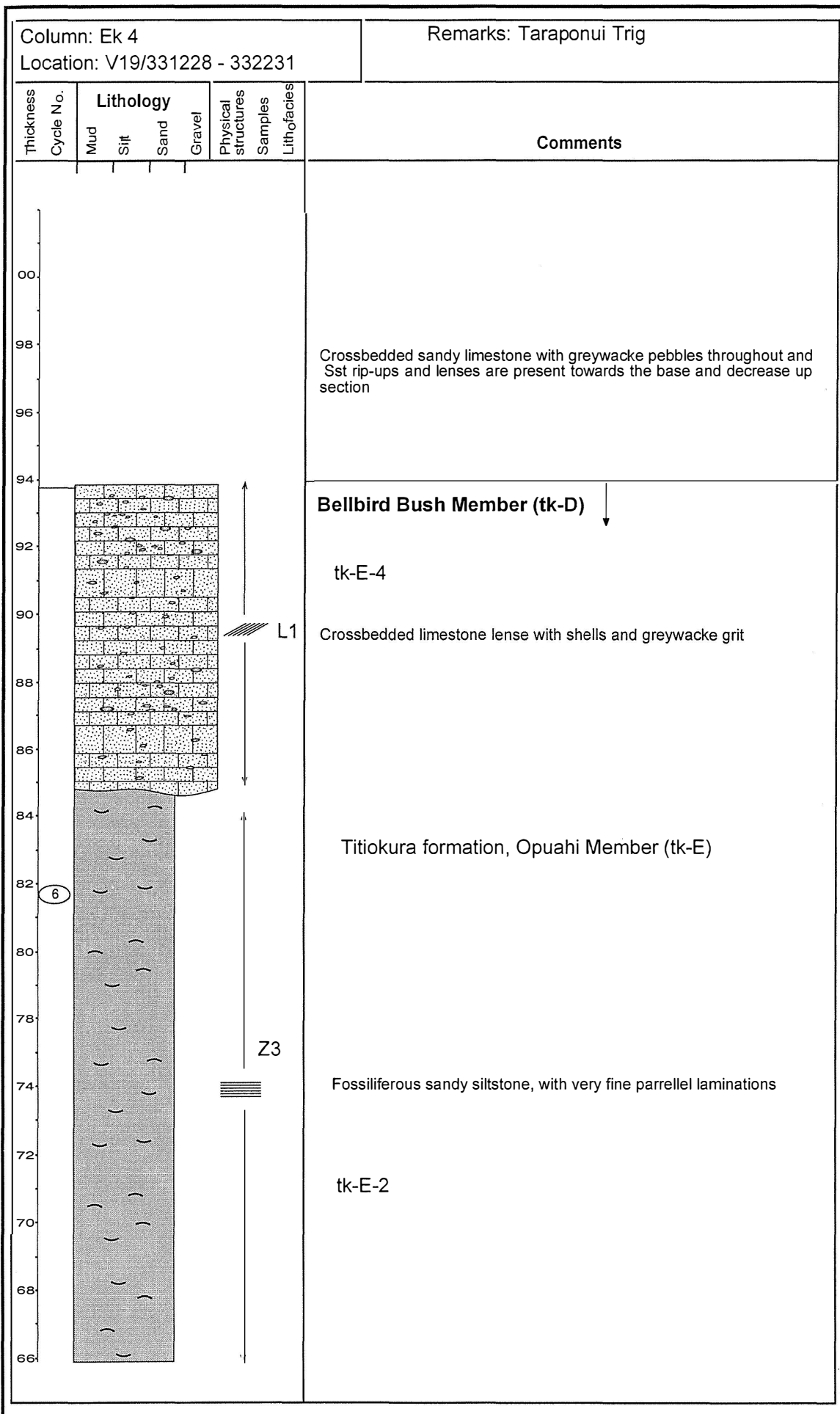
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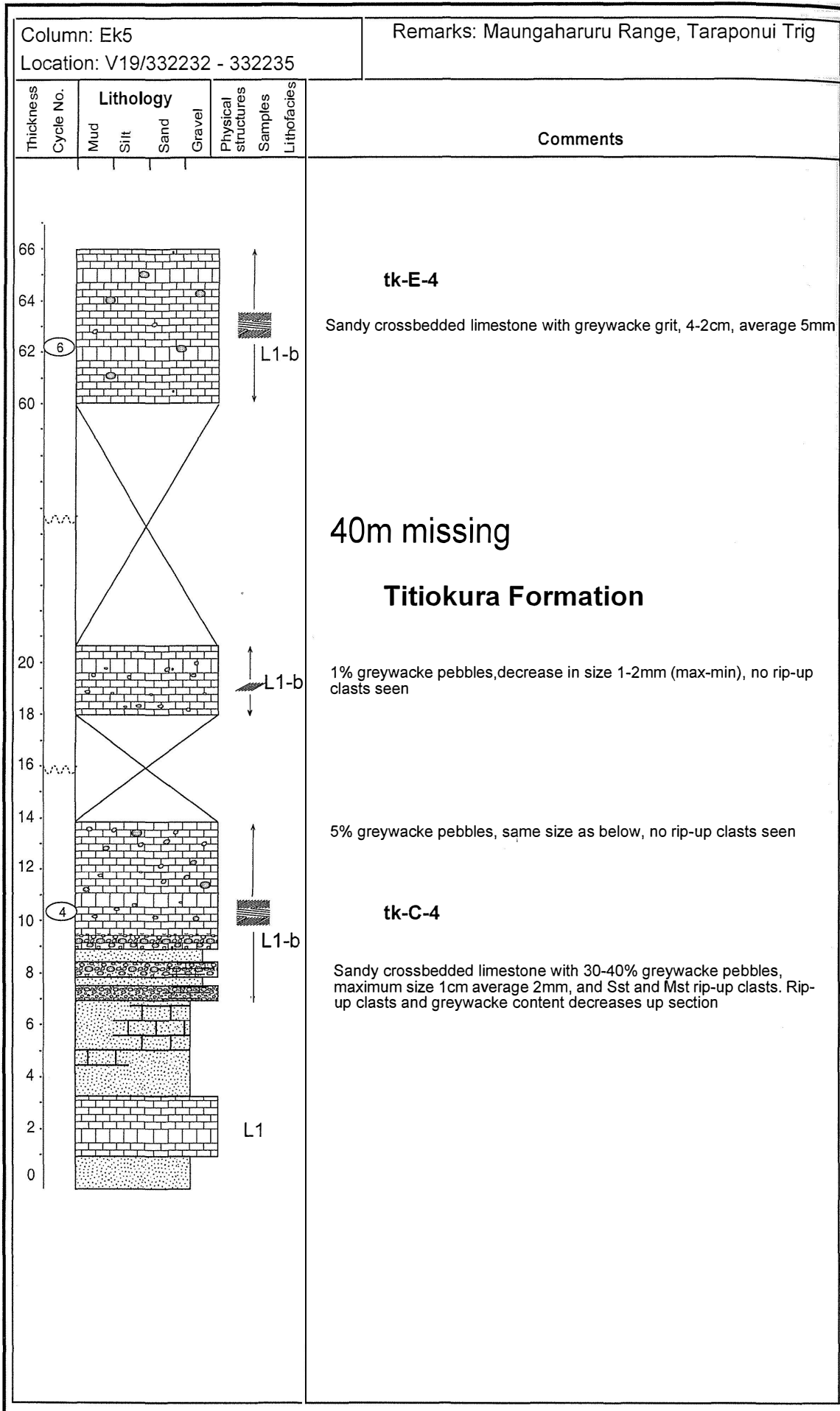
Appendix 1: Stratigraphic Columns



Appendix 1: Stratigraphic Columns



Appendix 1: Stratigraphic Columns



Appendix 1: Stratigraphic Columns

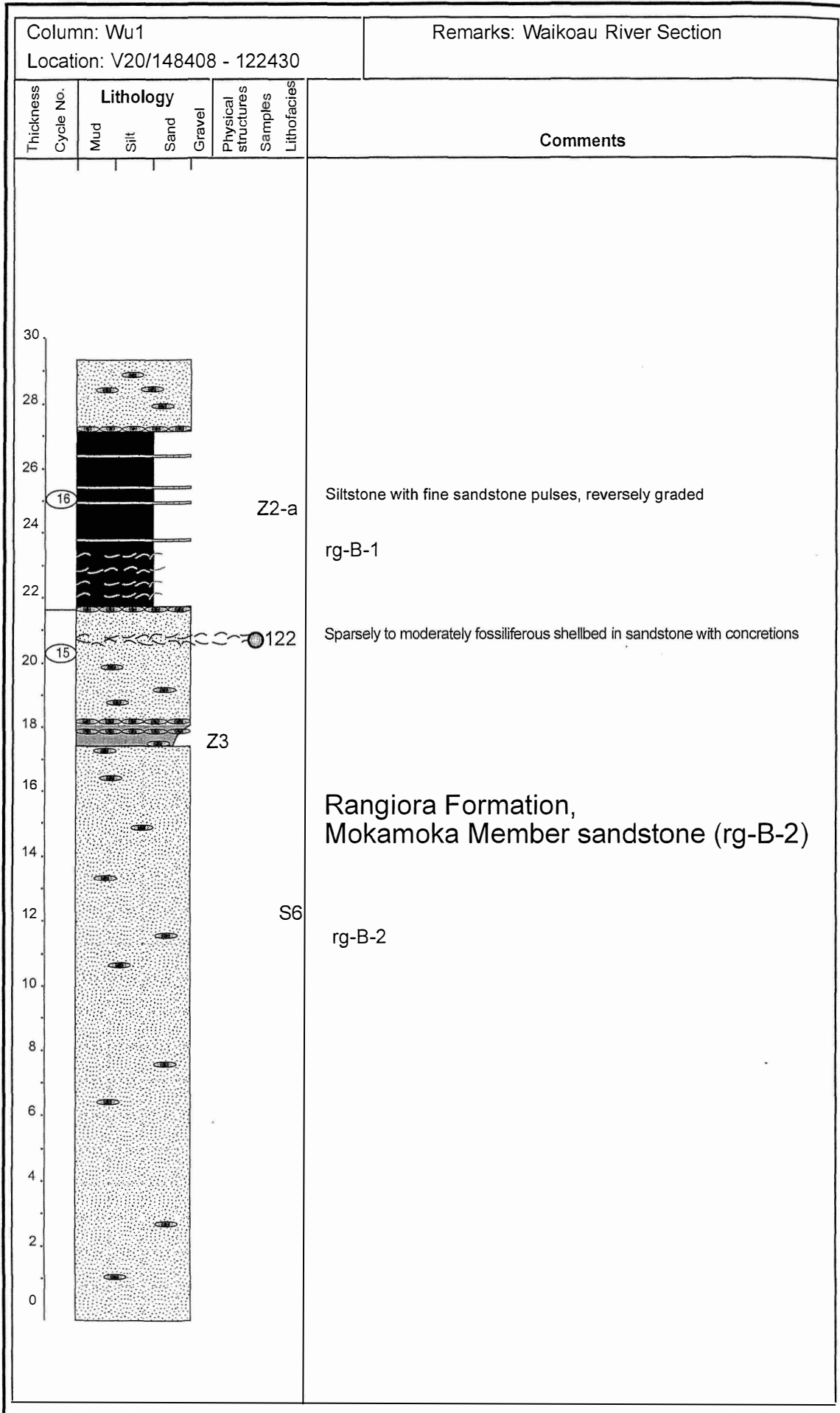
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Location: V19/327200 - 326210									
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		Mud	Silt	Sand	Gravel				
50									
48									
46									
44									
42									
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**Titikura Formation (tk)**

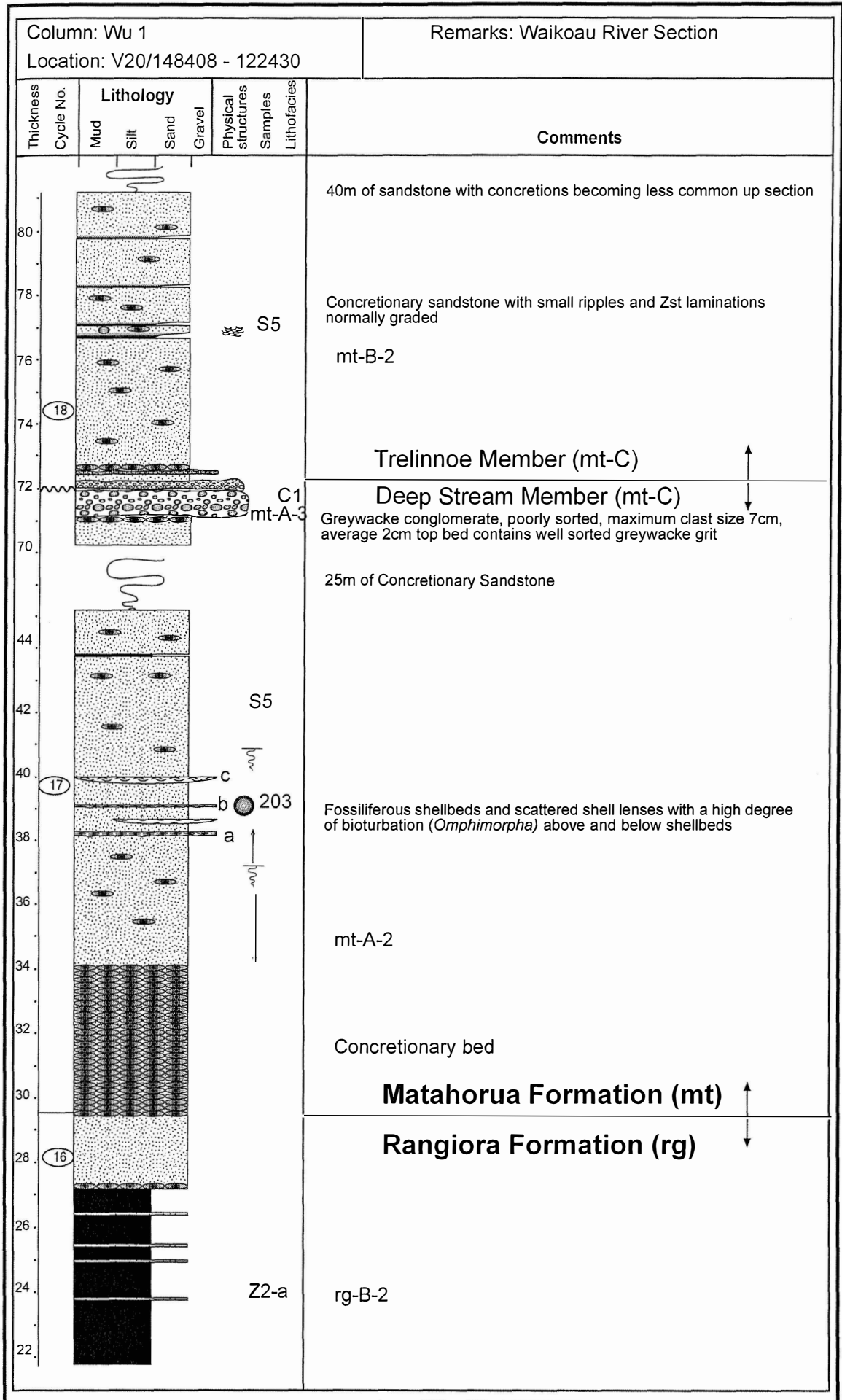
Tabular cross-bedded, very well sorted, sandy limestone coquina with small shell fragments (1-2 mm), and greywacke grit. Containing large barnacle plates, echinoids, bryozoans and pectens.

