

CRETACEOUS AND EOCENE
GEOLOGY
OF SOUTH WESTLAND

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Frontispiece

View looking east over the Paringa River which runs in the middle ground from right to left. Tititira Head lies in the middle ground to the left. The mouth of Gates Creek lies between cliffs in the middle foreground. On the far side of the Paringa River valley Lagoon, Yankee Dans and Lignite Creeks (see Map 1) are all visible. A saddle on Mt Arthur is visible to the far left in the background. (Photo - D.L. Homer N.Z.G.S.)



ABSTRACT

The Cretaceous and Eocene sequence of South Westland crops out within a 6km wide coastal area from Ship Creek to the Mahitahi River.

The oldest unit, the Otumotu Formation (Motuan - Arowhanan), lies with angular unconformity on the Paleozoic Greenland Group. It is divided into two members, an older Tauweritiki Member (new) overlain by the Topsy Member. Both are entirely clastic but the lower unit is significantly coarser ranging from boulder to pebble breccia and conglomerate to mudstone, while the upper member comprises granule conglomerate, sandstone and mudstone. Detailed analysis of sedimentary features suggests that the lower member represents alluvial fan and plain sedimentation in a tectonically active setting changing to a more stable semi-arid fluvial and lacustrine depositional regime in the younger deposits.

The Butler Formation (new) (Piripauan), which lies unconformably on the Otumotu Formation, consists of conglomerate, sandstone and mudstone, with high and medium volatile bituminous coal seams. The sediments represent an environment of rivers and coal forming swamps and lakes which produced thick (up to 3m) coal seams.

The Tauperikaka Formation (new), previously the Tauperikaka Coal Measures, (Haumurian) overlies the Butler Formation, with a disconformity marked by a low relief scour surface, and is divided into the Moeraki (lower), Paringa (middle) and Rasselas (upper) Members. The Moeraki Member consists of pebble conglomerate, cross-bedded and horizontally bedded pebbly and granular sandstone and carbonaceous massive silty mudstone. The sequence is thought to represent a coastal fluvial environment. The Paringa Member includes large scale planar tabular cross-bedding with mud drapes ("tidal bundles"), bi-directional flaser bedded, trough and planar cross-bedded sandstone, siltstone and mudstone. The depositional environment is interpreted as a tide dominated

coastline. The Rasselas Member, which consists of interbedded burrowed and structureless glauconitic sandstone in which both the density and diversity of burrows and the sediment grain size decrease upwards, was probably deposited in a large open marine bay.

The sediments of the Otumotu, Butler and Tauperikaka Formations are derived from a Greenland Group and Tuhua Group source which probably lay to the west of the basin. The change in depositional environment within the Tauperikaka Formation, from a marginal marine to an off shore marine environment is responsible for changes in relative proportions of constituents in the sediment composition, and the rock fragment component has been greatly depleted.

The eruption of the Arnott Basalt towards the end of the Haumurian is possibly related to extension which led to thinning of the crust.

The Eocene Law Coal Measures (new) (Kaiatan) are composed of clast supported very well rounded cobble to pebble conglomerate, well sorted medium sandstones, carbonaceous siltstone and mudstone and thick (up to 4m) high volatile bituminous coal seams. The sequence is interpreted as marginal marine, with coal forming reed swamps developing between fluvial clastic fans. A marine transgression from the east resulted in the end of coal measure sedimentation. The Tititira Formation (Miocene) lies unconformably on the Law Coal Measures.

Differences in coal type and coal geochemistry distinguish the coal in the Butler Formation from coal in the Law Coal Measures. The pH of the Law Coal Measure swamps was elevated by a marine influence which has produced a distinctive coal type characterised by a low Tissue Preservation Index. The coal also contains very little inertinite compared with coal from the Butler Formation. The coal in the Law Coal Measures can be distinguished using the relatively high Na_2O content which is totally organically associated and is present in a constant amount within

different seams. The Butler Formation coal contains a high proportion of clay compared to the coal in the Law Coal Measures and has negligible Na_2O .

A thrust system involving both Paleozoic basement and Cretaceous and Tertiary cover rocks has developed in post Miocene time and accounts for a substantial amount of shorting (in the range of 40km and possibly more). The Mistake fault, a splay off the Alpine Fault, is the sole thrust of the Mistake Thrust Sheet which is part of a duplex thrust system which has subsequently been buckled into an antiformal stack. The antiformal stack includes at least two other thrust sheets, one below and one above the Mistake Thrust Sheet. The thrust complex appears to extend south to Milford Sound and up to 100km north of the area mapped and it is likely similar thrust systems are developed along the entire length of the Alpine Fault.

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Maps 1 2 3 4 & 5, Cross Sections and Geological Legend are in the Map Pocket

CHAPTER ONE

1.0 INTRODUCTION

This thesis is primarily concerned with the detailed mapping, stratigraphy, sedimentology, selected aspects of coal geology, and environments of deposition of the Cretaceous, and locally Eocene sequences, of the South Westland province of New Zealand. A structural model to explain the complex faulting and folding patterns is also presented. The sequence crops out discontinuously along a 6km wide coastal area from Ship Creek in the south west ([169 09' Long. E, 043 46' Lat. S.] [N.Z.M.S.260: F37/2200057095]) to the Mahitahi River in the north east ([169 35' Long. E, 043 37' Lat. S.] [N.Z.M.S.260: G36/2234557285]), (Fig. 1.1).

The project evolved from an involvement in the mapping of the area between the Ohinemaka and Haast Rivers and the Alpine Fault for the South Westland Management and Evaluation Programme (S.W.M.E.P.). Regional mapping commenced in November 1984. More detailed field work and sampling was undertaken from February 1985 when a specific study on the Cretaceous and Eocene sequences evolved. Mapping was continued until the end of May and then sporadically throughout the remainder of 1985 and 1986.

1.1 Topography

The rugged topography rises to a maximum of 2785 feet at Bald Hill. Creeks have sporadic poor to moderate exposure, but almost continuous coastal cliffs provide excellent exposure (Fig. 1.2). The main road, State Highway 6, provides discontinuous outcrop between Lake Moeraki and Ship Creek (Fig 1.2). Dense rain forest covers the rest of the area yielding very few exposures. Towards the coast, the forest grades into dense scrub which considerably impedes progress.

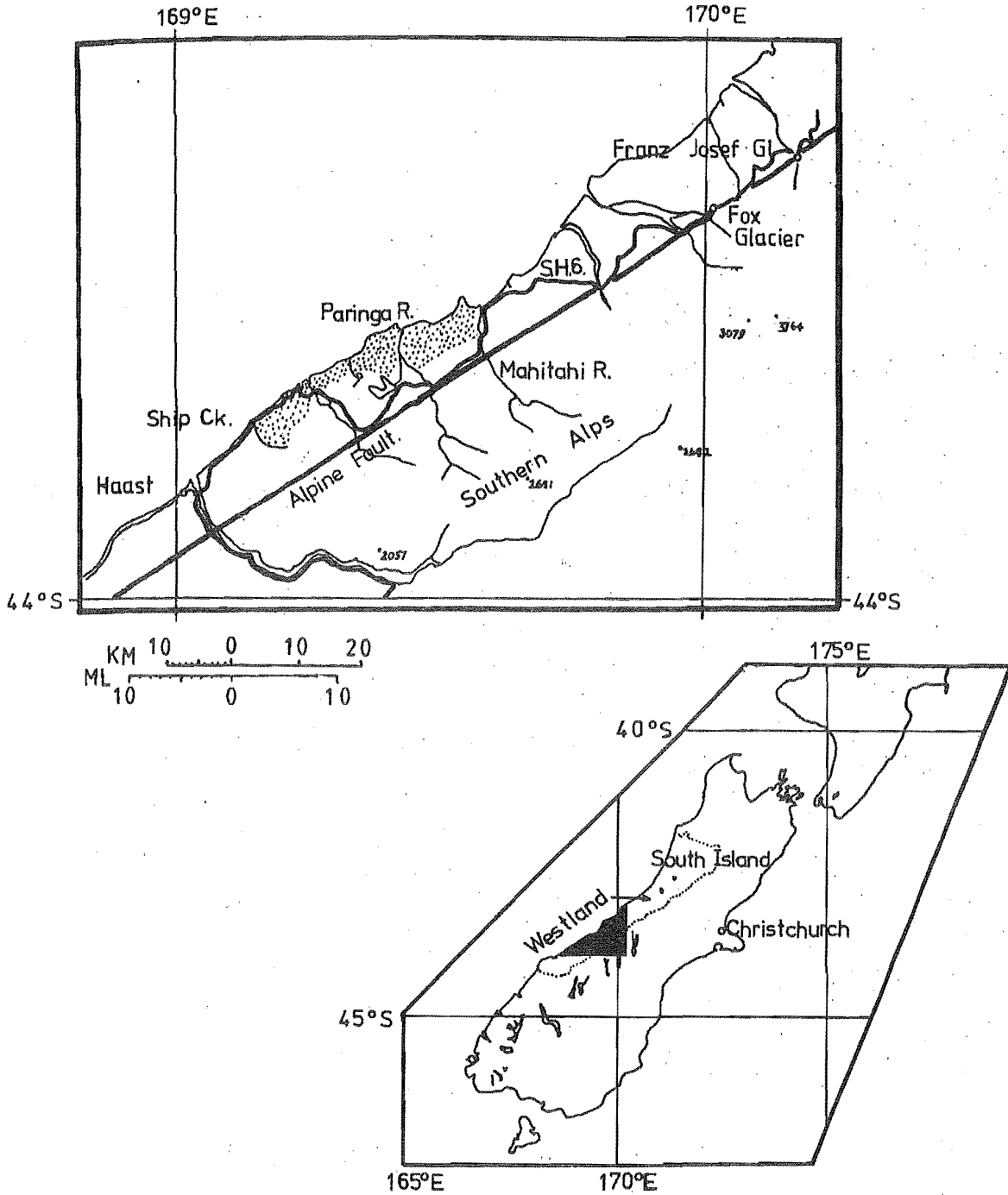


Figure 1.1
Locality map showing the extent of the South Westland study area, access route (State Highway 6) and surrounding settlements.

Figure 1.2

The coast in the vicinity of the Whakapohai River (far left foreground) and Knight Point (middle foreground). State Highway 6 runs along the top of the coastal cliff from middle foreground to the far right. Lake Moeraki lies in the middle ground and State Highway 6 runs inland along the left margin of the lake. (Photo - D.L. Homer N.Z.G.S.)



1.2 Climate

The north and north-westerly winds deliver abundant rainfall to South Westland and showers of torrential rain alternate with periods of blue sky throughout the day. Rain falls relatively heavily on 50% of field days which causes a rapid rise in river level. Water levels remain high for at least one day after rain, sometimes restricting or preventing access.

1.3 Access

State Highway 6, (abbreviated S.H.6) the only road through the area, runs parallel to the coast and provides access to most creeks (Fig 1.2 and Map 1). The remaining creeks are accessible from the coast. When river water is low the bed of the Paringa River can be traversed on foot or otherwise travelled by jet boat. The coast is also accessible from Monro Track (a foot track running from the northern tip of Lake Moeraki), another track running from State Highway 6 down the east bank of the Whakapohai River, and from where S.H.6 crosses near the mouth of Ship Creek (Map 1).

1.4 Thesis Objectives

Since only a minor amount of stratigraphic work (section 2.0), and no sedimentological work, have been previously attempted, the major objectives of this thesis are as follows:

1. To produce a geological map of the Cretaceous rocks of South Westland.
2. To produce detailed stratigraphic columns of the Cretaceous sequence and to revise the stratigraphy where necessary.
3. To characterize the detailed sedimentology of the formations, to describe selected aspects of the coal and to provide ways of distinguishing the formations.
4. To establish the most likely environments of deposition of the Cretaceous formations and explain the

occurrence or non occurrence of coal, and to assess the economic potential of the coal bearing sequences.

A further aim has evolved with the project which is:

5. To map the occurrence of Eocene coal measures within the area and to determine ways of distinguishing the Eocene sequence from the Cretaceous sequence.

CHAPTER TWO

2.0 PREVIOUS AND PRESENT WORK

Charles Douglass first produced a map of the area around Bullock (Cole) Creek¹ in 1890. Douglass recorded coal outcrops which were relocated by Evans (1937) who led one of two prospecting parties. The other party, led by Bolitho (1937), worked around the Paringa area. Both parties produced maps of their respective areas reporting on coal, including discussion of local rumours of unlocated seams, and also undertook prospecting for reefs. Other geologists who noted the Cretaceous-Tertiary rocks were Cox (1877), Haast (1879), and Wellman & Willet (1942). Wellman (1951, 1955) was the first to produce a regional map of the whole area and divide the Cretaceous and Tertiary rocks into Formations (Fig. 2.1). These divisions were based on the better known North Westland sequence.

Gair and Greg (1962) and Young (1968) visited the area to facilitate engineering geological investigations in conjunction with the construction of S.H.6 between Lake Moeraki and Haast. Nathan (1977) visited the area several times between 1961 and 1974, and, combining the work of Wellman (1955), Young (1968) and the 1962-1966 data, compiled generalised stratigraphic columns in which the Hawks Crag, Lower Coal Measures and Middle and Upper Coal Measures (Wellman 1955) were divided into the Otumotu Formation, Tauperikaka Coal Measures and Whakapohai Sandstone (Fig. 2.1). Nathan also mapped the Tertiary rocks along the shoreline south of the Paringa River mouth (Nathan 1978a).

Otter Minerals Exploration Limited was granted coal prospecting licence 35-175 in April 1982. The licence area extends from just north of Lake Paringa to the Ohinemaka

1. Maps drawn previous to road construction refer to the creek as Bullock Creek, but the road sign now reads Cole Creek.

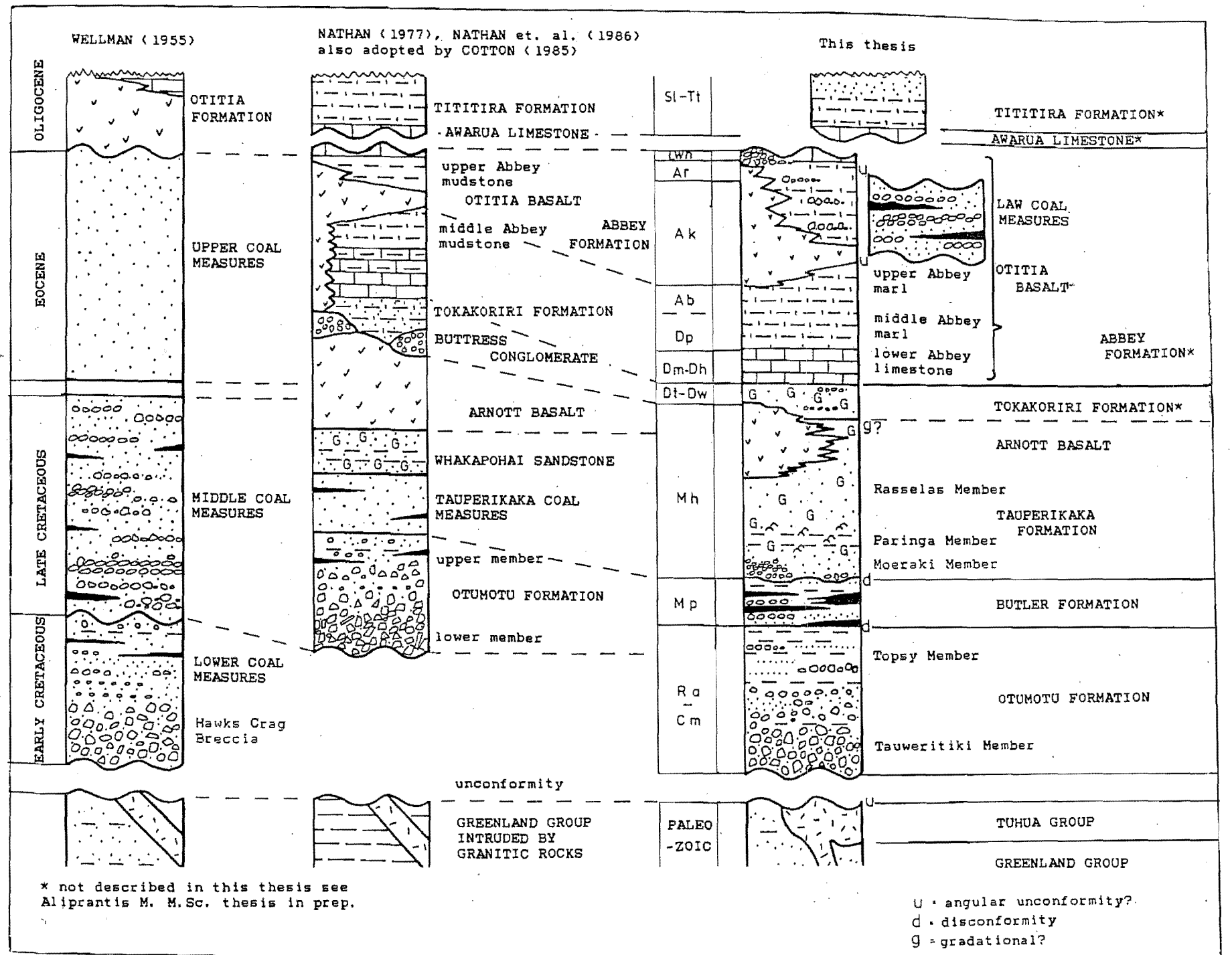


Figure 2.1
Stratigraphic sequence of the area between Ship Creek and the Mahitahi River.

River. Cotton (1985) mapped in this area intermittently from 1982 and during the present investigation. Cotton was primarily concerned with the location of coal in the "coal measures", and concluded that there is a lack of coal in the Tauperikaka Coal Measures and the licence has subsequently been dropped. Cotton (1985) adopted the stratigraphic column presented by Nathan (1977) but re-interpreted the Buttress Conglomerate as a member of the Otumotu Formation.

CHAPTER THREE

3.0 METHODS

3.1 FIELD WORK

The size of the area mapped, combined with the difficulties caused by the relief, vegetation and poor exposure inland from the coast, have greatly extended the amount of time required for mapping during this project. In addition to obtaining and locating outcrop data, substantial work was required to produce a satisfactory topographic base map, which was accomplished using aerial photographs (N.Z.G.S. Serial Number 5941). Streams are often obscured by thick vegetation on aerial photographs and in lower lying areas where streams are almost completely obscured, pace and compass traverses were required to plot both the streams and outcrop localities. A cotton chain, which is a bicycle meter, attached to a cotton reel which relays a cotton line from a trouser belt attachment, was used to determine distances walked between compass points and outcrops. Coal Creek and Wells Creek, on the flanks of Bald Hill, and Lagoon Creek, a tributary of the Paringa River, were compass and cotton chained using this method. In all of the other streams, a cotton chain was used to estimate the positions of outcrops along sections of creek courses lacking points of reference on aerial photographs.

Maps

Topographical maps at 1:15840 scale were compiled by the Forestry Division in the 1950's from aerial photographs of the same scale. The 1:50,000 scale topographical map, used as the location map (Map 1 in map pocket), is taken from N.Z.M.S.1 sheets S77, S78, S87 and S88 and has a superimposed N.Z.M.S. 260 metric grid.

Field data were transferred from aerial photograph overlays onto maps with scales of 1:7,920; 1:15,840 and 1:50,000. The amount of outcrop data often determined the

scale used. The field sheets are stored in the Christchurch Geological Survey map collection.

The course of streams, position of S.H.6, as well as other features of relief are often different on the 1:15,840 forestry compiled maps in comparison to the N.Z.M.S.260 1:50,000 map. As the geometry of the streams on the 1:15,840 maps is a better reproduction of the actual stream geometry than on the 1:50,000 map, the 1:15,840 scale is a better base for new data. The courses of the majority of the streams on the 1:15,840 maps in the map pocket of this thesis have been corrected by pace and compass traverses or refined by using stereoscopy. However, because of the differences in the shape of relief constituents between the two maps, the metric grid on the 1:50,000 map can not be placed on the 1:15,840 maps, whilst maintaining the same grid co-ordinates for the features of the relief, without marked grid distortions. Therefore, the grid intersections on the imperial 1:15,840 maps have been plotted, by using relief features as reference points, onto the 1:50,000 metric map, in order to provide a cross referencing system.

Stereoscopic photographic interpretation was used to a limited degree, in correlating faults and other contacts between outcrops.

Measured Sections

Detailed stratigraphic columns (Sections 4.1, 4.2, 4.3, and 4.5) were compiled using a metre rule and compass/clinometer. Descriptions of sedimentary features follows the methods outlined in Lewis (1982) and abbreviations and symbols are adopted and modified from Andrews (1982).

Coal Sampling

The coal samples were all taken from outcrop. Creek exposures were cleared of vegetation and slope wash and up to 50cm of weathered surface coal removed before the full seam of thickness was channel sampled. The seams were

sampled in plies, which were defined either by natural lithological subdivisions, or arithmetically where lithological variations were not apparent. Coal samples for palynological studies were also taken.

Palynological Sampling

Palynological sampling was undertaken to aid stratigraphic interpretations and to provide paleoenvironmental data (for example, the presence of dinoflagellates). The Tauperikaka Formation to the south of Otumotu Point has previously been sampled and the results presented in Nathan (1977). Therefore, sampling for this study was concentrated on the Tauperikaka Formation in the Paringa River basin, within the Otumotu Formation (the age of which was previously unknown) and the sections of outcrop at Mt. Arthur and Coal Creek which both contained sedimentological and coal petrographic characteristics which were unlike those of the established formations of the South Westland area.

The collection of palynological samples was undertaken using the methods outlined in the N.Z.G.S. Technical Guide (Mildenhall 1975). The pollen samples are listed in Appendix 3 and detailed descriptions of the location, stratigraphic positions, and sedimentary features are listed in the Geological Society of New Zealand Fossil Record File. All of the pollen sample numbers in this thesis have N.Z. fossil record file numbers. Samples were analysed by Dr J.I. Raine of the N.Z.G.S.

Plant Macrofossils

Several large blocks containing well preserved plant macrofossils were sampled from Mt. Arthur to aid stratigraphic and depositional environment interpretations. Where possible, leaves with complete margins and well preserved venation impressions were collected. The samples were submitted to Mr I. Daniel of the University of Canterbury Botany Department and the results are listed in Appendix 4.

3.2 LABORATORY WORK

Sandstone Petrography

Samples were collected from the formation type sections for petrography to determine provenance, basic differences in composition and texture between individual formations, and to detect any major paleoenvironmental indicators. Thin sections were made using the methods outlined in Lewis (1982). Thin sections and rock slabs were then stained to detect feldspars using the method outlined in Houghton (1980; In: Lewis, 1982).

The texture and composition of 23 sandstone thin sections have been visually estimated and the results presented in Section 5.0.

Modal Compositional Analysis

A compositional analysis by point counting has been undertaken on sample University of Canterbury 119891 to determine the reliability of visual estimates of composition on rock sample thin sections. A point space of 0.5mm was used, which is larger than the visually estimated mean. Dennison and Shea (1966) illustrated that the spacing has to be the same or larger than the average grain size for a binomial approximation of the results to be valid. In order to attain statistically representative results, the whole surface of the section was scanned as some components (for example, feldspar) are irregularly distributed within the specimen. Only one count was recorded per grain. The number of points is limited to 500 as Galehouse (1971) showed that although greater precision is achieved with an increasing number of points, above 500 points precision does not increase greatly.

The results of point counts are shown in Table 3.1; the cumulative frequencies and percentages are shown in Table 3.2. The result of visual estimates versus percentages calculated from the modal analysis is shown in Table

Table 3.1 The results of a 500 point point-count on sample University of Canterbury 119891 presented in two lots of 200 points and one of 100 points.

	f	%	f	%	f	%
Quartz mono	79	39.5	83	41.5	36	36
Quartz poly	18	9.0	17	8.5	10	10
Total Quartz	97	48.5	100	50	46	46
Rock fragments	29	14.5	27	13.5	23	23
Microcline	16	8.0	11	5.5	7	7
Muscovite	4	2	1	0.5	2	2
H & O	0	0	1	0.5	0	0
Matrix	25	12.5	35	17.5	15	15
Cement	16	8.0	17	8.5	4	4
Holes	13	6.5	8	4	3	3
Total	200	100	200	100	100	100

Table 3.2 Cumulative Frequences and Percentages of the results of a 500 point point-count on sample University of Canterbury 119891 (see table 3.1).

	200		400		500	
	No.	%	No.	%	No.	%
Quartz mono	79	39.5	162	40.5	198	39.6
Quartz poly	18	9.0	35	8.75	45	9
Total Quartz	97	48.5	197	49.3	243	48.6
Rock fragments	29	14.5	56	14	79	15.8
Microcline	16	8.0	27	6.75	34	6.8
Muscovite	4	2	5	1.25	7	1.4
H & O	0	0	1	.25	1	0.2
Matrix	25	12.5	60	15	75	15
Cement	16	8	33	8.25	37	7.4
Holes	13	6.5	21	2.5	24	4.8

3.3. The main differences are: a) under-estimation of quartz, specifically polycrystalline quartz; b) over-estimation of rock fragments; c) over-estimation of matrix and under-estimation of cement. The range of 5% -15% given for feldspars is a response to the uneven distribution of microcline grains between laminae within the sample. The point count percentage of feldspar as a portion of the whole rock (6.8%) may indicate feldspar numbers are slightly over-estimated which is probably due to the yellow stain on the feldspar which makes the grain very obvious to the eye, causing a selective bias.