L1-b

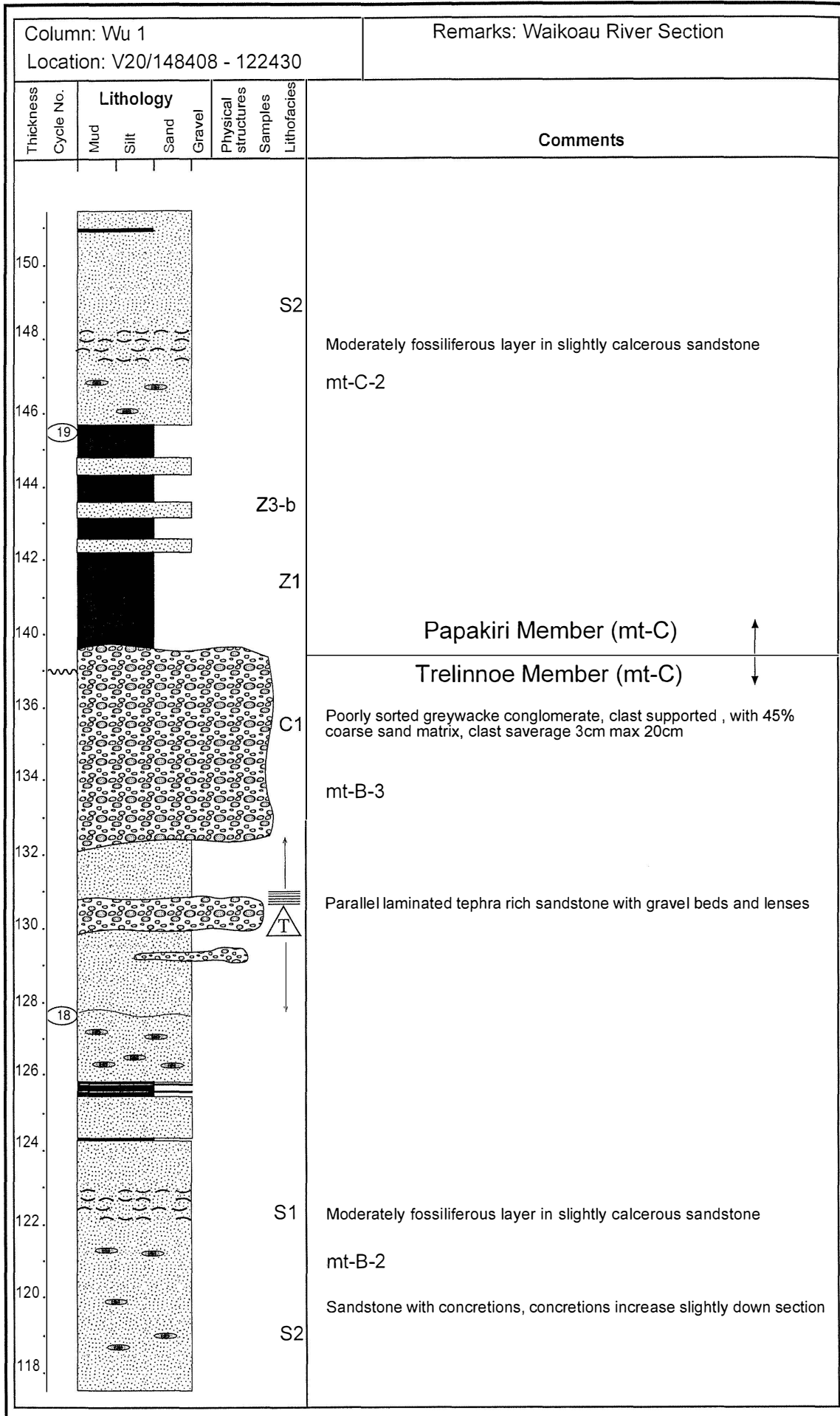
Appendix 1: Stratigraphic Columns



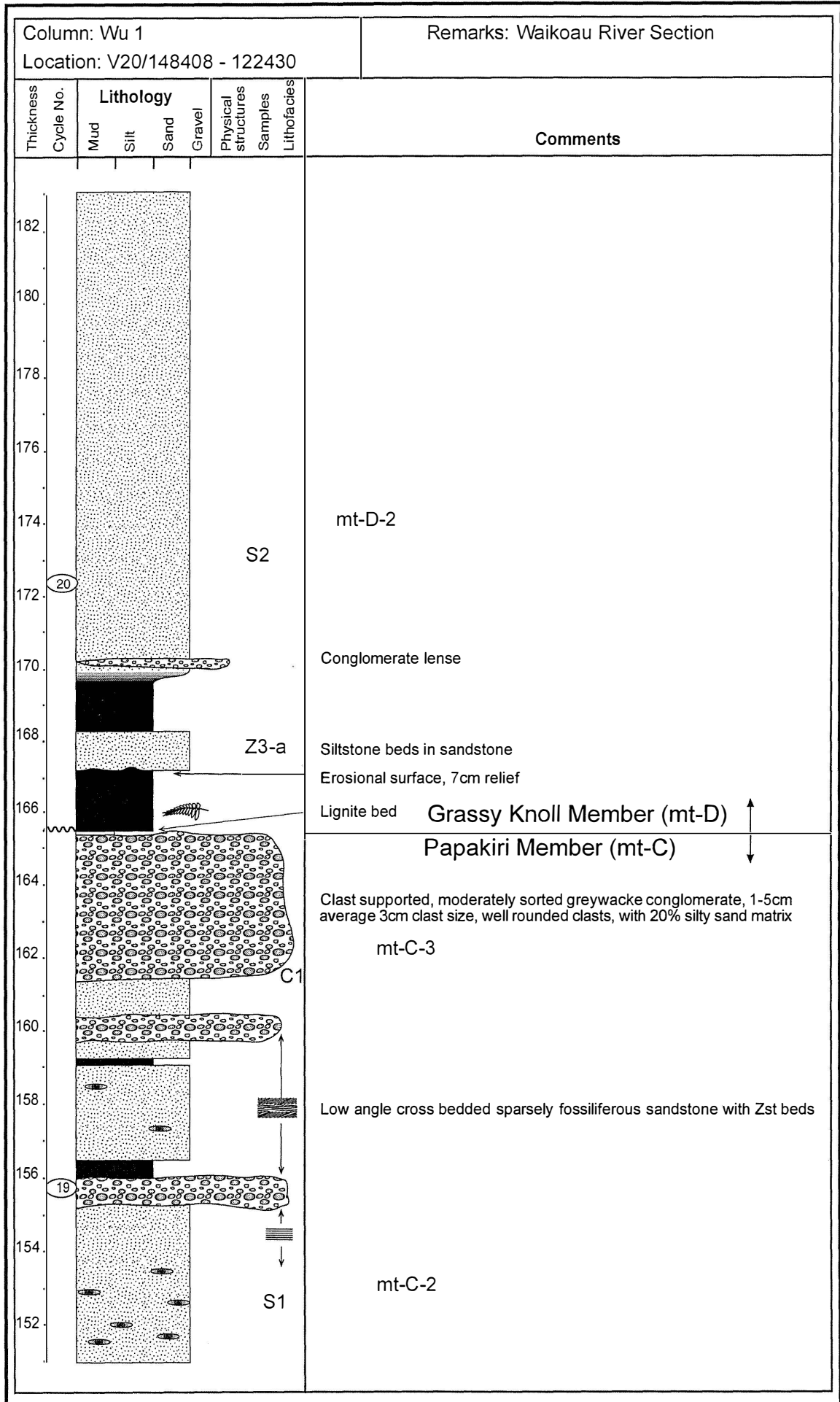
Appendix 1: Stratigraphic Columns



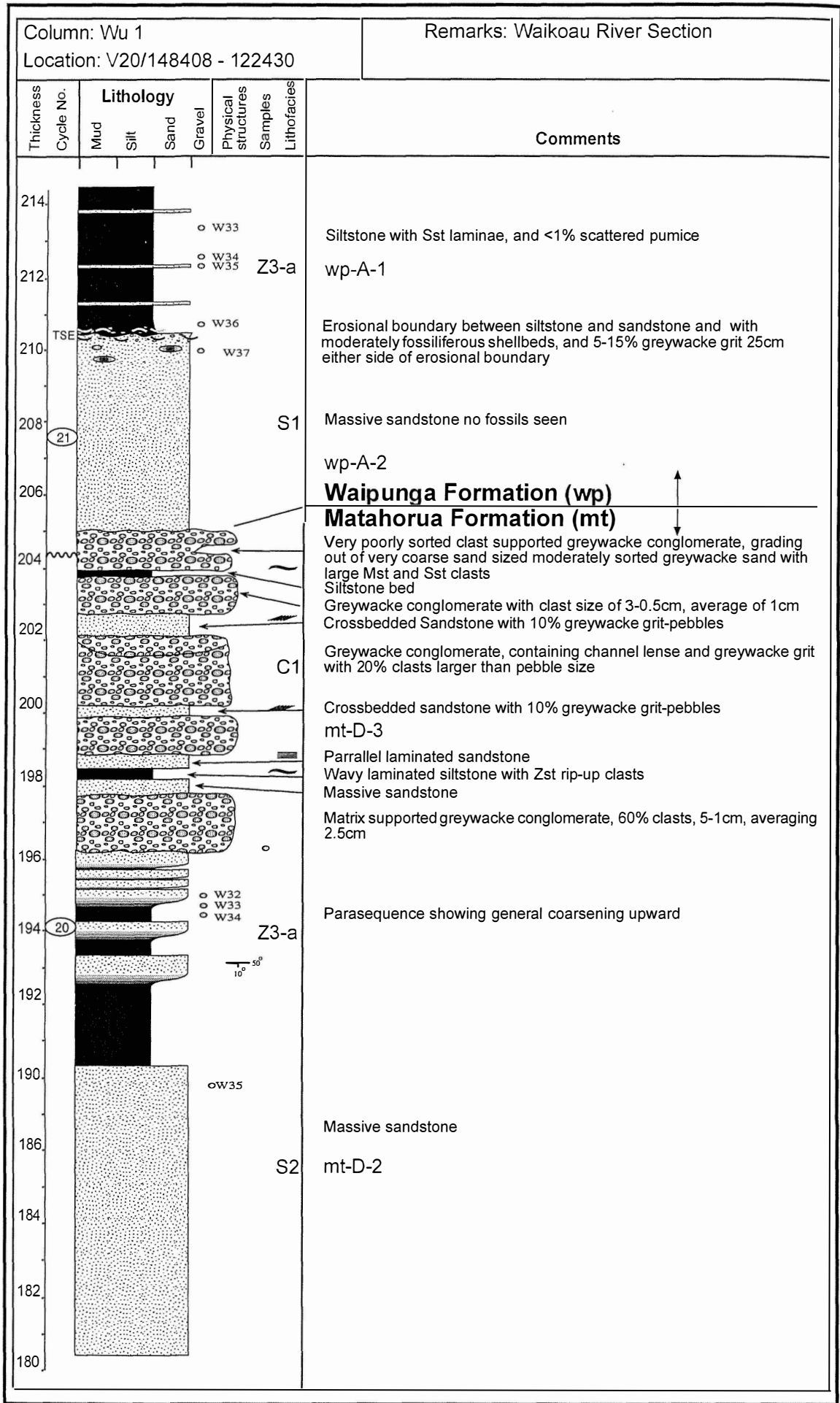
Appendix 1: Stratigraphic Columns



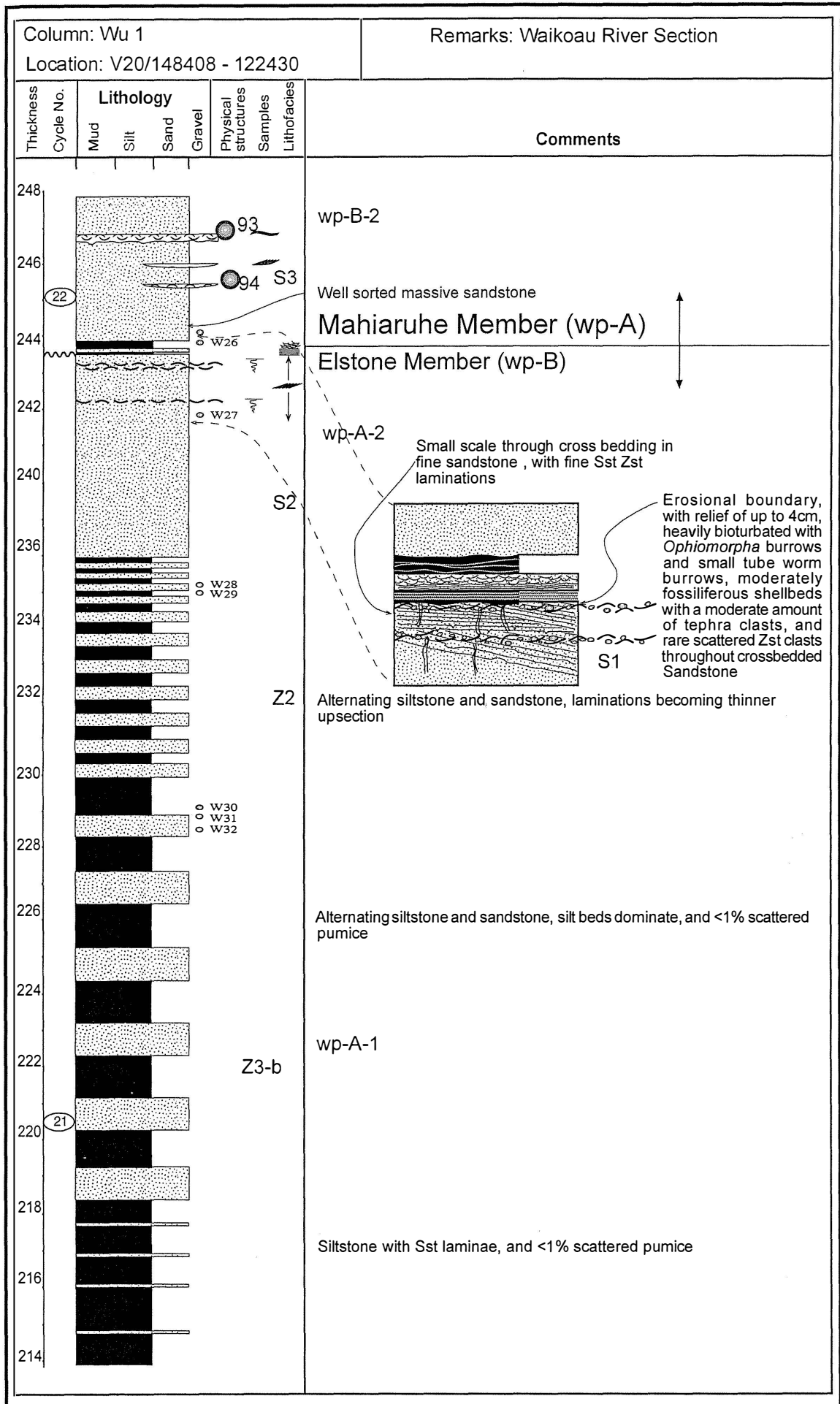
Appendix 1: Stratigraphic Columns



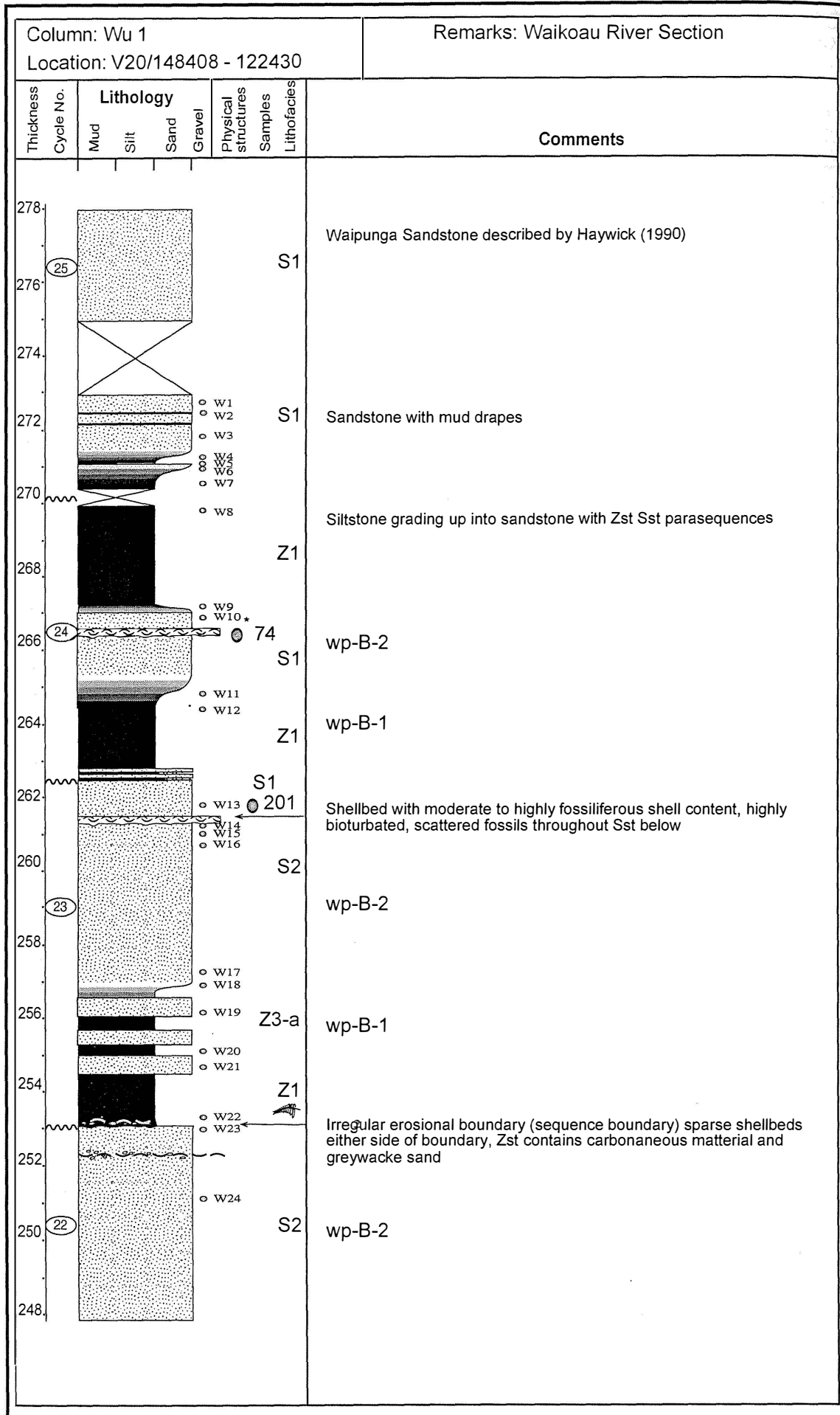
Appendix 1: Stratigraphic Columns



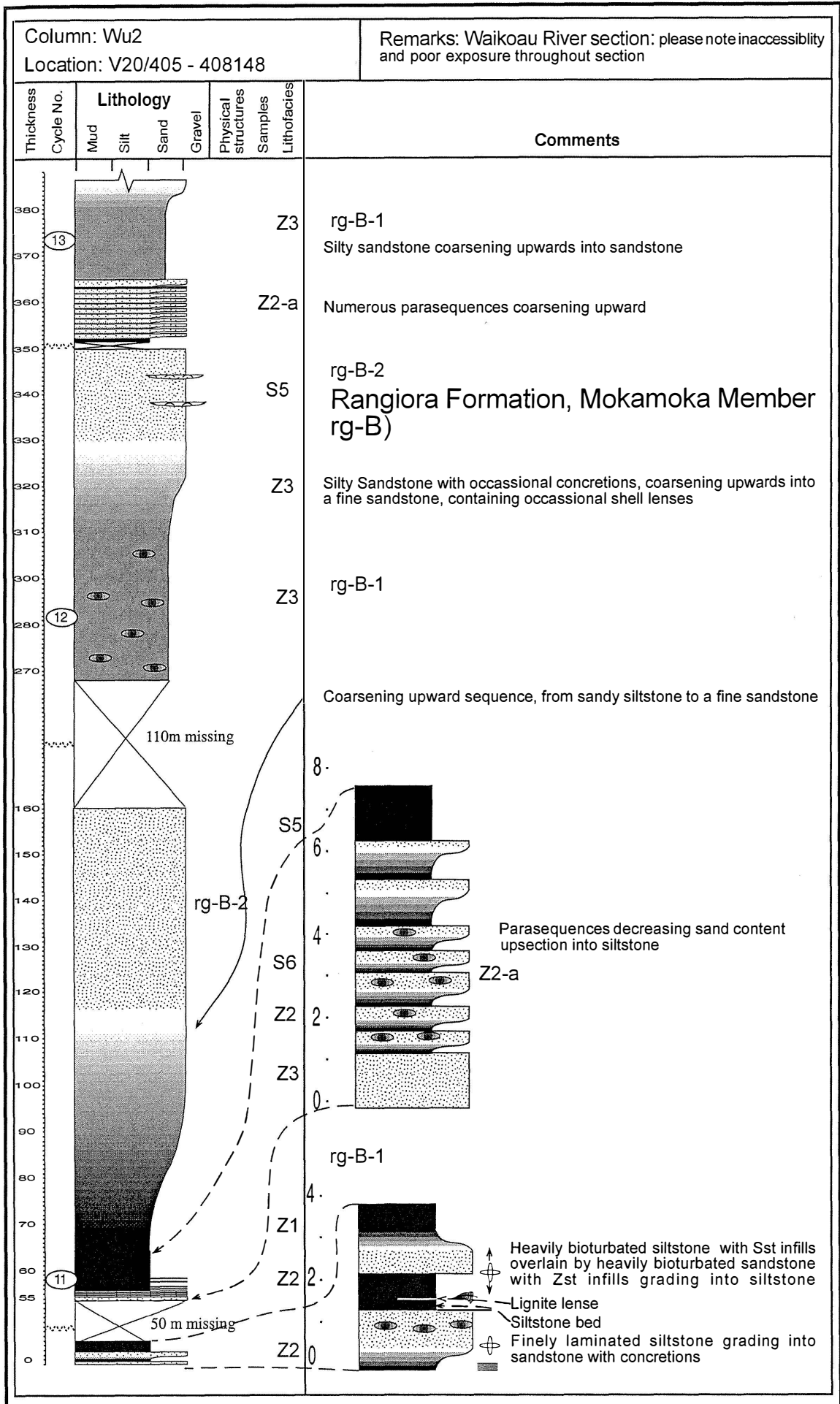
Appendix 1: Stratigraphic Columns



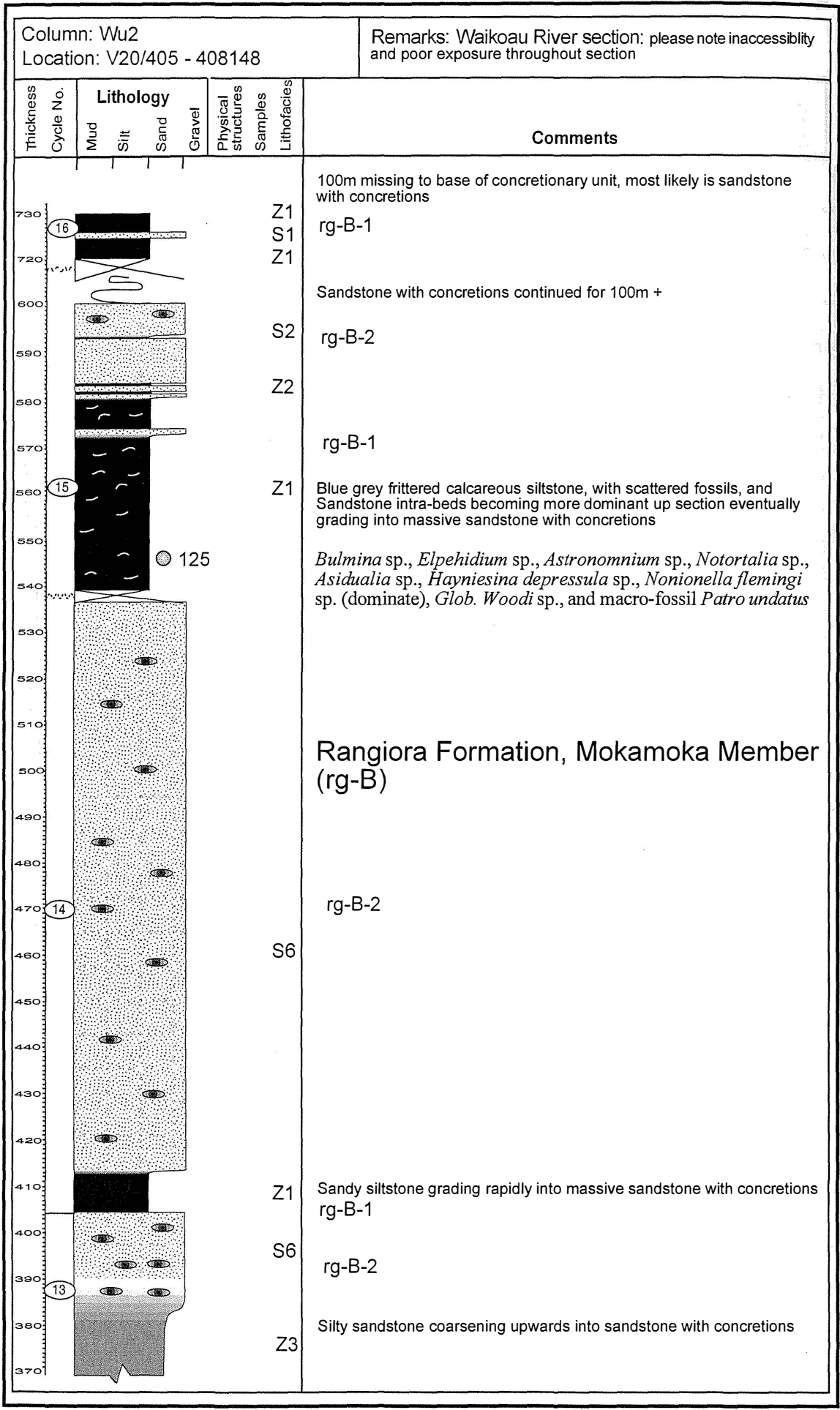
Appendix 1: Stratigraphic Columns



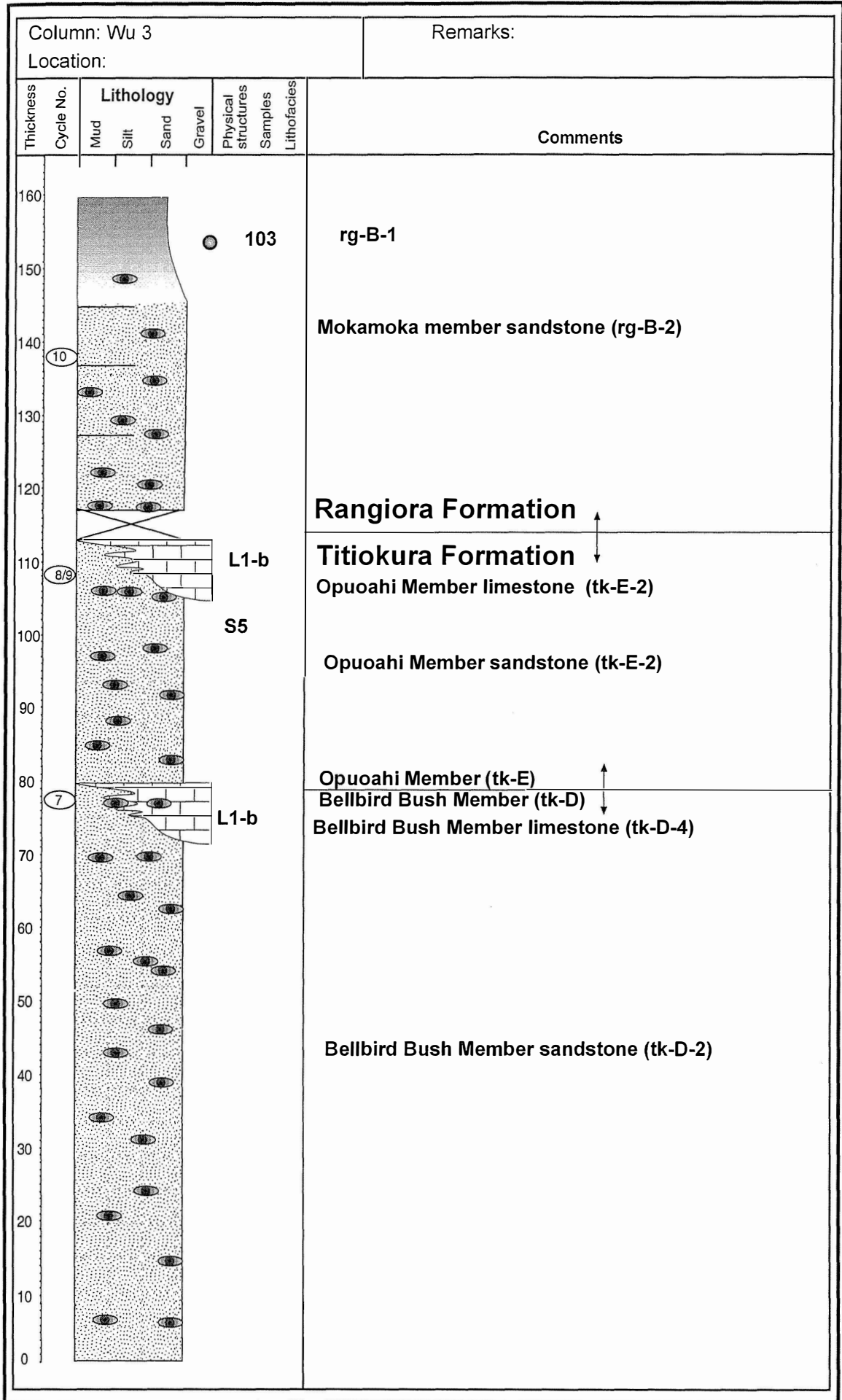
# Appendix 1: Stratigraphic Columns

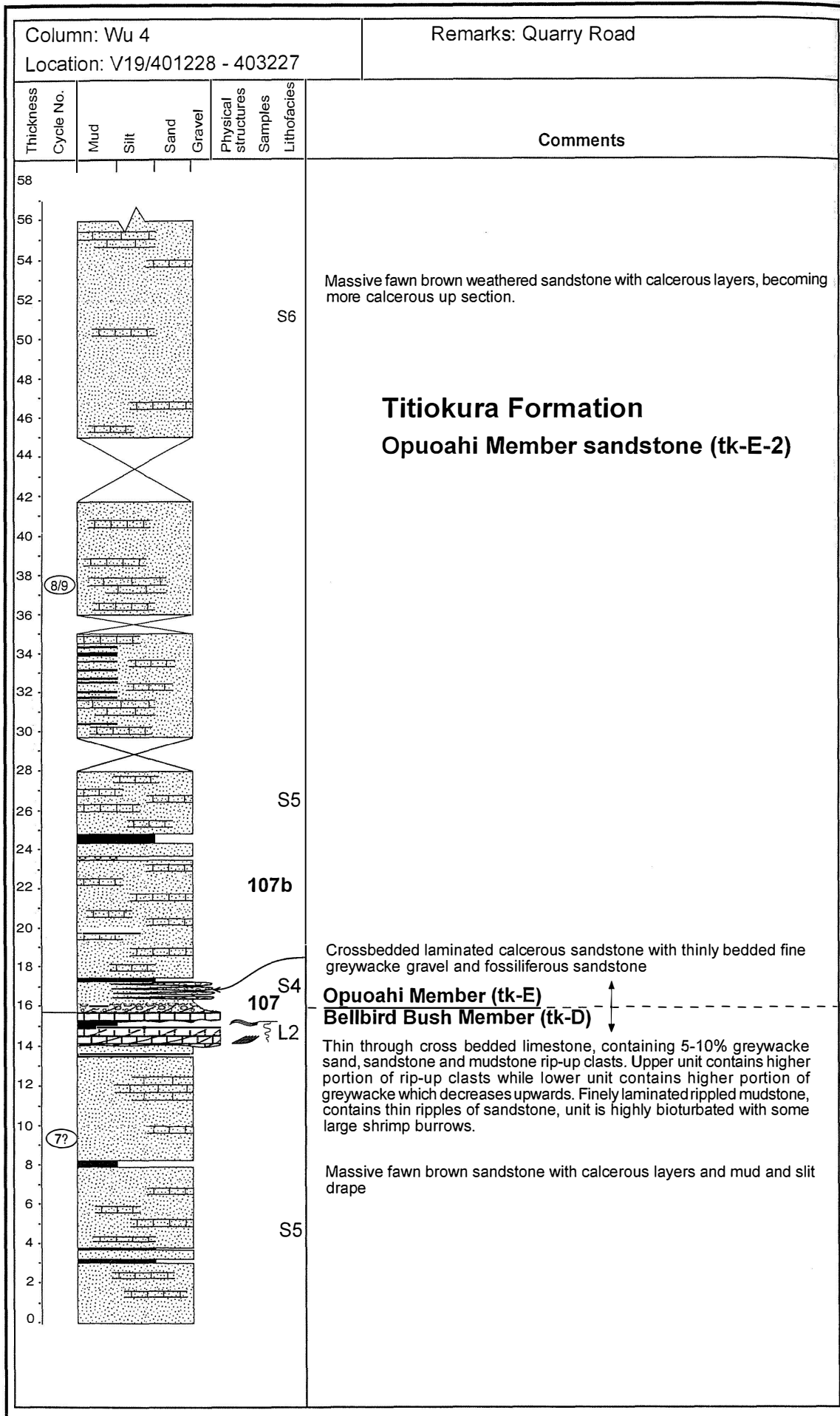


Appendix 1: Stratigraphic Columns



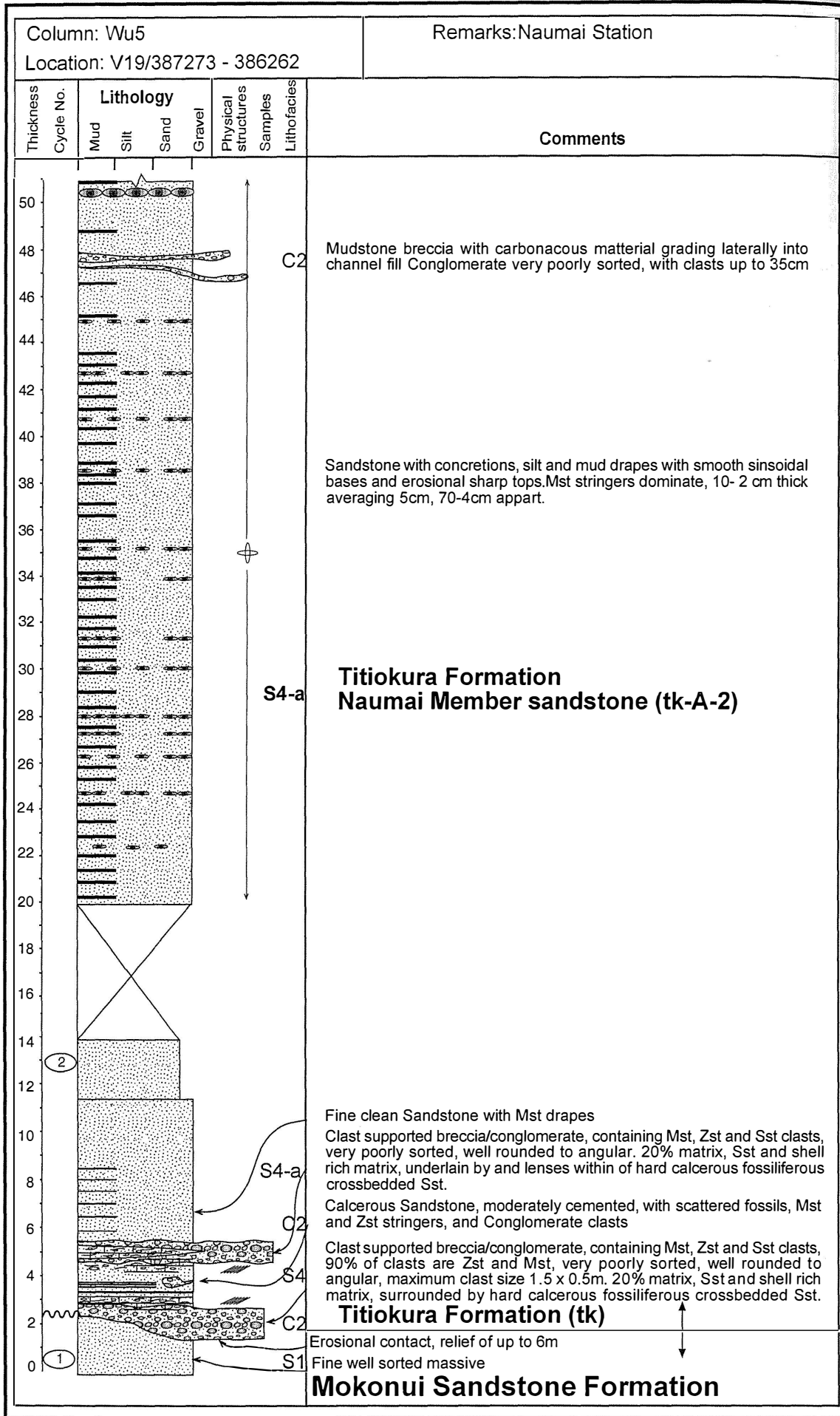
Appendix 1: Stratigraphic Columns



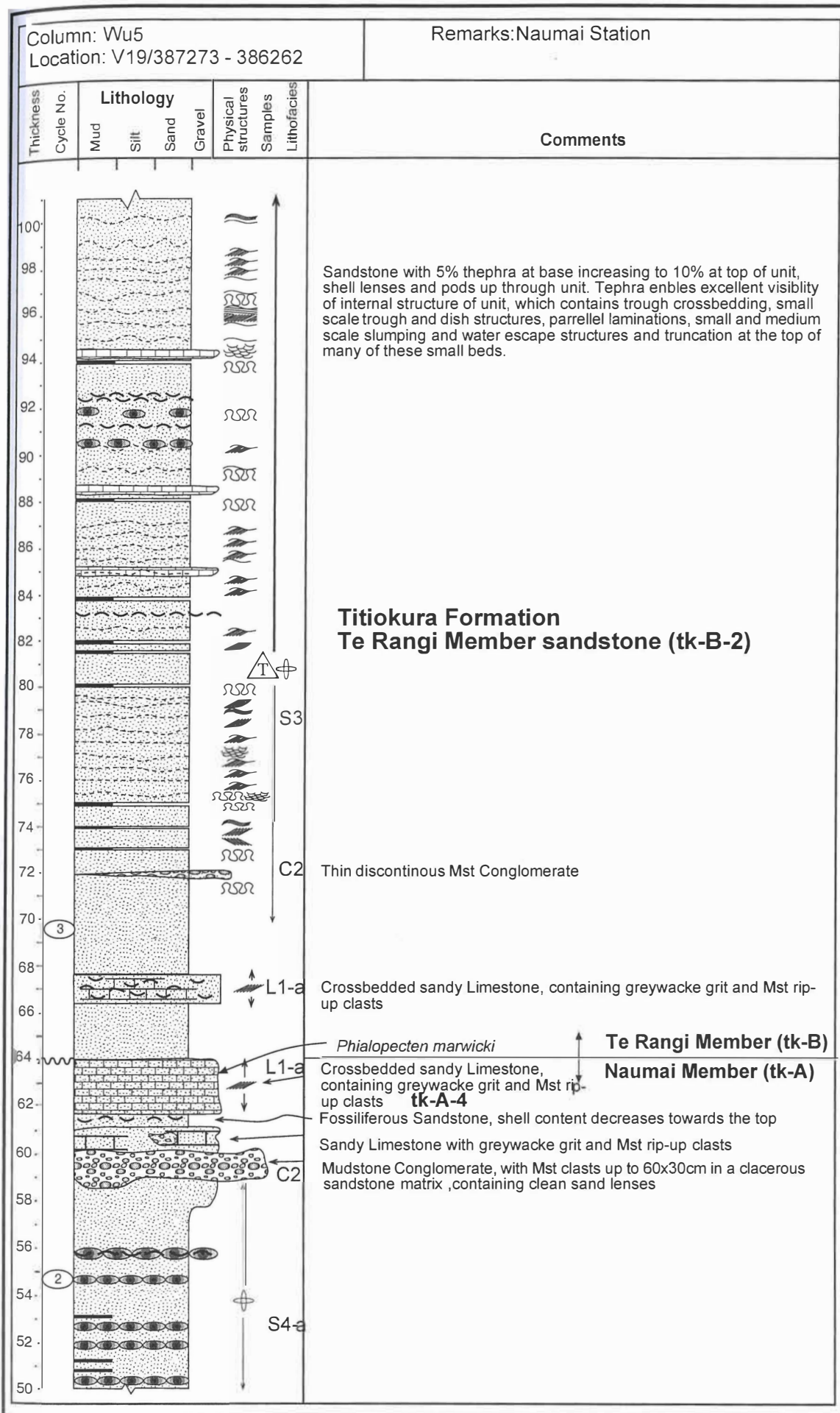


Column: Wu 4 Location: V19/401228 - 403227					Remarks: Quarry Road			
Thickness Cycle No.	Lithology				Physical structures	Samples	Lithofacies	Comments
	Mud	Silt	Sand	Gravel				
								<p><b>Titiohora Formation</b> <b>Opuoahi Member limestone (tk-E-4)</b></p> <p>Low angle cross bedded limestone with calcereous sandstone lenses, which contains &gt; 5% fossils and greywacke sand, decreasing up through the limestone. Basal units contain 10 -15% greywacke sand.