The over-estimation of both rock fragments and matrix is probably due to the difficulties of distinguishing the rock fragment component from the matrix component which appears to consist mostly of grains derived from the rock fragments disaggregated in the environment of deposition. The over-estimation of both rock fragments and matrix is responsible for the under-estimation of the quartz grain component.

X-Ray Diffraction

Petrography of samples from the Cretaceous sequence was qualitatively determined using x-ray diffraction and 5 representative samples are presented in Appendix 8. Pieces of whole rock were broken and crushed into a fine powder and analysed using a Philips XRD system.

Coal Petrography

Particulate mounts made from 17 coal samples have been prepared for petrography, using a procedure outlined in Appendix 7. Polished sections were examined and photographed using an Ortholux II POL-BK reflected light microscope with a 50X oil immersion lens and 10X ocular lenses. Familiarisation with the coal type and reflectance was necessary before the maceral analyses were undertaken.

Table 3.3 Visual estimates compared with the modal analyses on sample University of Canterbury 119891.

	Visual %	Modal Analyses %
Quartz monocrystalline	38	39.6
Quartz polycrystalline	2	9
Quartz Total	40	48.6 15.8
Rock fragments	25	15.8
Microcline	5 - 15	6.8
Muscovite	2	1.4
H & O	> 1	0.2
Matrix	18	15
Cement	5	7.4
Holes	-	4.8

Maceral analyses were undertaken using the methods outlined in Stach et al. (1975). A point to point and line to line distance of 0.5mm was used to count 500 points on each sample. The whole area of the polished surface was analysed in order to counter any irregularly distributed macerals, and only one count per particle was recorded. The number of points counted for each individual maceral, maceral group and mineral are expressed as a percentage of the total of points recorded. The individual macerals and maceral groups were then expressed on a mineral free basis.

The terminology used for macerals in this thesis is summarised in Table 3.4. A description of the macerals is given in Stach et al. (1975) and in the International Handbook of Coal Petrology (1971).

Coal Reflectance

The reflectance of the vitrinite maceral telocollinite has been assessed in 12 South Westland samples. All reflectance determinations have been made with a Leitz Orthoplan MPV 2 system, either at the New Zealand Geological Survey, Lower Hutt or at the Geology Department, University of Auckland. The machine at Wellington was calibrated using a garnet standard of 0.98% reflectance, whereas at Auckland, the calibration was obtained with glass standards which cover the range between 1.25 and 0.545.

Coal Mineral Matter

The identification and distribution of the four main mineral groups (quartz, clay minerals, sulphides and carbonates) were assessed under reflected light during maceral analyses. The various mineral species were identified using x-ray diffraction after the samples had been ashed using an RF low temperature asher at temperatures less than 150°C.

The method for low temperature ashing is as follows: each coal sample was ground to a powder and spread thinly on a glass tray. The sample was then oxidized for up to 12

Table 3.4 Summary of the macerals of hard coals (after Stach et al., 1975).

Group Maceral	Maceral	Submaceral*
<u>Vitrinite</u>	<u>Telinite</u>	Telinite 1
		Telinite 2
	<u>Collinite</u>	<u>Telocollinite</u>
		Gelocollinite
		<u>Desmocollinite</u>
	<u>Corpocollinite</u>	
	<u>Vitrodetrinite</u>	
<u>Exinite</u>	<u>Cutinite</u>	
	<u>Sporinite</u>	
	<u>Resinite</u>	
	<u>Suberinite</u>	
	<u>Liptodetrinite</u>	
	Alginite	
	<u>Exsudatinite</u>	
<u>Inertinite</u>	Micrinite	
	Macrinite	
	<u>Semifusinite</u>	
	<u>Fusinite</u>	<u>Pyrofusinite</u>
		<u>Degradofusinite</u>
	<u>Sclerotinite</u>	Fungosclerotinite
	<u>Inertodetrinite</u>	
	<u>Meta-exsudatinite</u>	

* incomplete can be expanded as required

- macerals underlined are those recognized in maceral analyses reported in this thesis.

hours until the organic fraction was completely oxidized. The residue was then prepared and analysed using a Philips XRD system, as outlined by N.A. Newman (1985).

Coal Geochemistry

The major elements present within high temperature ash were determined for 8 samples by x-ray fluorescence.

Approximately 10g of coal, subsampled from 1mm stock was ground to a fine powder, weighed, and ashed at 815°C. The ash was then weighed after cooling, and prepared and analysed by x-ray fluorescence spectrometer (Philips PW1400), using the method of Norrish and Hutton (1969). Weight percentages of each major element oxide have been recorded on a loss on ignition-free basis.

CHAPTER FOUR

4.0 STRATIGRAPHY

Introduction to Stratigraphy

The Cretaceous sequence in South Westland is summarised by Fig. 2.1 with the sequences proposed by Wellman (1955) and Nathan (1977).

The subdivision of part of Wellman's Coal Measure sequence into the "Otumotu Formation (Upper Member)" and "Tauperikaka Coal Measures" (Nathan 1977) (see Fig. 2.1) was based on a change from "greywacke derived arkosic sandstone" to "granite derived quartzose sandstone" across a "conformable but sharp" contact exposed at the south western end of the Otumotu Formation type section. The Whakapohai sandstone was defined on the appearance of glauconite, associated with bioturbation and burrows within the sequence.

Mutch and McKellar (1964) originally named the Arnott Basalt as the Arnott Volcanics. The present name was introduced by Nathan (1977) as the Formation is wholly composed of basalt. The Buttress Conglomerate (Nathan 1977) was named after the exposure of conglomerate at Buttress Point, east of the Paringa River mouth. The type locality for the Buttress Conglomerate was selected as an exposure of conglomerate on the north side of Porphyry Point, just north of Tokakoriri Creek.

The revisions to the stratigraphy are discussed below and then the stratigraphy of each formation is discussed separately. A brief discussion on composition is included with the Buttress Conglomerate as the formation is not described in Section 5 on sedimentology.

Revisions to Stratigraphy

The stratigraphy proposed by Nathan (1977) is accepted with the following amendments:

1. The Otumotu Formation is Motuan to Arowhanan age. The new dates are based on a recent pollen analysis (Section 4.1).
2. The Otumotu Formation is divided into two members based on lithofacies. The members are the Tauweritiki Member (Section 4.1), which replaces the Lower Member (Nathan 1977), and the Topsy Member (Section 4.1) which replaces the Upper Member (Nathan 1977).
3. The conformable sedimentary contact described by Nathan (1977) which separated the Otumotu Formation and the "Tauperikaka Coal Measures" at the southwestern end of the Otumotu Formation type section is a fault contact. The fault contact separates the Otumotu Formation from the Butler Formation (new). Elsewhere the Butler Formation lies disconformably on the Otumotu Formation.
4. The Butler Formation is a new formation encompassing a diverse group of terrestrial coal bearing sediments deposited during the Piripauan (Section 4.2).
5. The change in composition from "greywacke derived arkosic sandstone" to "granite derived quartzose sandstone" across the contacts between the Otumotu Formation and the Butler Formation, or between the Butler Formation and the overlying "Tauperikaka Coal Measures" (Nathan 1977) has not been confirmed by current investigation. It is probable that the rock fragment components of the "Tauperikaka Coal Measure" sediments were previously misidentified as matrix, and the amount of feldspar in the Otumotu Formation was over estimated. Feldspar percentages in rocks from the Butler and Tauperikaka Formations (new) are higher than percentages of feldspar in rocks from the Otumotu Formation. A Greenland Group and Tuhua Group provenance is envisaged for all three formations (see respective sections on composition), although the Greenland Group was the main sediment source during

deposition of the Otumotu Formation, and the Tuhua Group may have been a more prominent source rock than the Greenland Group during deposition of the Butler and Tauperikaka Formations (new).

6. The Tauperikaka Coal Measures (Nathan 1977) are renamed the Tauperikaka Formation (new) due to the lack of coal in the formation and because a large part of the formation was deposited in a marine environment. The connotation of "coal measures" is therefore, misleading.

7. The Whakapohai Sandstone (Nathan 1977) is abandoned as a formation and these rocks are encompassed within the Tauperikaka Formation for the following reasons. The sequence from the base of the Tauperikaka Formation to the top of the Whakapohai Sandstone is essentially an unbroken gradational sequence. There is not a distinctive easily recognisable boundary that separates the "Whakapohai Sandstone" from the Tauperikaka Formation and as the "Whakapohai Sandstone" is defined by Nathan (1977) the Formation is not a practical or convenient unit for mapping. The contact between the "Tauperikaka Coal Measures" and the "Whakapohai Sandstone" was supposed to represent a change from a non-marine environment, during deposition of the "Tauperikaka Coal Measures", to a shallow marine environment during deposition of the "Whakapohai Sandstone" (Nathan 1977). However, a large part of the rock exposure in the "Tauperikaka Coal Measure" type section as defined by Nathan (1977) was deposited in a shallow marine near-shore environment.

The appearance of glauconite in outcrop, which was used to distinguish between the "Tauperikaka Coal Measures" and the "Whakapohai Sandstone" (Nathan 1977), is unreliable as: (a) glauconite may appear, disappear and re-appear along the strike of a single bed which has been deposited by the same process in the same environment, and it is not reasonable to map

separate parts of that bed as different formations; (b) glauconite is the first mineral to disappear with weathering, which is apparent in many road outcrops; (c) glauconite appears within the "Tauperikaka Coal Measure" type section defined by Nathan (1977) as do other criteria (for example burrowing) for distinguishing the "Whakapohai Sandstone".

8. The Tauperikaka Formation is divided into three members which are the Moeraki Member (Section 4.3), Paringa Member (Section 4.3) and the Rasselas Member (Section 4.3). The members are defined by their characteristic lithofacies.

9. The Buttress Conglomerate, named after exposures of conglomerate at Buttress Point (Nathan 1977), may not crop out in the type section defined by Nathan at Porphyry Point (Section 4.6). The conglomerate in the type section is lithologically different from the exposures east and west of Buttress Point and has been re-defined as a minor member of the Tokakoriri Formation by Aliprantis (MSc thesis in prep. U.of C.). Therefore, the Buttress Conglomerate from Buttress Point (N.Z.M.S. 260 G36/226257) to the mouth of the Ohinemaka River (G36/273252) is the new type section for the Buttress Conglomerate. At present, there is no conclusive evidence to suggest that the Buttress Conglomerate was deposited in the Tertiary period. The formation remains unplaced within the stratigraphy as field evidence in the vicinity of Buttress Point only indicates the Formation was deposited either during, or before deposition of the Otitia Basalt, of Kaiatan to Runangan age. Cotton (1985) interpreted the Conglomerate as a facies equivalent of the Otumotu Formation. No evidence has been found during this study to substantiate Cotton's interpretation (see Section 4.6).

10. The Law Coal Measures (new), a previously undefined part of the Otumotu Formation (Cretaceous age),

which consists of a coal seam bearing sequence unlike any of the Cretaceous or Eocene sequences (Section 5.4), are here interpreted as a separate formation which was deposited during the Kaiatan (Eocene), (Section 4.5).

pre Cretaceous Rocks

The age of the Greenland Group within South Westland has not been determined. In North Westland, it has been dated as earliest Ordovician (approximately 495 m.y.) based on geochronology and paleontology (Adams 1975, Cooper 1974).

The Greenland Group rocks in South Westland consist of indurated, greenish grey alternating sandstones and subordinate mudstones. The sandstone, varying in thickness from thin partings to 2m thick, is usually massive and contains predominantly detrital, poorly sorted quartz with only minor rock fragments and feldspar, in a recrystallized sericite/chlorite and quartz matrix. Calcite occurs as porphyroblasts, vein fillings and as concretionary pods (Stewart and Nathan in prep.).

Over much of the area, Greenland Group sediments have been thermally metamorphosed to a biotite hornfels. Lowest grade rocks are lowest greenschist facies. The rocks increase in metamorphism towards the pegmatite and granite intrusions in the east parallel to the Alpine Fault. On the 1:250,000 maps all the granite rocks in South Westland were mapped as Tuhua Group, and that name is used in this study.

Mason (1961) described the granite in the Paringa pluton (N.Z.M.S.260 G36/285169) in the quarry as a "granite consisting of quartz, microcline, plagioclase, biotite and hornblende with accessory sphene, apatite and zircon." The granite is also rich in muscovite (observation during a recent visit to the quarry).

4.1 OTUMOTU FORMATION

The Otumotu Formation (Nathan 1977) is named after Otumotu Point, (Otumotu Point is composed of Tauperikaka Formation sediments), to the east of which the Otumotu type section is defined. The type section is the coastal strip northeast of Otumotu Point from N.Z.M.S. 260 F36/093167 to F36/100168.

The Otumotu Formation crops out in four separate areas which are: (a) the flanks of the Paringa Hill and Mt. Gates; (b) in Tokakoriri Creek; (c) in the type section along Otumotu Beach; (d) Bald Hill in the southwest (Fig. 4.1).

The lower part of the Otumotu Formation consists of thick sequences of massive or imbricated, green and grey, hard, angular to sub-rounded, boulder to pebble breccia and conglomerate which weathers to a maroon colour. Stratigraphically higher in the sequence light green grey, angular cobble and pebble conglomerate is interbedded with cross-bedded sandstone (Fig. 4.2 in map pocket).

The upper part of the sequence is characterised by centimetre and millimetre bedded, grey white, hard, coarse medium and fine sandstones and grey and black, carbonaceous silty mudstones (Fig. 4.3 in map pocket). The sediments are cemented by dolomite.

Stratigraphic Relationships

The Otumotu Formation is 520 metres thick in the type section. Elsewhere the outcrop is relatively poor and thickness estimations are dubious. The Otumotu Formation is considered to be hundreds of metres in stratigraphic thickness rather than thousands of metres.

Contacts onto Greenland Group have not been seen but regional evidence suggests an angular unconformity. In the type section on Otumotu Beach the upper contact of the Otu-



Figure 4.1
Bald Hill (Map 1: F37/049081) looking to the east. Otumotu Formation, Tauweritiki Member (Motuan-Arawhanan) crops out intermittently in foreground. Maroon hard cobble-pebble sandy breccia.

motu Formation is faulted against the Butler Formation. On both sides of the Paringa River the Formation is unconformably overlain by the Butler Formation. The contact is marked by a low relief irregular surface between a weathered layer of conglomerate (Otumotu Formation) and a coal seam and silty mudstone (Butler Formation). In Tokakoriri Creek the Formation is unconformably overlain by the Arnott Basalt and the Tititira Formation.

The Otumotu Formation is divided into two members which roughly correlate with the lower member and the upper member of the Otumotu Formation identified by Nathan (1977). The members are the Tauweritiki and the Topsy members respectively. The two members are defined by their respective characteristic lithofacies and stratigraphic positions.

4.1.1 Tauweritiki Member (new)

The Tauweritiki Member (new) is named after the Tauweritiki Lakes. The type locality is the coastal section east of Otumotu Point from F36/100168 to F36/094167 (Map 1). The member is at the base of the sequence in four separate areas which are: (a) the flanks of Paringa Hill and Mt. Gates; (b) in Tokakoriri Creek; (c) in the type section along Otumotu Beach; (d) Bald Hill in the Southwest (Fig. 4.1)

The distinctive characteristics of the member are beds of breccia comprised of angular to sub-angular cobble to pebble clasts of green, grey or maroon sandstone and quartz pebbles, in a green, weathered maroon, sandstone matrix derived from Greenland Group lithologies. Conglomerate beds are either vertically continuous or inter-bedded with green sandstones which weather a distinctive maroon colour (Fig. 4.2).

Stratigraphic Relationships

A thickness of 400m is exposed in the type section, which is a minimum thickness as the lower contact is not exposed. Due to structural complexities and a lack of a basal contact, thickness estimations elsewhere are dubious. The Member is more likely to be in the order of hundreds of metres rather than thousands of metres.

Cotton (1985) described a basal contact with the Greenland Group in a tributary of the Paringa river which could not be relocated, but regional evidence suggests an angular unconformity.

In the type section on Otumotu Beach the Tauweritiki Member grades up into the Topsy Member in an inter-layered relationship. Elsewhere the Member is overlain by the Butler Formation on both sides of the Paringa River, by the Tauperikaka Formation on the East side of the Paringa Hill, and by the Tititira Formation in Tokakoriri Stream.

Age of the Tauweritiki Member

Samples from the Tauweritiki Member examined by I. Raine for pollen are non-fossiliferous and yielded woody detritus only. The age of the Tauweritiki Member can only be assessed indirectly. The Tauweritiki Member gradationally underlies the Topsy member of the Otumotu Formation. The Topsy Member contains the Trichotomosulcites subgranulatas Assemblage of upper Motuan - Arowhanan, (Fig. 4.3). The Hawks Crag Breccia of North Westland, which contains very similar lithofacies to the Tauweritiki Member, is dated as late Albian (Motuan) on a miospore assemblage (Laird in press).

4.1.2 Topsy Member (new)

The Topsy Member is named after Lake Topsy. The type section is the coastal beach cliff east of Otumotu Point from N.Z.M.S.260 F36/093167 to F36/094167 (Map 1). The Member has not been identified outside the type section.

Distinctive characteristics of the Topsy Member are centimetre bedded, light brown, brown-orange, white and maroon, cross bedded, hard, moderately sorted, medium and fine sandstones interbedded with laminated carbonaceous silty mudstones. Sandstone units are lensoidal with sharp erosional bases and have sharp or gradational upper contacts with silty mudstones (Fig. 4.3). Definitive characteristics are, the large amount of interbedded siltstone and mudstone, the thinness of the bedding and a dolomite cement.

In the lower to middle part of the Topsy Member, thick sequences (up to 5m) of cross bedded, imbricated cobble to pebble sandy conglomerates and sandstones of the Tauweritiki Member (Section 4.1.2) are interbedded with the thinner bedded, finer grained lithologies of the Topsy Member (Fig 4.3).

Stratigraphic Relationships

Approximately 120m thickness is exposed in the type section. The bottom half of the Topsy Member is inter-layered with the underlying Tauweritiki Member sediments. The upper contact of the Topsy Member exposed in the beach cliff, approximately 60m from the east side of Otumotu Point, was interpreted as an unconformity with overlying Tauperikaka sediments (Nathan 1977). The contact is here interpreted as a fault contact (Fig 4.4). The sediments on the south-west side of the fault do not resemble the Tauperikaka Formation and are now part of the Butler Formation (see Section 4.2). A period of approximately seven million years is not recorded by the stratigraphy between the top of the Otumotu Formation, of Arowhanan age and the Butler Formation, of Piripauan age (Section 4.2).



Figure 4.4
Otumotu Beach (Map 1: F36/093168). Fault contact with pug zone
between Otumotu Formation, Topsy Member (Motuan-Arowhanan) to
the right and Butler Formation (Piripauan) to the left. Boulder in
foreground to right "not in situ."

Age of the Topsy Member

The Topsy Member has been dated by pollen as mid Cretaceous age (upper Motuan - Arowhanan). The Trichotomosulcites subgranulatus Assemblage is a low diversity flora dominated by coniferous pollen, with a few pteridophyte spores, but apparently no angiosperms (Raine 1986). The assemblage is non-marine. The microfloras are similar to those analysed by Raine from the Puysegur Formation of Fiordland, the Gridiron Formation of Marlborough and the Kyeburn Formation.

4.2 BUTLER FORMATION (new)

The Butler Formation (new) is named after Butler Creek in which the formation crops out. The name "Butler" is derived from Butler's Farm, which stands at the foot of Mt. Arthur. The type locality is the sequence exposed in Butler creek from N.Z.M.S.260 G36/324255 to 327255, where a stratigraphic thickness of up to 100m is exposed.

The formation is exposed in 8m of discontinuous beach cliff, and wave cut platform on the east side of Otumotu Point N.Z.M.S.260 G36/093168 which provides an easily accessible reference section. The Butler Formation is also exposed on the western and eastern flanks of the Grave Creek Valley, in cuttings on S.H.6, and on hills adjacent to the Paringa River and Lake Paringa.

The name "Butler Formation" is introduced for a diverse group of conglomerate, cross-bedded sandstone, siltstone, mudstone, coal seam and fossil plant bearing sediments of Piripauan age. They strongly resemble sediments of the Topsy Member (Otumotu Formation), due to a derivation from the same source rocks, and a similar depositional environment, but the two formations are separated by a disconformity which represents a considerable amount of geological time, approximately 5 to 10 million years, and the formations represent different parts of the geological history. Confusion would result if the two formations were coupled together. Therefore the Butler Formation is introduced and further sedimentological analyses are recommended, to distinguish the occurrence and characteristics of the Butler Formation and to divide the Butler Formation into recognisable members.

Stratigraphic Relationships

At Mt. Arthur, approximately 100m are exposed (Fig 4.5). Poor outcrop and structural complexities in the vicinity of Mt. Gates render thickness estimations dubious. On Otumotu Beach, 8m are exposed and up to 20m may be buried in

the colluvium of a slip.

In Butler Creek the base of the Cretaceous sequence, (interpreted as the Butler Formation) rests with an angular unconformity on Greenland Group rocks. The upper contact of the Butler Formation with the overlying Tauperikaka Formation is described in Section 4.3.2.

To the east of Otumotu Point, the lower contact of the Butler Formation is faulted against the Topsy Member of the Otumotu Formation and the Butler Formation is disconformably overlain by the Paringa Member of the Tauperikaka Formation (contact described in Section 4.3.2)

In the road cuttings on S.H.6 at Grave Creek, the lower contact of the Butler Formation is faulted against Greenland Group on both the western and eastern sides of the valley. The upper contact on the western side of the valley is a fault contact with the younger Paringa Member of the Tauperikaka Formation. To the east of Grave Creek, where S.H.6. leaves the valley, the Butler Formation is in disconformable contact with the younger Moeraki Member of the Tauperikaka Formation (contact described in Section 4.3.1). The upper contact of the Butler Formation with the Moeraki Member of the Tauperikaka Formation is also exposed in a tributary of the Paringa River (Section 4.3.1).

Age of the Butler Formation

The presence of Taeniopteris and Eretmophyllum amongst plant fossil assemblages suggests the age can not be younger than Haumurian. The presence of dicotyledonous leaves shows it can not be older than mid Cretaceous (Albian) but their well organised venation suggests Upper Cretaceous. The similarity of both podocarps and dicotyledonous leaves to those from Pakawau strongly suggests the age is Piripauan to Haumurian (Upper Senonian to Maastrichtian) (Daniel, see Appendix 4).

Samples collected during this study for pollen analysis (F36/f9 and F36/f10) from Otumotu Beach contain microflora in which the key species for correlation are Phyllocladidites mawsonii and Cicatricosporites (F36/f9) and Tricolpites sabulosus and Nothofagus (=Nothofagidites) senectus. A similar assemblage is present in a coal seam from the Butler Formation on the Mathers Creek-Gates Creek divide (G36/f31). The latter key species enable placement in the upper part of Zone PM1 (Piripauan). No marine influence has been detected (Raine 1986).

4.3 TAUPERIKAKA FORMATION

The Tauperikaka Formation is a name modified after the Tauperikaka Coal Measures of Nathan (1977), (see revision to stratigraphy, Section 4.0). The Tauperikaka Coal Measures are named after Ship (or Tauperikaka) Creek near the southern edge of Map 1. The type section is the coastal outcrop south-west of Otumotu Point, between N.Z.M.S.260 F36/091167 and F36/093169 (Fig. 4.6).

The Tauperikaka Formation crops out in five areas: (1) as a folded and faulted strip between Ship Creek and the north east side of Otumotu Point; (2) and (3) within two faulted blocks; one crops out in Waterfall Creek, the other in Pearson Creek; (4) on both sides of the Paringa River; (5) at Mt.Arthur, where it is best exposed in Butler Creek.

The Tauperikaka Formation is divided into three Members each of which are defined on the basis of lithofacies associations, which in turn reflect the processes operating in their respective environments of deposition. The successive members of the Formation are the Moeraki Member (new), Paringa Member (new) and Rasselas Member (new) (Fig. 2.1).

Distinctive characteristics of the Moeraki Member, at the base of the Tauperikaka Formation, are decimetre and centimetre bedded, cross-bedded, white, granular coarse and medium sandstones stained a distinctive yellow brown from the weathering of pyrite. Occasional decimetre and centimetre bedded well lithified green grey and white, poorly sorted, sub-angular to well rounded pebbles and granules contain quartz and lithic clasts derived from the Greenland and Tuhua Groups. The lithic clasts are well rounded as opposed to the more angular quartz clasts.

The outcrop appearance of the Moeraki Member differs from the appearance of stratigraphically older formations with respect to the fresh and weathered colours, the thicker bedding, larger scale of cross-bedding and the general absence of finer grained lithologies.

Figure 4.6
Monro Beach from Otumotu
Point (Map 1: F36/093169)
Tauperikaka Formation
(Haumurian) type section.



Figure 4.7 (Stratigraphic column, Tauperikaka Formation, Monro Beach) and Figure 4.8 (Stratigraphic column, Tauperikaka Formation, Breccia Creek) are both in Map pocket.