</p> <p>Crossbedded limestone lenses with high fossil and greywacke contents, also contains laminated mudstone layer at base of major limestone unit</p> <p>Grading out of sandstone into limestone, fossil and greywacke pebble content increases up section</p> <p><b>tk-E-4</b> Mudstone at base of limestone is 'ripped up' into limestone</p> <p><b>tk-E-2</b></p>

Appendix 1: Stratigraphic Columns

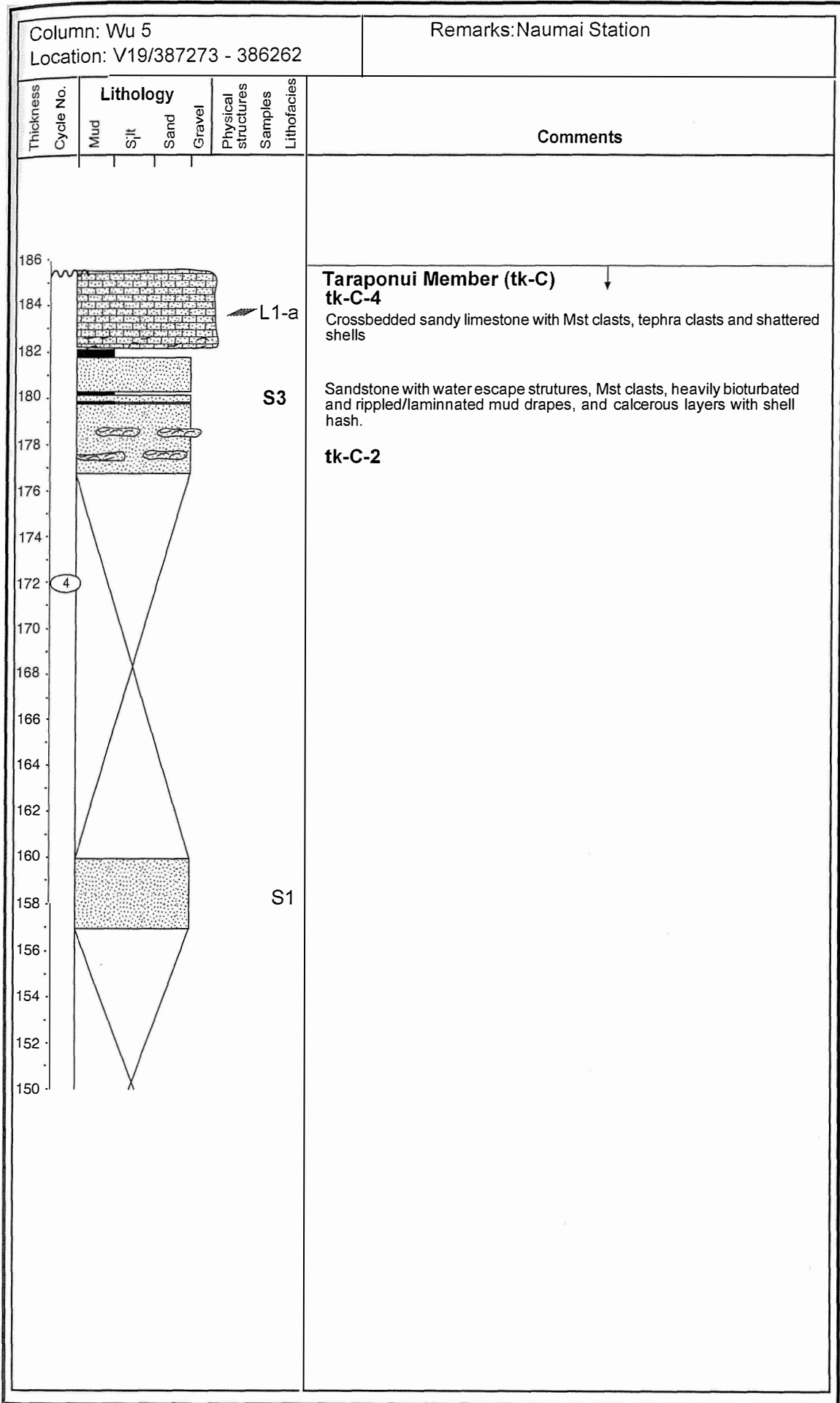


Appendix 1: Stratigraphic Columns





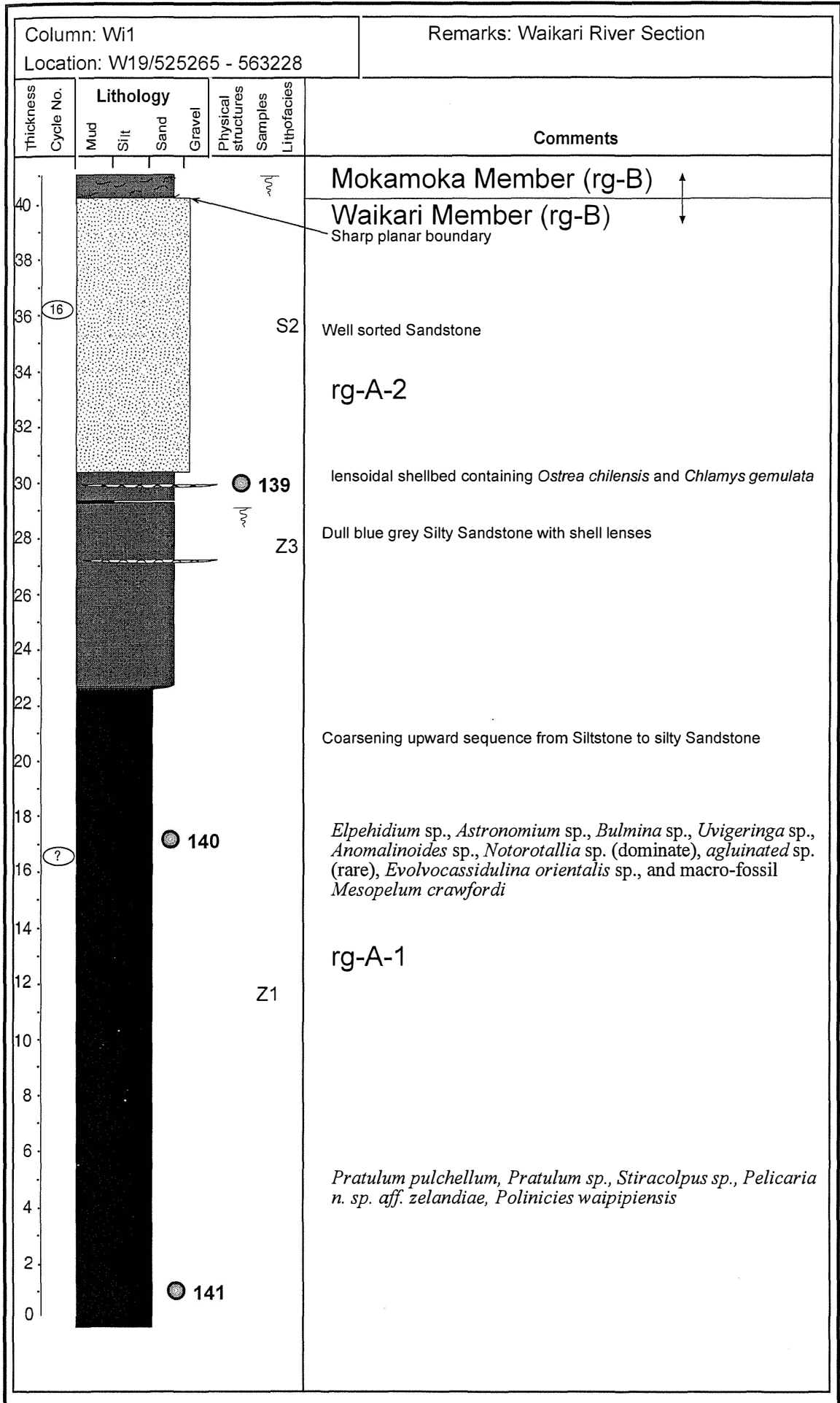
Appendix 1: Stratigraphic Columns



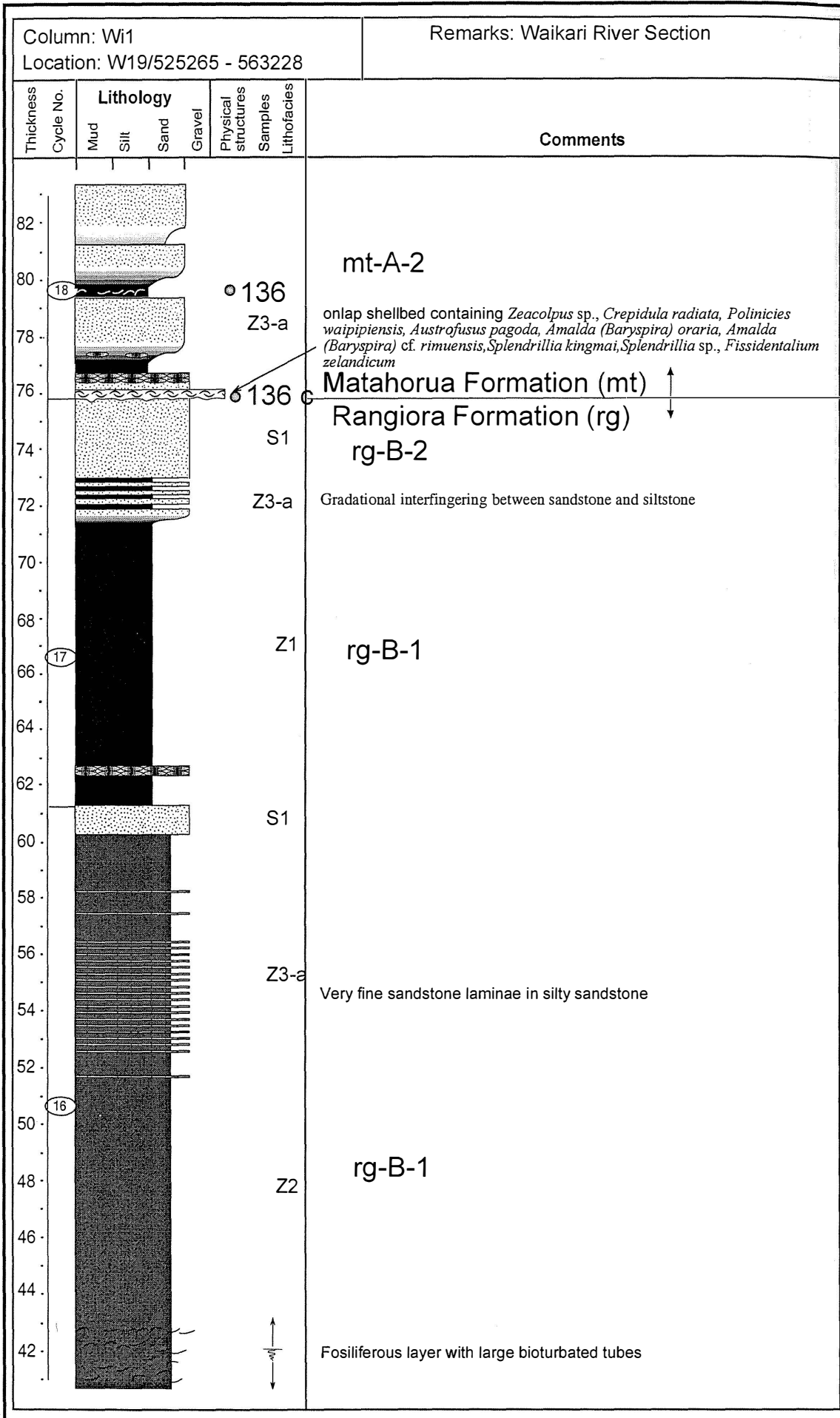
Appendix 1: Stratigraphic Columns

Column: Wu6		Remarks: Toronui Station						
Location: V19/368208								
Thickness Cycle No.	Lithology				Physical structures	Samples	Lithofacies	Comments
	Mud	Silt	Sand	Gravel				
20								<p>Fossiliferous, calcareous sandy siltstone with large (2-3 m) round concretions, and fossil lenses/pods</p> <p><b>Rangiora Formation</b> Mokamoka Member siltstone rg-B-1</p> <p>Silty sandstone with scattered shells, lenses, and large concretions (1 x3m), possibly fining upwards</p> <p>Fossiliferous calcareous Siltstone</p>
18								
16								
14							● r192a	
12							Z2-a	
10							● r192b	
8							● r192d	
6							● r192f	
4								
2								
0								

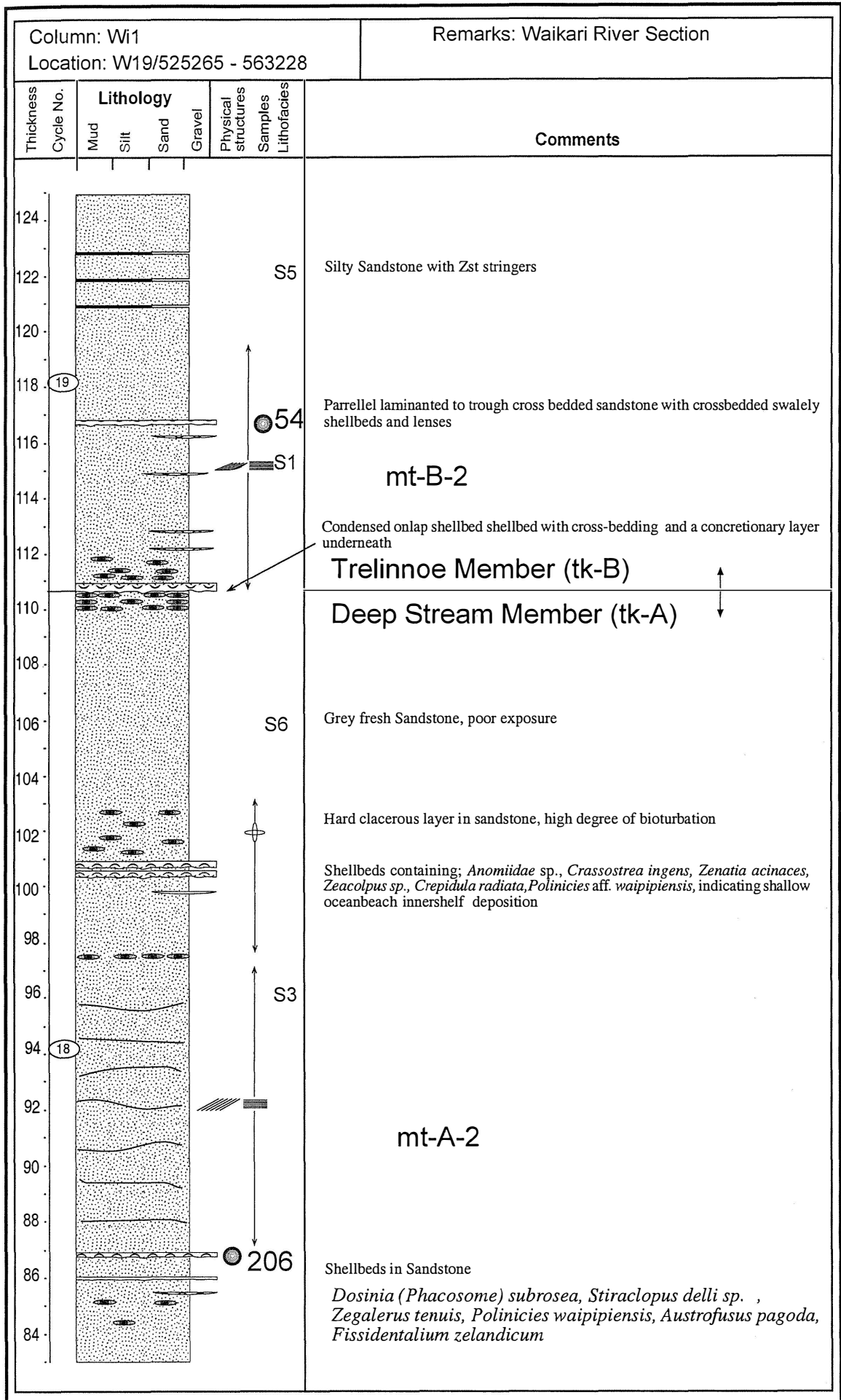
Appendix 1: Stratigraphic Columns



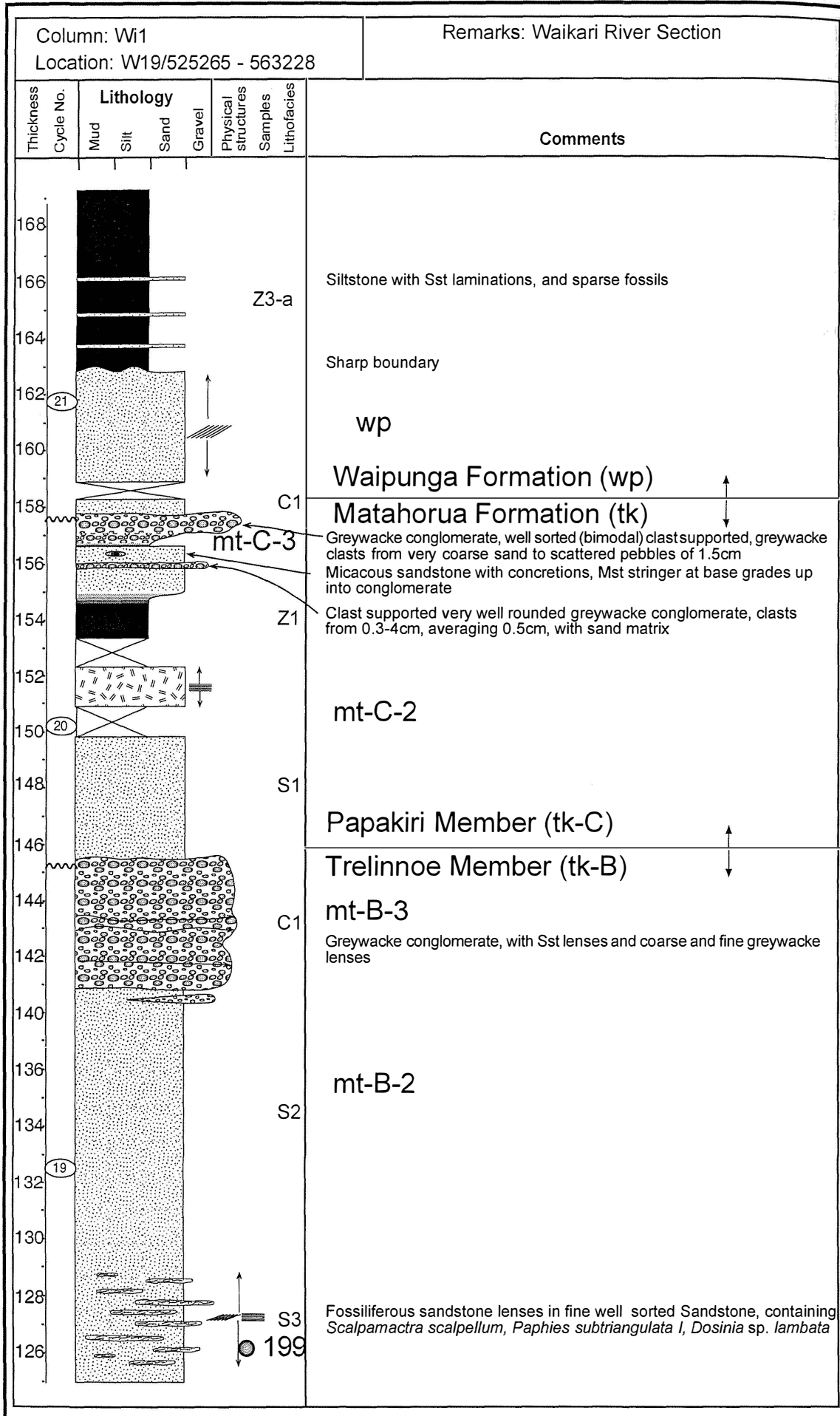
Appendix 1: Stratigraphic Columns



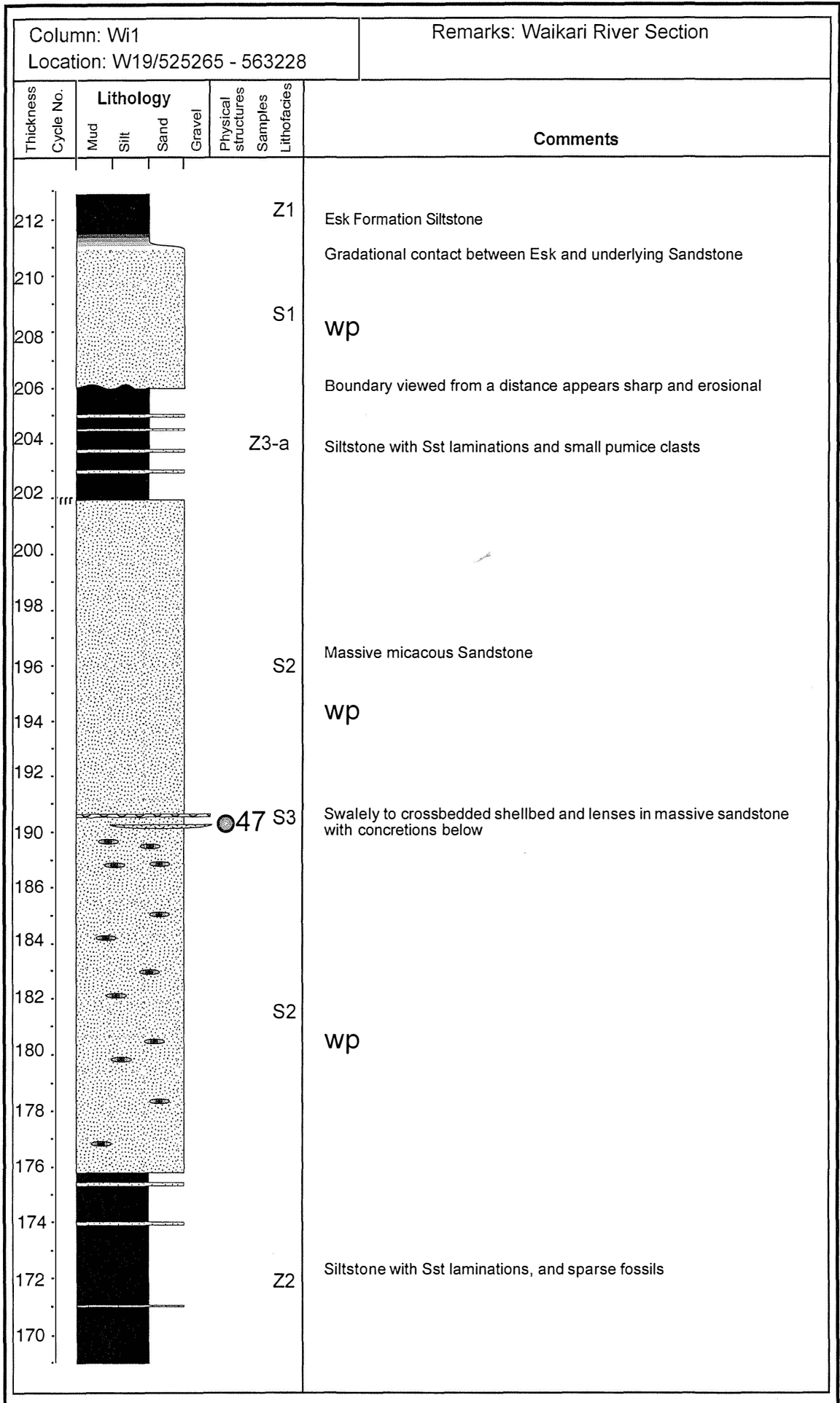
Appendix 1: Stratigraphic Columns



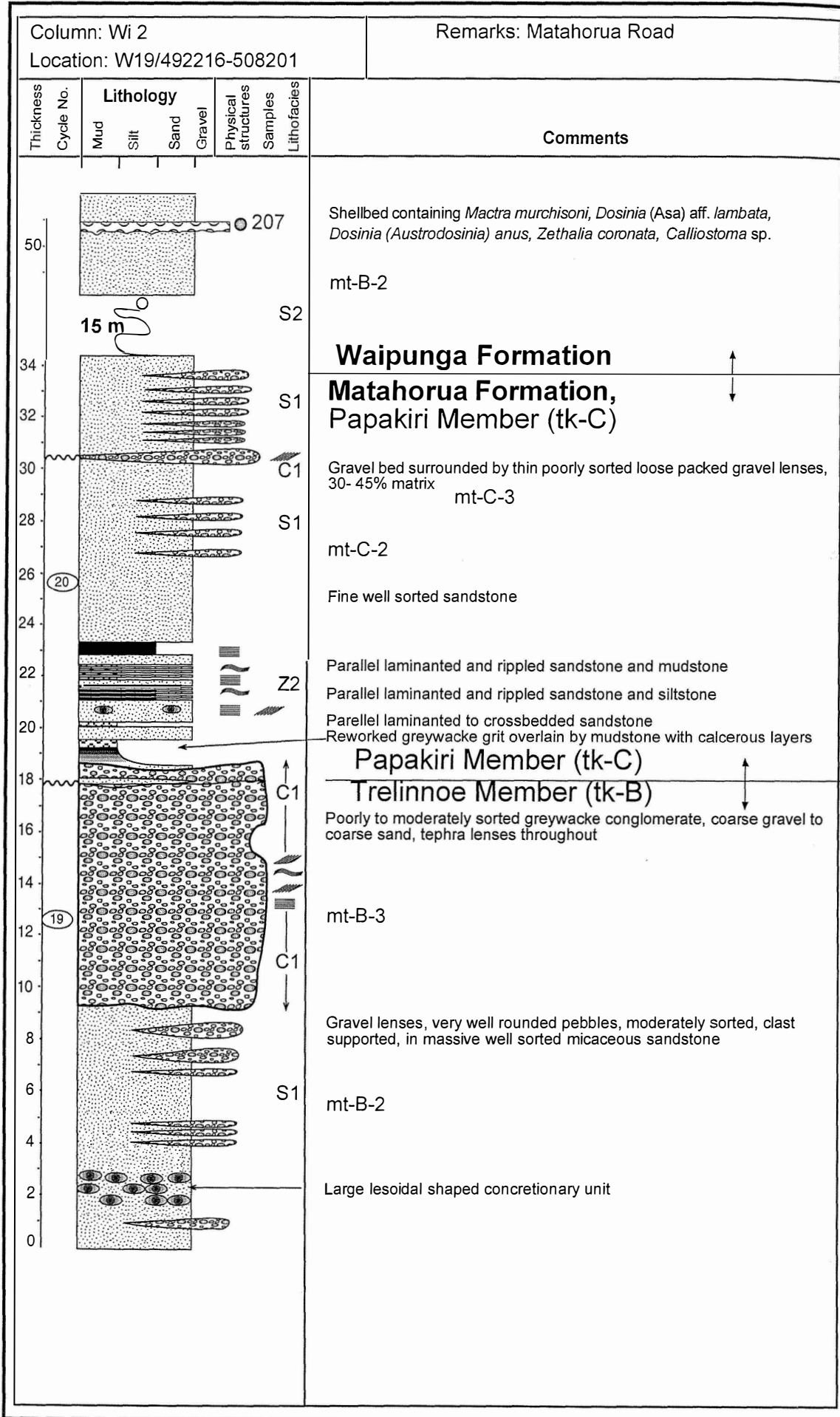
Appendix 1: Stratigraphic Columns



Appendix 1: Stratigraphic Columns



Appendix 1: Stratigraphic Columns



Appendix 1: Stratigraphic Columns

Column: W13		Remarks: Flat Hill Road							
Location: V19/439236 - 449235									
Thickness	Cycle No.	Lithology				Physical structures	Samples	Lithofacies	Comments
		Mud	Silt	Sand	Gravel				
84									
82									
80									
78									
76									
74									
70									
68									
66									
64									
62									
60									
58									
56									
54									
52									
50									
48									
46									
44									
42									
40									
38									
36									
34									
32									
30									
28									
26									
24									
22									
20									
18									
16									
14									
12									
10									
8									
6									
4									
2									
0									