The Paringa and Rasselas Members of the Formation consist of sequences of lenticular and wavy bedded green glauconitic sandstones and dark grey siltstones interbedded with light and dark cross-bedded or bioturbated centimetre to decimetre bedded, glauconitic sandstone beds. Burrowing appears in the white cross-bedded sandstones at the top of the Moeraki Member and slowly increases in density upward into the Rasselas Member, as does the appearance and gradual increase of the mineral glauconite.

stratigraphic Relationships

On Monro Beach and around Otumotu Point, 70m of the Tauperikaka Formation is exposed (Figs 4.6 and 4.7), although the lower contact on Monro Beach is not seen. To the east side of Otumotu Point the Paringa Member of the Formation rests disconformably on the Butler Formation on a surface marked by a low relief scour with lenses of a boulder to pebble conglomerate (Section 4.3.2). Approximately 50m offshore from the steeply dipping, stratigraphically uppermost exposures on Monro Beach, islands composed of Arnott? Basalt occur. Thickness estimations for the Formation on either side of the Paringa River are not possible as the sequence is repeated, by faulting and folding. Outcrop is restricted to creeks and is incomplete.

In Breccia Creek, the structural complications render thickness estimations dubious (Fig. 4.8). In one outcrop in Breccia Creek, recumbent folding repeats the sequence three times in 12m of outcrop. Between the Whakapohai River and Ship Creek faulting has also stacked the Formation in a series of fault bounded slices, the stratigraphic relationships of which can only be indirectly assessed from comparisons to the type section.

The Moeraki Member is in disconformable contact with the Butler Formation at a contact marked by a low relief scour surface, which is exposed in a road cutting on S.H.6. to the north-east of Grave Creek (Section 4.3.1). In Butler Creek, (which is in the north-east of the area on Mt.

Arthur), the Paringa Member? rests either disconformably or with an angular unconformity on the Butler Formation (section 4.3.2). Wellman (1955) describes sediments similar to the Tauperikaka Formation sediments in track cuttings between Bullock (Cole) and Ship Creeks where the Formation is inferred to lie directly on the Greenland Group and with an angular unconformity. The tracks have long since reverted to bush and the outcrop is no longer available, however the observation is consistent with other regional evidence. Elsewhere, the lower contact of the Tauperikaka Formation is faulted or not exposed.

Where exposed the upper contact of the Rasselas Member is conformable with the Arnott Basalt, which may inter-finger with the uppermost Rasselas Member sediments. Sedimentological similarities suggest that where Arnott Basalt does not occur, as is likely in some present day offshore areas, the Rasselas Member grades up into the Tokakoriri Formation (Fig 2.1), although this relationship has not been seen on land.

4.3.1 Moeraki Member (new)

The Moeraki Member is named after Lake Moeraki. The type section is the beach cliff exposure to the east of Monro Track on Monro Beach and includes the first 26m of stratigraphic section from N.Z.M.S.1. 30305339 to 30315341.

The Moeraki Member is exposed in tributaries of the Paringa River (e.g. Lagoon Creek), in Waterfall Creek, in road outcrops along S.H.6. between the Whakapohai River and Grave Creek, on both sides of the Breccia Creek Valley where S.H.6. crosses Breccia Creek, in Bishop's Folly and in Wells Creek.

In the type section on Monro Beach, the distinctive characteristics of the Moeraki Member are centimetre bedded, cross-bedded, white weathering to yellow and brown, hard, coarse to medium sandstones. Sandstones are lensoidal and

fine upward from quartz and lithic pebble and granule lags. In exposures at Breccia Creek and Lagoon Creek, the Moeraki Member displays a larger scale of cross-bedding and grain-size than in the type section. Centimetre to decimetre, cross-bedded, sandstones crop out at Breccia Creek and decimetre and metre bedded, trough cross-bedded and wedge shaped, poorly sorted, pebbly granule and pebbly coarse sandstones crop out between N.Z.M.S.260 G36/234244 and G36/235244 at the base of Lagoon Creek, which is provided as a reference section.

At Monro Beach occasional beds of carbonaceous silty mudstone are present, and at Breccia Creek, sheared carbonaceous mudstones up to 1m thick are preserved.

Stratigraphic Relationships

At the Breccia Creek S.H.6 exposure approximately 70m of vertically dipping bedding is exposed. However, the sequence contains several faults and shows localised shearing and the location does not show a basal contact and so thickness estimations are uncertain (Fig. 4.8).

The Moeraki Member is in disconformable contact with the Butler Formation at a contact which is exposed in a S.H.6 bench cutting 250m north-east of the Grave Creek valley, where the sequence is overturned and so the Butler Formation crops out on top of the Moeraki Member. The contact is marked by a low relief undulatory surface between a yellow-brown, cross-bedded coarse sandstone, of the Moeraki Member and, lying structurally above the Moeraki Member, a rounded, cobble to pebble conglomerate, of the Butler Formation. The lower contact of the Moeraki Member is exposed in a tributary of the Paringa River south of Lignite Creek (N.Z.M.S.260 G36/235214) where a coal seam and associated carbonaceous mudstones of the Butler Formation are overlain disconformably by a thick sequence of yellow brown sandstones of the Moeraki Member. Elsewhere, the lower contact was either not visible or faulted. Upper contacts on the Member are discussed in Section 4.3.2.

Age of the Moeraki Member

The bottom part of the Tauperikaka Formation was dated by Wilson (in Nathan 1977) who suggested a Haumurian age by the presence of the pollen Nothofagidites Kaitangata (Te Punga). Assemblages were described by Wilson as very sparse, highly carbonised, and poorly preserved. A lack of dinoflagellate cysts was interpreted as an indication of sediment accumulation under non-marine conditions.

More recently, Raine (1986) analysed samples collected by this author from the Paringa Member in Lagoon Creek. The Paringa Member contains miospores and dinoflagellates of early to mid-Haumurian age (see Section 4.3.2). The Moeraki Member is therefore inferred to be of early to mid-Haumurian age.

4.3.2 Paringa Member(new)

The Paringa Member is named after Lake Paringa. The type section is the beach cliff exposure to the east of Monro Track on Monro Beach and encompasses approximately 12 metres of stratigraphic thickness from N.Z.M.S.1. 30315341 to 30325342. A reference section from N.Z.M.S.1. 30285339 to 30285339 is situated to the west of Monro Track on Monro Beach and encompasses approximately 30 metres of stratigraphy. A second reference section from N.Z.M.S.260 G36/235244 to G36/245242 that encompasses the Lagoon Creek section is provided.

The Paringa Member is exposed in Butler Creek, Lagoon Creek, Pearson Creek, along Monro Beach, exposures along S.H.6. south of the Whakapohai River to Ship Creek, in Grave and Breccia Creeks and in Bullock (Cole) Creek and tributaries of Bullock Creek.

In the type section on Monro Beach, the distinctive characteristics of the Paringa member are thick beds (1.3m) of bi-directional, lenticular, wavy and flaser bedded silt-

stone and sandstone and ripple bedded sandstone, interbedded with green, mega-ripple scale, flaser bedded, glauconitic, medium sandstones and large scale (0.5m -1m) planar forset beds of well sorted, glauconitic, coarse and medium sandstones. All of the lithologies contain a few scattered burrows.

Stratigraphic Relationships

On Monro Beach, in the type section, the lower contact of the Paringa Member with the Moeraki Member is well exposed and shows a gradational transition over 2m up to a thin extensive conglomerate layer above which there are only Paringa Member lithofacies. In cuttings along S.H.6. at Breccia Creek the two members interfinger and in Lagoon Creek the contact between the Moeraki and Paringa members is gradational.

The Paringa Member is at the base of the Tauperikaka Formation in two areas: (1) in the wave-cut platform on the north-east side of Otumotu Point and (2) in Butler Creek on Mt. Arthur. The lower contact to the north-east of Otumotu Point is exposed at low tide where the Paringa Member rests disconformably on the Butler Formation on a surface marked by a low relief scour with lenses of a boulder to pebble conglomerate (Fig. 4.9). The corresponding contact in the beach cliff exposure is presently buried in a slip. In Butler Creek on Mt. Arthur the Paringa Member overlies the Butler Formation with either a disconformable contact or a low angled angular unconformity (the nature of the large scale cross-bedding in the yellow brown sandstones of the Paringa Member which overlie finer lithologies of the Butler Formation makes interpretation of the contact, in the cliff exposure, difficult).

On the south-west side of Grave Creek the Paringa member is faulted against the Butler Formation and although the contact between the Paringa and Moeraki Members is not exposed in Bishop's Folly the general field relationships



Figure 4.9
Otumotu Beach, wave cut platform (Map 1: F36/093169). A disconformable contact, marked by lenses of boulder to pebble conglomerate, between Butler Formation (Piripauan) to the right and Tauperikaka Formation, Paringa Member (early to mid Haumurian) to the left.

suggest a fault contact.

The Paringa Member is everywhere overlain by the Rasselas Member and the contacts are discussed in Section 4.3.3.

Age of the Paringa Member

Six samples collected from Lagoon Creek (Appendix 3) contain pollen assemblages of early to mid-Haumurian age (Raine 1986). All spores belong to miospore zone (PM2) (Raine 1984) and dinoflagellate zone (*Odontochitina Costata* Zone). Key miospores include *Tricolpites lilliei*, *Nothofagus Kaitangata*, *Camarozonosporites aff. ohaiensis*, *Densoisporites microrugulatus*, *Proteacidites retiformis*, *P. cf. granoratus*, *Clauifera rudis*, *Aequitriradites sp.*, etc. The dinoflagellate *Odontochitina spinosa* is present. Further examination for dinoflagellates is being continued by Graeme Wilson.

The miospore dinoflagellate assemblages belong to a shallow marine facies. Miospore assemblages contain a diversity of angiosperm pollen, including *Tricolpites lilliei*. Coniferous pollen (*Phyllocladites mawsonii*), and a variety of pteridophyte and bryophyte spores suggest a more humid environment than prevailed previously in the Cretaceous sequence (Raine 1986). The palynological zone is widely recognised around New Zealand including the bulk of the Paparoa Coal Measures.

4.3.3 Rasselas Member (new)

The Rasselas Member is named after Lake Rasselas. The type section is the beach cliff exposure on the headlands at both ends of Monro Beach including Otumotu Point from N.Z.M.S.260 F36/093169 to F36/093170 and the headland at the western end from F36/689167 to F36/089167. The Rasselas Member is exposed in Lagoon Creek and in the road cuttings along S.H.6 between Grave Creek and Bullock (Cole) Creek, in

Breccia and Grave Creeks and intermittently along the coast between the Whakapohai River and Ship Creek.

In the type section on Monro Beach (Fig 4.7), the distinctive characteristics of the Rasselas Member are; decimetre bedded or massive, green, glauconitic, medium and silty fine sandstones either with scattered burrows or more usually, totally bioturbated. The Rasselas Member quickly loses signs of bedding upward within the column (Fig. 4.7). Weathering of S.H.6. outcrop and outcrops along the coast may be responsible for the lack of evidence of cross-bedding in sandstone beds which have not been bioturbated.

Stratigraphic Relations

In the type section on Monro Beach the Rasselas Member is approximately 20m thick, the upper contact with the Arnott Basalt is not exposed. The Rasselas Member overlies the Paringa Member at the south-west end of Monro Beach with an abruptly gradational contact. On the east side of Otumotu Point, the Rasselas and Paringa Members interfinger and the transition from one member to the next is continuously gradational over several metres. The contact between the Paringa and Rasselas Members seems to be gradational along S.H.6. and abrupt in Lagoon Creek but is not well exposed in either locality.

The Rasselas Member is overlain by the Arnott Basalt in exposures between Otumotu Point and Tauperikaka Point and in Waterfall Creek. Folding in Breccia Creek reproduces the contact between the Rasselas Member and the Arnott Basalt down stream and it has not been possible to ascertain whether the relationship between the two Formations is interfingering or is represented by a single contact. The contact is often marked by a layer of basaltic rubble in a sandstone matrix.

Offshore, in areas not covered by the Arnott Basalt, the Rasselas Member is probably gradational with the overly-

ing Tokakoriri Formation (Fig. 2.1) as the two Formations have similar sedimentation characteristics and were deposited in similar, genetically related environments. The contact has not been seen on shore.

Age of the Rasselas Member

Assemblages of pollen are fairly sparse, carbonised and poorly preserved. Wilson G J, McIntyre D J and Norris G have made identifications (in Nathan 1977). Age ranges for the dinoflagellate cysts, spores, and pollen indicate a Haumurian (uppermost Cretaceous) age (Wilson in Nathan 1977). Macrofossil specimens from fine grained, bioturbated sandstone indicate a Haumurian age (Speden in Nathan 1977).

4.4 ARNOTT BASALT

The Arnott Basalt is named after Arnott Point. Mutch & McKellar (1964) named the formation the Arnott Volcanics. Nathan (1977) named the Formation the Arnott Basalt and designated the type section, the section between Grave Creek (N.Z.M.S.260 F36/052140 and and the coast near Arnott Point (F36/047140).

The Arnott Basalt crops out in a discontinuous strip from Tauperikaka Point (N.Z.M.S.260 F36/000097) to the Whakapohai River (F36/075156) and is then exposed in islands off shore to Otumotu Point (F36/092170) (Map 1). The Arnott Basalt is also exposed in Tokakoriri Creek (N.Z.M.S.260 G36/106173) and Waterfall Creek (G36/119183) and intermittently along the coast from Tokakoriri Creek to Cascade Creek (G36/129189) (Map 1).

The Arnott Basalt is a black, either aphyric or porphyritic (clinopyroxene and olivine), basalt (e.g. sample U.of C. 11992). Along the coast south-west of Arnott Point, and near Waterfall Creek, it is columnar jointed (Fig. 4.10) and pillow lavas are exposed to the south-east of Tokakoriri Creek.

Stratigraphic Relationships

The Arnott Basalt is underlain by the Tauperikaka Formation and overlain by the Tokakoriri Formation (Fig. 2.1). The Formation has previously been estimated as up to 370m thick near Grave Creek (Nathan 1977). The lower contact of the Arnott Basalt, which consists of up to 5m of basaltic breccia and baked glauconitic silty sandstone of the Rasselas Member (Tauperikaka Formation), is repeated down Breccia Creek due either to folding or interlayering. Evidence of recumbent folding in Breccia Creek within the Tauperikaka Formation combined with intermittent outcrop is responsible for difficulties in determining the nature of the contact. Thickness estimates for the Arnott Basalt



Figure 4.10
Coast, east of Waterfall Creek (Map 1: G36/122185). Arnott Basalt
(Haumurian?). Columnar jointing.



Figure 4.11
Otumotu Beach (Map 1: F36/094168). Altered orange basaltic dykes
(Haumurian?) (right of hammer) intruded through Otumotu Formation, Topsy
Member (Motuan- Arowhanan). Note large grey xenoliths which are
argillaceous.

along the coast between Breccia Creek and Arnott Point, are therefore dubious due to the structural complications. The Formation may be between 150m and 250m thick.

The Arnott Basalt is likely to vary in thickness as the basalt was erupted on to the sea floor, which must have had a moderate relief. The upper contact is highly irregular over lateral distances of hundreds of metres. The Tokakoriri Formation appears to fill lows in the paleo-relief (Aliprantis MSc thesis in prep.). In Tokakoriri Creek, Arnott Basalt lies with an angular unconformity on the Otumotu Formation. The Arnott Basalt is overlain with an angular unconformity by the Tititira Formation.

Sewell (Sewell and Nathan in prep.) has analysed two samples from the Arnott Basalt for major elements and trace elements, to determine differences between the Arnott and Otitia Basalts. On an alkali-silica diagram, both the Arnott and Otitia samples are classed as mildly alkaline. In view of the degree of alteration of samples analysed and the small number of samples involved, there are insufficient data on which to draw petrogenetic conclusions.

Dykes in Cretaceous Rocks

Hard, pink-orange, fine grained dykes containing a variety of xenoliths, including coarse quartz sand grains, angular clasts of mudstone and large baked argillite xenoliths measuring 70cm x 30cm, are intruded through the Butler and Otumotu Formations on Otumotu Beach (Fig. 411). The dykes intersect bedding at 70 degrees and measure 2.5m and 4.5m thick with smaller offshoots, consisting of brecciated country rock and altered basalt, measuring 30cm, intruding country rock from the main dykes. The sheet dyke margins are irregular and country rock is baked along contacts. Pyrite-marcasite nodules are evident.

The dykes on Otumotu and Monro Beach texturally resemble altered forms of Arnott Basalt (sample nos U.of C.

11991 and 11993). The dykes have been identified as altered lamprophyre dykes (Nathan 1977) however this author could not find evidence to support the latter identification.

A small, black, aphyric basaltic dyke and sill complex cuts the Moeraki Member sediments of the Tauperikaka Formation on Monro Beach.

Age of the Arnott Basalt

The age of the Arnott Basalt can only be inferred indirectly. The underlying Tauperikaka Formation contains microflora of Haumurian age (Section 4.3) and the overlying Tokakoriri Formation contains forminifera indicating a Teurian age (Nathan et. al. 1986). Therefore the Arnott Basalt may either be restricted to the Haumurian or continue through to the Teurian.

4.5 LAW COAL MEASURES (new)

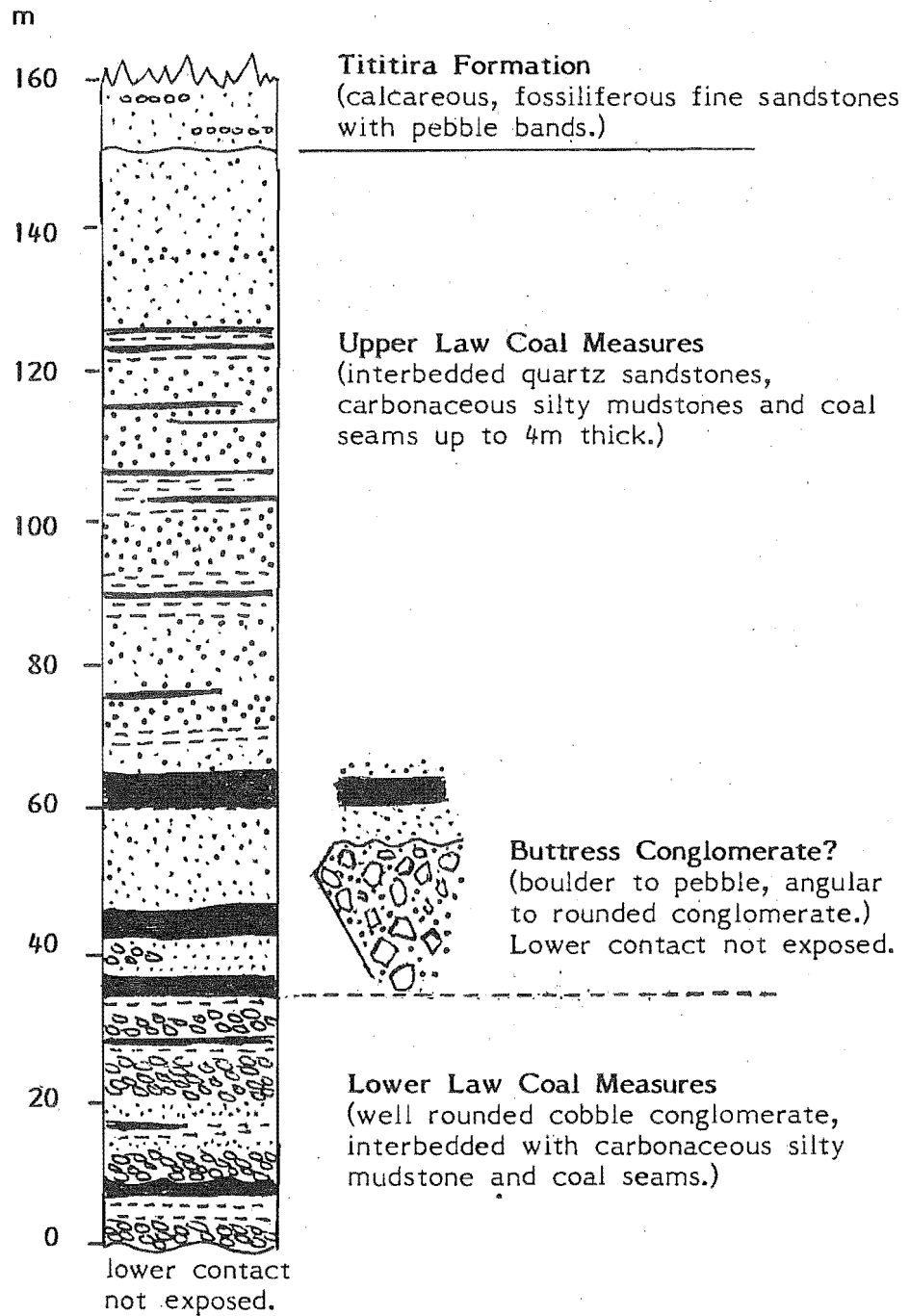
The name "Law Coal Measures" is introduced for a conglomerate, sandstone, mudstone, and coal bearing sequence of Kaiatan age (Fig. 4.12). As set out below the Law Coal Measures have an individual set of sedimentological, coal geological and paleontological characteristics, and cannot be placed in any Cretaceous, Paleocene or Eocene Formation. They are described as a separate formation. As the Kaiatan pollen dates compliment the limited stratigraphic evidence at Coal Creek the Law Coal Measures are assumed to be Kaiatan.

The Law Coal Measures are named after Lake Law and "Coal Measures" is used to emphasize the relatively thick seams (up to 4m thick) of coal within the formation. The type section is the exposure in Coal Creek, a tributary of Wells Creek, from N.Z.M.S.260 F37/036091 to F37/042086.

The Law Coal Measures in Coal Creek consist of clast supported, very well rounded and well sorted, cobble and pebble conglomerates (derived dominantly from Greenland Group lithologies) interbedded with green or white, carbonaceous, quartz rich sandstones, dark grey or black carbonaceous sandstones, siltstones, mudstones and high volatile bituminous coal seams. The lower Law Coal Measures consist of interbedded well rounded conglomerate, siltstone and coal seams, and can be distinguished from the upper Coal Measures which consist of interbedded well sorted quartz rich sandstones, siltstones and coal seams (Fig. 4.12). A sequence of angular to rounded boulder to pebble conglomerates with rounded volcanic (chloritised dacite and rhyolite - pers. comm. R. Sewell, Geological Survey), and angular Greenland Group derived clasts crops out beneath quartzose sandstone and coal and is either interbedded with, or underlying the coal measures (see Stratigraphic Relations).

Distinctive characteristics of the Law Coal Measures are the textural maturity of both the conglomerate and the sandstone, the sequence also contains coal with a coal type

Figure 4.12
A Generalised Stratigraphic Column of the Eocene Law Coal Measures (Kaiatan), Coal Creek, South Westland.



that is unlike the coal within the Cretaceous sequence (Section 6.3). Other rocks of Kaiatan age consist of marine marls, basalts and basaltic breccias and it is unreasonable to couple the coal measures with the corresponding late Eocene sequence.

Distribution of the Law Coal Measures

The Law Coal Measures crop out in three main areas: (1) Coal Creek, which I have mapped in detail; (2) tributaries of Ship Creek on the west and south-west flanks of Bald Hill (the coal measures here were located by Douglass [1890] and have not been described since); and (3) in two areas south of the area mapped in this study, that crop out south of Jacksons Bay, one at the base of the Jacksons Head sequence and one south of Martins Bay in the Kaipō River basin, which have been mapped by Mutch and McKellar (1964).

Stratigraphic Relationships

The lower contact of the Law Coal Measures in Coal Creek has not been conclusively identified. Nathan (pers. comm. 1986) revealed volcanic clasts within angular to rounded boulder to pebble conglomerates in the Coal Creek succession. The conglomerate was exposed beneath a low relief, undulatory contact with overlying quartzose sandstone and coal (N.Z.M.S.1 297300525500 - Maps 2 and 5), characteristic of the upper part of the Law Coal Measures, but a lower contact on the conglomerate was not exposed. Both the position of the conglomerate in relationship to the overlying coal measures (upper Law Coal Measures) and the local geology, which shows consistent dips and strikes (dipping 13°- 28° to the N.W. and N.) indicates the conglomerate is interbedded with the Law Coal Measures unless; (a) the sequence is upthrown, relative to the sequence downstream, on a nearby fault (Map 5) and (b) the lower stratigraphy of the Law Coal Measures is not represented on the uplifted block. Volcanic clasts have not been located within the well rounded conglomerate that is interbedded with the coal seams.

The upper contact of the Law Coal Measures with the Tititira Formation is not well exposed. The Law Coal Measures are Kaiatan and the Tititira Formation is mid Miocene therefore an unconformity which represents approximately 25 million years separates the two Formations. The inclusion of rounded pebbles, characteristic of the Law Coal Measure conglomerates, in the first few metres of Tititira Formation sediments may indicate the sediments from the Law Coal Measures have been reworked and included within the Tititira Formation.

The Law Coal Measures were previously included with the Cretaceous, Tauperikaka Coal Measures (of Nathan 1977) (Nathan 1977, Nathan et.al. 1986, and Cotton 1985). The Law Coal Measures are unlikely to be part of the Tauperikaka Formation, Butler Formation or of the Otumotu Formation due to combinations of; (1) stratigraphic; (2) sedimentological; (3) coal geological and (4) palynological grounds. Each is discussed in turn.

(1) Stratigraphy

The Law Coal Measures are unlike the Tauperikaka Formation on stratigraphic grounds as the Tauperikaka Formation is everywhere overlain by the Arnott Basalt, whereas in Coal Creek the coal measures are overlain by the Tititira Formation and no basalt is exposed. If the Coal Creek succession was Cretaceous an unconformity representing the whole of the Paleocene, Eocene, Oligocene and early Miocene period would be present at the top of the sequence.