Rangiora Formation,  
Mokamoka Member

Massive sandstone

S6

rg-B-2

Z2

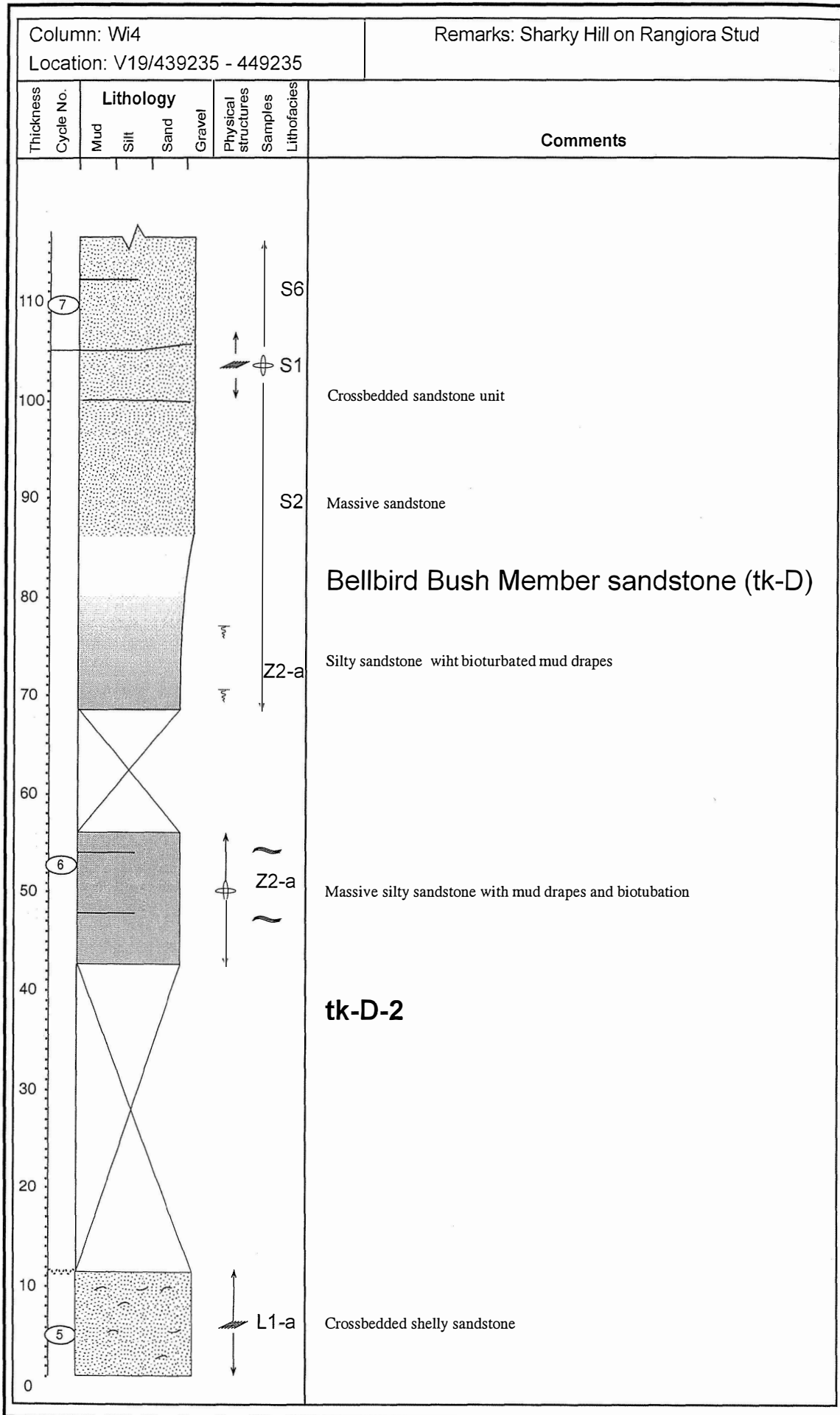
rg-B-1

Fossiliferous calcareous Siltstone

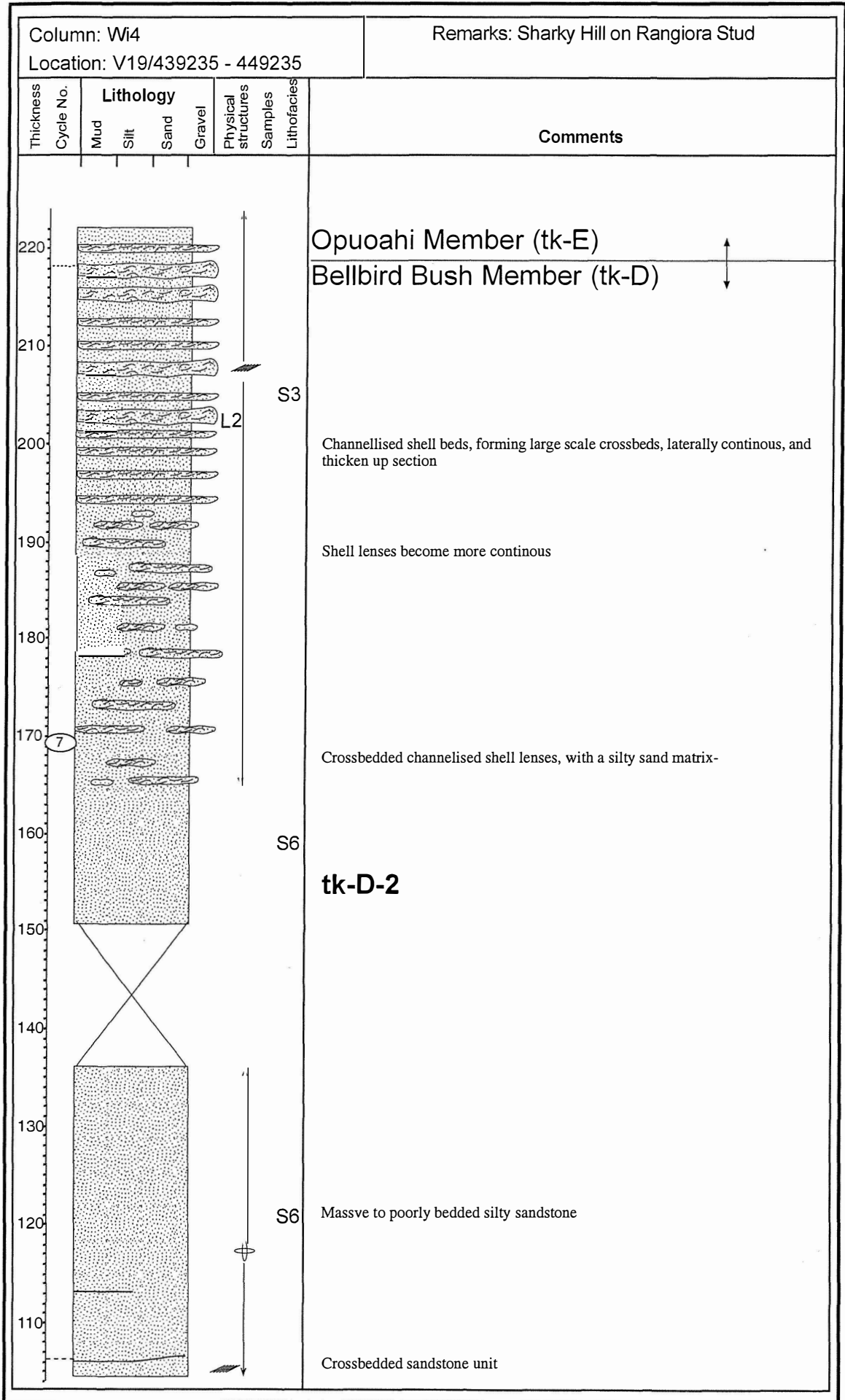
● 204

Z1

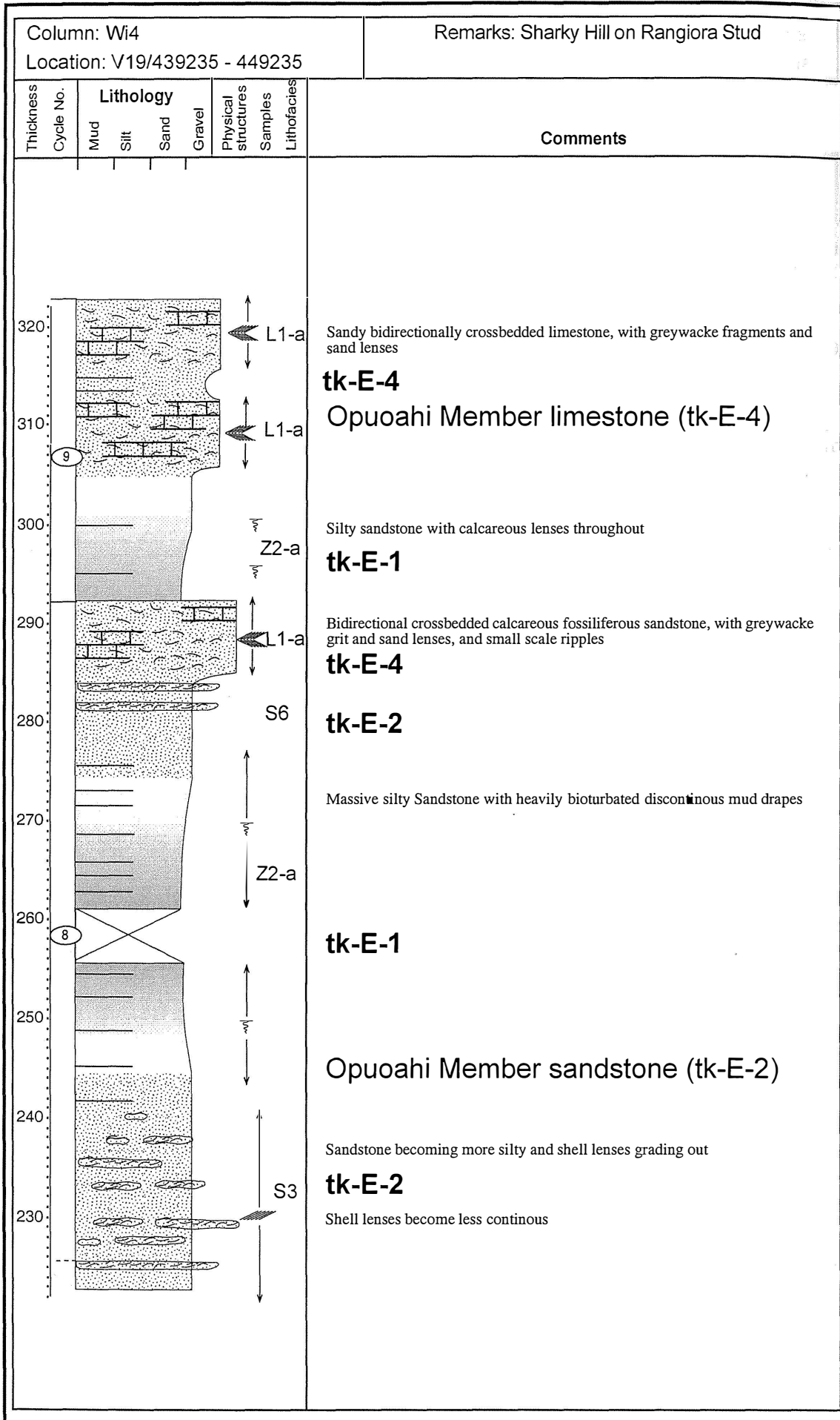
Appendix 1: Stratigraphic Columns



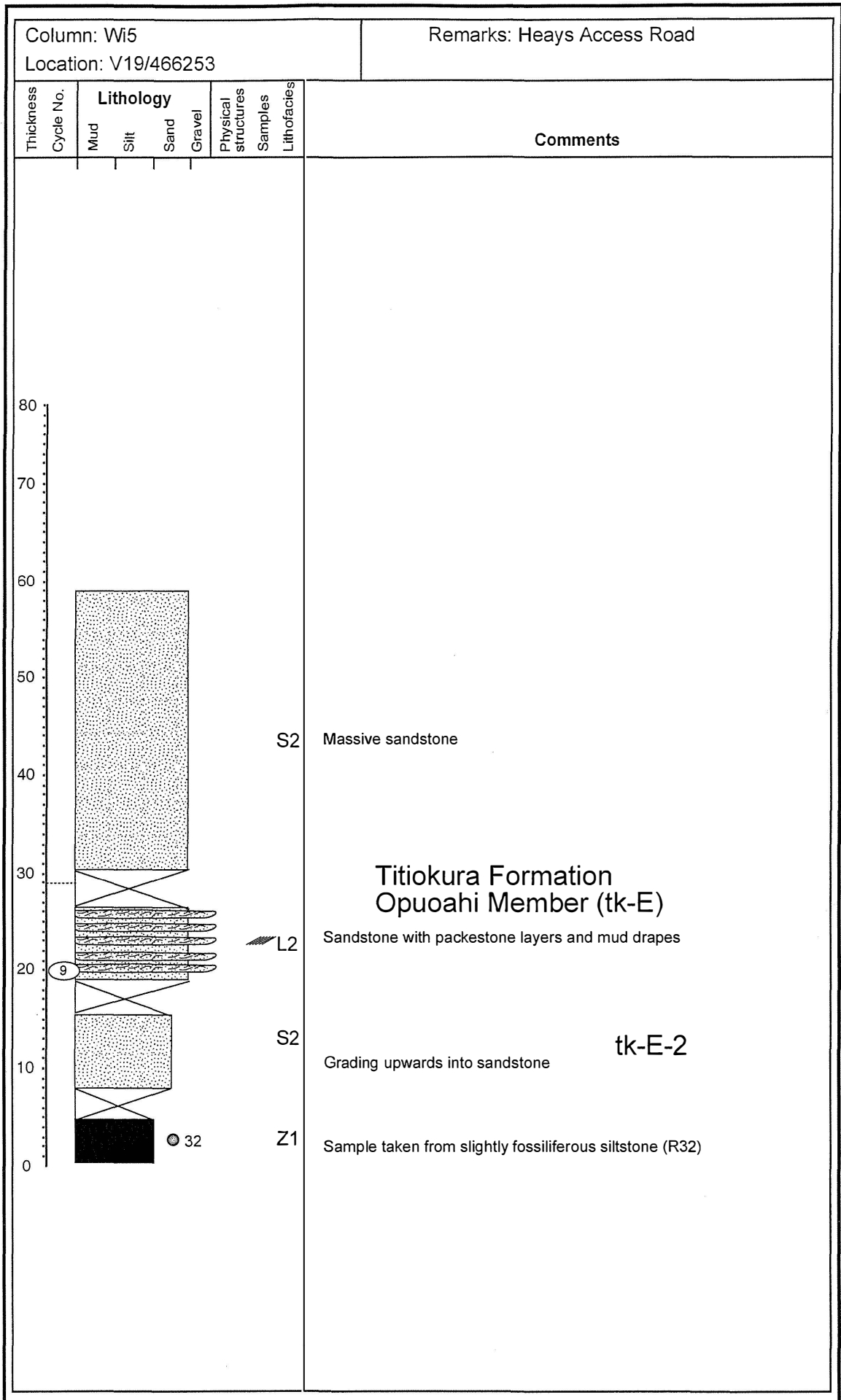
Appendix 1: Stratigraphic Columns



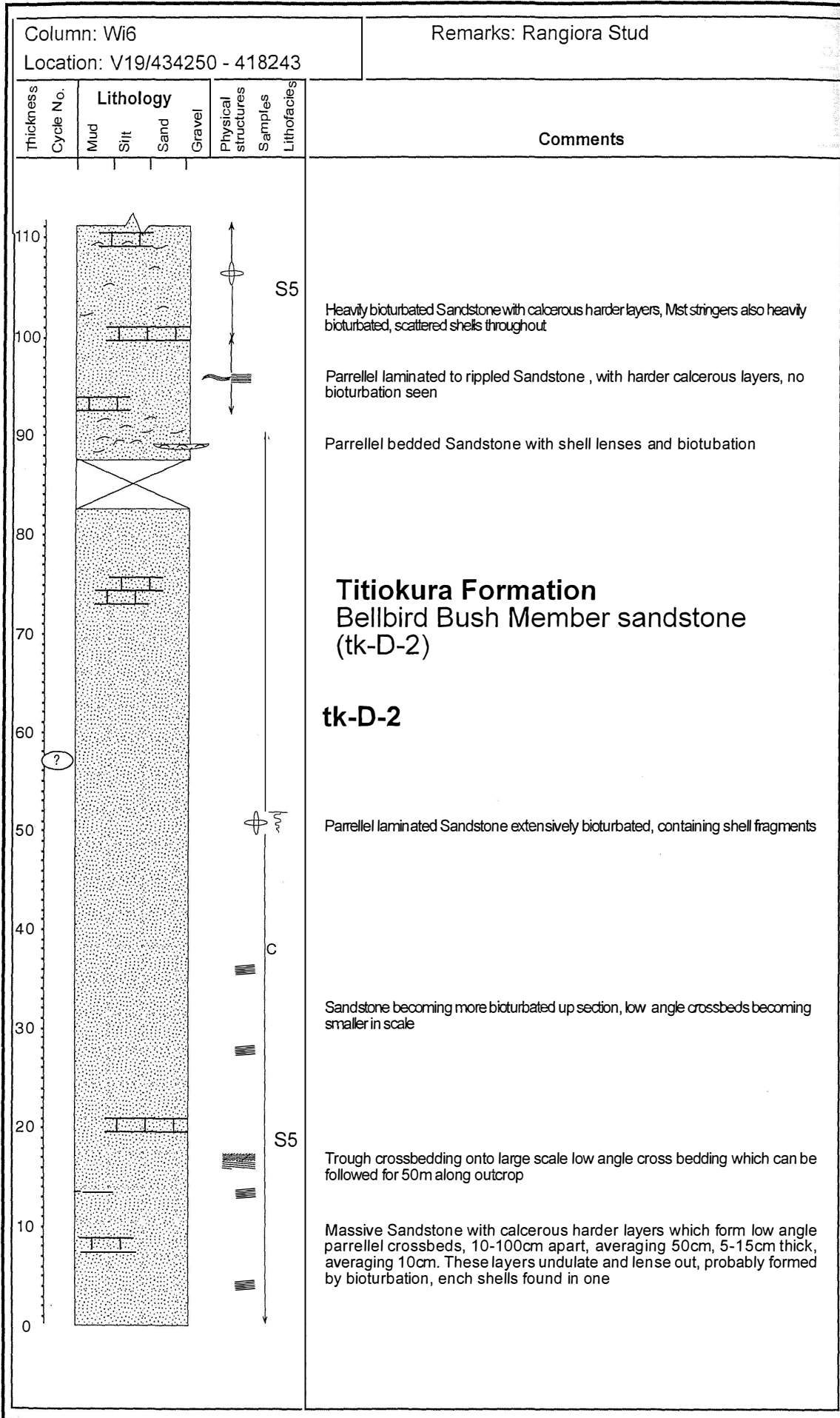
Appendix 1: Stratigraphic Columns



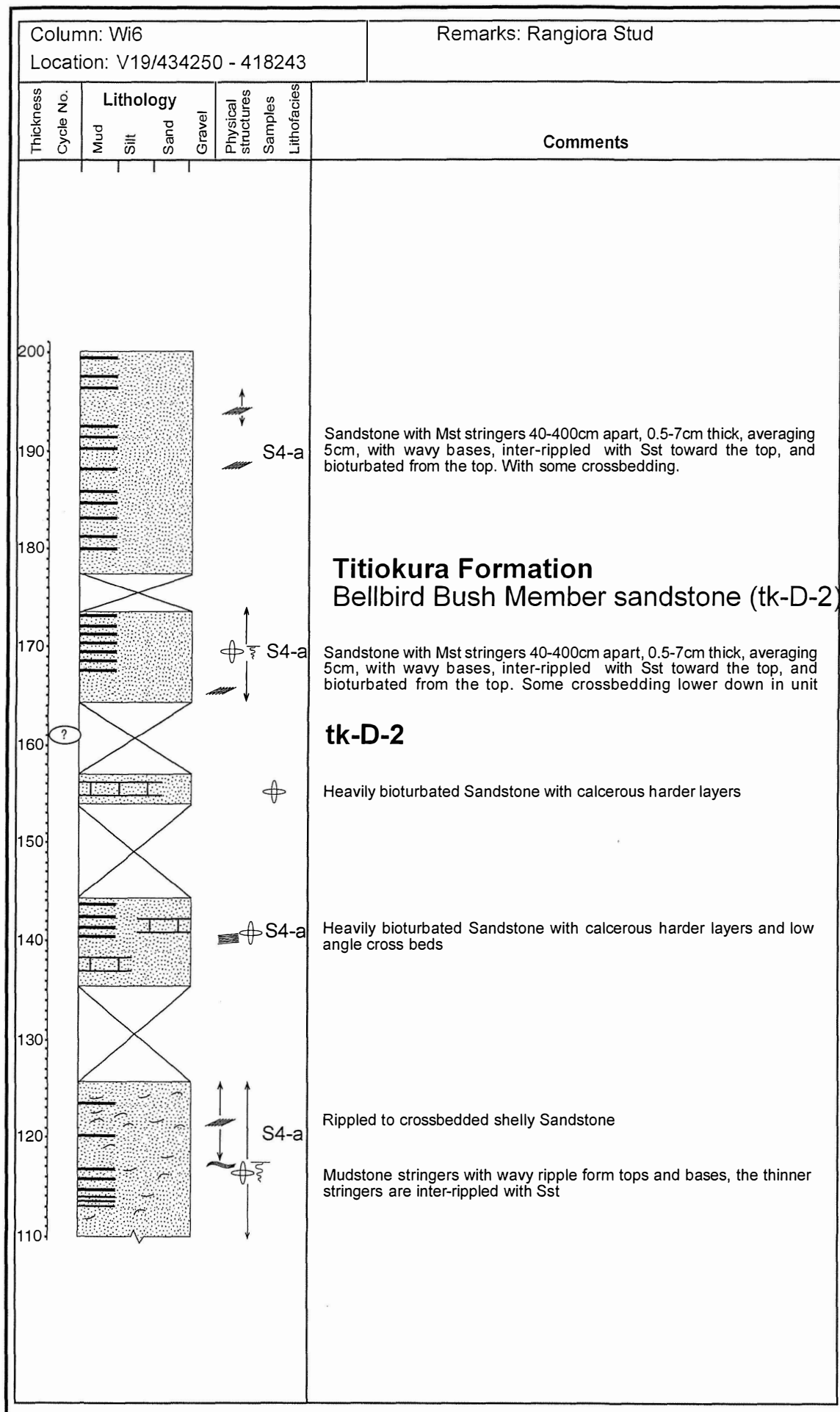
Appendix 1: Stratigraphic Columns



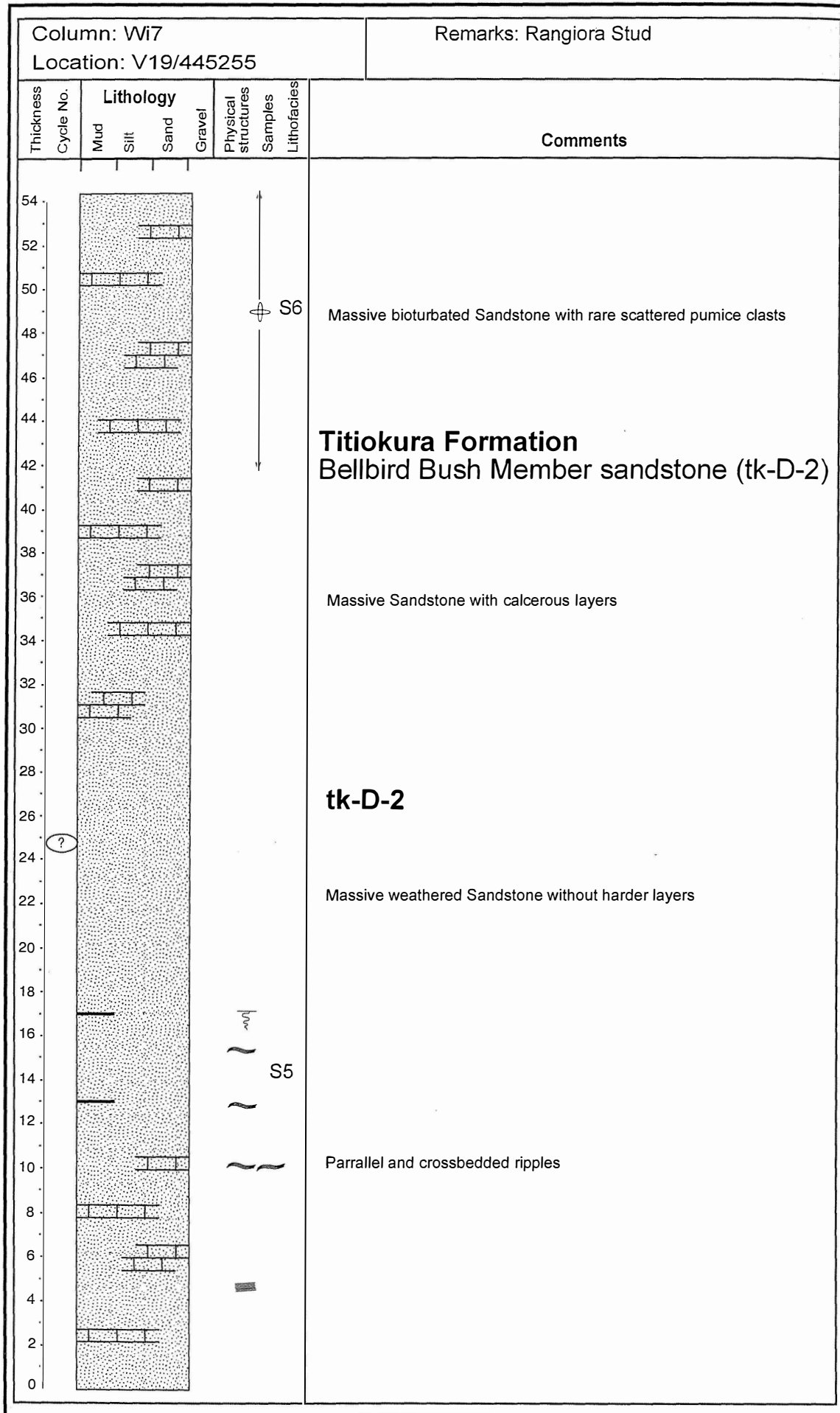
Appendix 1: Stratigraphic Columns



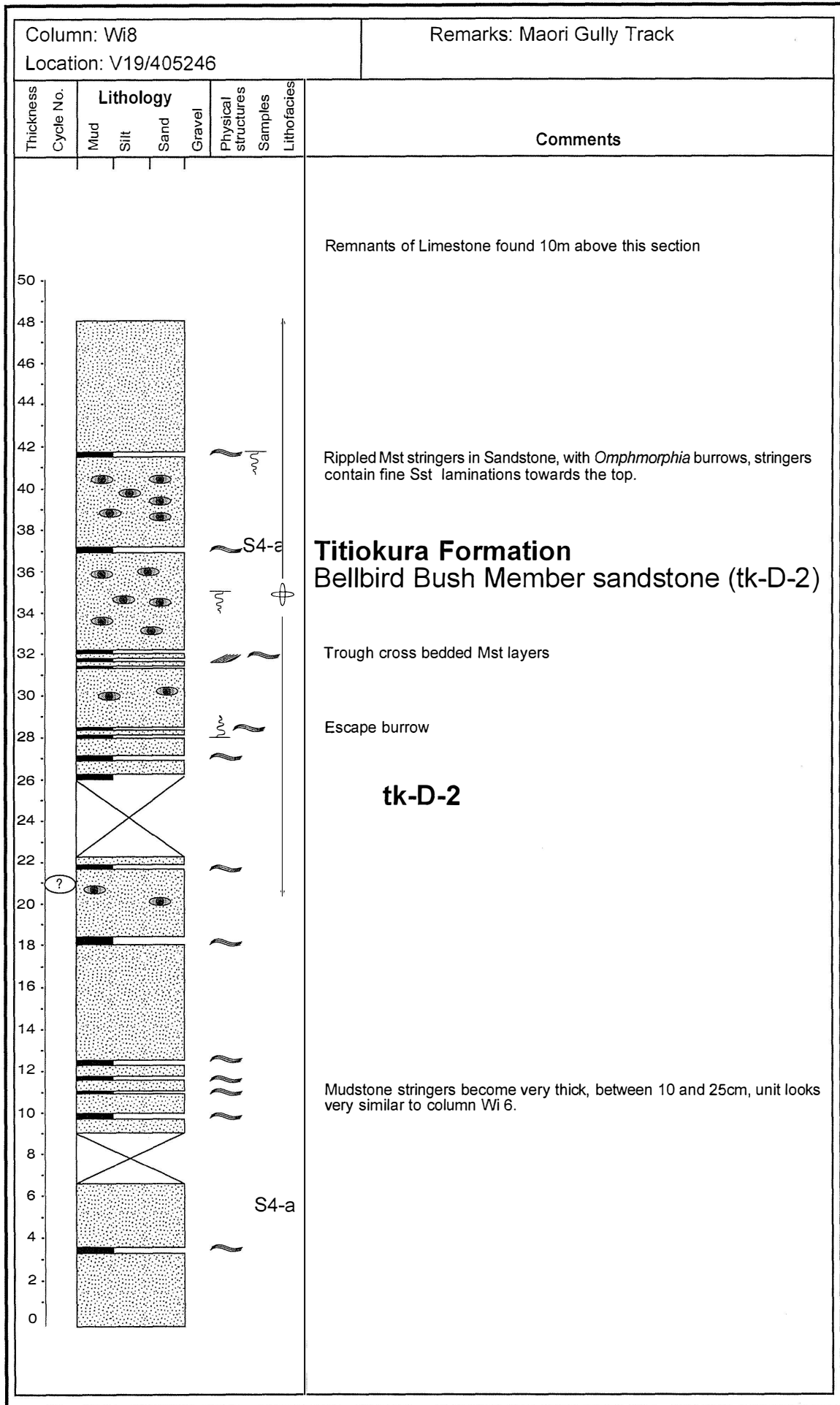
Appendix 1: Stratigraphic Columns



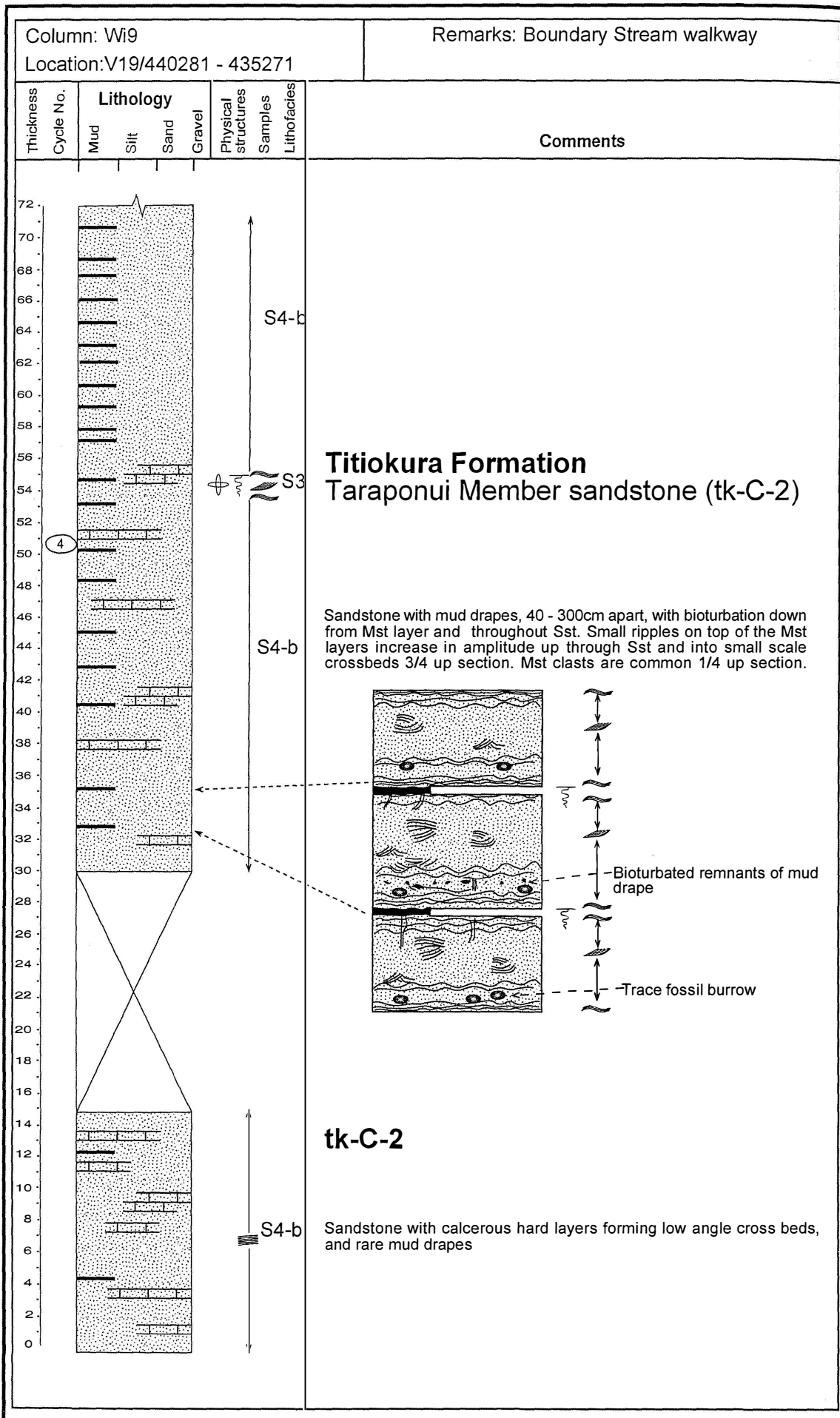
Appendix 1: Stratigraphic Columns



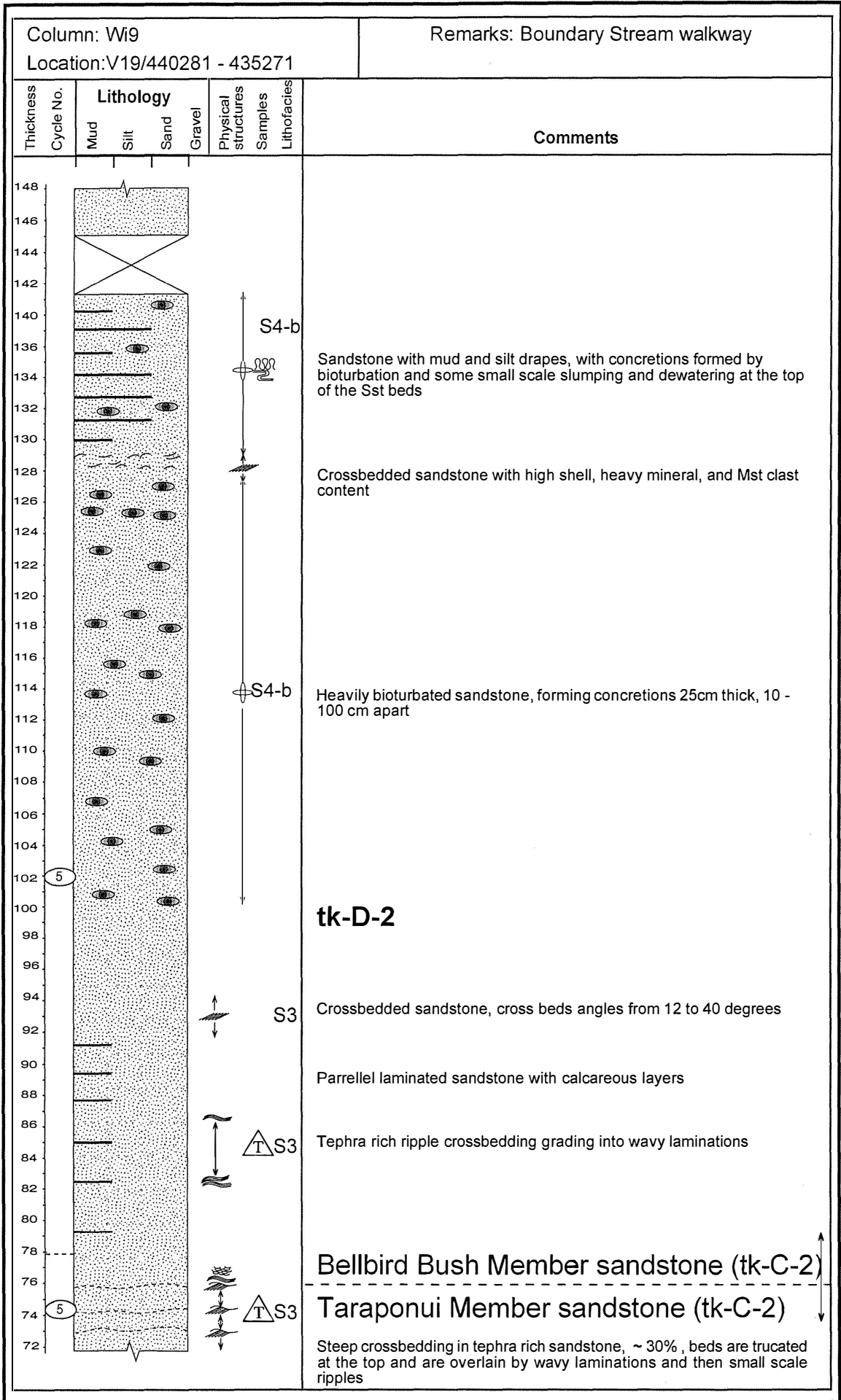
Appendix 1: Stratigraphic Columns



Appendix 1: Stratigraphic Columns



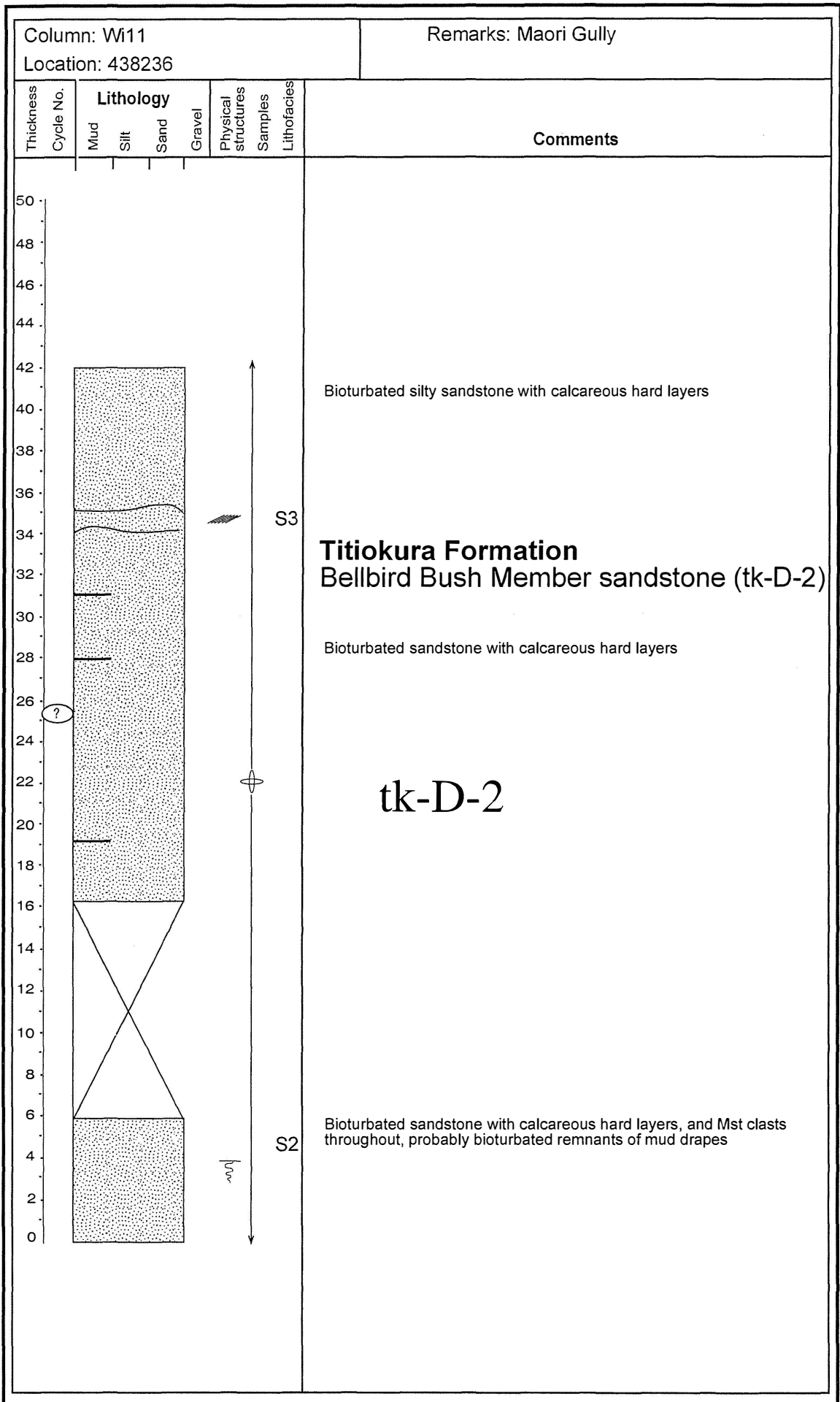
Appendix 1: Stratigraphic Columns



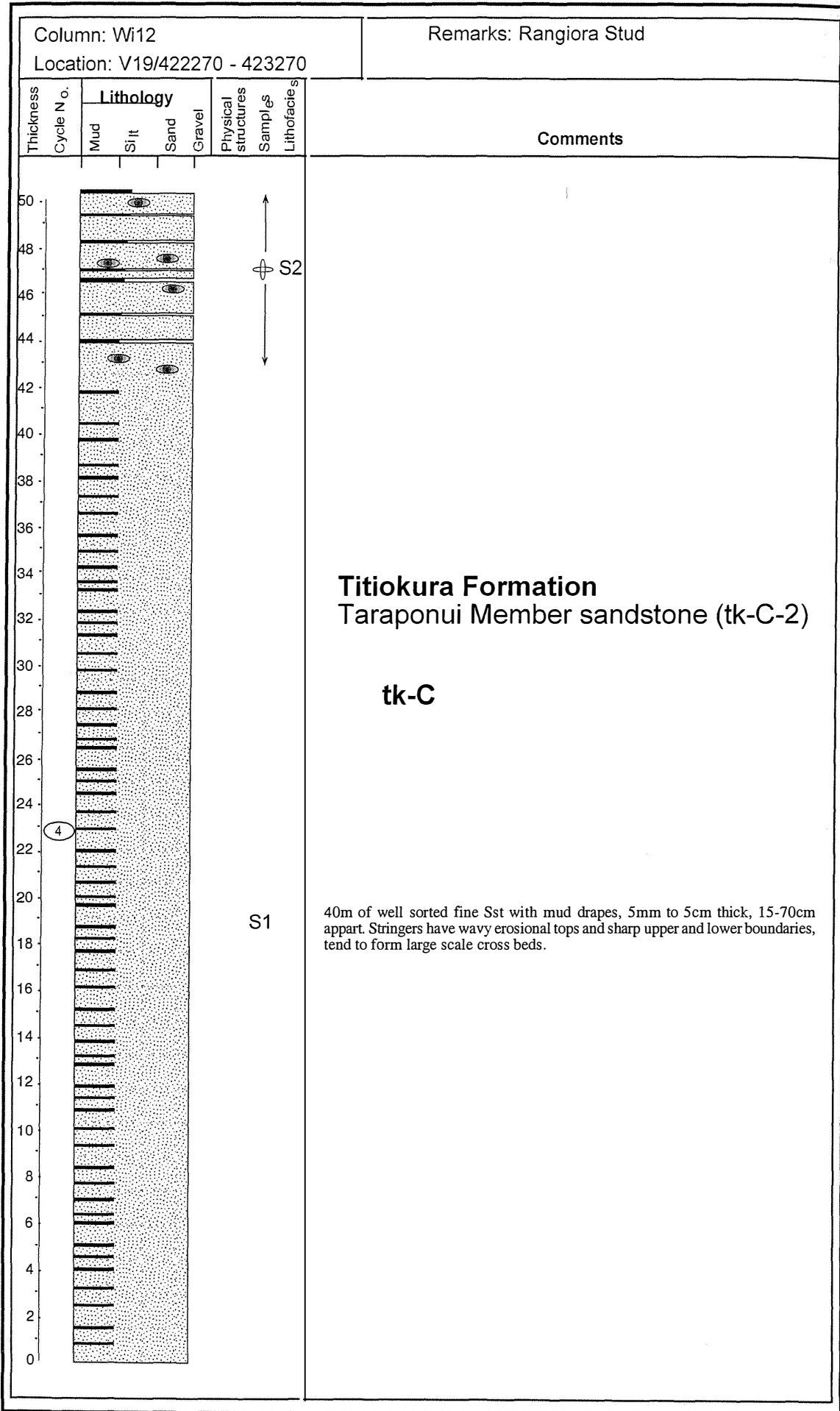
Appendix 1: Stratigraphic Columns

Column: W19 Location: V19/440281 - 435271		Remarks: Boundary Stream walkway						
Thickness Cycle No.	Lithology				Physical structures	Samples	Lithofacies	Comments
	Mud	Silt	Sand	Gravel				
186							<p><b>Titiokura Formation</b> Bellbird Bush Member sandstone (tk-D-2)</p> <p><b>tk-D-2</b></p> <p>S5 Massive to parallel laminated sandstone with rare Zst stringers</p>	
184								
182								
180								
178								
176								
174								
172								
170								
168								
166								
164								
162								
160								
158								
156								
154								
152								
150								
148								