The only sequences that the coal measures in Coal Creek are similar to on stratigraphic grounds are the Buttress Conglomerate at Buttress Point and the coal measures south of Jacksons Bay. The Law Coal Measures contain Kaiatan microflora and are overlain by Miocene sediments (Tititira Formation) and the Buttress Conglomerate (position in stratigraphy uncertain [see Section 4.6.]) is overlain and possibly interbedded with the Otitia Basalt which is Kaiatan-Runungan. The stratigraphy is also comparable to the coal measures south of Jacksons Bay which are of Arnold

age and which are overlain conformably by white crystalline Landon limestone (Mutch and McKellar 1964).

(2) Sedimentology

The coal measure lithofacies in Coal Creek are very different from the Otumotu Formation lithofacies (see sections 5.1.1, 5.1.2 and 5.4), and represent different environments of deposition. The most obvious difference is in the conglomerates of a similar size range, which in the Otumotu Formation are angular and poorly sorted, whereas in the Law Coal Measures are dominantly texturally very mature.

The Tauperikaka Formation is also sedimentologically unlike the Law Coal Measures as it does not contain decimetre bedded, cobble conglomerates and the sediments of the Moeraki Member are relatively texturally immature compared to the well sorted and rounded conglomerates and sandstones in the Law Coal Measures. Neither the Otumotu nor the Tauperikaka Formations contain thick coal seams and the respective environments of deposition for the two Formations are not conducive to preservation of thick seams.

The volcanic derived conglomerate exposed in Coal Creek, in terms of both textures and composition, is similar to conglomerate in the Buttress Conglomerate but is not related to the Otumotu, Butler, or Tauperikaka Formations as there are no volcanic clasts within the type sections of any of the Cretaceous Formations. The similarities are;

(i) both the Law Coal Measures and the Buttress Conglomerate contain a large proportion of well rounded Greenland Group derived clasts;

(ii) both the sequence in Coal Creek and the Buttress Conglomerate contain boulder to pebble conglomerate composed of rounded volcanic boulders (dacite and rhyolite) and angular Greenland Group derived boulders. The similarities suggest the Buttress Conglomerate may either be interbedded with or underlie the Law Coal Measures.

(3) Coal Geology

The coal in the Law Coal Measures is very different in coal type compared to coal from any of the Cretaceous Formations (Section 6.3.4). The coal also displays some very different chemical (Section 6.2) and geochemical (section 6.4) properties compared to coal sampled from bands and wedges from the Otumotu and Tauperikaka Formations and seams sampled from the Butler Formation.

(4) Palynology

Pollen within the coal of the Law Coal Measures is Kaiatan (Section 4.5 - "Age of the Law Coal Measures") whereas the Otumotu Formation contains mid-Cretaceous flora and the Tauperikaka Formation contains Haumurian flora.

In conclusion the possibility that the Law Coal Measures and Buttress Conglomerate are facies equivalents is proposed. Further work, which could include; (a) detailed mapping to locate dacite and rhyolite clasts, of the type exposed at Buttress Point, within Law Coal Measure sediments and (b) a geochemical analysis on volcanic clasts from both localities to determine whether an association is viable, is suggested to help prove or disprove the proposition.

Age of the Law Coal Measures

Crushed coal and uncrushed coal from coal seams in Coal Creek yielded a well preserved microflora of Zone MH3 age (Kaiatan). The microflora is characterised by abundant pollen of Myricipites harrisii (probably representing Cascarina) with Nothofagus matauraensis as the principle, and usually sole Nothofagus species (Raine 1986). The pollen assemblage of F37/F6 does not differ from zone MH3 microfloras of the Brunner Coal Measures of North Westland, or of the Kapuni Group of the Taranaki Basin. A marine influence is not indicated as dinoflagellate cysts are absent. Samples F37/F4 and F37/F5 are characterised by abundant angiosperm pollen, mainly Myricipites harrisii and are probably from the same zone as F36/F6 (Raine 1986).

A recent intensive pollen sampling programme in Coal Creek undertaken by Simon Nathan, to check the validity of the results presented in the preceding paragraph, has revealed more of the same microflora (Kaiatan) and further analysis of the samples is continuing (Nathan, pers. comm.).

4.6 BUTTRESS CONGLOMERATE

The Buttress Conglomerate (Nathan 1977) is named after Buttress Point where the formation is best exposed (Map. 1). The type section was defined by Nathan (1977) as the coastal section on the north side of Porphyry Point. Although the 45m of conglomerate within the Tokakoriri Formation north of Porphyry Point contains volcanic clasts with generally similar compositions to the clasts at Buttress Point, there is no conclusive evidence that conglomerate at Porphyry Point is directly related or contemporaneous with the ~ 2000m exposure of conglomerate at Buttress Point. The conglomerate at Porphyry Point is interpreted as the lower member of the Tokakoriri Formation (pers. comm. Aliprantis MSc thesis in prep.) and is interbedded with sediments of Teurian to Waipawan age (Nathan 1977). The conglomerate at Buttress Point is overlain by Otitia Basalt which is Kaiatan to Runangan (pers comm. Aliprantis, MSc thesis in prep.). Therefore, if the two conglomerates are related stratigraphically, an unconformity representing a considerable amount of time is present at Buttress Point.

The type section of the Buttress Conglomerate is redefined as the main exposure of conglomerate from Buttress Point (N.Z.M.S.260. G36/266257) to the mouth of the Ohine-maka River (G36/273252). A conglomerate texturally and compositionally similar to the Buttress Conglomerate crops out in Coal Creek beneath a sequence of Law Coal Measure sediments and may be interbedded with, or underlie the Law Coal Measures (see Section 4.5). There is no conclusive evidence that they are contemporaneous,

The Buttress Conglomerate is a well indurated, green, massive or occasionally poorly bedded, sub-angular to well rounded, poorly sorted to moderately well sorted, boulder to pebble conglomerate (Figs. 4.13 and 4.14) with occasional green, poorly sorted sandstone beds (Fig. 4.15). The conglomerate shows imbrication in some places (Fig. 4.16). Some sheets of sandstone may represent sandstone dykes.



Figure 4.13
East of Buttress Point (Map 1: G36/268257), Buttress Conglomerate
(pre Runangan). Massive cobble to pebble breccia.
(Photo - M Aliprantis).



Figure 4.14
East of Buttress Point (Map 1: G36/267258), Buttress Conglomerate
(pre Runangan). Sub rounded to well rounded boulder to pebble
conglomerate with altered dacite, rhyolite and Greenland Group clasts.

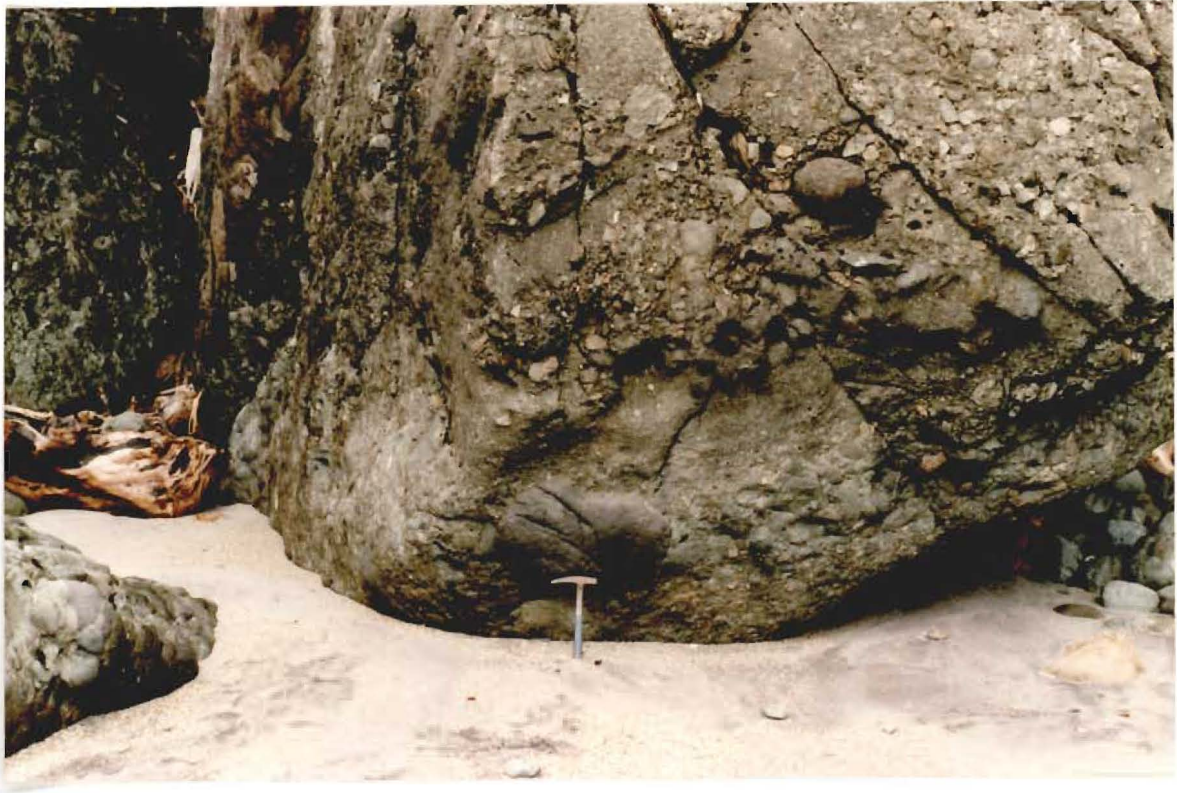


Figure 4.15
East of Buttress Point (Map 1: G36/267258), Buttress Conglomerate
(pre Runangan). Poorly sorted sandstone beds interbedded with boulder to
pebble conglomerate. (Photo - M Aliprantis)



Figure 4.16
East of Buttress Point (map 1: G36/272253), Buttress Conglomerate
(pre Runangan). Imbrication in pebble conglomerate.

Nathan (1977) described the composition of the conglomerate as Greenland Group derived lithologies, quartz, biotite-plagioclase microgranodiorite, plagioclase (pseudomorph) andesite, - plagioclase dacite, and basalt (similar to Arnott Basalt). Mapping during this thesis suggests the majority of the volcanic clasts are composed of altered dacite and rhyolite. Random composition percentage counts on beds yielded Greenland Group derived lithics to volcanic clasts as 95:5; 70:30; 60:40 and 55::45 respectively and show that constituents vary from locality to locality, but overall, Greenland Group lithologies are dominant. The Greenland Group derived lithic clasts are composed of sandstone which, usually shows good foliation, siltstone and mudstone.

The conglomerate is intruded by basalt, andesite, and dacite (Fig. 4.17).

Stratigraphic Relationships

Stratigraphic relations are uncertain. A layer of basalt overlies the conglomerate in the cliff exposure west of Buttress Point. In the creek running south from the coast at N.Z.M.S. 260 G36/263256, Otitia Basalt is exposed on the west side of the creek and Buttress Conglomerate on the east side of the creek. The two Formations may be in sedimentary contact or may have been juxtaposed by faulting. If the Buttress Conglomerate is interbedded with the Otitia Basalt, it is Kaiatan Runangan, however, if the basalt overlies the Buttress conglomerate and has intruded into the conglomerate, the conglomerate may have been deposited at any time before the Kaiatan.

Cotton (1985) suggested the Buttress Conglomerate represents a facies equivalent of the Otumotu Formation, there is no evidence to support the relationship. The Buttress Conglomerate is unlikely to be related to the Otumotu Formation as proportions of the Buttress Conglomerate are texturally mature, whereas the conglomerate in the Otumotu



Figure 4.17
East of Buttress Point (Map 1: G36/272253), Basalt (age unknown)
intruding Buttress Conglomerate (pre Runangan). Dyke of fine grained
basalt to right of and above pack. In background, continuous cliff
exposure to the east of Buttress Point is visible. (Photo - M Aliprantis)

Formation is texturally immature, and, more importantly, there are no volcanic clasts in the type section of the Otumotu Formation or elsewhere in the Cretaceous sequence.

The Buttress Conglomerate has textural and compositional similarities to the Law Coal Measures as both Formations contain sequences of well rounded cobbles and pebbles of Greenland Group lithologies.

Age of the Buttress Conglomerate

Material submitted for paleontological dating was non-fossiliferous. The stratigraphic relationships indicate the Buttress Conglomerate is Kaiatan or older.

Further work is required to establish the stratigraphic position of the Buttress Conglomerate. I suggest the conglomerate most likely represents a marine facies (see environmental interpretation in Nathan 1977) of the Law Coal Measures as a source of dacite, rhyolite and Greenland Group is available either before or during deposition of the Law Coal Measures, a combined source which is not represented in the sediments of the South Westland Cretaceous sequence.

CHAPTER FIVE

5.0 SEDIMENTOLOGY OF CRETACEOUS AND EOCENE FORMATIONS

5.1 OTUMOTU FORMATION

5.1.1 Tauweritiki Member

Sedimentary structures and textures

Introduction

The Tauweritiki Member is divided into 7 lithofacies which are based on characteristic sedimentary structures and textures. Each lithofacies is assigned a code for brevity during reference in the text. The codes are explained in appendix 2 but briefly the codes are: TwBm; TwSm; TwZm; TwCim; TwSCb; TwCc; TwZl. Each lithofacies is discussed in turn.

(i) Lithofacies TwBm: Massive Boulder to Pebble Breccia

In the type section on Otumotu Beach the lower part of the Tauweritiki Member consists of thick sequences (up to 50m) of massive boulder to pebble breccia (Fig.4.2). Angular to sub-rounded clasts are matrix supported in a poorly sorted, silty, coarse to fine sand matrix. Generally, the breccia does not show imbrication or sorting (Fig. 5.1). Occasionally the breccia grades up over 10cm to a sand supported, moderately sorted pebble breccia. This is gradationally overlain by 10cm of medium to fine sandstone, containing trains of small pebbles. The upward change from pebbles to predominantly sand is sharp (Fig. 5.2). The overlying, unsorted cobble to pebble breccia is in erosional contact with the underlying sandstone bed (Fig. 5.2). The shortest distance measured between successive sandstone layers in outcrop is 4m.

The lack of imbrication or sorting, combined with grain size parameters, and the supporting matrix, indicate a sediment gravity flow mechanism for transport and deposition. The sandstone beds are interpreted as products of waning energy flow conditions. The short transition to sand



Figure 5.1
Otumotu Beach (Map 1: F36/097168) Otumotu Formation, Tauweritiki
Member (Motuan - Arowhanan). Massive boulder to pebble breccia.
Lithofacies TwBm.

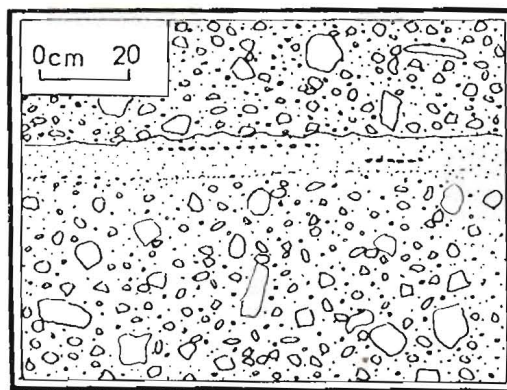


Figure 5.2
Otumotu Beach (Map 1: F36/098168) Otumotu Formation, Tauweritiki
member (Motuan - Arowhanan). Diagram showing the contact between
two breccia units. A breccia overlies a thin layer of medium to fine
sandstones on a low relief scour surface.

indicates the energy of the flow dropped off sharply to be replaced by a period of low energy water transport and deposition. The preservation potential of the sandstone beds must be low as the beds are overlain by breccias with low relief erosive contacts. This suggests a reason for the scarcity of the sandstone beds within the lithofacies which is responsible for preventing estimations of flow thickness and thickness variation.

(ii) Lithofacies TwSm: Massive Sandstones

In the type section on Otumotu Beach, the lower to middle parts of the Tauweritiki Member contain massive, grey, weathered maroon, poorly sorted sandstones with randomly distributed and oriented clasts of angular cobbles, pebbles and granules (Fig. 5.3). The beds are up to 10.5m thick and have sharp basal contacts.

The lack of stratification and other sedimentary structures, including imbrication, and the presence of dispersed angular clasts, suggests a sediment gravity flow mechanism. The dominance of sand sized grains over conglomerate reflects the available detritus as the flows have the competence to move large cobbles. The thicker beds may either represent one large flow or several amalgamated flows in which the flow boundaries are no longer discernable. The angularity of the clasts reflects the method of transportation.

(iii) Lithofacies TwZm: Massive Siltstones

Lithofacies TwZm occurs in the middle to upper parts of the type section of the Taweritiki Member exposed on Otumotu Beach. The massive grey siltstones are up to 3m thick with sharp lower contacts and contain occasional dispersed pebbles or sand grains, and abundant dispersed carbonaceous fragments of random orientation. In thin section (U.of C. 11978) the siltstone is poorly sorted and grains



Figure 5.3
Otumotu Beach (Map 1: F36/097168) Otumotu Formation, Tauweritiki
Member (Motuan - Arowhanan). Massive sandstone with randomly distributed
cobbles, pebbles and granules. Lithofacies TwSm.

are very angular to sub-rounded.

The same mechanism of deposition as suggested for lithofacies TwSm is envisaged. The angularity of grains reflects the method of transportation.

(iv) Lithofacies TwCim: Interbedded Slightly Imbricated Conglomerates And Sandstones

Decimetre bedded, angular to sub-rounded cobble to pebble conglomerates lie with basal erosional contacts on underlying subordinate sandstones (Fig. 5.4). The conglomerate, which is poorly imbricated, shows some degree of sorting with cobbles lying in patches within pebble beds and coarse lags of cobbles forming the upper contacts of conglomerate beds. The conglomerate is clast supported with a sandy matrix. The sandstones are planar bedded with low angle cross lamination and sharp lower and upper contacts. The sandstone sometimes contains trains of pebbles and granules.

The conglomerate - sandstone association differs from lithofacies TwBm as the conglomerate beds are thinner and sandstone beds are thicker. The conglomerates also show a degree of sorting and imbrication and are clast supported. Sandstone beds are cross-bedded and show a better degree of grain sorting.

Bluck (1967) interpreted similar lithofacies as sheet flood deposits whereby conglomerate is deposited in a single high-energy event. Then as the flood energy wanes a conglomerate lag¹ is deposited which is followed by deposition of sandstone as the energy continues to drop off. The next sheet flood episode then erodes the upper contact of the

1. A lag is used to describe coarse grained material left behind after currents have winnowed or washed away finer material.



Figure 5.4
Otumotu Beach (Map 1: F36/096168) Otumotu Formation, Tauweritiki
Member (Motuan - Arowhanan). Interbedded, slightly imbricated
conglomerate and low angle cross stratified sandstones. Youngs from
bottom to top. Lithofacies TwCim, Otumotu Beach.

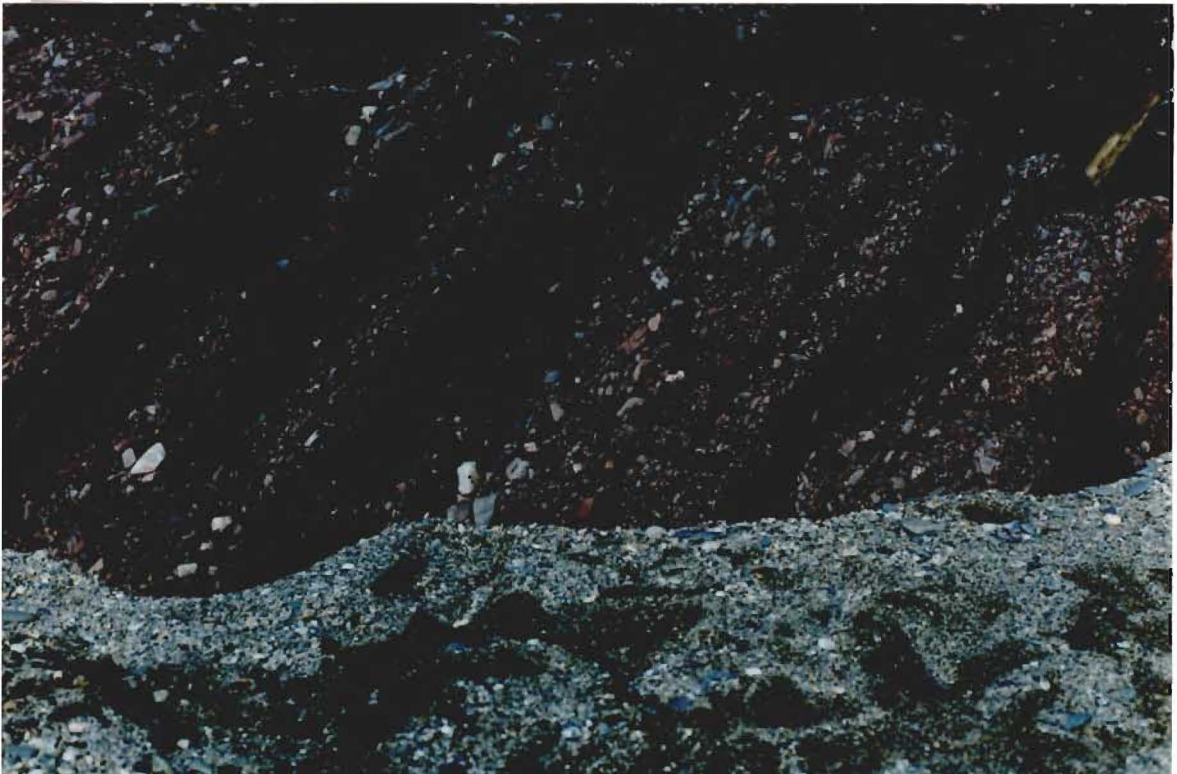


Figure 5.5
Otumotu Beach (map 1: F36/097168) Otumotu Formation, Tauweritiki
Member (Motuan - Arowhanan). Not in situ. Interbanded poorly sorted
sandstones and cobble to granule conglomerate. Youngs from left to
right? Lithofacies TwSCb.

sandstone. A reverse situation may occur where the sandstones are deposited with high energy, laminar flow, overbank sheet floods while the conglomerates are still filling channels. The conglomerate then spreads as a sheet deposited through clast by clast accretion under high energy flow conditions over the top of the sandstones, eroding the upper contact of the sandstone. When the flood energy wanes a coarse conglomerate lag remains. The latter interpretation better explains the presence of a conglomerate lag.

The matrix could have been deposited with the conglomerate or sand could have filtered through the conglomerate after deposition. The conglomerate beds also compare with the Gm facies of Miall (1978) which he interpreted as longitudinal bars deposited through clast by clast accretion. The scale of the outcrop is too small for recognition of channel structures which prohibits interpretation on whether the flow was restricted by channel margins.

(v) Lithofacies TwSCb: Interbanded Poorly Sorted Sandstones And Cobble To Granule Conglomerates

Lithofacies TwSCb consists of interbanded poorly sorted sandstones and cobble to granule conglomerates (Fig. 5.5). Conglomerates grade upward and downward towards lags. The conglomerates are poorly imbricated, poorly sorted or sorted beds of pebbles or granules supported in a poorly sorted sandy matrix. The lensoidal sandstones contain imbricated stones, trains and lenses of pebbles and there are numerous erosion surfaces. Contacts between conglomerate and sandstone beds are either sharp or gradational.

The intimate stratification and lensoidal nature of the beds combined with the erosional surfaces, lags, and sorting of grain sizes, together indicate several phases of erosion and deposition by traction currents that show

repeated cycles of waning and increasing energy.

The conglomerates are relatively poorly sorted and angular indicating they have not travelled far from the primary source and may represent reworked gravels and sands of nearby debris flows or sheet flood deposits.

(vi) Lithofacies TwCc: Trough Cross And Planar Cross-Bedded Pebble Conglomerates And Subordinate Sandstone

Lithofacies TwCc crops out at the top of the Tauweritiki Member and interfingers with the overlying Topsy Member of the Otumotu Formation. The lithofacies consists of a decimetre bedded, trough cross and planar cross-bedded pebble conglomerate with inclined and horizontal internal stratification delineated by pebble imbrication. Shallow erosional troughs at the base of sets have a high width to depth ratio and are an order of metres wide. Individual sets decrease in total set size upward. Texturally the conglomerate consists of poorly sorted sub-angular to rounded cobble to pebble clasts, supported in a poorly sorted sand matrix and the sets grade upward or downward in grain size.

The subordinate sandstones are lensoidal and fill scours (Fig 5.6) with low angle trough cross sets which show internal foreset lamination and have pebbly basal lags. Lensoidal sandstone beds also show horizontal and ripple lamination. Sandstones are moderately sorted and coarse to medium grained. Horizontally laminated sand contains trains and lenses of granules and scattered pebbles. Ripple laminated sandstones are moderately well sorted and fine grained.

All of the lithologies include carbonaceous rafts from flecks to logs (Fig. 5.7).

The complete lithofacies is up to 4m thick, has an erosional lower contact and usually an undulatory upper contact. Overlying sand, silts and muds of the Topsy Member



Figure 5.6
Otumotu Beach (Map 1: F36/095168) Otumotu Formation, Tauweritiki Member (Motuan - Arowhanan). Lenses of sandstone resting on scour surfaces within a pebble conglomerate (far left and to right of hammer). Youngs from left to right. Lithofacies TwCc.