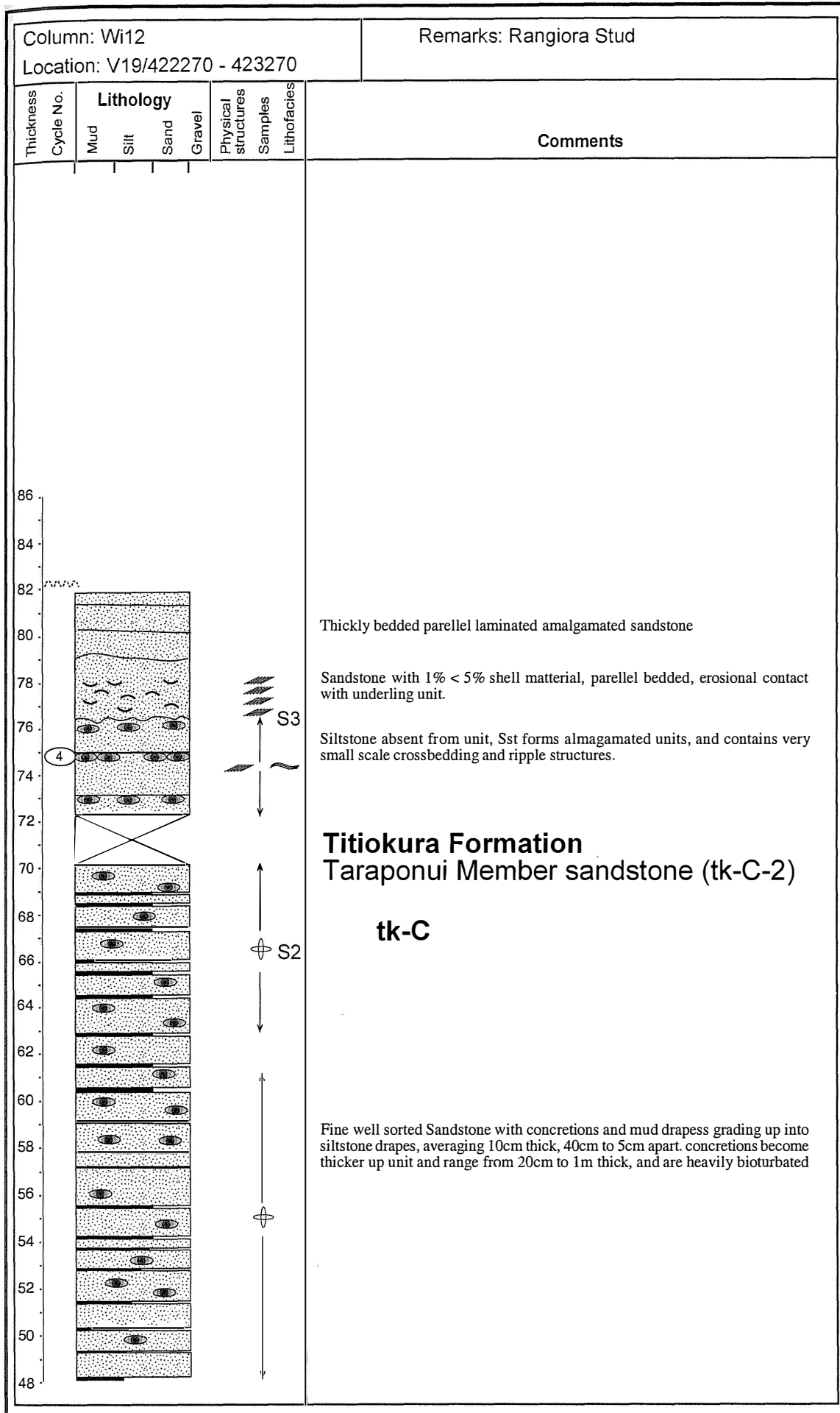
Appendix 1: Stratigraphic Columns



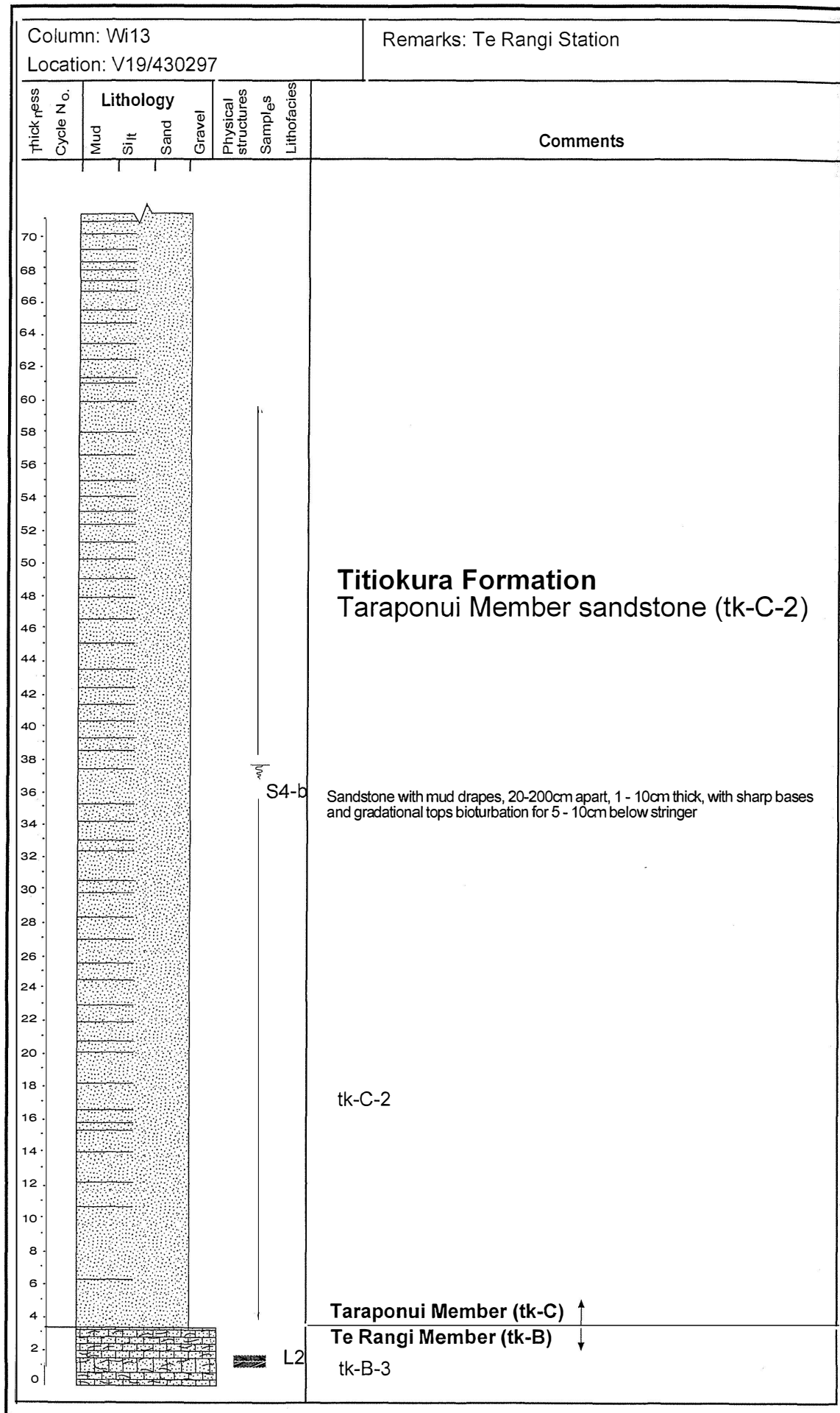
Appendix 1: Stratigraphic Columns



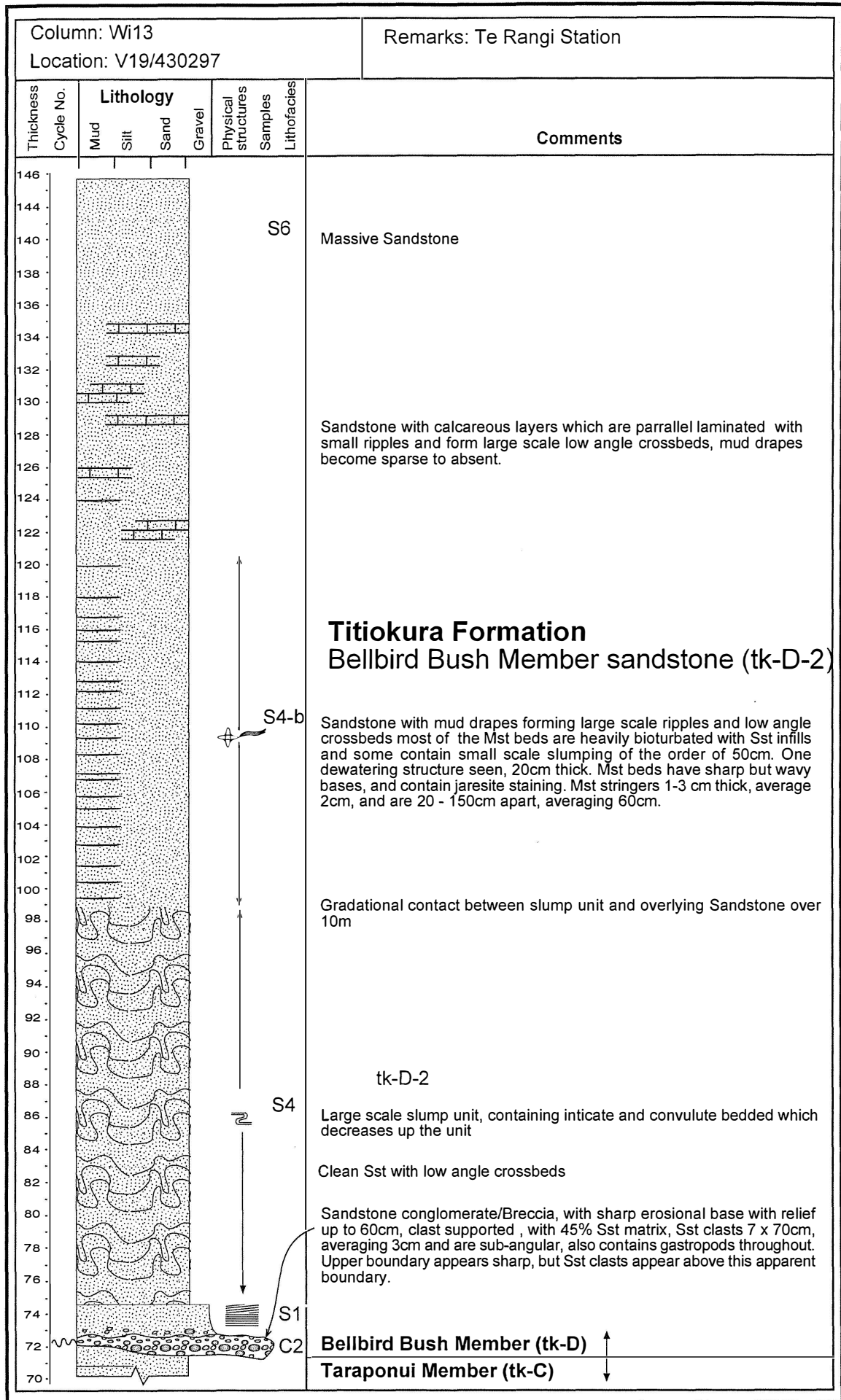
Appendix 1: Stratigraphic Columns



Appendix 1: Stratigraphic Columns



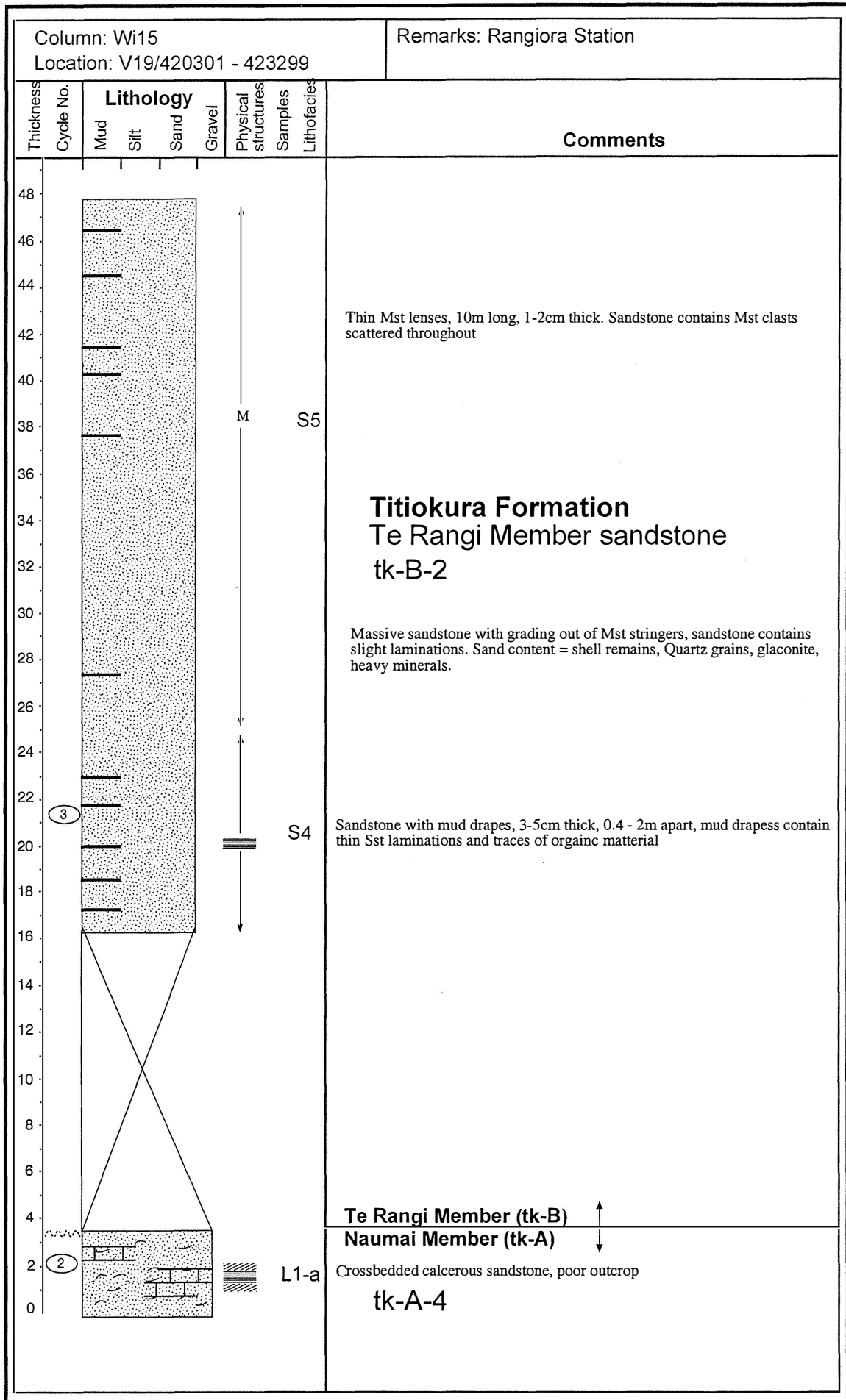
# Appendix 1: Stratigraphic Columns



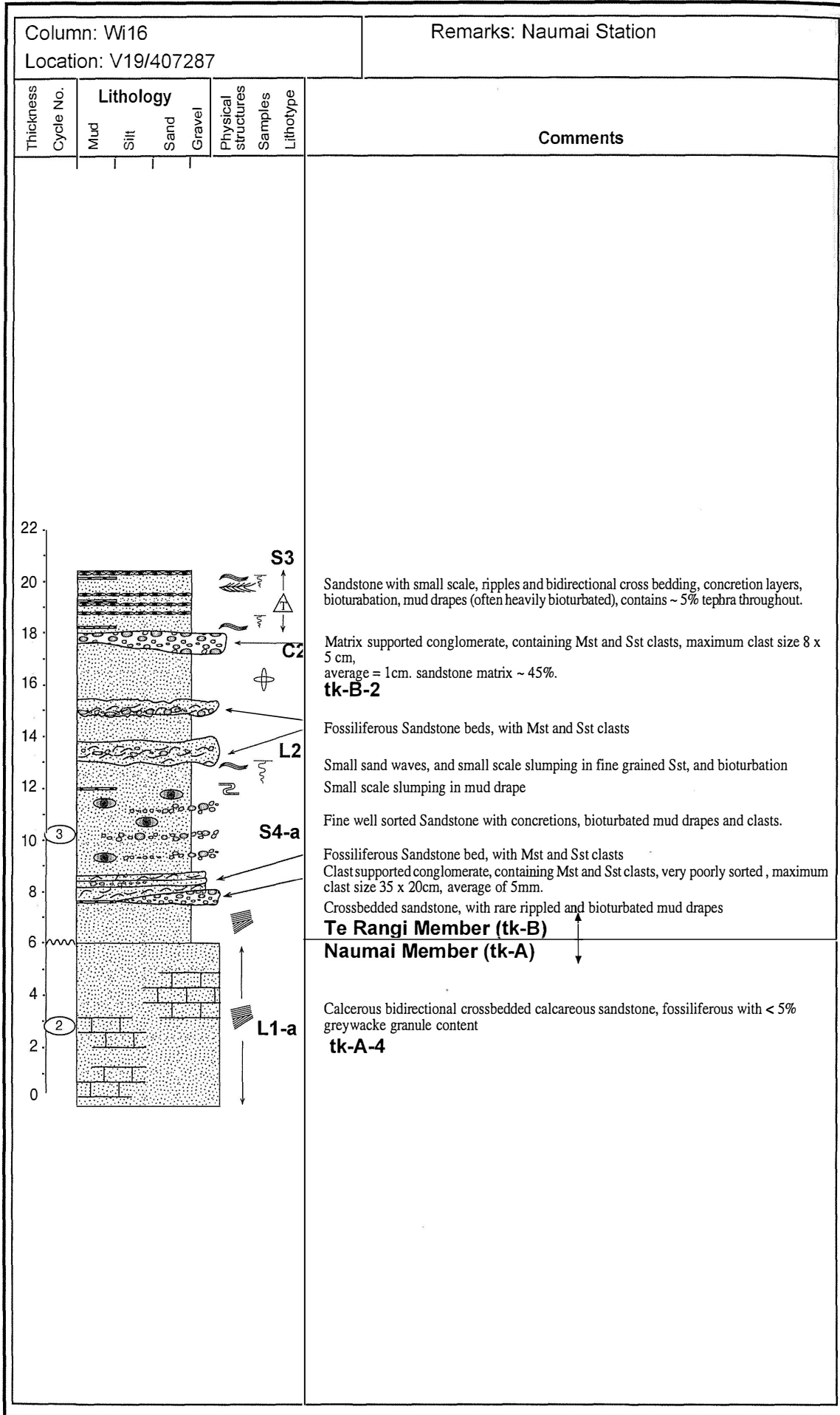
Appendix 1: Stratigraphic Columns

Column: Wi 14 Location: V19/408284		Remarks: Naumai Station							
Thickness	Cycle No.	Lithology				Physical structures	Samples	Lithofacies	Comments
		Mud	Silt	Sand	Gravel				
0									
2	(2)							S6	Sandstone with calcerous layers
4								C2 tk-C-3	<p><b>Taraponui Member (tk-C)</b> ↑</p> <p><b>Te Rangi Member (tk-B)</b> ↓</p> <p><b>tk-B-4</b> Sandy limestone bed</p>
6	(3)							S2	<p><b>tk-C-2</b></p> <p>Shellbed with rip-up clasts and flame structures at base</p> <p>Very hard calcerous mass flow conglomerate, containing large Mst and Sst rip-up clasts through-out unit, maximum 30 x 70cm, averaging 7 x 7cm. Also contains greywacke pebble component, which coarsens upwards until the middle, then fines towards the top at which pebble component becomes rare to absent. Contains high shell content</p>
8									
10									

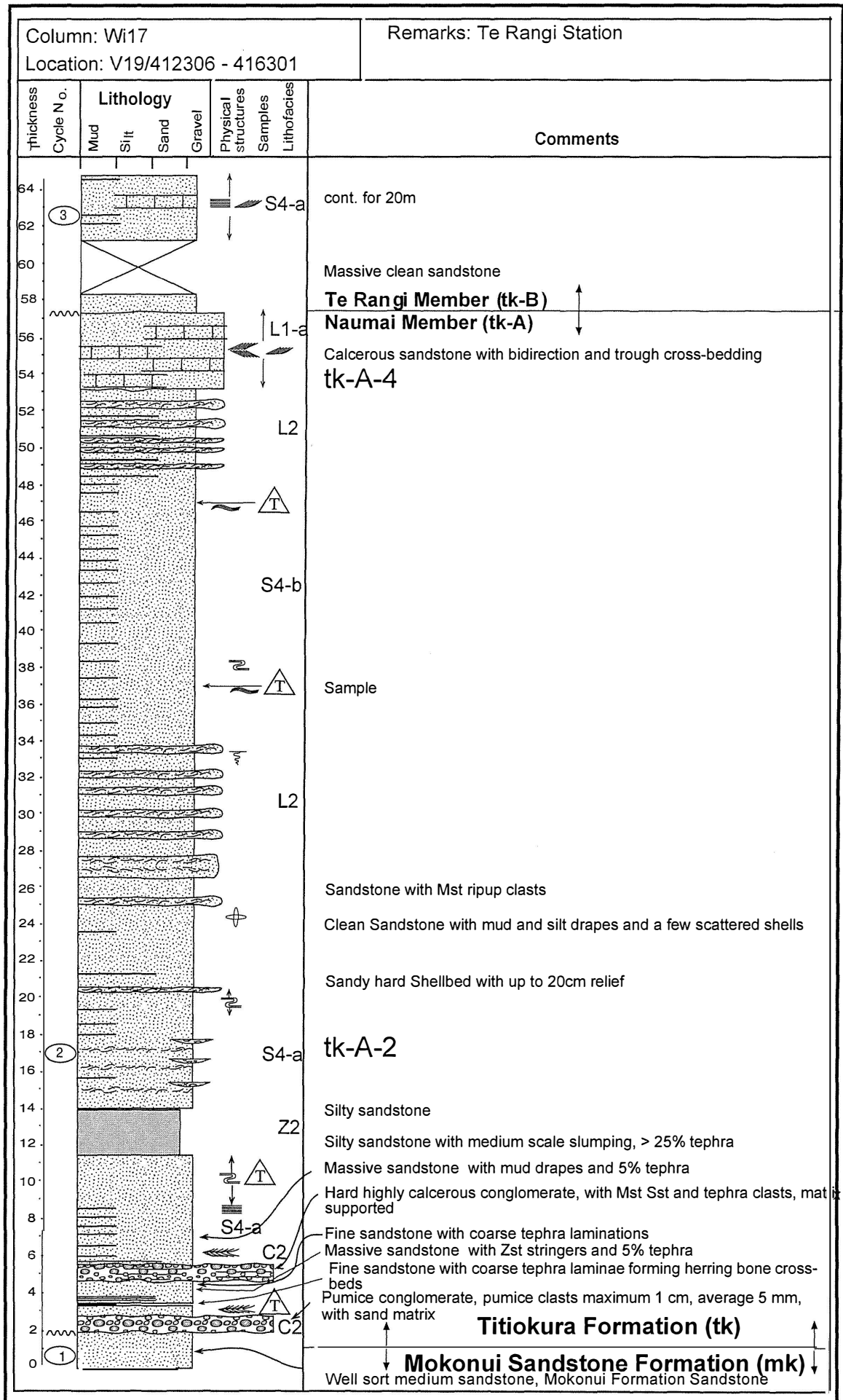
# Appendix 1: Stratigraphic Columns



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# Appendix 1: Stratigraphic Columns



AREA	Waikoa River												
	W13	201	74	R1e	R1f	R1g	93	94	W30	122	203	103	85
<b>SAMPLE NUMBER</b>													
<b>BIVALVES</b>													
<i>Nucula nitidula</i> Adams, 1856.		x									x t m		
<i>Nucula</i> sp.				x		x							
<i>Sacella</i> sp.													
<i>Niolo sublaevis</i> Marwick, 1926.					x								
<i>Niolo</i> sp.													
<i>Atrina pectinata zelandica</i> (Gray, 1835).			x			x					x t		x
<i>Chlamys gemmulata</i> (Reeve, 1853).													x
<i>Mesopeplum</i> sp.													
<i>Anomidae</i> sp.													
<i>Patto undatus</i> Gray, 1850.													
<i>Crassostrea ingens</i> (Zittel, 1864).													
<i>Crassostrea</i> sp.													
<i>Ostrea chilensis</i> (Hutton, 1873).								x					
<i>Ostrea</i> sp.									x				
<i>Pteromyrtea dispar</i> (Hutton, 1873).													x a
<i>Diplodonta globus</i> (Finlay, 1926)							x						
<i>Pleuromeris</i> sp.					x	x							
<i>Talabrica senecta</i> Powell, 1931.							x						
<i>Pratulum pulchellum</i> (Gray, 1843).												x	
<i>Pratulum</i> sp.									x				x
<i>Macra</i> aff. <i>discors</i> Gray, 1837.											x t		
<i>Macra murchisoni</i> (Deshays in Reeve, 1854)													
<i>Maorimacra</i> sp.													
<i>Maorimacra chrydaea</i> (Suter, 1911)	x										x t		x
<i>Maorimacra ovalinaria</i> (Smith, 1898)											x m b		
<i>Scalpomacra scalpellum</i> (Reeve, 1854).		x											
<i>Scalpomacra</i> sp.	x						x						
<i>Zenatia acinaces</i> (Quoy & Gaimard, 1835).													
<i>Paphies subtriangulata</i> (Gray in Wood, 1828)												x t b	
<i>Rexithaerus spenceri</i> (Suter, 1907)										x			

AREA	Waikoa River												
	W13	201	74	R1e	R1f	R1g	93	94	W30	122	203	103	85
<b>SAMPLE NUMBER</b>													
<b>BIVALVES</b>													
<i>Nucula nitidula</i> Adams, 1856.		x									x t m		
<i>Nucula</i> sp.				x		x							
<i>Sacella</i> sp.													
<i>Niolo sublaevis</i> Marwick, 1926.													
<i>Niolo</i> sp.				x									
<i>Atrina pectinata zelandica</i> (Gray, 1835).													x
<i>Chlamys gemmulata</i> (Reeve, 1853).			x			x					x t		x
<i>Mesopeplum</i> sp.													
<i>Anomiidae</i> sp.													
<i>Patto undatus</i> Gray, 1850.													
<i>Crassostrea ingens</i> (Zittel, 1864).													
<i>Crassostrea</i> sp.													
<i>Ostrea chilensis</i> (Hutton, 1873).								x					
<i>Ostrea</i> sp.									x				
<i>Pteromyrtea dispar</i> (Hutton, 1873).													x a
<i>Diplodonta globus</i> (Finlay, 1926)								x					
<i>Pleuromeris</i> sp.					x	x							
<i>Talabrica senecta</i> Powell, 1931.								x					
<i>Pratulium pulchellum</i> (Gray, 1843).								x				x	
<i>Pratulium</i> sp.										x			x
<i>Macitra</i> aff. <i>discors</i> Gray, 1837.											x t		
<i>Macitra murchisoni</i> (Deshays in Reeve, 1854)													
<i>Maorimacra</i> sp.	x												x
<i>Maorimacra chrydæa</i> (Suter, 1911)											x t		
<i>Maorimacra orinaria</i> (Smith, 1898)											x m b		
<i>Scalpomacra scalpellum</i> (Reeve, 1854).			x										
<i>Scalpomacra</i> sp.	x							x					
<i>Zenatia acinaces</i> (Quoy & Gaimard, 1835).													
<i>Paphies subtriangulata</i> (Gray in Wood, 1828)											x t b		
<i>Rexithaerus spenceri</i> (Suter, 1907)												x	

AREA	SAMPLE NUMBER	Waikoa River												
		W13	201	74	R1e	R1f	R1g	93	94	W30	122	203	103	85
<b>BIVALVES</b>														
	<i>Serratina charlottae</i> (Smith, 1885).													x a
	<i>Serratina</i> sp.													
	<i>Gari linoleata</i> (Gray, 1835).											x t m		
	<i>Gari</i> sp.													
	<i>Dosina crebra</i> (Hutton, 1873)		x a											
	<i>Dosina zelandica</i> Gray, 1835.													
	<i>Bassina parva</i> Marwick, 1927.		x									x b		x
	<i>Bassina yatel</i> (Gray, 1835).											x b		
	<i>Tawera</i> sp.							x						
	<i>Dosinia (Asa) lambata</i> (Gould, 1850).											x t m b		
	<i>Dosinia (Asa) aff. lambata</i> (Gould, 1850).													
	<i>Dosinia (Austrodosinia) anus</i> (Philippi, 1848)								x					
	<i>Dosinia (Kereia) greyi</i> Zittel, 1864.								x			x t m b		
	<i>Dosinia (Phacosoma) subrosea</i> (Gray, 1835).		x									x b		
	<i>Dosinia (Raina) nukumaruensis</i> (Marwick, 1927).													
	<i>Eumaricia (Atamarcia) benhami</i> Marwick, 1927.											x t		
	<i>Eumaricia</i> sp.													x
	<i>Panopea zelandica</i> (Quoy & Gaimard, 1835).													
	<i>Myadora stephaniae</i> Carter, 1972.													
	<i>Myadora</i> sp.								x					
<b>GASTROPODA</b>														
	<i>Zethalia coronata</i> (Marwick, 1948).													
	<i>Calliostoma hawera</i> (Oliver, 1926).		x a											
	<i>Calliostoma</i> sp.													
	<i>Maoricolpus roseus</i> (Quoy & Gaimard, 1834)													x
	<i>Stiracolpus dellii</i> sp.													
	<i>Stiracolpus</i> sp.													
	<i>Zeacolpus vittatus</i> (Hutton, 1873)													x
	<i>Zeacolpus</i> sp.													

AREA	SAMPLE NUMBER	Waikoaou River												
		W13	201	74	R1e	R1f	R1g	93	94	W30	122	203	103	85
<b>GASTROPODA</b>														
	<i>Pellicaria</i> n.sp. aff. <i>zelandiae</i> (Marshall & Murdoch, 1920).													
	<i>Struthiolaria pupulosa</i> (Martyn, 1784)													
	<i>Crepidula radiata</i> (Hutton, 1873).													
	<i>Sigapatella</i> sp.				x									
	<i>Zegalerus tenuis</i> (Gray, 1867).													
	<i>Taniella planisutularis</i> (Marwick, 1924).		x											
	<i>Taniella</i> sp.											x b		
	<i>Friginatica marshalli</i> (Marwick, 1924)													
	<i>Pollinicles</i> sp.									x				
	<i>Pollinicles waipipiensis</i> (Marwick, 1924).													
	<i>Galeodea</i> sp.													
	<i>Semicassis (Kahua) fibrata</i> (Marshall & Murdoch, 1920).													
	<i>Tonna</i> (Brunnich, 1772)													
	<i>Aeneator elegans</i> (Suter, 1971)											x t		
	<i>Aeneator</i> sp.											x b		
	<i>Austrofuscus pagoda</i> (Finlay, 1924).										x			
	<i>Austrofuscus pliocineus</i> (Powell, 1931).													
	<i>Austrofuscus</i> sp.													
	<i>Penion</i> aff. <i>cuvierianus</i> (Powell, 1927).													
	<i>Penion sulcatus</i> (Lamarck, 1816).											x m		
	<i>Penion</i> sp.													
	<i>Xymene ambiguus</i> (Phillipi, 1844).													
	<i>Amalda (Baryspira) depressa</i> (Sowerby, 1859).		x										x b	
	<i>Amalda (Baryspira) mucronata</i> (Sowerby, 1830).													
	<i>Amalda (Baryspira) oraria</i> (Olson, 1956).		x											
	<i>Amalda (Gracilispira)</i> cf. <i>rimuensis</i> (Olson, 1956).													
	<i>Lamprodomina neozelandica</i> (Hutton, 1885).													
	<i>Alcithoe (Leptomax) brevis</i> Marwick, 1926.												x t	
	<i>Alcithoe</i> sp.													
	<i>Pervicacia tristis</i> (Deshayes, 1859).													x b

AREA	W13	Waikoaou River					W30	122	203	103	85
SAMPLE NUMBER		201	74	R1e	R1f	R1g	93	94			
<b>GASTROPODA</b>											
<i>Splendrillia aequistriata</i> (Hutton, 1886).											
<i>Splendrillia kingmai</i> Marwick, 1965.											
<i>Splendrillia</i> sp.											
<i>Crenilabium starboroughense</i> (King, 1935)									x b		
<b>SCAPHOPODA</b>											
<i>Antalis nana</i> (Hutton, 1873).											
<i>Antalis</i> sp.											
<i>Fissidentaltium zelandicum</i> (Sowerby, 1860).											
<i>Fissidentaltium</i> sp.										x a	
<b>AREA</b>											
<b>SAMPLE NUMBER</b>	W13	Waikoaou River					W30	122	203	103	85
<b>BRACOPODA</b>		201	74	R1e	R1f	R1g	93	94			
<b>ECHINOIDEA</b>											
<i>Fellaster zelandiae</i>											
<b>OTHERS</b>											
Pebbles											

AREA	SAMPLE NUMBER	80	66	Waikari River							Range			
				47	199	54	136	206	139	140		204	141	190
<b>BIVALVES</b>														
<i>Nucula nitidula</i> Adams, 1856.														
<i>Nucula</i> sp.	x													
<i>Sacella</i> sp.														
<i>Niela sublaevis</i> Marwick, 1926.														
<i>Niela</i> sp.														
<i>Atrina pectinata zelandica</i> (Gray, 1835).														
<i>Chlamys gemmulata</i> (Reeve, 1853).										x				x 2
<i>Mesopeplum</i> sp.														
<i>Anomiidae</i> sp.														
<i>Patro undatus</i> Gray, 1850.														
<i>Crassostrea ingens</i> (Zittel, 1864).														
<i>Crassostrea</i> sp.														
<i>Ostrea chilensis</i> (Hutton, 1873).														
<i>Ostrea</i> sp.														
<i>Pteromyrtea dispai</i> (Hutton, 1873).														
<i>Diplodonta globus</i> (Finlay, 1926)														
<i>Pleuromeris</i> sp.														
<i>Talabrica senecta</i> Powell, 1931.														
<i>Pratulium pulchellum</i> (Gray, 1843).														
<i>Pratulium</i> sp.														
<i>Macitra</i> aff. <i>discors</i> Gray, 1837.														
<i>Macitra murchisoni</i> (Deshays in Reeve, 1854)														
<i>Maorimacitra</i> sp.														
<i>Maorimacitra chrydaea</i> (Suter, 1911)														
<i>Maorimacitra ordinaria</i> (Smith, 1898)														
<i>Scalpomacitra scalpellum</i> (Reeve, 1854).														
<i>Scalpomacitra</i> sp.														
<i>Zenatia acinaces</i> (Quoy & Gaimard, 1835).														
<i>Paphies subtriangulata</i> (Gray in Wood, 1828)														
<i>Rexithaerus spenceri</i> (Suter, 1907)														



AREA	80	66	47	199	54	136	206	139	140	204	141	Range
<b>SAMPLE NUMBER</b>	80	66										190
<b>GASTROPODA</b>												
<i>Pellicaria</i> n.sp. aff. <i>zelandiae</i> (Marshall & Murdoch, 1920).									x			
<i>Struthiolaria pupulosa</i> (Mairyn, 1784)				x								
<i>Crepidula radiata</i> (Hutton, 1873).						x 2						
<i>Sigapatella</i> sp.												
<i>Zegalerus tenuis</i> (Gray, 1867).							x a					
<i>Taniella planisutularis</i> (Marwick, 1924).				x								
<i>Taniella</i> sp.												
<i>Friginatica marshalli</i> (Marwick, 1924)												
<i>Polinicies</i> sp.												
<i>Polinicies waipiensis</i> (Marwick, 1924).						x 1 x	x a		x			
<i>Galeodea</i> sp.										x		
<i>Semicassis (Kahua) fibrata</i> (Marshall & Murdoch, 1920).										x		
<i>Tonna</i> (Brunnich, 1772)												
<i>Aeneator elegans</i> (Suter, 1971)												
<i>Aeneator</i> sp.												
<i>Austrofus pagoda</i> (Finlay, 1924).						x 1	x a					
<i>Austrofus plicineus</i> (Powell, 1931).		x										
<i>Austrofus</i> sp.					x							
<i>Penion</i> aff. <i>cuvierianus</i> (Powell, 1927).												
<i>Penion sulcatus</i> (Lamarck, 1816).												
<i>Penion</i> sp.		x										
<i>Xymene ambiguus</i> (Phillipi, 1844).				x								
<i>Amalda (Baryspira) depressa</i> (Sowerby, 1859).												
<i>Amalda (Baryspira) mucronata</i> (Sowerby, 1830).												
<i>Amalda (Baryspira) oraria</i> (Olson, 1956).												
<i>Amalda (Gracilispira)</i> cf. <i>rimuensis</i> (Olson, 1956).						x						
<i>Lamprodromina neozelandica</i> (Hutton, 1885).						x 3						x 2
<i>Alcithoe (Leptomax) brevis</i> Marwick, 1926.												
<i>Alcithoe</i> sp.												
<i>Pervicacia tristis</i> (Deshayes, 1859).												

AREA	80	66	47	199	54	136	206	139	140	204	141	Range
<b>SAMPLE NUMBER</b>	80	66	47	199	54	136	206	139	140	204	141	190
<b>GASTROPODA</b>												
<i>Splendrillia aequistriata</i> (Hutton, 1886).												
<i>Splendrillia kingmai</i> Marwick, 1965.					x							
<i>Splendrillia</i> sp.					x 3							
<i>Oreilabium starboroughense</i> (King, 1935)												
<b>SCAPHOPODA</b>												
<i>Antalis nana</i> (Hutton, 1873).												
<i>Antalis</i> sp.												
<i>Fissidentalium zelandicum</i> (Sowerby, 1860).					x	x 3 x	x a					
<i>Fissidentalium</i> sp.												
<b>AREA</b>			<b>Waikari River</b>									<b>Range</b>
<b>SAMPLE NUMBER</b>	80	66	47	199	54	136	206	139	140	204		190
<b>BRACOPODA</b>												
<b>ECHINOIDEA</b>												
<i>Fellaster zelandiae</i>		x										
<b>OTHERS</b>												
Pebbles												

## Appendix 2: Faunal List

AREA	SAMPLE NUMBER	174	198	196	194	101	105	193	192
186	189								
	<b>BIVALVES</b>								
	<i>Nucula nitidula</i> Adams, 1856.								
	<i>Nucula</i> sp.								
	<i>Sacella</i> sp.	x							
	<i>Niello sublaevis</i> Marwick, 1926.								
	<i>Niello</i> sp.	x							
	<i>Atrina pectinata zelandica</i> (Gray, 1835).								
x 123	<i>Chlamys gemmulata</i> (Reeve, 1853).			x		x			
	<i>Mesopeplum</i> sp.						x		
	<i>Anomidae</i> sp.								
	<i>Patro undatus</i> Gray, 1850.								
	<i>Crassostrea ingens</i> (Zittel, 1864).								
	<i>Crassostrea</i> sp.							x 1	
	<i>Ostrea chilensis</i> (Hutton, 1873).								
	<i>Ostrea</i> sp.								
	<i>Pteromyrtea dispai</i> (Hutton, 1873).								
	<i>Diplodonta globus</i> (Finlay, 1926)								
	<i>Pleuromeris</i> sp.								
	<i>Talabrica senecta</i> Powell, 1931.								
	<i>Pratulum pulchellum</i> (Gray, 1843).								x 2
	<i>Pratulum</i> sp.								x 4
	<i>Macira</i> aff. <i>discors</i> Gray, 1837.	x							
	<i>Macira murchisoni</i> (Deshays in Reeve, 1854)								
	<i>Maorimacira</i> sp.								
	<i>Maorimacira chrydaea</i> (Suter, 1911)								
	<i>Maorimacira ordinalia</i> (Smith, 1898)								
	<i>Scalpomacira scalpellum</i> (Reeve, 1854).								
	<i>Scalpomacira</i> sp.								
	<i>Zenatia acinaces</i> (Quoy & Gaimard, 1835).								
	<i>Paphies subtriangulata</i> (Gray in Wood, 1828)								
	<i>Rexithaerus spenceri</i> (Suter, 1907)								

AREA	SAMPLE NUMBER	174	198	196	194	101	105	193	192
186	189								
	<b>BIVALVES</b>								
	<i>Serrafina charlottae</i> (Smith, 1885).								
	<i>Serrafina</i> sp.	x							
	<i>Gari inoleata</i> (Gray, 1835).								
	<i>Gari</i> sp.								
	<i>Dosina crebra</i> (Hutton, 1873)								
	<i>Dosina zelandica</i> Gray, 1835.								
	<i>Bassina parva</i> Marwick, 1927.								
	<i>Bassina yafei</i> (Gray, 1835).								
	<i>Tawera</i> sp.								
	<i>Dosinia (Asa) lambata</i> (Gould, 1850).								
	<i>Dosinia (Asa)</i> aff. <i>lambata</i> (Gould, 1850).								
	<i>Dosinia (Austrodosinia) anus</i> (Philippi, 1848)								
	<i>Dosinia (Kereia) greyi</i> Zittel, 1864.								
	<i>Dosinia (Phacosoma) subrosea</i> (Gray, 1835).								
	<i>Dosinia (Raina) nukumaruensis</i> (Marwick, 1927).								
	<i>Eumarca (Atamarca) benhami</i> Marwick, 1927.								
	<i>Eumarca</i> sp.								
	<i>Panopea zelandica</i> (Quoy & Gaimard, 1835).								
	<i>Myadara stephaniae</i> Carter, 1972.								
	<i>Myadara</i> sp.								
	<b>GASTROPODA</b>								
	<i>Zethalia coronata</i> (Marwick, 1948).								
	<i>Calliostoma hawera</i> (Oliver, 1926).								
	<i>Calliostoma</i> sp.								x 2
	<i>Maoricolpus roseus</i> (Quoy & Gaimard, 1834)								
	<i>Stiraclopus dellii</i> sp.								
	<i>Stiraclopus</i> sp.								
	<i>Zeacolpus vittatus</i> (Hutton, 1873)								
	<i>Zeacolpus</i> sp.								