Figure 5.7
Otumotu Beach (Map 1: F36/095168) Otumotu Formation, Tauweritiki Member (Motuan - Arowhanan). A log within conglomerate of lithofacies TwCc . Note the sandstone lens resting on a scour surface on the downstream side of the log. Youngs from bottom to top (the outcrop dips vertically in the field).

contain perigenic pebble clasts which may have been eroded from lithofacies TwCc.

The stratified conglomerates represent bed load deposited by traction currents. Lenticular units of conglomerate represent a phase of scour followed by a phase of channel filling with bedload. Planar cross beds represent accretion by migrating bars.

Sandstone is only preserved in scoured areas and is a result of filling the incised irregularities in a channel floor. The trough cross-bedding in sandstone represents the migration of dunes in a flow from the upper part of the lower flow regime. The horizontal stratified sands represent flows in either the lower or upper flow regime. Small lenses of granules within the horizontal stratified sandstones represent a pause in the deposition of the sandstone and a fluctuation in the energy of the flow, in which a short period of scour was followed by deposition of a granular bedload by a relatively low energy traction current. Rippled sandstones represent the transportation and deposition of sand in ripple form under lower flow regime conditions.

The conglomerate is similar to the Miall (1977) Gt and Gp facies. The sandstones are similar to the st, sr, and sh facies respectively. The units together represent a series of migrating channels in which the respective flows were fluctuating in energy. Channel bars were migrating down separate channels within the stream system and channels were alternately scoured and filled. Sandstone bodies have a low preservation potential and are therefore represented in scoured areas which were protected from the flow energy of the stream current. The lithofacies is consistent with the channel facies of a fluvial depositional environment. Similar lithofacies have been described by Miall (1977) as deposits of a braided stream or braid plain environment.

(vii) Lithofacies TwZ1: Interbedded Fine Sandstone, Siltstone And Mudstone

In the upper part Tauweritiki Member on Otumotu Beach grey mudstone is inter-laminated with lenses and patches of fine sandstone and occasional black carbonaceous layers. Silty mudstone, with carbonaceous fragments, also contains lenses and patches of well sorted fine sandstone. Carbonaceous laminae and occasional erratic coarse quartz sand grains are also present. The basal contact of lithofacies TwZ1 is usually undulatory, conforming to the relief on underlying lithofacies. The upper contact is usually eroded with an overlying conglomerate or sandstone.

Lithofacies TwZ1 equates with Mialls (1977) F1 facies. The facies represents inactive tracts protected from channel facies where low energy currents vertical accrete fine sediment, and vegetation is supported. The mudstone and siltstone represent background sedimentation. The fine sandstone is either sediment delivered by minor inundations of water or is water reworked deposits that have been previously deposited by wind. Scattered quartz grains may represent dropstones from rafted vegetation.

Sedimentary Dykes

Towards the bottom of the Tauweritiki type section on Otumotu beach, a 14.5cm sedimentary dyke (one of three recorded in the immediate vicinity) cuts through massive maroon conglomerate. The walls of the dyke are parallel with sharp boundaries. The overall shape is a planar sheet. A 1cm weathered yellow-brown rind marks the outside boundaries of the grey coloured dyke.

In outcrop the dyke is very fine grained. In thin section the rock is a moderately sorted, fine sandy, muddy glauconitic siltstone with abundant polyzoa fragments, foraminifera, gastropod fragments and bivalve fragments. Therefore the dyke is not derived by water expulsion from

the surrounding sediments and must represent younger sediment than the Tauweritiki Member. The dyke sediment is unlikely to be derived from the marine sediments in the Tau-perikaka Formation as there are very few body fossils preserved in the Cretaceous sequence. The sediment resembles sediments in the marine Tertiary formations and is most likely to have been derived from either the Tokakoriri Formation or the Tititira Formation which lies with an angular unconformity on the Otumotu Formation in Tokakoriri Creek.

Composition of the Tauweritiki Member

Conglomerate in the lower parts of the Tauweritiki Member, exposed along Otumotu Beach, consists of clasts composed of approximately 25-35% fine sandstone; 20-30% fine sandstone with a slight foliation; 5-15% metamorphic clasts with well developed foliation; 10% quartz; and between 1 and 10% of both medium grained sandstones and siltstone. Between 10% and 20% of the clasts are stained maroon.

The matrix consists of a maroon or green poorly sorted coarse to fine silty sand. The maroon colour gradually dies out upward through the sequence until, in the overlying Topsy Member conglomerates, have a dominantly green or light brown coloured matrix. In thin sections, the matrix contains a high proportion of an opaque limonitic ground mass.

The conglomerate clasts are all derived from Greenland Group lithologies. Wellman (1955) related the red colour of the matrix to an absence of carbonaceous material. Nathan (1977) compared a chemical analysis of a typical sample of red matrix with an average Greenland Group sample. Fe_2O_3 is much greater than FeO , whereas in the Greenland Group most of the iron is in the ferrous state. MgO is markedly lower in the Greenland Group. Nathan (1977) attributed this to deposition of sediments in a terrestrial oxidising environment causing oxidation of Fe and leaching of Mg. This suggests Mg enrichment in the depositional

environment which may be a source of Mg for the dolomite cement that cements the sediments in the Topsy Member of the Otumotu Formation (Section 5.1.2: Composition).

Environment of Deposition of the Tauweritiki Member

A combination of debris flow deposits and water laid deposits of coarse angular material derived from adjacent basement rock indicates alluvial fan type sedimentation. Stratigraphically upwards within the type section the Tauweritiki Member grades from coarse breccia deposited by debris flow mechanisms, to interbedded finer grained debris flows and sheetflood deposits and deposits reworked by stream flow. Minor deposits of silty mudstone and fine sandstone interbedded with conglomerates of lithofacies TwCc indicate the graded transition from the Tauweritiki Member to the Topsy Member.

Alluvial fans are typified by coarse gravel in proximal reaches and rapidly decreasing grain size from proximal to distal areas. Bull (1972) recognised four main types of product based on a summary of many observations of fan deposits. These were debris flow deposits, sheet flood deposits, stream channel deposits and sieve deposits.

The likelihood of debris flows on alluvial fans is enhanced by a readily weathered source which will produce abundant coarse and fine material. Steep slopes, a lack of vegetation and periods of abundant water supply are also necessary. Debris flows tend to occur near the fan apex (Reading 1978).

Reading (1978) compares a semi-arid fan with humid fan models. In a semi-arid fan the sequence becomes finer distally and debris flows pass distally into sheetflood deposits. The sheetfloods expand at the downstream end of channels in which debris flows are confined. This is usually below the intersection point of the channel and the fan surface (Bull 1972). Both types of deposits may have

upper surfaces reworked by stream processes. Lateral changes within the fan are gradational but the transition from the fan to the more distal environments may be so sharp that the deposits interfinger, reflecting extension and retraction of the fans due to tectonic or climatic changes (Reading 1978). Different lithofacies are likely to be randomly interbedded at any one site in the fan due to the lateral shift of the lobes of deposition on the fan surface. However, the sequence usually coarsens or fines upward to show an overall change from the transition from a distal to proximal environment or visa versa (Reading 1978).

Humid fans, however, are dominated by channel processes (Reading 1978) and are, therefore, more likely to show braided stream type lithofacies such as bar forms and channel fill deposits.

The Tauweritiki Member sequence is a perfect analogy to the semi-arid model of Reading (1978). The series of preserved high energy flood events is indicative of intense ephemeral flood discharge. The appearance of channel processes on a large scale are not manifested until the transition from the Tauweritiki Member to the Topsy Member (lithofacies TwCc). The channel facies may not be confined to a relatively small area but may be spread as a sheet over a large flood plain. The appearance and major abundance of "braided stream like lithofacies" in the Tauweritiki Member is interpreted as marking the transition from alluvial fan wedge sediments to alluvial plain sedimentation (see Section 5.12). Lithofacies interpreted as having been influenced by channel processes are only a minor manifestation of the lower and middle parts of the Tauweritiki Member.

Preferential reddening to the maroon colour of the Tauweritiki Member in comparison to the Topsy Member, may be indicative of a more highly oxidising terrestrial environment. The origin of red beds is a frequently discussed controversy outlined by Glennie (1970). Walker (1967) revealed that reddening in modern Californian sediments is essentially a diagenetic process which operates quite

slowly. However, in deserts and arctic environments, surficial reddening occurs more rapidly. The pigment could be detrital or diagenetic, however the red colour is not dominant and is probably diagenetic.

The immature textural and compositional characteristics are not only a reflection of processes operating within an alluvial fan "wedge" environment, but also of the short distances of transport of the sediment from the relatively local Greenland Group source rocks.

The presence of alluvial fan sedimentation in the four separate areas mentioned (Section 4.1) indicate relatively local areas of substantial topographic relief and thus tectonic activity prior to and during deposition of the Tauweritiki Member sediments.

The sedimentary dykes belong to one of the marine Tertiary Formations which was deposited on top of the Otumotu Formation in the type section area but has since been removed by erosion.

5.1.2 Topsy Member

Sedimentary Structures and Textures

Introduction

Each lithofacies is assigned a code for brevity during reference in the text. The codes are explained in Appendix 2 but briefly the codes are: ToGm; ToSt; ToSp; ToSl; ToSh; ToSr; ToMl.

(i) Lithofacies ToGm: Structureless or slightly imbricated granules.

Thin beds (10-20 cm) composed of ungraded, randomly oriented or slightly imbricated, clast supported, moderately to well sorted granules with a sandy matrix lie on low to moderate relief scour surfaces. The lithofacies is bounded by sharp upper and lower contacts.

A lack of internal stratification inhibits a flow regime interpretation. The sediment was probably deposited by a traction flow. The latter factor is indicated by the scouring, slight imbrication and the clast supported texture. The deposit is interbedded with other traction flow deposits.

Allen (1964) described similar deposits as "intraformational conglomerates" and interpreted the lithofacies as the result of erosion at the floor of a wandering river followed by deposition of a channel lag during partial aggradation of a channel.

(ii) Lithofacies ToSt: Trough Cross-Bedded Pebbly Granules and Coarse to Medium Sandstones.

Trough cross-bedded moderately sorted pebbly granules and moderately sorted coarse to medium sandstones occur as beds up to 50cm thick. The beds are lensoidal with erosive lower contacts. Where the lithofacies overlies mudstones load structures are evident.

Lithofacies ToSt is interpreted as a traction flow deposit of the lower flow regime. Miall (1977 and 1978) interpreted his similar "St" lithofacies as the product of dune migration under flows of lower flow regime.

(iii) Lithofacies ToSp: Planar Cross-Bedded Granules and Coarse to Fine Sandstones.

Planar cross-bedded sets of granules and coarse to fine sandstones are 10 to 20cm thick (Fig. 5.8). Individual sets are elongate lenses that pinch out laterally on upper and lower contacts of other sets. Some fining upward cosets have pebble lags and grade upward into a layer of ripple laminated fine sandstone. Otherwise upper contacts are generally sharp with overlying silty mudstones and the lithofacies pinches out laterally into silty mudstones. In thin section (U.of C. 11973) the grains show good imbrication are poorly sorted and are very angular to sub-angular.

The lithofacies is interpreted as a traction flow deposit of lower flow regime. The cross bedding represents migration of small dunes and megaripples. Fining upward sequences and vertical transitions to ripple laminated bedding record a waning of energy of the depositing currents. The textural characteristics indicate the sediments have not been transported far from the primary sediment source.

(iv) Lithofacies ToSl: Low Angle ($<10^\circ$) Stratified Medium Fine Sandstones.

Sets of horizontal to low angle stratified white, well sorted, medium fine sandstones contain cross bedding with dips less than 10° from bedding (Fig. 5.9). The coset is up to 22cm thick with flat upper and lower contacts, with load casts evident on the lower contact. Individual laminae show lateral thickening and occasionally laminae are cut by steeply dipping scour surfaces or slip faces. Lithofacies "ToSl" is usually associated with underlying 1cm to 5cm coal



Figure 5.8 (above)
Otumotu Beach
(Map 1: F36/094168) Otumotu
Formation, Topsy Member
(Motuan - Arowhanan).
Planar cross bedded sets
of granules and coarse to
fine sandstones interbedded
with horizontally laminated
mudstones and fine sand-
stones. Youngs left to
right. Lithofacies ToSp and
ToMl.

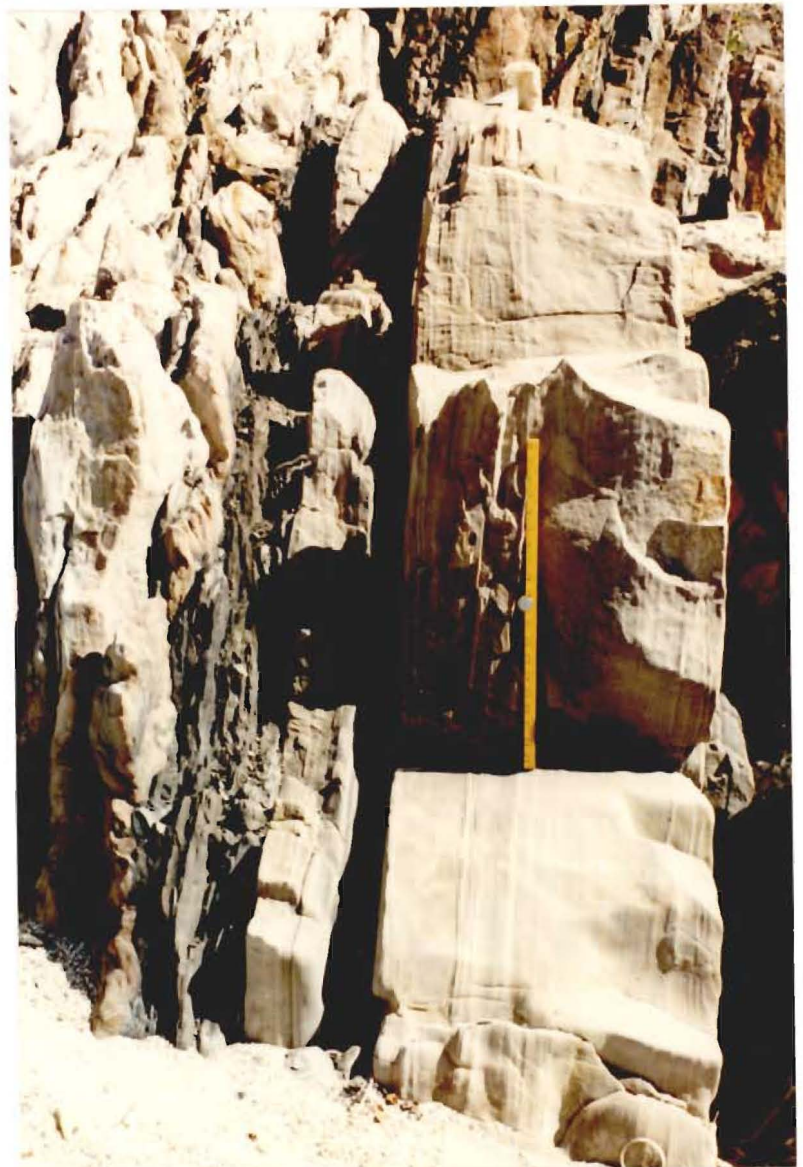


Figure 5.9 (right)
Otumotu Beach
(Map 1: F36/094168) Otumotu
Formation, Topsy Member
(Motuan - Arowhanan). Sets
of low angle, cross bedded
medium fine sandstones
overlying 1cm - 5cm coal
bands. Angle between cross
bedding and bedding plane is
apparent alongside ruler.
Youngs left to right.
Lithofacies ToSl.

bands which are interpreted as log rafts.

The deposit is interpreted as a traction flow deposit of upper flow regime. McKee et. al. (1967) and Stear (1985) described modern ephemeral flood deposits which are dominated by horizontal and near horizontal stratification deposited in upper flow regime conditions. McKee (1967) also noted occasional small scours. Stear (1985) showed that the textural characteristics are governed by the source material available.

(v) Lithofacies "ToSh" Horizontally Stratified Granules and Coarse Sandstone

Centimetre bedded, laterally continuous planar beds of horizontally stratified, interlaminated, size sorted granules and coarse sand have sharp lower contacts and sharp, slightly wavy upper contacts.

Sorting of grain size indicates a traction flow but a lack of cross stratification inhibits a flow regime energy interpretation. Moss (1972) shows that flow instability causing inconsistent current directions can result in planar stratification even though a ripple stage or dune stage energy flow is operating. The lithofacies is overlain by ripple cross bedded and planar stratified medium to fine sandstones.

(vi) Lithofacies ToSr: Ripple Laminated, Horizontally Stratified, And Structureless Fine Sandstones

Beds of maroon and white, moderately to well sorted medium to fine grained sandstones are usually 10cm to 20cm thick. The beds are either structureless or more frequently contain ripple cross-lamination showing internal foreset laminae. The ripples appear to be asymmetric. The beds have sharp lower contacts, which are often marked by a granule layer or millimetre bedded coarse sandstone lenses, or

gradational lower contacts. Upper contacts are either sharp, and may show a ripple surface, or are gradational with overlying finer grained lithologies. The geometry of the ripple laminated beds is elongate and lensoidal.

Beds up to 1m thick show climbing ripple structures and horizontal stratification in sandstone that is moderately well sorted and medium to fine grain. The ripple sets which show internal cross stratification climb at a minimum angle of 12° (Fig. 5.10). The ripple pattern in plan view, and the shape and continuity of the ripple crest line, are not revealed in the two dimensional outcrops. Considerable compaction has also modified the ripple shape.

In thin section (U.of C. 11976, 11979, 11975, 11972) the fine sandstones are poorly to moderately sorted and very angular to sub angular. Rounding of grains does not improve upwards within the Topsy Member within lithofacies ToSr. The angularity and poor sorting gives the sandstones the appearance of micro breccias.

The lithofacies is interpreted as a traction flow deposit which was deposited under lower flow regime conditions. The cross lamination is the result of migration of the ripples. A high rate of sediment supply is reflected in the climbing ripple cross lamination in which the angle of climb reflects the balance between the rate of upward bed growth and ripple migration (Collinson & Thompson 1982). Micro breccia textures indicate the sediment has not travelled far from the primary source.

(vii) Lithofacies ToM1: Horizontally Laminated Mudstones And Fine Sandstones

Centimetre bedded and laminated grey mudstone beds are separated by white, brown or maroon fine sandstones which show horizontal lamination and occasionally ripple cross lamination (Fig. 5.11). Inter-laminated mudstones and sandstones show lenticular bedding and ripples show load



Figure 5.10
Otumotu Beach (Map 1: F36/094168) Otumotu Formation, Topsy Member
(Motuan - Arowhanan). Beds of climbing ripples in medium fine
sandstone. Youngs bottom to top. (Photo - on its side). Lithofacies
ToSr.



Figure 5.11
Otumotu Beach (Map 1: F36/093168) Otumotu Formation, Topsy Member
(Motuan - Arowhanan). Centimetre bedded laminated mudstones and
laminated and ripple cross-bedded fine sandstones. Youngs bottom to top.
(Photo on its side) Lithofacies ToMl.

casting. Occasionally, the upper contacts on mudstone layers have mud crack structures that have been infilled with fine sand (Fig. 5.12). Some beds of mudstones and sandstones are bioturbated and occasionally burrows are apparent (Fig. 5.13). Minor carbonaceous laminae and plant fragments are present.

The mudstone represents vertical accretion from standing water over long periods of aggradation. Silt and fine sandstone represent deposition as bedload by low energy currents. Fine sandstone lenses that pinch and swell and lenticular bedded sandstone could be produced by a wave or a current process. The preservation of mud cracks indicates periods of drying out. Burrows and bioturbation indicate occasional colonisation by animals. The load structures maybe the result of deposition of sand over a hydro plastic mud layer, leading to unequal loading, which results in mainly vertical adjustment at the sand mud interface (Reineck & Singh 1980).

Soft Sediment Deformation Structures

Double recumbent folds in lithofacies ToM1 (Fig. 5.14) occur with load structures. Allen & Banks (1972) identified a series of folds with or without overturning as common in water laid sediments. The slump structure is due to penecontemporaneous deformation of sediment layers, mainly under the action of gravity. Faulting associated with the folding in lithofacies ToM1 is not evident which indicates that the sediment behaved as a fluid gel and moisture content played an important role in the genesis of the deformation.

Composition of Topsy Member Sediments

A detailed study of the composition and diagenesis of the Topsy Member sediments was not attempted. The main objectives are, to establish any major differences in compo-



Figure 5.12 (above)
Otumotu Beach
(Map 1: F36/093168)
Otumotu Formation, Topsy
Member (Motuan -
Arowhanan). Mud cracks
in filled with fine sandstone
beds. Youngs bottom to
top. Lithofacies ToMl.



Figure 5.13 (right)
Otumotu Beach
(Map 1: F36/093168)
Otumotu Formation, Topsy
Member (Motuan -
Arowhanan). Burrows in
a bioturbated muddy fine
sandstone. Youngs
bottom to top. Lithofacies
ToMl.



Figure 5.14
Otumotu Beach (Map 1: F36/095168) Otumotu Formation, Topsy Member
(Motuan - Arowhanan). Recumbant folds due to soft sediment deformation
in fine sandstone. Shearing between beds is a product of post Miocene
deformation.

sition between the Topsy Member and younger formations, and to identify the provenance.

A series of samples from the Topsy Member have been analysed by microscope (see discussion under methods, Section 3.0). The composition of typical sandstones is shown in Table 5.1. Sandstones from the Topsy Member are litharenites and sublitharenites (Fig. 5.15).

Quartz

Quartz grains are predominantly monocrystalline (Table 5.1). However, a higher proportion of the larger grains in the sample are polycrystalline in comparison to smaller grains. Therefore, the percentage of polycrystalline to monocrystalline quartz is a function of grain size as well as provenance. Between 50% and 80% of the quartz grains have undulatory extinction. The variation of extinction angle is usually small (5° or less). A minor proportion of the quartz grains reveal lines of vacuoles and disseminated vacuoles.

Up to 10% of the whole rock composition is quartz cement which is in the form of crystal overgrowths which are distinguishable by their shape and protrusive nature. The margin of parent crystals is not usually apparent and rounding of overgrowths is not apparent. Some crystals show interlocking overgrowths with other grains, but usually overgrowths jut out into surrounding dolomite cement or into rock fragments. Quartz grains also show replacement by dolomite cement.

Feldspar

Feldspars are only a minor component of the framework grain population. Both microcline and albite are identified in the samples. Microcline occurs as angular granules as well as sand and silt sized particles and is reasonably fresh but shows the beginning stages of kaolinization (U. of C. 11975). Both microcline and albite show replacement

Table 5.1
 Modal analyses (in %) of typical sandstone samples from the Otumotu
 Formation.

SAMPLE NO. U. of C. D.S.I.R.	11972 F36/p36	11973 F36/p37	11975 F36/p39	11979 F36/p47	11976 F36/p43	11977 F36/p45	11978 F36/P46
APPARENT GRAINSIZE (mm)							
max.	0.69	1.05	----	0.41	1.00	0.70	0.58
mode(s).	0.14	0.17/0.65	----	0.08	0.32/≈0.1	0.25	----
min.	0.01	>0.01	----	>0.01	>0.01	>0.01	>0.01
ROUNDING	v.a.-s.a.	v.a.-s.a.	v.a.-r.	v.a.-s.r.	v.a.-s.r.	v.a.-s.r.	v.a.-r
SORTING	m.s.-w.s.	p.s.	v.p.s.	m.s.	p.s.	p.s.	p.s.
QUARTZ	50	40	25	36	25	40	40
mono.	98	90	95	90	99	99	90
poly.	2	10	5	10	1	1	10
undul.	60	50	50	80	80	80	95
MICROCLINE	3	3	1	0	5	--	--
other .ALK.F.	0	>1	0	0	0	>1	>1
PLAG.FELD.	0	>1	0	>1	>1	0	0
ROCK FRAG.	15	15	35	7	20	10	5
MICA	2	5	>1	3	5	5	10
H AND O	>1	>1	>1	>1	>1	>1	>1
OTHER	>1	1	>1	>1	0	>1	0
MATRIX CEMENT:	5	7	8	3	5	5	15
QUARTZ	5	10	2	>5	5	5	5
DOLOMITE	20	25	25	30	30	35	25
SIDERITE	"	"	5	15	5	"	--

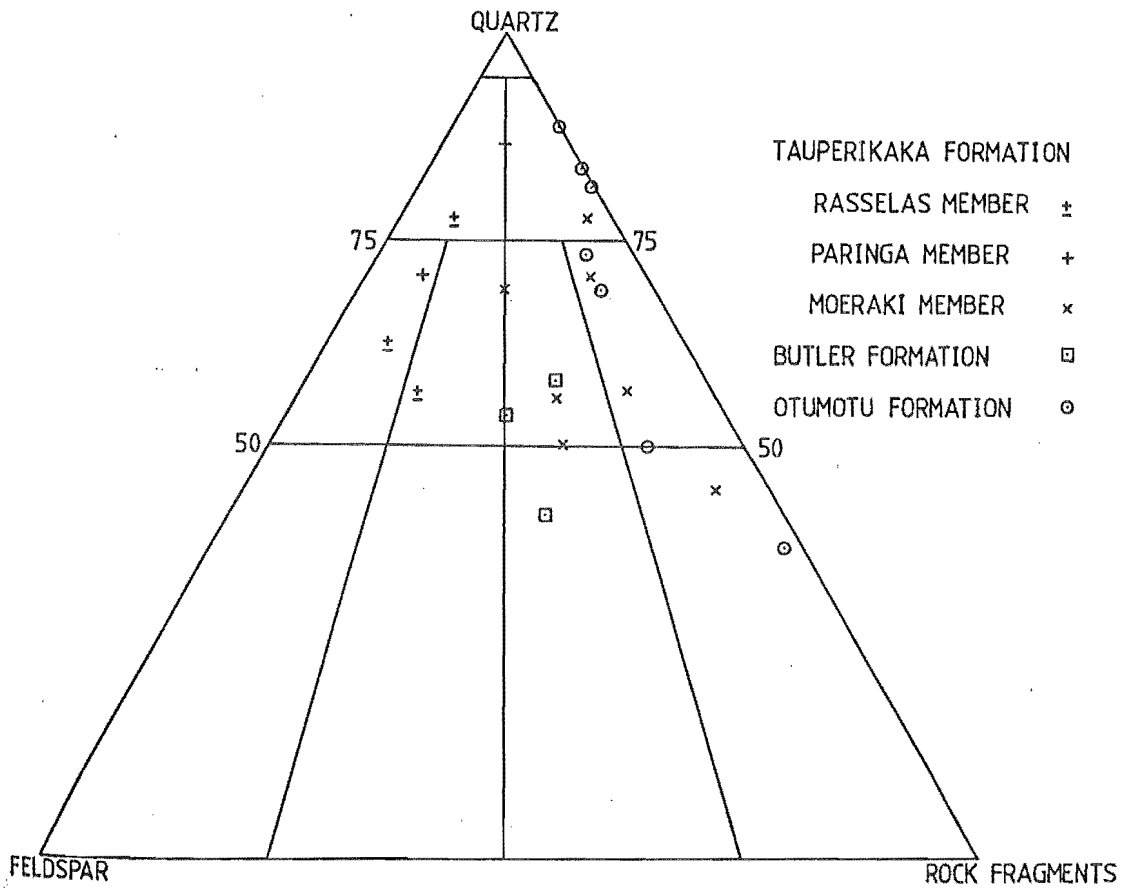


Figure 5.15
The parent triangle for Aránite Classification showing typical samples from the Cretaceous sequence of South Westland (after Folk et al. 1970).

along cleavages and grain boundaries by dolomite cement. Large "rafts" of microcline in sample U.of C. 11973 show no signs of alteration. Microcline grains in sample U.of C. 11976 are angular or sub-rounded and show signs of vacuolisation and kaolinitization.