## Appendix 2: Faunal List

186	189	AREA	174	198	196	194	101	105	193	192
		<b>SAMPLE NUMBER</b>	174	198						
		<b>GASTROPODA</b>								
		<i>Pellicaria</i> n.sp. aff. <i>zelandiae</i> (Marshall & Murdoch, 1920).								
		<i>Struthiolaria pupulosa</i> (Martyn, 1784)								
		<i>Crepidula radiata</i> (Hutton, 1873).								
		<i>Sigapatella</i> sp.								
		<i>Zegalerus tenuis</i> (Gray, 1867).								
		<i>Taniella planisutularis</i> (Marwick, 1924).								
		<i>Taniella</i> sp.								
		<i>Friginatica marshalli</i> (Marwick, 1924)								x 1
		<i>Polinicies</i> sp.								
		<i>Polinicies wajpiensis</i> (Marwick, 1924).							x 3	
		<i>Galeodea</i> sp.								
		<i>Semicassis (Kahua) fibrata</i> (Marshall & Murdoch, 1920).								
		<i>Tonna</i> (Brunnich, 1772)								x 1
		<i>Aeneator elegans</i> (Suter, 1971)								
		<i>Aeneator</i> sp.								
		<i>Austrofusus pagoda</i> (Finlay, 1924).								x 2
		<i>Austrofusus pliocineus</i> (Powell, 1931).								
		<i>Austrofusus</i> sp.								x 2
		<i>Penion</i> aff. <i>cuvierianus</i> (Powell, 1927).							x 1	
		<i>Penion sulcatus</i> (Lamarck, 1816).								
		<i>Penion</i> sp.								
		<i>Xymene ambiguus</i> (Phillipi, 1844).								
		<i>Amalda (Baryspira) depressa</i> (Sowerby, 1859).								
		<i>Amalda (Baryspira) mucronata</i> (Sowerby, 1830).			x					x 2 4
		<i>Amalda (Baryspira) oraria</i> (Olson, 1956).								
		<i>Amalda (Gracilispira)</i> cf. <i>rimuensis</i> (Olson, 1956).							x 1	
		<i>Lamprodomina neozelandica</i> (Hutton, 1885).								
		<i>Alcithoe (Leptomax) brevis</i> Marwick, 1926.								x 4
		<i>Alcithoe</i> sp.		x						
		<i>Pervicacia tristis</i> (Deshayes, 1859).								



AREA	SAMPLE NUMBER	Others																		
		71	103	100	87	207	107	101	94	125										
194																				
	<b>BIVALVES</b>																			
	<i>Nucula nitidula</i> Adams, 1856.	x																		
	<i>Nucula</i> sp.																			
	<i>Sacella</i> sp.																			
	<i>Nielo sublaevis</i> Marwick, 1926.																			
	<i>Nielo</i> sp.																			
	<i>Atrina pectinata zelandica</i> (Gray, 1835).			x																
	<i>Chlamys gemmulata</i> (Reeve, 1853).										x x 2	x								
	<i>Mesopeplum</i> sp.																			
	<i>Anomidae</i> sp.																			
	<i>Patro undatus</i> Gray, 1850.																			x
	<i>Crassostrea ingens</i> (Zittel, 1864).																			
	<i>Crassostrea</i> sp.																			
	<i>Ostrea chilensis</i> (Hutton, 1873).																			
	<i>Ostrea</i> sp.																			
	<i>Pteromyrtea dispar</i> (Hutton, 1873).																			
	<i>Diplodonta globus</i> (Finlay, 1926)																			
	<i>Pleuromeris</i> sp.																			
	<i>Talabrica senecta</i> Powell, 1931.																			
	<i>Pratulum pulchellum</i> (Gray, 1843).									x	x									
	<i>Pratulum</i> sp.																			
	<i>Macrta</i> aff. <i>discors</i> Gray, 1837.																			
	<i>Macrta murchisoni</i> (Deshays in Reeve, 1854)													x						
	<i>Maorimacra</i> sp.																			
	<i>Maorimacra chrydaea</i> (Suter, 1911)																			
	<i>Maorimacra orainaria</i> (Smith, 1898)													x						
	<i>Scalpomacra scalpellum</i> (Reeve, 1854).																			
	<i>Scalpomacra</i> sp.																			
	<i>Zenatia acinaces</i> (Quoy & Gaimard, 1835).																			
	<i>Paphies subtriangulata</i> (Gray in Wood, 1828)																			
	<i>Rexithaerus spenceri</i> (Suter, 1907)																			

AREA	SAMPLE NUMBER	Others												
		71	103	100	87	207	107	101	94	125				
194	<b>BIVALVES</b>													
	<i>Serratina charlottae</i> (Smith, 1885).													
	<i>Serratina</i> sp.													
	<i>Gari lineolata</i> (Gray, 1835).		x											
	<i>Gari</i> sp.		x											
	<i>Dosina crebra</i> (Hutton, 1873)				x									
	<i>Dosina zelandica</i> Gray, 1835.													
	<i>Bassina parva</i> Marwick, 1927.	x												
	<i>Bassina yatei</i> (Gray, 1835).	x												
	<i>Tawera</i> sp.													
	<i>Dosinia (Asa) lambata</i> (Gould, 1850).					x								
	<i>Dosinia (Asa) aff. lambata</i> (Gould, 1850).	x												
	<i>Dosinia (Austrodosinia) anus</i> (Phillipi, 1848)						x						x	
	<i>Dosinia (Kereia) greyi</i> Zittel, 1864.	X												
	<i>Dosinia (Phacosoma) subrosea</i> (Gray, 1835).													
	<i>Dosinia (Raina) nukumaruensis</i> (Marwick, 1927).													
	<i>Eumarcia (Atamarcia) benhami</i> Marwick, 1927.													
	<i>Eumarcia</i> sp.													
	<i>Panopea zelandica</i> (Quoy & Gaimard, 1835).													
	<i>Myadara stephaniae</i> Carter, 1972.													
	<i>Myadara</i> sp.													
	<b>GASTROPODA</b>													
	<i>Zethalia coronata</i> (Marwick, 1948).						x							
	<i>Caillostoma hawera</i> (Oliver, 1926).										x			
	<i>Caillostoma</i> sp.									x				
	<i>Maoricolpus roseus</i> (Quoy & Gaimard, 1834)													
	<i>Stiraclopus delli</i> sp.				x									
	<i>Stiraclopus</i> sp.													
	<i>Zeacolpus vittatus</i> (Hutton, 1873)													
	<i>Zeacolpus</i> sp.													

AREA	SAMPLE NUMBER	Others																		
		71	103	100	87	207	107	101	94	125										
194																				
	<b>GASTROPODA</b>																			
	<i>Pellicarta</i> n.sp. aff. <i>zelandiae</i> (Marshall & Murdoch, 1920).																			
	<i>Struthiolaria pupulosa</i> (Martyn, 1784)																			
	<i>Crepidula radiata</i> (Hutton, 1873).																			
	<i>Sigapatella</i> sp.																			
	<i>Zegalerus tenuis</i> (Gray, 1867).																			
	<i>Taniella planisutularis</i> (Marwick, 1924).																			
	<i>Taniella</i> sp.	x																		
	<i>Fraginatica marshalli</i> (Marwick, 1924)																			
	<i>Polinicies</i> sp.																			
	<i>Polinicies wajipiensis</i> (Marwick, 1924).																			
	<i>Galeodea</i> sp.																			
	<i>Semicassis (Kahua) fibrata</i> (Marshall & Murdoch, 1920).																			
	<i>Tonna</i> (Brunnich, 1772)																			
	<i>Aeneator elegans</i> (Suter, 1971)																			
	<i>Aeneator</i> sp.																			
	<i>Austrofusus pagoda</i> (Finlay, 1924).																			
	<i>Austrofusus pilocineus</i> (Powell, 1931).																			
	<i>Austrofusus</i> sp.																			
	<i>Penion</i> aff. <i>cuvierianus</i> (Powell, 1927).																			
	<i>Penion sulcatus</i> (Lamarck, 1816).																			
	<i>Penion</i> sp.																			
	<i>Xymene ambiguus</i> (Phillipi, 1844).																			
	<i>Amalata (Baryspira) depressa</i> (Sowerby, 1859).																			
	<i>Amalata (Baryspira) mucronata</i> (Sowerby, 1830).																			
	<i>Amalata (Baryspira) oraria</i> (Olson, 1956).																			
	<i>Amalata (Gracilspira) cf. rimuensis</i> (Olson, 1956).																			
	<i>Lamprodromina neozelandica</i> (Hutton, 1885).																			
	<i>Alciithoe (Lepromax) brevis</i> Marwick, 1926.																			
	<i>Alciithoe</i> sp.																			
	<i>Pervicacia tristis</i> (Deshayes, 1859).																			

Inner-most shelf assemblages

**W17**                      **inner-innermost shelf**

*Maorimactra* sp.

*Scalpomactra* sp.

**Stop 201**                      Based on the abundance of *Dosina creba* and *Zethalia coronata* this facies is considered a **shoreface to inner-most shelf** sandstone.

*Nucula nitidula*

*Scalpomatra scalpellum*

*Dosina creba* (a)

*Bassina parva*

*Dosinia (phacosoma) subrosea*

*Zethalia coronata* (a)

*Taniella planisutlaris*

*Amalda (Baryspira) depressa*

*Amalda (Baryspira) oraria*

**Stop 207**    **Lower shoreface assemblage**

*Mactra murchisoni*

*Dosinia* (Asa) aff. *lambata*

*Dosinia (Austrodosinia) anus*

*Zethalia coronata*

*Calliostoma* sp.

**Stop 94**                      **Innermost shelf**

*Dosinia (Austrodosinia) anus*                      0-10 m offshore beach

*Dosinia (Kereia) greyi*                      soft muds, harbours

**Stop 99**                      **Innermost shelf – inner shelf**, presence of shallow water

*Paphies subtriangulata* indicates reworking

<i>Scalpomactra scalpellum</i>	0-200 m, sandy/muddy
<i>Paphies subtriangulata</i>	shoreface
<i>Dosinia (Asa) lambata</i>	5-50 m, fine grained soft substrate

**Stop 66**    **Innermost shelf**

<i>Zenatia acinaces</i>	0-40 m (innermost shelf)
<i>Rexithaerus spenceri</i>	(inner shelf)
<i>Dosina zelandica</i>	(harbour)
<i>Dosinia (Phacosoma) subrosea</i>	(inner shelf)
<i>Zethalia coronata</i>	(shoreface)
<i>Austrofusus pagoda</i>	(inner shelf to mid shelf))
<i>Fellaster zealandiae</i>	(shoreface)

**Stop 203**    **Innermost shelf and shoreface** assemblages,  
probably with some reworking

<i>Nucula nitidula</i>	
<i>Chlamys gemmulata</i>	
<i>Mactra</i> aff. <i>discors</i>	(shoreface)
<i>Maorimactra chrydaea</i>	(innershelf)
<i>Maorimactra ordinaria</i>	(innershelf)
<i>Zentatia acinaces</i>	(innershelf)
<i>Gari</i> sp.	(shoreface)
<i>Bassina parva</i>	
<i>Bassina yatei</i>	shoreface
<i>Dosinia (Asa) lambata</i>	(innershelf)
<i>Dosinia (Kereia) greyi</i>	(innershelf)
<i>Dosinia (Phacosoma) subrosea</i>	(innershelf)
<i>Eumarcia (Atamarcia) benhami</i>	(innershelf)
<i>Panopea zelandica</i>	
<i>Myadora</i> sp.	(shoreface)

*Zethalia coronata* (shoreface)

*Taniella* sp.

*Aeneator elegans*

*Aeneator* sp.

*Penion sulcatus*

*Xymene ambiguus*

*Lamprodomina neozelandica* shallow

*Pervicacia tristis* (shoreface)

*Crenilabium starboroughense*

**Stop 47** Lower shoreface to innermost shelf, with high energy bypassing currents, based on dominance of *Ostrea chilensis*.

*Ostrea chilensis* (dominate)

*Dosinia (Asa) anus*

### Inner shelf assemblages

**Stop 71** Similar to modern inner shelf communities, with *Scalpomactra-Maorimactra* association of McKnight (1969), on a sand and mud substrates, 20-60 m water depth.

*Nucula nitidula*

*Maorimactra ordinaria*

*Bassina parva*

*Bassina yatei*

*Dosinia (Asa) aff. Lambata*

*Dosinia (Kereia) greyi*

*Taniella* sp.

*Fissidentalium zelandicum*

**Stop 80** Inner shelf sandstone

*Nucula* sp.

### Appendix 3: Fossil Assemblages

*Serratina charlottae* 10-60 m  
*Penion sulcatus* intertidal-outershelf, soft substrate, 0-90 m

**Stop 122**            **inner shelf sandstone**, all taxa probably fit into a paleo-shoreface innermost shelf community

*Rexithaerus spenceri*                      nearshore  
*Dosinia (Austrodosinia) anus*            shoreface  
*Dosinia (keria greyi*                        soft muds harbours  
*Eumaricia (Atamarcia) benhami*        shallow soft sand within diverse assemblages  
*Myadora stephaniae*                        nearshore sandstone  
*Zethalia coronata*                         shoreface  
*Polinicies sp.*  
*Austrofusus pagoda*                        inner-mid shelf

**Stop 193**        sheltered **inner shelf assemblage**

*Crassostrea sp.*  
*Polinicies waipipiensis*                    shallow nearshore, soft substrate  
*Penion aff. cuvierianus*                    90-110 m or 5-10 m  
*Amalda (Gracilispira) cf. rimuensis*  
*Splendrillia aequistriata*                 0-40 m siltstone

**Stop 103**            **inner shelf sandy siltstone**, could be eusturine but presence of *Pratulium pulchellum* indicates a deeper water setting.

*Atrina pectinata zelandica*            0-60 m, estuary to open coast  
*Pratulium pulchellum*                    300-200 m, muddy  
*Gari linoleata*                                0-40, coastal beach  
*Gari sp.*  
*Maoricolpus roseus*                        0-40 m, inter-tidal, mud flats, shallow channels

**Stop 54**            Mixed assemblage, dominance of *Dosinia (Asa) lambata* indicates **inner shelf** (Bea and Maxwell, 1990)

*Crassostrea ingens*

### Appendix 3: Fossil Assemblages

*Ostrea chilensis*  
*Zenatia acinaces*  
*Gari linoleata*  
*Dosinia (Asa) lambata* (dominate)  
*Dosinia (Raina) nukumaruensis*  
*Zethalia coronata*  
*Struthiolaria pupulosa*  
*Taniella planisutularis*  
*Austrofuscus* sp.  
*Penion* sp.  
*Fissidententalium zelandicum*

#### Inner-mid shelf assemblages

**Stop 100**                    **inner-mid shelf**, could be estuarine but presence of *Pratulium pulchellum* indicates a deeper water setting.

*Atrina pectinata zelandica*                    0- 60m, estuary to open coast  
*Pratulium pulchellum*                    30- 200m muddy  
*Gari* sp.  
*Amalda*

#### **Stop 85**                    **inner – mid shelf**

*Atrina pectinata zelandica*                    eustuary to open coast 0- 60m  
*Chlamys gemmulata*  
*Pteromyrtea dispar* (a)                    soft substrate nearshore  
*Pratulium* sp.  
*Maorimactra* sp.                    0- 30 m  
*Serrantina charlottae*                    15- 90m  
*Bassina parva*                    shallow sandy  
*Eumarcia* sp.                    shallow soft sand  
*Calliostoma* sp.

Appendix 3: Fossil Assemblages

*Fissidentalium zelandicum* (a)

**Stop 136** reworked diverse assemblage of **inner shelf to mid shelf** fossils

*Zeacolpus* sp.

<i>Crepidula radiata</i>	inner-mid shelf
<i>Polinicies waipipiensis</i>	shallow nearshore, soft substrate
<i>Austrofuscus pagoda</i>	mid-outer self mudstone
<i>Amalda (Baryspira) oraria</i>	shallow sandstone shellbed
<i>Amalda (Baryspira) cf. rimuensis</i>	
<i>Splendrillia kingmai</i>	0-40 m
<i>Splendrillia</i> sp.	inner shelf to bathyal
<i>Fissidentalium zelandicum</i>	inner to outer shelf

**Stop 206** abundance of *Austrofuscus pagoda*, within a diverse assemblage indicates that this is a **inner-mid shelf sandstone** with common inner shelf and shore face fossils transported onto mid shelf

<i>Dosinia (Phacosome) subrosea</i>	variety of soft substrates, usually low tide sands, or coast (typically shallow)
<i>Stiraclopus delli</i> sp.	harbour-
<i>Zegalerus tenuis</i>	inner-outer shelf
<i>Polinicies waipipiensis</i>	shallow nearshore, soft substrate within diverse assemblages, inner shelf
<i>Austrofuscus pagoda</i>	mid to outer shelf
<i>Fissidentalium zelandicum</i>	inner to outer shelf

**Stop 192** **inner to mid shelf**, shelter low energy environment

<i>Pratulium pulchellum</i>	30-200 m muddy
<i>Pratulium</i> sp.	
<i>Calliostoma</i> sp.	0-40 m
<i>Friginatic marshalli</i>	
<i>Tonna</i> sp.	
<i>Austrofuscus pagoda</i>	inner-mid shelf

### Appendix 3: Fossil Assemblages

*Austrofusius* sp.

*Amalda (Baryspira) mucronata* inner-mid shelf

*Alcithoe (Lepromax) brevis* shallow-moderately deep water sand and mud

*Splendrillia* sp. inner shelf to bathyal

*Antalis nana* 15-300 m soft muddy substrate

*Antalis* sp.

**Stop 204** Inner to mid shelf, based on presence of *Pratulium pulchellum* and *Semicassis (Kahua) fibrata*.

*Pratulium pulchellum* (inner-mid shelf)

*Galeodea* sp.

*Semicassis (Kahua) fibrata* (innershelf)

#### Mid-outer shelf assemblages

**Site 141** Sheltered basin-wards assemblage, **mid-outer shelf**, with transport of inner-shelf sediments

*Elpehidium* sp.

*Astronomium* sp.

*Bulmina* sp.

*Uvigeringa* sp.

*Anomalinoidea* sp.

*Notorotalia* sp. (dominate)

*agluinated* sp. (rare)

*Evolvocassidulina orientalis* sp.

*Mesopelum crawfordi*

**Site 125** Mid-outer shelf to upper slope assemblage, high plantics content indicates deep water setting

*Bulmina* sp.

*Elpehidium* sp.

*Astronomium* sp.

*Notortalia* sp.

*Asidualia* sp.

*Hayniesina depressula* sp.

*Nonionella flemingi* sp. (dominate)

*Glob. Woodi* sp.

*Patro undatus*

**Site 140**                      **Mid-shelf fauna**

*Pratulium pulchellum*

*Pratulium* sp.

*Stiracolpus* sp.

*Pellicaria* n. sp. aff. *zelandiae*

*Polinicies waipipiensis*

**Site 32**                      **Outer shelf to upper slope with re-deposited fauna**

*Astononmiuma* sp.

*Elpehidium asdidualina*

*gyroidina* sp.

*Gavelinopus hamatus* sp.

*Cibicides deliquatus* sp.

*Anomalinoidea* sp.

*Uvigerina* sp.

*Polinaia* sp.

*Cibicides horticatus*

*Cibicides marboroughensis* (dominate)

*Zeaflorilus pari*

*lagina* sp.

## Appendix 4

## Location and description of fossil localities

Site Name	Section (see Appendix 1)	Grid Reference	Lithology (see chapter 2)
W13	Wu1	V20/434124	Wp-B-2
201	Wu1	V20/432126	Wp-B-2
74	Wu1	V20/434124	Wp-B-2
R1e	Wu1	V20/439138	Wp-B-1
R1f	Wu1	V20/439138	Wp-B-1
R1g	Wu1	V20/439138	Wp-B-2
93	Wu1	V20/439135	Wp-B-2
94	Wu1	V20/439135	Wp-B-2
W30	Wu1	V20/439138	Wp-A-1
122	Wu1	V20/412147	rg-B-1
203	Wu1	V20/414146	mt-A-2
103	-	V20/403198	rg-B-1
85	-	V20/411139	mt-B-2
80	-	V20/411134	mt-C-2
66	-	V20/440185	rg-B-2
47	Wi1	W19/553235	wp
199	Wi1	W19/543241	mt-B-2
54	Wi1	W19/545244	mt-B-2
136	Wi1	W19/545260	mt-A-2
206	Wi1	W19/543262	mt-A-2
139	Wi1	W19/535256	rg-B-1
140	Wi1	W19/527264	rg-A-a
204	Wi3	V19/486243	rg-B
190	Wi4	V19/441233	tk-D-2
186	Wi6	V19/436253	tk-D-2
189	Wi6	V19/438236	tk-D-2
174	Wi16	V19/407287	tk-B-2
198	Ek5	V19/331228	tk-B-4
196	Ek2	V20/346197	tk
194	Ek3	V19/350202	tk
101	-	V19/409218	tk-E-2
105	Wu3	V19/402227	rg?
193	-	V20/362183	rg
192	Wu6	V19/368208	rg
194	Ek3	V19/350202	tk
71	-	V20/474189	tk-B-2
103	Wu3	V20/403198	rg
100	-	V19/387209	rg
87	Wu1	V20/414145	tk-A-2
207	Wi2	W19/508201	mt?
107	Wu4	V19/401228	tk-D-4
94	Wu1	V20/439137	wp-B-2
125	Wu1	V20/407150	rg-B-1
33	Wi5	V19/466253	tk-E-2
141	Wi1	W19/534262	rg-A-1

Appendix 5: Grainsize Data

Grainsive Data from the Waikoau River (section Wu1)

Sample No.	metres	% Sand
1	0	43.59
2	0.5	1.99
3	1.5	29.69
4	2	26.89
5	2.5	10.04
6	3.1	33.18
7	2.5	21.84
8	3.5	25.16
9	6	25.16
10	6.5	40.96
11	8	22.77
12	8.5	23.73
12a	8.6	0
13	11	23.45
14	11.5	21.64
15	11.6	37.93
16	11.7	67.76
17	16	21.14
18	16.5	26.01
19	17	6.3
20	18	6.68
21	18.5	52.13
22	20	14.78
23	20.5	10.18
24	22	31.53
25	31	78.97
26	31.5	0
27	33	50.78
28	38	44.76
29	38.5	13.26
30	44	17.84
31	44.25	42.36
32	44.5	20.43
33	60	22.25
34	60.5	28.94
35	61	34.67
36	63	43.4