Rock Fragments

The amount of rock fragments varies from sample to sample between approximately 10% and 40%. The total percentage of rock fragments in a sample is directly influenced by the amount of dolomite cement as rock fragments are the first major detrital component to be totally replaced by cement. Low grade metamorphic clasts are the predominant rock fragment and are composed of sand and silt sized quartz crystals and oriented micas. Some samples contain granule sized, platy, angular rock fragments in which slaty cleavage is oblique to bedding within the granule (Fig. 5.16). Vein chlorite and chert rock fragments (U.of C. 11972) also form a minor rock fragment component. Chert fragments are apparent in all the samples analysed.

A minor proportion of the rock fragment population now resembles a pseudo matrix. Rock fragments have succumbed to compaction and structural pressures by squeezing around the more resistant quartz grains. The curvature in the line of oriented micas within rock fragments indicates the latter deformation where rock fragment boundaries are difficult to distinguish. A complete gradation from the majority of undisturbed rock fragments, with both well defined boundaries and internal structure, to a minority of structurally disturbed rock fragments, which now resemble a mass of silt sized particles with dispersed flecks of mica, is represented within the whole suite of samples. Due to the structural deformation of rock fragments, the distinction between soft perigenic clasts and detrital rock fragments is not possible.

Some rock fragments contain pockets of carbonate (U.of C. 11975). As the carbonate is seen to be replacing

quartz fragments, feldspars and other rock fragments, the pockets of carbonate are interpreted as a secondary diagenetic feature rather than a primary feature of the grain.

Micas

Micas occur in quantities up to 5% but are usually in quantities less than 1%. Samples with relatively large flakes of muscovite correlate with samples containing large granules of quartz and feldspar (e.g. sample U.of C. 11976). The modal grain size of sample U.of C. 11977 is approximately 0.25mm. The sample contains flakes of muscovite with an apparent length of 0.5mm and a chlorite grain with an apparent length of 0.7mm. Matrix and pseudo matrix contains randomly oriented sericite.

Heavy Minerals

Heavy minerals occur in quantities less than 1% of the whole rock. The most common opaque mineral is leucoxene (U.of C. 11975; 11976). Pyrite and hematite? occur occasionally (U.of C. 11979 and 11975 respectively). Translucent minerals include relatively abundant tourmaline and zircon (U.of C. 11978). Clinozoisite - epidote is present in sample U.of C. 11979.

Matrix And Cement

As special techniques are generally necessary to determine the composition of grains less than 0.03mm in diameter, this arbitrary level is set as the cut off point for materials relegated to the status of matrix (Lewis 1982).

Matrix is a minor component present in quantities as high as 10%. Much of the matrix could may be derived from the disaggregation of rock fragments within the environment of deposition.

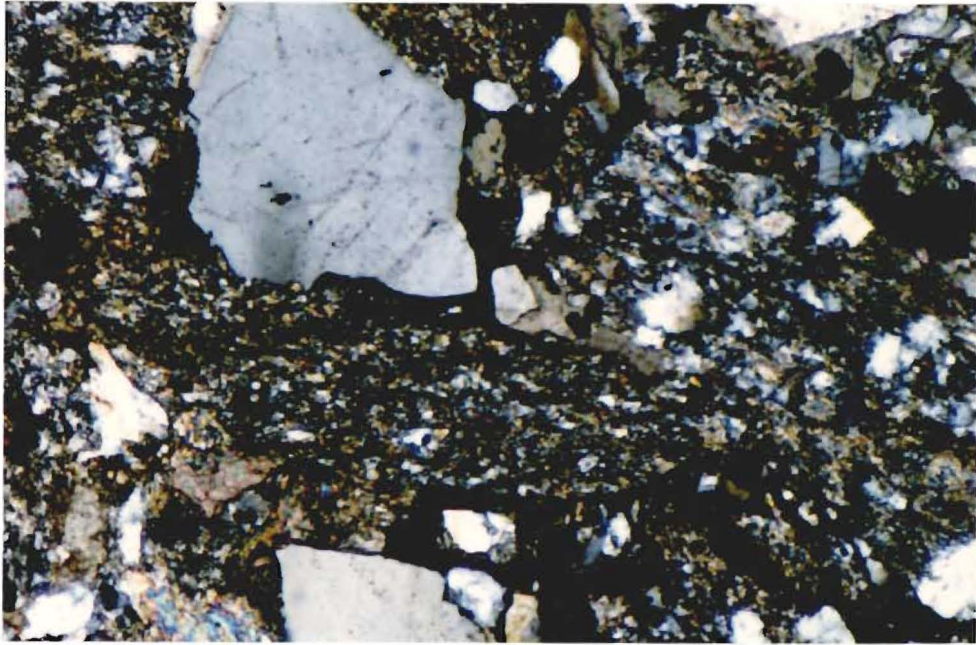


Figure 5.16
Granule size, platy, metamorphic rock fragments and quartz grains.
Sample U.of C. 11975.

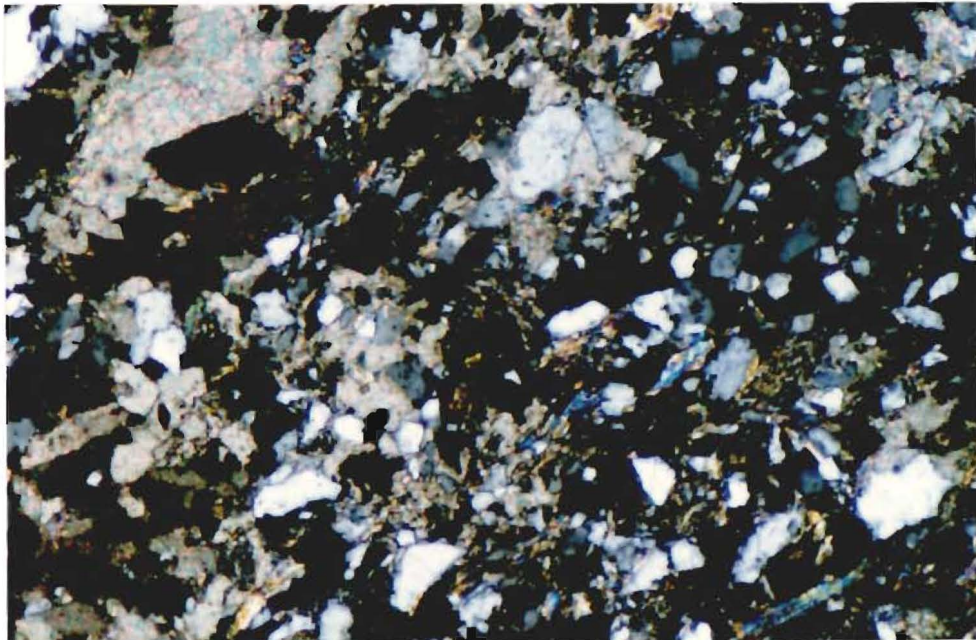


Figure 5.17
Dolomite cement replacing quartz, most of the rock fragments have been replaced. Large flakes of muscovite (top left). Sample U.ofC. 11979.

Cement, which primarily replaces rock fragments, has filled any primary or secondary pore space and is also seen replacing quartz and feldspar grains. The cement covers between 20% and 53% of the thin section area (Fig 5.17). The dominant cement consists of masses of a colourless anhedral crystal with extreme birefringence resembling calcite (Fig. 5.17). However x-ray diffraction analysis of crushed samples show strong dolomite peaks and calcite peaks are absent (Appendix 8, diffractograms 1 and 2) with the exception of a very minor peak representing high Mg calcite.

Opaque grains with euhedral form are surrounded by adjacent aggregates of crystals, which have been stained a dark brown colour, are interpreted as siderite crystals that are exsolving to high Mg calcite. Siderite is in abundance in some sections (U.of C. 11975, U.of C. 11979) where the mineral is present as scattered dark red rhombs. The major peak of siderite also shows up on X.R.D. trace (Appendix 8, diffractogram 1).

Interpretation of the Composition of the Topsy Member

The mineralic assemblage of rock fragments, abundant quartz, and heavy minerals (which includes zircon, tourmaline and leucosene), indicates a sedimentary provenance. Slaty cleavage in rock fragments and the presence of aligned micas and muscovites in rock fragments indicate a low rank metamorphic provenance. There is no evidence for a higher rank of metamorphic rocks in the provenance area. Occasional large fresh microcline granules, occurring together with large granules of quartz and muscovite, indicate a granitoid input which may also account for a proportion of the smaller sized quartz grains. As the Greenland Group is mainly composed of medium sand sized, or smaller grains all of the quartz grains larger than medium sand sized must be derived from another source, and the granitoid source is the most likely. Minor albite is also present.

The Greenland Group rocks include indurated sandstones and mudstones composed predominantly of detrital, poorly sorted quartz grains with a minor percentage of rock fragment and feldspar grains. The Tuhua Group, which consists of granite plutons, intrudes into the Greenland Group sediments. Over much of the area mapped, Greenland Group rocks are thermally metamorphosed to a biotite hornfels. Lowest grade rocks are of the lower greenschist facies. The composition of the sandstone in the Otumotu Formation is akin to the composition of the interbedded conglomerate. The Greenland Group is interpreted as the major source, and the Tuhua Group is interpreted as a local source providing minor amounts of feldspar quartz and muscovite. The albite has two possible sources. Both the granite and the Greenland Group sediments, around granite intrusions, contain albite. The hydrothermal vein quartz is common in the Greenland Group rocks. The amount of feldspar within Otumotu Formation sediments may have been significantly reduced as in steep streams feldspar grains are significantly reduced in size by fracture along twin composition planes within a distance of 30km to 40km (Pittman 1969 in Blatt et al 1980). The Tauweritiki Member of the Otumotu Formation is likely to have been characterised by high gradient streams and much of the sediment in the Topsy Member is also likely to have been derived through the alluvial fans of the Tauweritiki Member. For this reason the importance of the Tuhua Group as a source rock may be underestimated.

Since deposition of the sediments in the Topsy Member, a complex diagenetic history has altered the composition. Only a model of the most recent diagenetic stages is possible as crystallisation, solution and redistribution of cement could have occurred numerous times and the time and method of the emplacement of dolomite and Mg calcite is not certain. Siderite is being replaced by high Mg calcite or dolomite and dolomite cement could be replacing high Mg calcite, some Mg calcite still exists. Dolomite is replacing quartz rock fragments and feldspar. Before and/or during replacement of framework grains by dolomite, rim cement on quartz grains precipitated from solution.

The siderite could be detrital or secondary. Iron in solution or as part of a coagulated gel reaches the depositional basin where it precipitates. The abundance of organic matter in the floor sediments causes reduction to Fe CO₃. Siderite can also be introduced diagenetically. A calcite cement or matrix is sideritised to produce rhombs of siderite. The dark red colour of the siderite in thin section is interpreted as the oxidation of iron on the outside of crystals caused by the weathering. If the siderite is detrital the oxidation could have occurred around the time of deposition. The siderite now shows replacement by either dolomite or high Mg calcite.

Nathan (1977) shows that MgO within the matrix of sandstones within the Tauweritiki Member is markedly lower than MgO in the matrix of the Greenland Group and suggests that during terrestrial sedimentation Mg has been depleted by leaching. This provides a source for the Mg in the dolomite cement within the Topsy Member sediments.

Lithofacies Sequences and the Environment of Deposition of the Topsy Member

Three lithofacies sequences from the Topsy Member are presented and each is discussed in turn. Lithofacies sequence 1 is taken from the lower part of the Topsy Member, lithofacies sequence 2 is taken from the middle part of the Topsy Member and lithofacies sequence 3 is taken from the upper part of the Topsy Member. The sequences represent typical progressions of lithofacies within the Topsy Member.

Lithofacies Sequence 1

The lower part of lithofacies sequence 1 contains some lithofacies from the Tauweritiki Member as the two Otumotu Formation Members interdigitate (Fig. 5.18).

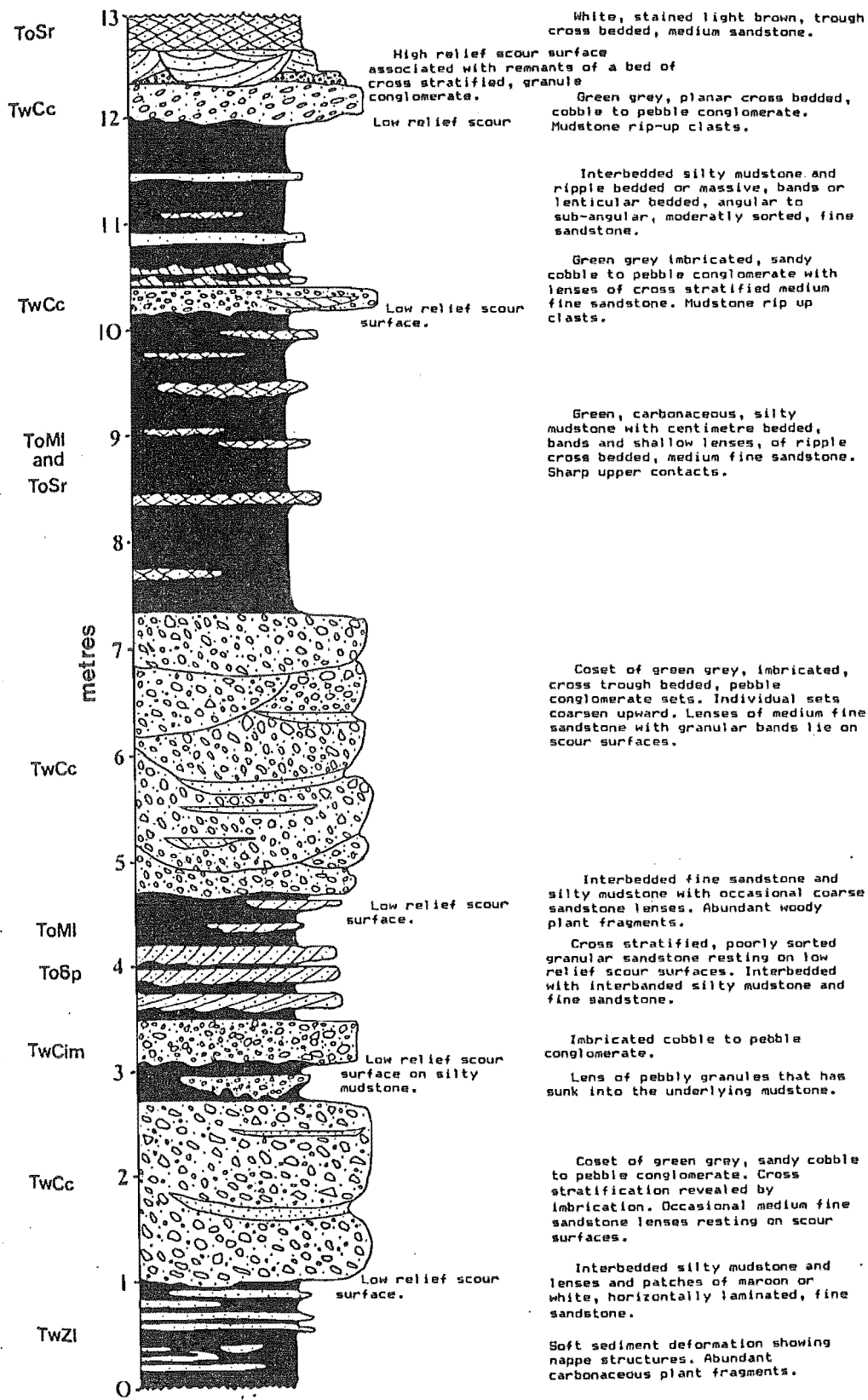


Figure 5.18
Lithofacies Sequence 1. Generalised succession of lithofacies at the base of the Otumotu Formation, Topsy Member (Motuan - Arowhanan), on Otumotu Beach, South Westland.

The processes represented by the rocks in lithofacies sequence 1 are probably fluvial and represent an alternating high energy active environment with a low energy and inactive environment. Both Miall (1978) and Rust (1978) describe similar sequences as representing braided stream environments. A vertical succession of conglomerate, lithofacies TwCc, represents gradual filling of an active channel complex. Eventually, active tracts migrate elsewhere on the flood plain. Once areas become inactive they accumulate silty mudstones and plant material.

In the lower part of sequence 1 processes associated with lithofacies TwZl indicate an inactive tract. Soft sediment deformation and load structures at the base of lithofacies TwCim indicates the underlying fine sediment is supersaturated with respect to water. A sudden influx of conglomerate, lithofacies TwCim, with the associated relatively high kinetic energy, is interpreted as a flood event. The finer sediments and low kinetic energy sediment structures often associated with the waning energy of a flood deposit, or migration away or abandonment of a channel facies, are not represented above the coarser lithofacies (TwCc and TwCim) (Fig. 5.18). Finer sediment must have been carried to more distal areas of the inactive tract and a high water table is inferred to facilitate fine sediment dispersion. A high water table is also required to raft vegetation and to place dropstones. The latter evidence combined with the lack of drying out or emergent indicators such as mudcracks, oxidised sediment, plant colonisation, soil development or late stage emergent run off structures, indicates the inactive tract may represent a semipermanent pond or lake.

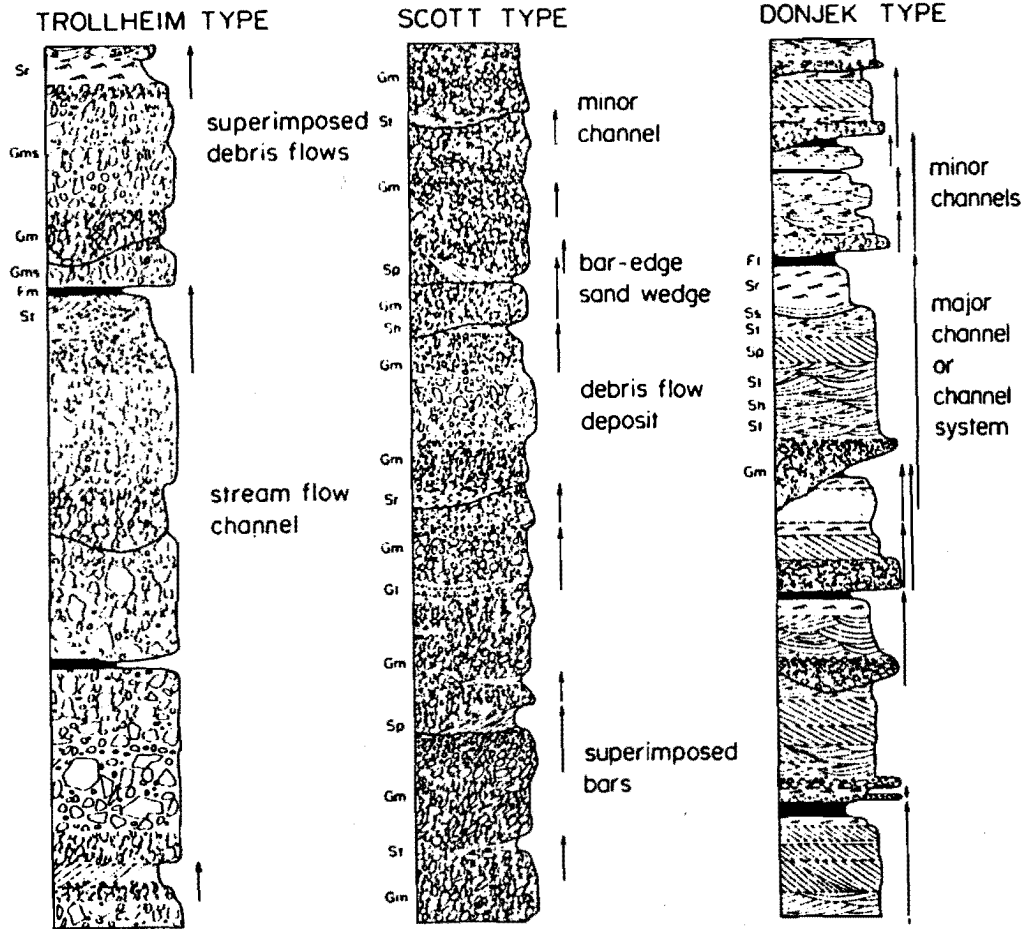
Higher in lithofacies sequence 1 (Fig. 5.18), the inactive tract sediments (ToMl and ToSr), represent a protected area characterised by vertical accretion of fine sediment in standing water. Periodically, low energy currents directed in shallow channels or broad sheets moved fine sand in ripple form across the inactive tract. There is no evidence of emergence. Sharp upper contacts on the sandstone beds indicates a sudden cessation of energy and the disper-

sion of finer sediment in suspension further into the back-swamp area. Rust (1978) interprets similar deposits as the products of minor channels in the inactive tract during a flood event.

At the top of the lithofacies sequence (Fig 5.18) a fining upward sequence shows a gradual waning of energy regime. The sequence indicates several periods of erosion and deposition and may record deposition of sediment in a gradually decreasing water depth. The basal scour probably represents a channel bottom and the conglomerate an in-channel bedload deposit. Cut and fill structures with cross-bedded sandstone represent in-channel migration of dunes under lower flow regime conditions. Ripples indicate shallow water deposition on a bar top or levee.

As the conglomerate is the dominant lithotype of the active tract and there is a conspicuous lack of fining upward sandy channel sequences commonly regarded as typical of meandering fluvial deposits (Allen 1965a), the sequence is similar to Rust's (1978) facies assemblage G111 : Distal Braided Rivers and Alluvial Plains. Comparing Miall's (1977) models, the sequence is comparable with the Donjeck Type (Fig 5.19). The major difference between lithofacies sequence 1 and the Donjeck type is the large amount of inactive tract lithofacies represented in sequence 1. Rust (1978) explains that the Donjeck River is confined within its glacial valley and has not got the space to develop extensive inactive tracts. Therefore, lithofacies sequence 1 may represent an alluvial plain environment in which braided streams were relatively unconfined. The relative prominence of conglomerate over sand lithofacies in the sequence as opposed to the sand dominance in the Donjeck type model is a reflection of the source.

An immediate source of gravel for the braided streams is the fan wedge sediments of the lower and middle Tauweritiki Member. The stream channel conglomerates of lithofacies sequence 1 are generally finer in grain size than the fan wedge sediments of the Tauweritiki Member. Allen (1965)



Facies Code	Lithologies	Sedimentary structures	Interpretation
Gms	massive, matrix supported gravel	none	debris flow deposits
Gm	massive or crudely bedded gravel	horizontal bedding, imbrication	longitudinal bars, lag deposits, sieve deposits
Gf	gravel, stratified	trough crossbeds	minor channel fills
Gp	gravel, stratified	planar crossbeds	linguoid bars or deltaic growths from older bar remnants
St	sand, medium to v. coarse, may be pebbly	solitary (theta) or grouped (pi) trough crossbeds	dunes (lower flow regime)
Sp	sand, medium to v. coarse, may be pebbly	solitary (alpha) or grouped (omikron) planar crossbeds	linguoid, transverse bars, sand waves (lower flow regime)
Sr	sand, very fine to coarse	ripple marks of all types	ripples (lower flow regime)
Sh	sand, very fine to very coarse, may be pebbly	horizontal lamination, parting or streaming lineation	planar bed flow (l. and u. flow regime)
Sl	sand, fine	low angle (<10°) crossbeds	scour fills, crevasse splay, anastomosing
Se	erosional scours with intraclasts	crude crossbedding	scour fills
Ss	sand, fine to coarse, may be pebbly	brided, shallow scours including eta cross-stratification	scour fills
Sae, She, Spe	sand	analogous to Sa, Sh, Sp	scour deposits
Fi	sand, silt, mud	line lamination, very small ripples	overbank or waning flood deposits
Fac	silt, mud	laminated to massive	backswamp deposits
Fcd	mud	massive, with freshwater molluscs	backswamp pond deposits
Fm	mud, silt	massive, desiccation cracks	overbank or drape deposits
Fr	silt, mud	rootlets	swamp deposits
C	coal, carbonaceous mud	plants, mud firms	swamp deposits
P	carbonate	pedogenic features	soil

Figure 5.19
Models for braided stream deposits (Miall 1977).

presented hypothetical models of typical alluvial facies. Model 36A is a facies model for an intermontane basin from which there is drainage to the sea in which stream channel deposits are finer grained than fan wedge deposits but include coarser material where the streams cut into the toes of fans. Allen's environmental interpretation for the Old Red Sandstone in Wales (Allen 1965b, in Reading 1978) is also comparable to the South Westland sequence (Fig. 5.18) as stream channel and fan deposits are embedded in the finer "argillaceous" sediments from the inactive tract which may represent lakes or playas (Fig. 5.20).

Lithofacies Sequence 2

Lithofacies sequence 2 is identified by rocks and processes that are probably fluviatile and lacustrine (Fig 5.21). In comparison with sequence 1, from lower in the stratigraphic column, there is a conspicuous lack of conglomerate, and sandstone lithofacies are dominant.

Two minor fining upward sequences are apparent (labelled 1 and 2). The lower cycle shows a decreasing gradation in process energy from low angle planar cross stratification (ToSl), through ripples and horizontal lamination (ToSr), to silty muds with lenticular bedded fine sandstone (ToMl). The upper cycle (labeled "2") shows a similar decreasing energy gradient from a bed of structureless granules (ToGm) to ripple laminated and horizontally laminated fine sandstones (ToSr). In both cycles, the waning of energy is not gradual but is illustrated in defined jumps across sharp boundaries. The upper cycle is overlain with an erosional contact by planar cross bedded sands (ToSp) indicating a jump back to a higher energy flow. The amount of sequence lost at the erosional contact is unknown and the planar cross bedded sands represent the start of another cycle.

The classic fining upward sequence which represents an upwards waning of stream power is described by Bernard

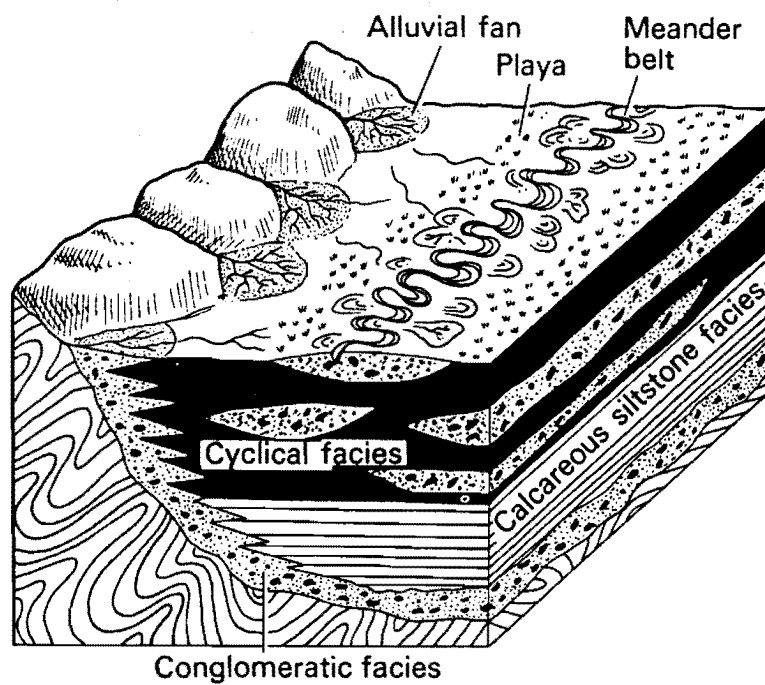


Figure 5.20
A facies sequence and environmental interpretation for the Old Red Sandstone of Anglesey, Wales (Allen 1956 in Reading 1978). The calcareous siltstone facies represents playa deposition which may have been deposited between the fans and the meander belt as the source area retreated.

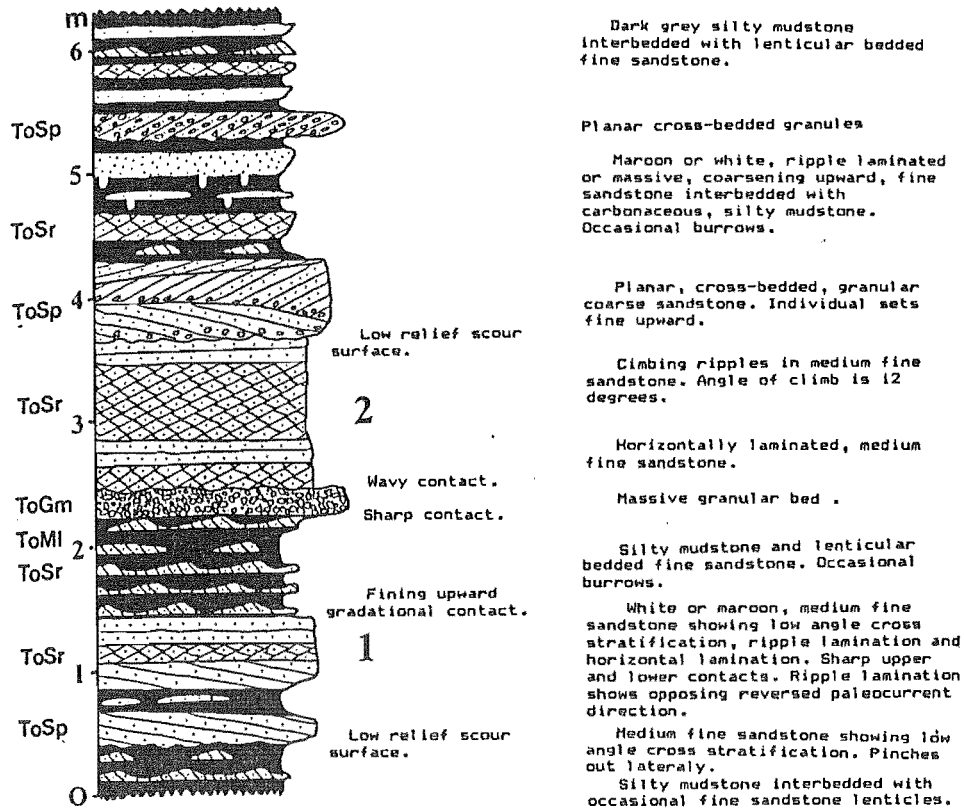


Figure 5.21
Lithofacies Sequence 2. Generalised succession of lithofacies from the middle part of the Otumotu Formation, Topsy Member (Motuan - Arowhanan), on Otumotu Beach, South Westland. Fining upward cycles labelled 1 & 2.

and Major (1963) and Allen (1964, 1965a, 1965b, 1970a, 1970b, 1974); Visher (1965) and others. The sequence is described as a sandstone overlying a horizontal erosion surface which shows a vertical transition from cross bedding to parallel and/or ripple cross lamination before grading to an overlying fine member. Lag conglomerates may form a base. Sequences from the Old Red Sandstone (Allen 1964, 1965b) illustrate that members of the fining upward sequence may be individually stranded in the fine inactive tract sediment (Fig. 5.22). The classic models have been interpreted as the products of point bar sedimentation in meandering streams. Cant and Walker (1976) developed a complex model combining paleocurrent direction with lithofacies (Fig. 5.23) for a low sinuosity stream deposit. The large scale troughs are due to dune migration in deeper parts of the channel and tabular sets are interpreted as products of transverse bars on high areas. The sequences described by Allen are, however, ambiguous as overbank sheet flood deposits can also show similar waning energy cycles, with horizontal erosional surfaces at the base of the sequence associated with overlying coarse lags, different members of which may be isolated in finer inactive tract sediments.

A facies sequence interpreted as semi-arid in an enclosed basin (Demicco R.V. & Kordesch E.G. 1986) includes a sand facies with trough cross-bedded, planar stratified sand and lesser amounts of ripple cross lamination, some of which is climbing. The sand units are 0.1m to 1m thick, cut into underlying mudstones and fine upward. The sand beds are separated by grey, green, or red planar laminated mudstone with lenticular bedded fine sandstone, showing soft sediment deformation such as load casted ripples and small ball and pillow structures, and mud cracks. Demicco & Kordesch interpreted the bulk of the deposits as sheet flood deposits that were carried over the surface of ephemeral flood plains away from shallow channel complexes. Ponding of flood waters allows the top of a flood deposit to be reworked into wave ripples. Stacked units a few decimetres thick are interpreted as channel deposits. The mud facies is interpreted as the products of the expansion and contrac-

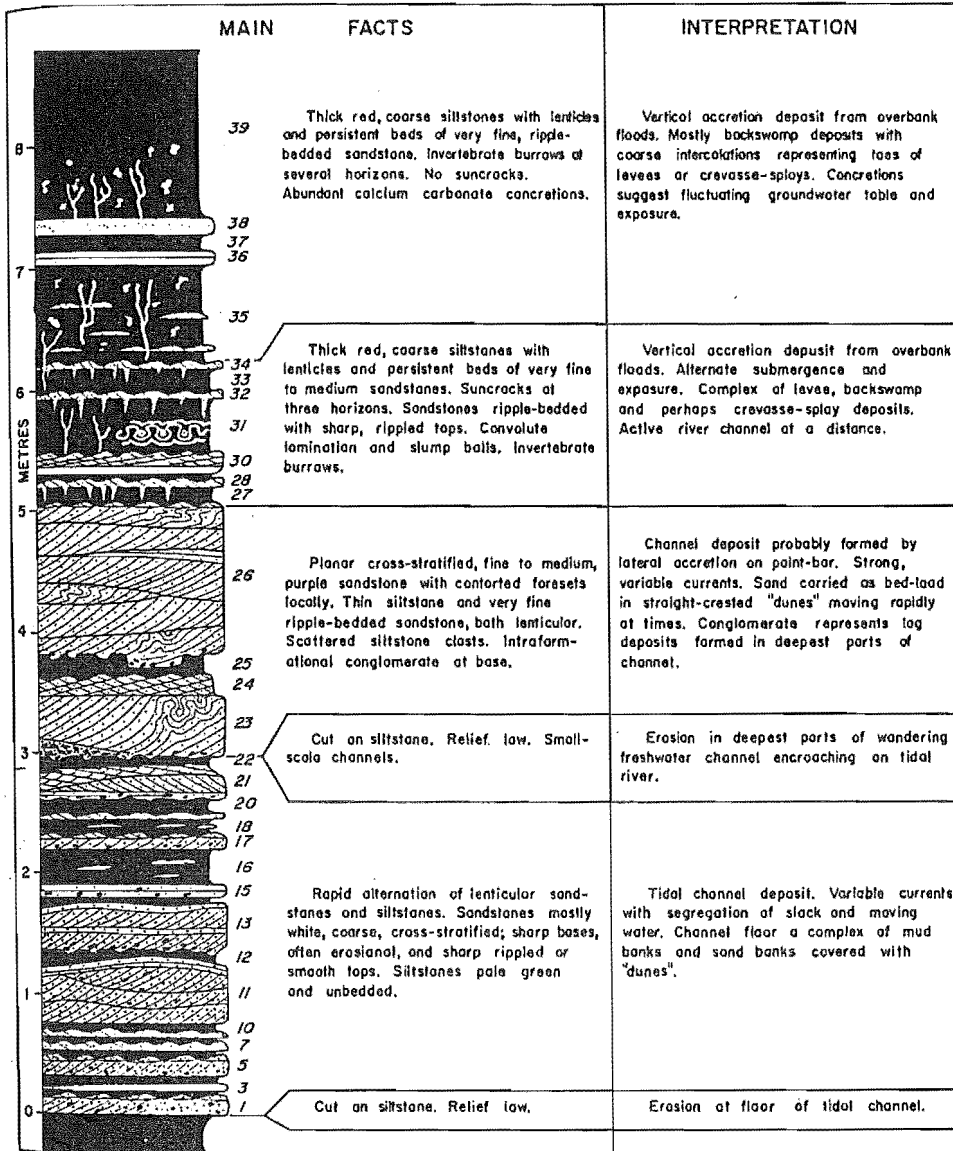


Figure 5.22
A generalised succession and interpretation of the cyclothem at Lydney, Anglo-Welsh region (Allen 1964).

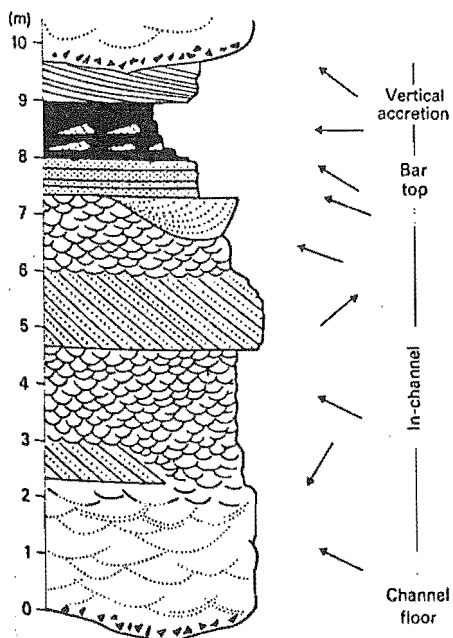


Figure 5.23
Facies model for the Battery Point Sandstone (Devonian Quebec). The model combines paleocurrent direction with lithofacies and is interpreted as a low sinuosity stream deposit.

tion of perennial lakes.

In comparison to these models and sequences the two stacked units, encompassing three cycles of sedimentation, in lithofacies sequence 2, may represent either meandering or low sinuosity stream channel facies, or sheet flood deposits. The low angle planar cross stratification, together with the thickness of the sandstone beds, lends support to the sheet flood model.

As with the Abergavenny Cyclothem (Allen 1964) (Fig. 5.24), evidence of exposure being absent, the backswamp area represented by the ToMl, ToSr and ToSm lithofacies may represent a semi-permanent lake. The processes interpreted from lithofacies ToSm and the presence of burrowing support a semi-permanent lake model. Lenticular bedding and ripple bedding may be a result of wave reworking as in the Demicco and Kordesch (1986) model. The lack of fossil fauna is probably due to the diagenesis that the sediment has undergone since deposition. The very immature textural and compositional characteristics (Lithofacies ToSr) are typical of lacustrine deposits (Reading 1978). The immaturity is due to the lack of high energy wave activity and tidal currents and the sediment has been transported a relatively short distance from the Greenland Group and sub-ordinate Tuhua Group provenance.

In conclusion, lithofacies sequence 2 represents an alluvial plain environment which is relatively close to an uplifted area undergoing erosion, and which is fringed by alluvial fans. The plain is swept by streams that probably fall between low sinuosity and meandering. The rock record mainly records the inactive tract, away from the channel facies, which probably consisted of a series of semi-permanent lakes. The backswamp area was subject to periodic flooding whereby sandy sheets spread from flooded nearby channels. Where sandy sheets spread into lakes, or where ponds remained after flooding, sand bodies may have been reworked by wave or current processes operating within the lakes or pond environments. Minor broad and shallow channel

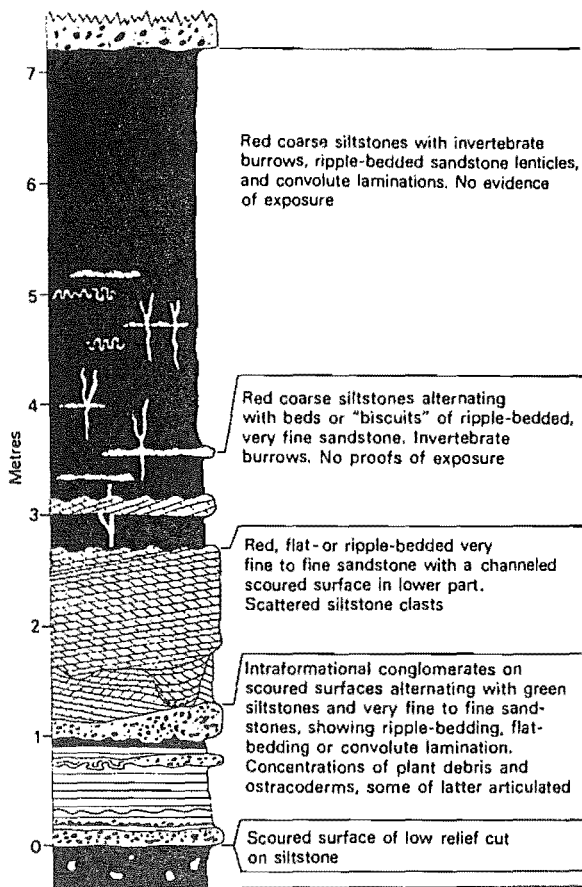


Figure 5.24

A generalised succession and interpretation of the cyclothem at Abergavenny, Anglo-Welsh region (Allen 1964).

facies may also be represented in the waning energy cycles, however, there is no reason to assume that these stacked lithofacies are not products of pulsatory larger flood events.

Lithofacies Sequence 3

Lithofacies sequence 3 (Fig. 5.25) is representative of the upper part of the Topsy Member as the member crops out in the type section. The rocks and processes are interpreted as representing a series of inactive tract perennial lakes fed by flood water which introduce sheets of sand. The dominant lithotypes represented are ToM1 and subordinate ToSr. Sandy facies are thin (centimetres thick) and are isolated in the finer facies. There is a conspicuous lack of stacked sandstone lithofacies.

The major process operating is the deposition of fine sediment from standing water, over long periods of time. Intermittent low energy currents deposit silt and fine sand. The environment shows periods of super-saturation recorded in the rock record by abundant soft sediment deformation structures. Periods of drying out are recorded by the preservation of mudcracks. Occasional influxes of coarser sediment, lithofacies TwCim and ToGm, confined in channels with highly scoured lower surfaces, indicate the interruption of low energy processes by high energy currents. The lithofacies do not show upward gradational relationships in texture or cross-bedding which are usually associated with a waning of energy and so any sand present as the energy of depositing processes waned, was probably carried further into the environment of deposition. Sharp upper contacts on sandstone beds indicate that the energy of depositing currents dropped quickly. Upper contacts have been subsequently reworked by low energy wave or current processes. The environment was occasionally suitable for colonisation by fauna.

Similar lithofacies have been described in the upper part of the Lydney and Breconian Cyclothem in the Old Red

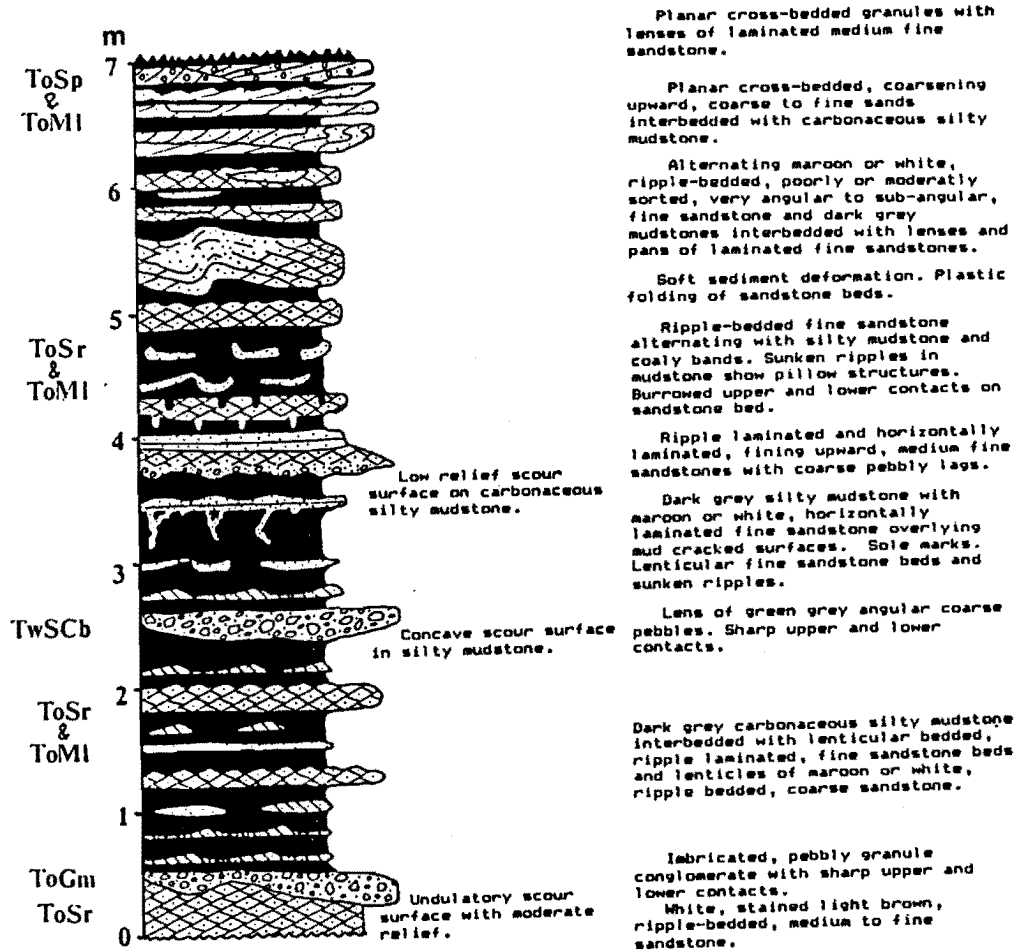


Figure 5.25
Lithofacies Sequence 3. Generalised succession of lithofacies from the upper part of the Otumotu Formation, Topsy Member (Motuan - Arowhanan) on Otumotu Beach, South Westland.

Sandstone (Allen 1964). Allen interpreted the processes as representing top stratum overbank regimes where the active channel had been abandoned, or migrated away. The paleoenvironment was compared to the environment of deposition in the present day backswamp of the Mississippi Valley. Ponding of floods provided temporary lakes.

The sequence and processes in sequence 3 are identical to those described by Demicco & Kordesch (1986) who interpreted their sequence as the product of expansion and contraction of perennial lakes followed by long periods of playa and mudflat aggradation.

At the top of sequence 3 (Fig. 5.25), a series of planar cross-bedded, coarsening upward sands and granules of lithofacies ToSp record relatively high energy currents in the upper part of the lower flow regime. The beds are isolated in lithofacies ToM1 and the upper surfaces are reworked into wave or current ripples. These beds may coarsen upward for one of two reasons. Either the coarser sediment arrived after the deposition of the finer sediment, or finer sediment has been winnowed out of the upper layers of the sandstone bed leaving a lag deposit of coarser material. The beds probably represent flood deposits that have subsequently been remobilized by a current and transported in megaripple form. In this way, coarser sands from a more proximal area migrate over finer sands from a relatively distal area.

In the upper part of sequence 3 the gradual increase in the presence of lithofacies ToSr to lithofacies ToSp, with an associated increase in grain size from sand to granules, relates to an increase in the flow regime energy and suggests that the active tract channel facies may be migrating towards the environment of deposition. Pans of laminated fine sandstone may indicate late emergent run off by minor channels preventient to periods of exposure.

In conclusion lithofacies sequence 3 is interpreted as representing a series of inactive tract perennial lakes fed by flood water which introduce sheets of sand. The flood flows experience a sharp fall off in their capacity and competence to transport clastic sediment on entering the standing bodies of water. Minor currents and wave ripples rework the top surfaces of sand deposits. Most of the deposition on the lake floor is from suspension. The lake is subject to repeated periods of drying out and during these periods, mudcracks form and small run off channels wash out surface current ripples. Hooke (1972) established that occasional major flood events may produce distal fan bed load sediment into marginal playa lake sediments.

5.2 BUTLER FORMATION

Sedimentary Structures and textures

Introduction

A detailed lithofacies analysis of the Butler Formation has not been undertaken. The descriptions below are based on field notes made during regional mapping of the area in 1985.

(i) Cobble Conglomerate

In a road cutting on S.H.6 on the west side of Grave Creek, a massive, green, weathered rusty orange, sub-angular to rounded boulder to pebble conglomerate is clast supported, and predominantly consists of rounded cobbles of green hard fine sandstone. The clast supported nature and textural maturity of the conglomerate suggests the conglomerate was deposited by a traction current and transported a considerable distance.

(ii) Pebbly Sandstone and Laminated Medium and Fine Sandstones

In Hydroslide Creek, a tributary of the north eastern arm of the Lake Paringa (N.Z.M.S.1 G36/197169), a thick sequence of low angle cross-bedded pebbly sandstones is interbedded with laminated carbonaceous medium fine sandstones. Pebbly sandstone beds, which are up to 1.5m thick, have matrix to clast ratios of 40/60. Clasts consist predominantly of sub-angular to sub-rounded quartz (a proportion of clasts are lithic and stained maroon, and a subordinate group are composed of grey sandstone). Sandstone beds are 50cm - 70cm thick, consist of medium to fine sandstone, and contain laminae of granules and carbonaceous fragments.

In Butler Creek 2m thick beds of matrix supported pebbles and granules in sand consist of 40% angular to sub-rounded quartz and 60% sub-rounded to rounded lithic clasts.

(iii) Graded Bedded Sandstone

In road cuttings on S.H.6, on the west side of Grave Creek, repeated beds of sandstone (0.5m thick) grade up from coarse basal layers, of rounded lithic pebbles, through fine sandstone to silty sandstone. Quartz pebbles in the basal lags are sub-angular. Cross-bedding is not apparent.

The coarse basal deposits, sorting of grain size and mature textures suggest deposition by traction flows which decrease in competence from a flow in the upper flow regime to a flow in the lower flow regime. The cycle is repeated. A mature texture also suggests the pebbles have been transported a relatively long distance from the source rock area.

(iv) Trough Cross-Bedded Fine Sandstone

In Butler Creek, a trough cross-bedded fine sandstone is 1m thick and contains abundant plant fragments. The sandstone is overlain by a thick sequence of banded fine sandstone and mudstone. The lower contact is not exposed.

The cross-bedding probably resulted from a traction current with a flow in the upper part of the lower flow regime.

(v) Ripple Bedded Sandstone

On Otumotu Beach, beds of ripple laminated, and flaser bedded medium fine sandstone are up to 1m thick. Each bed is an aggregate of concave downward lenses. The lithofacies overlies interlaminated siltstone and fine sandstone. The upper contact is not exposed.

The sedimentary structures suggest a flow in the lower part of the lower flow regime that alternated between periods of flow and periods of slack water.

(vi) Interlaminated Fine Sandstone, Mudstone and Coal

In Butler Creek, the dominant lithology is interlaminated and ripple laminated, dark grey or black carbonaceous mudstone and fine sandstone or siltstone. The fine sandstone contains abundant mica and carbonaceous flecks. In Butler Creek and on S.H.6 on the north-east side of Grave Creek (N.Z.M.S. 260 F36/054138), both the fine sand, and predominantly the mud, contain abundant plant stems and leaves. Coal occurs as laminae, bands and seams up to 70cm thick at Mt. Arthur and in Hydroslide Creek. Seams up to 3m occur in the Paringa River basin (Section 6.1)

The lithofacies represents a very low energy environment that alternated between periods of still-stand and flow. The coal is discussed in Section 6.0.

(vii) Massive Carbonaceous Siltstone and Mudstone

In Butler Creek a massive, fine, sandy siltstone crops out for over 100m along strike and contains occasional randomly dispersed isolated granules or sand grains amongst abundant small logs, twigs and stems. The bed rests on 6m of centimetre bedded fine sandstone, siltstone and mudstone. The lithofacies is overlain by 5m of massive mudstone, carbonaceous mudstone and coal.

The deposit represents deposition of suspended material from a standing body of water over long periods of time. Rafts of vegetation probably dropped the isolated granules and sand grains. The water was too deep for colonisation of the sediment by plants that probably grew around the margins of the body of water.

Composition of the Butler Formation

The composition of typical sandstones is shown in Table 5.2. The samples from the Butler Formation are feldspathic litharenites (Fig. 5.15).

Quartz

The sections studied are coarse to fine and fine grained sandstones. Quartz grains are predominantly monocrystalline, with only 5% polycrystalline grains, and 80% to 95% of the grains show undulatory extinction. Silica rim cement on quartz grains comprises 10% of the rock and is apparent by its protruding nature into surrounding grains and mutually interlocking grain boundaries. A small proportion of polycrystalline grains show a pronounced elongation of quartz crystals and these grains are included under rock fragments.

Feldspars

Feldspars occur in quantities between 15% and 20% and consist almost entirely of microcline with small (less than 1%) amounts of albite. The amount of alteration of feldspars differs between samples, in some samples feldspars are generally fresh but a small proportion show signs of vacuolisation and kaolinitisation. Microclines in other samples (U.of C. 11970) have undergone vacuolisation and a subordinate proportion show signs of kaolinitisation and illitization. Both microcline and kaolinite are identified by XRD and no other feldspars are obvious (Appendix 8, diffractogram 3).

Rock Fragments

The percentage of rock fragments falls between 20% and 25% and consists of chert, silt sized quartz crystals and oriented flecks of mica, large grains combining muscovite and quartz and drawn out polycrystalline grains.

Table 5.2
 Modal analyses (in %) of typical sandstone samples from the Butler
 Formation.

SAMPLE NO. U. of C. D.S.I.R.	11984 -----	11971 F36/p36	11970 F36/p33
APPARENT GRAINSIZE (mm)			
max.	0.52	1.23	0.4
mode.	0.2	0.75/0.4	0.25
min.	0.03	0.03	0.03
ROUNDNESS	v.a.-s.r.	v.a.-r.	a.-s.r.
SORTING	m.w.s.	m.s.	w.s.-v.w.s
QUARTZ	43	48	25
mono.		95	95
poly.		5	5
undul.		95	80
MICROCLINE	20	15	15
other.ALK.F.	>1	>1	>1
PLAG.FELD.	0	>1	>1
ROCK FRAG.	20	25	20
MICA	3*(muscov)	>1	1
H and O	>1	>1	3* ²
CARBONATE	0	>1	0
OTHER	>1	>1	>1
MATRIX	10	5	9
CEMENT:			
QUARTZ	5	5	2
DOLOMITE	0	2	25
SIDERITE	0	0	0

*¹Muscovite

*²Leucocoxene and tourmaline

Deformation of rock fragments due to compaction and microfaulting (U.of C. 11972) has formed a pseudomatrix, and distorted a large percentage of rock fragments. Perigenic clasts may be represented but are not distinguishable from the squeezed detrital rock fragments.

Mica

Large muscovite grains up to 0.3mm apparent grain size in sample U.of C. 11984 (apparent modal grain size = 0.2mm) make up 3% of the sample. Muscovite also gave strong peaks in an XRD analysis (Appendix 8 diffractogram 3).

Heavy Minerals

Leucoxene, tourmaline and sub-rounded zircons are present in most samples in quantities less than 1%. Leucoxene occurs in large quantities in some samples (U.of C. 11970), with a lesser amount of tourmaline, and contributes to 3% of the rock composition.

Matrix and Cement

Matrix is used to describe interstitial material, which is not conclusively pseudomatrix, and forms up to 10% of the rock composition. The matrix consists of quartz and randomly oriented sericite (the sericite may be derived from disaggregated rock fragments or may be diagenetic). The presence of kaolinite is confirmed by XRD (Appendix 8, diffractogram 3).

Silica cement is discussed under "Quartz". Carbonate cement is present in two samples (U.of C. 11970 and 11972) and is a light brown carbonate which looks identical to the carbonate in the Topsy Member sediments of the Otumotu Formation and is probably dolomite or ankerite. The cement, which occurs in quantities up to 27% (U.of C. 11970), is mostly interstitial, however, one grain (U.of C. 11972) appears to be detrital.

Interpretation of Composition

The fine grained sedimentary rock fragments, cherts and sub-rounded zircons and tourmaline indicate a sedimentary source. Textures in rock fragments with oriented networks of mica indicate a low rank metamorphic provenance. The composition and texture in cobble conglomerate clasts indicate a sedimentary provenance metamorphosed to a low rank. The Greenland Group as a source rock is therefore clearly implicated.

The abundance of microcline, muscovite-quartz rock fragments and coarse quartz grains are unlikely to have been derived from the Greenland Group, although hydrothermal deposits in the Greenland Group may be supplying small amounts of quartz. A granitic provenance is indicated which implies the local Tuhua Group. The proximity of granites combined with the amount of mechanical breakdown in streams will determine the amount of feldspar in samples from the Butler Formation.

The degree of alteration of feldspars may indicate relatively long periods of exposure to chemical corrosion and development of relatively thick soils. The alteration might also imply a relatively more humid climate than during the deposition of the Otumotu Formation where feldspars show a lesser degree of alteration.

The high proportion of leucoxene may be derived from the Greenland Group sediments, or may be an alteration product of ilmenite derived from either the Greenland Group or from the Tuhua Group.

The carbonate cement is a diagenetic feature and probably relates to the period when dolomite was crystallising throughout the South Westland sequence. Clastic grains of dolomite may be derived from the Otumotu Formation, which would imply two phases of dolomite cementation. More work is required to determine the sequence of diagenetic events.

Plant Macrofossils From Mount Arthur

Fossil material collected from Mt. Arthur during this study has been identified by Ian Daniel, of the Botany Department, University of Canterbury, and the results presented in Appendix 4. The main plants represented by plant fossils are: Equisetum sp., Taeniopteris cf. stipulata, Eretomophyllum sp., Ginkgo sp., at least 4 species and possibly 6 species of Coniferales, Nothofagus sp., Carpolithus sp. and 3 separate species comparable with Dryandroides pakawauica, Grewiopsis pakawauica and Beilschmeidia tatairoides. The species are described in Appendix 4. Very few of the samples contain comminuted, mixed plant material typical of stream deposition. The presence of variously aged leaves of the same species of dicotyledon, of putative male and female reproductive structures of podocarps, and of a complete leaf of Eretmophyllum, 14.5cm long, suggests periodic wind of some strength as the dispersal agent rather than seasonal leaf fall. The plant material may have been deposited by wind or flotation in a lacustrine environment. The vegetation in proximity to the lacustrine environment is floristically relatively poor and lacking in understory representatives, especially ferns (Daniel, Appendix 4).

Environment of Deposition

A complete lack of marine indication, such as indicative trace fossils and mineral assemblages, the textural immaturity of sandstones, the abundance of coal forming swamps and evidence of podocarp forests, all implies a non-marine setting. The abundance of inactive tract sediment characterised by large areas of standing water, and accumulations of leaves that suggest a "lacustrine" environment indicates the back-swamp areas were semi-permanent or permanent lakes.

High energy traction currents and currents of waning energy in a terrestrial environment suggest flood deposits or stream deposits. The mature texture of the cobble con-

glomerate indicates it has been transported a relatively long distance from source which suggests a river system. The interbedded sequence of pebbly sandstone and laminated fine sandstone may indicate flood cycles.

Feldspathic litharenites probably indicate uplift and erosion in the Greenland Group and Tuhua Group source rocks. The increase in the amount of feldspars in the Butler Formation compared to the Otumotu Formation, especially with evidence that feldspar numbers in the Butler Formation have been reduced by chemical weathering, may indicate the Tuhua Group is better exposed than it was in mid Cretaceous times. The increase in feldspar percentages might also be related to an environmental factor. The lacustrine and fluvial system of the Butler Formation has more gentle gradients than the streams of the Tauweritiki Member of the Otumotu Formation where feldspar numbers may have been significantly reduced in short distances due to high stream gradients (Section 5.1.2: Interpretation of Composition).

5.3 TAUPERIKAKA FORMATION

5.3.1 Moeraki Member (new)

Sedimentary Structures and Textures

Introduction

The Moeraki Member is divided into nine lithofacies which are based on combinations of characteristic sedimentary structures and textures. Each lithofacies has been assigned a code, for the sake of brevity during references to a lithofacies in the text. The codes are explained fully in Appendix 2, but briefly the codes are: MoC; MoSt; MoSp; MoSe; MoSh; MoSr; MoSZ1; MoMm.

(i) Lithofacies MoC: Pebble Conglomerate

Beds of cobble to pebble conglomerates are usually thin, a few clasts thick, and are associated with an underlying low relief scour surface. The conglomerates are dominantly composed of poorly imbricated, angular to sub-rounded quartz pebbles or angular to sub-rounded quartz pebbles and rounded to well rounded Greenland Group derived lithic pebbles.

Thicker beds of conglomerate (0.5 - 1m), at the base of Lagoon Creek, are well imbricated and show low angle cross-bedding and horizontal lamination. The well sorted pebble population is matrix supported in granules or coarse to medium sandstone and consists of rounded to well rounded Greenland Group lithologies and a subordinate percentage of angular to sub-rounded quartz pebbles. Lithofacies MoC usually rests at the base of lithofacies MoSt, MoSp or MoSh (Fig. 5.26).

The sediment was transported by a traction current of the upper flow regime which is eroding the underlying sediments. As the energy of the transporting current waned portions of the bedload with higher settling velocity become stationary.

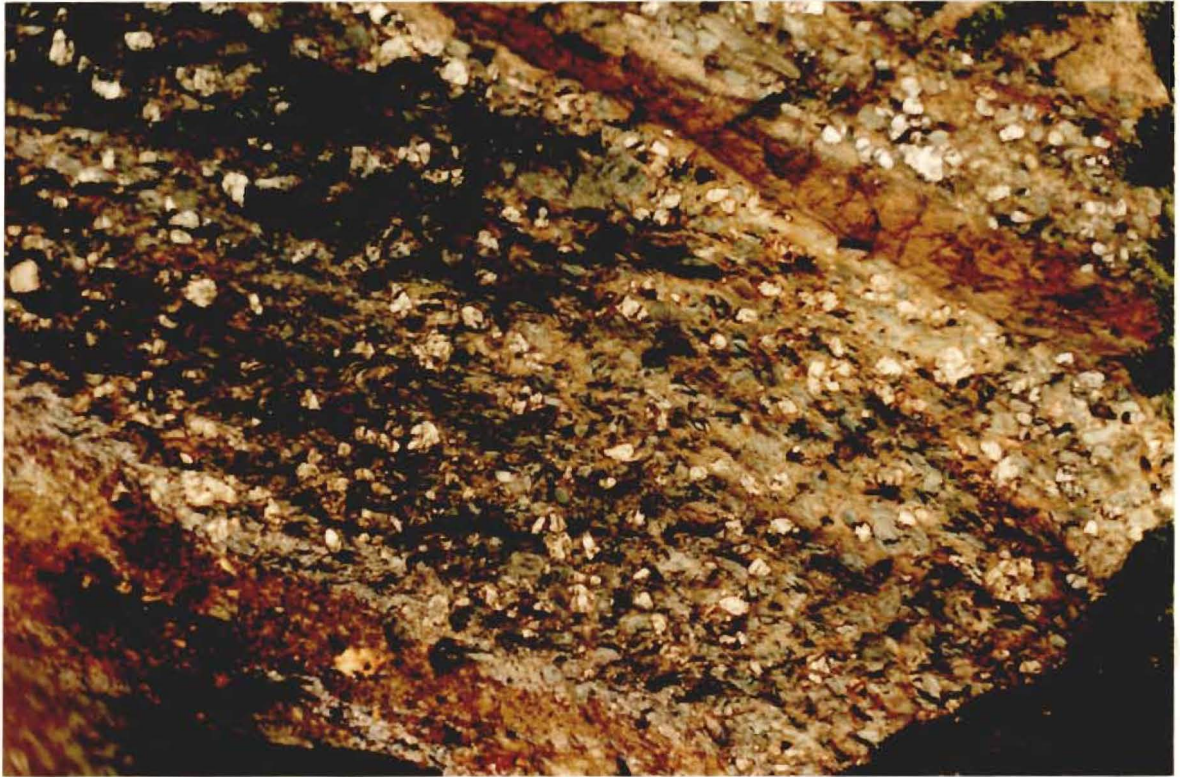


Figure 5.26
Lagoon Creek (Map 1: G36/234244) Tauperikaka Formation, Moeraki Member (early to mid Haumurian). Imbricated Greenland Group derived lithic and quartz pebbles. Lithofacies MoC.



Figure 5.27
Lagoon Creek (Map 1: G36/ 235244) Tauperikaka Formation, Moeraki Member (early to mid Haumurian). Decimetre to metre bedded wedge shaped sets of pebbles and granules. Youngs bottom right to top left. Lithofacies MoSt.

(ii) Lithofacies MoSt: Trough Cross-Bedded Pebbly Granules, Pebbly Sandy Granules And Granular Sandstones

Decimetre to metre bedded, trough cross-beds exposed at Lagoon Creek consist of green, grey and white speckled sub-angular to well rounded poorly sorted pebbles and granules. The sets show a frequency grading from matrix supported pebbles in granules, to granules containing a minor amount of scattered pebbles. Some beds also consist of ungraded granules and poorly sorted granular sands. Occasional black carbonaceous or silty mudstone laminae delineate internal cross stratification.

Contacts between individual sets are sharp and either concave downward or straight. The two dimensional nature of many outcrops makes differentiation between planar cross-bedding and trough cross-bedding difficult and some sets maybe wedge shaped transitions between the two cross-bedding types (Fig. 5.27). The assessment of paleocurrent directions is restricted by the two dimensional nature of the outcrop and different outcrops are often difficult to relate to each other because of structural complications. However cosets from individual outcrops indicate a unidirectional trend. Cross-bedding is laterally continuous for the extent of the outcrops and channel margins are not apparent.

Lithofacies MoSt also occurs in road outcrop along S.H.6, south of the Whakapohai River bridge and in Breccia Creek and tributaries of Bullock Creek. Trough cross-bedded, coarse granular sands in cross-bedded sets are up to 1m thick. The cosets grade up from lithofacies MoC and fine upward in grain size. Lithofacies MoSt is associated with MoSp with which it is interbedded.

The cross-bedding is interpreted as the product of a traction current with a flow in the upper part of the lower flow regime. The cross stratification is a result of avalanching of sediment down the lee slope of bedforms encroaching on the depositional site. The silty mudstone drapes accumulated on some avalanche foresets between avalanches.

The relative paucity of the silty mudstone may be a reflection of the relatively low preservation potential of fine sediment drapes due to a high rate of bed load movement causing continuous sediment avalanches on the lee slope of bedforms. However, the presence of drapes indicates periods of still-stand between currents.

(iii) Lithofacies MoSp: Planar Cross-Bedded Pebbly And Granular Sandstones

Small scale, centimetre bedded planar cross-bedded sandstones in the type section on Monro Beach consist of maroon or white, weathered orange brown, hard, granular, coarse and medium micaceous sandstones with scattered pebbles (Fig 5.28). Sets occasionally show coarse basal lags with rip-up clasts of siltstone. Some sets fine upward from sharp lower contacts and each set is lensoidal and pinches out laterally between other sets. Some cosets show carbonaceous silty mudstone laminae draped between individual sets. The forsets are either asymptotic or angular planar based. Cross bedding is laterally continuous for the extent of outcrop and flow margins are not apparent.

Towards the top of the Moeraki Member the lithofacies contains glauconite and burrows which are up to 2cm in length and resemble those formed by suspension feeders in Seilacher's (1967) skolithos facies.

In Breccia and Wells Creeks thick stacked sequences of planar cross-stratified, coarse pebbly granules, granules, coarse sandstone and coarse to medium sandstones, crop out in decimetre bedded concave downward channels with coarse, pebbly, basal lags. Channels are up to 1m deep and have flat top surfaces or undulatory top surfaces where scouring has occurred before deposition of an overlying bed. The outcrops in Breccia Creek on S.H.6 are sheared and weathered and this has masked or destroyed some bedding relationships and sedimentary structures. Abundant plant fragments including carbonised twigs, and logs are present

within the lithofacies at Breccia Creek.

The process of transportation is interpreted as a traction current, which lies in the upper part of the lower flow regime. The migration of sandwave bedforms, with the two types of foreset, indicate periods of relatively strong flow and periods of relatively weak flow (Collinson & Thompson 1982). Deposition of suspended sediment in drapes between sets indicates periods of standing water between periods of current flow.

The presence of abundant glauconite and burrows indicates a marine influence and periods of still-stand may, therefore, relate to the turning of the tide.

(iv) Lithofacies MoSe: Epsilon Cross-Bedding In Medium Fine Sandstone

The epsilon cross-bedding consists of 5cm to 20cm tabular units that show decreasing set thickness upward. The medium to fine sandstone is white or maroon, hard, moderately sorted, micaceous and contains carbonaceous flecks. Mudstone drapes sometimes coat internal foresets which are unidirectional. The planar cross-bedded sets are sometimes interbedded with small silty sandstone lenses. The lithofacies eventually fines up to silty fine sandstone. The geometry of the bed is sheet like.

Epsilon cross-bedding, which was first named by Allen (1963), has been recognised by numerous authors. Allen and Friend (1968) and Beuf et. al. (1971) (in Reading 1978) recognised internal erosion surfaces which break the cross-bedding development. The lithofacies is usually interpreted as the product of lateral accretion on an inclined surface, usually taken as point bar surfaces (Reading 1978). The facies is also recognised in tidal creeks (Van Straaten 1951 in Reading 1978).



Figure 5.28 (above)
Monro Beach
(Map 1: F36/091167)
Tauperikaka Formation,
Moeraki Member (early to
mid Haumurian). Planar
cross-bedded sandstone.
Youngs bottom to top.
Lithofacies MoSp.

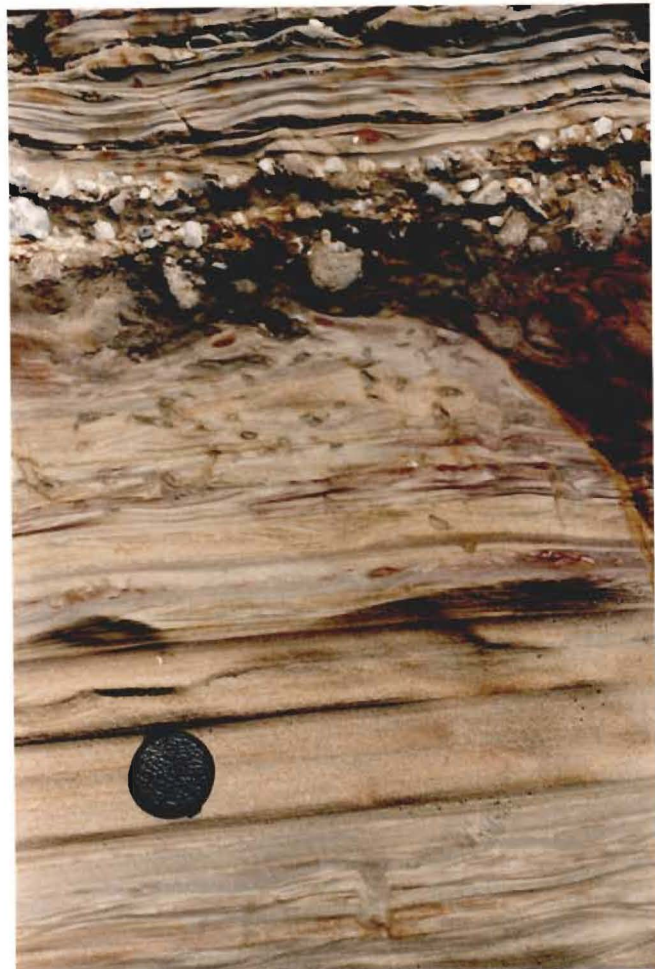


Figure 5.29 (right)
Monro Beach
(Map 1: F36/091168)
Tauperikaka Formation,
Moeraki Member (early to
mid Haumurian). Ripple
and horizontally laminated
glauconitic sandstones. The
conglomerate layer (top) is
the contact between the
Moeraki and Paringa
Members. Younging bottom
to top. Lithofacies MoSr.

(v) Lithofacies MoSh: Horizontally Stratified Pebbly And Granular Sandstones

Horizontally stratified moderately sorted coarse sandstones grade up from lithofacies MoC which lies on a flat erosional scour surface. The lithofacies is stacked in 50cm sets with sharp contacts and each unit is either ungraded or fining upward in grain size. The sets contain angular to sub-rounded cobbles and pebbles in bands, and laminae of carbonaceous material. Mudstone rip-up clasts are abundant. The geometry of each stacked unit is usually sheet like with a flat or undulatory top surface overlain by a finer grained lithofacies.

The base of each bed indicates a period of erosion followed deposition of sediment by a traction current from the lower flow regime. Individual fining upward units each record a waning flow energy. Mudstone rip-up clasts may indicate periods of quiescence characterised by standing water during which fine sediment vertically accreted from suspension, followed by subsequent relatively high energy events, which, due to the low preservation potential, removed the finer sediment by scouring. However the mudstone clasts may be derived from elsewhere. The high energy events become amalgamated into thick (1.5cm) units of lithofacies MoSh.

The texture of the grains indicate a relatively short distance of transport from source without previous exposure to high energy processes in, for example, a nearshore marine environment.

(vi) Lithofacies MoSr: Ripple Bedded And Horizontally Bedded Medium And Fine Sandstones

Beds of ripple laminated sandstone are not evident in the type section until the top part of the Moeraki Member. Rippled bedded sandstones, interbedded with horizontally laminated medium and fine sandstones, occur in beds up to 1m

thick in which the ripples are apparently bi-directional, asymmetric and symmetric, (the two dimensional nature of the outcrop inhibits further evaluation of paleocurrent directions). The beds are white or maroon, weathered orange brown and contain grey siltstone laminae and black carbonaceous laminae (Fig. 5.29).

Burrows are up to 2cm long and vertical or up to 0.5cm thick and on oblique angles to bedding and burrowing increases in frequency towards the tops of beds. The larger burrows resemble suspension feeders from Seilacher's (1967) *Glossifungites* facies. The small burrows represent mining programmes by sediment feeders of the *Cruziana* facies (Seilacher 1967) (Fig. 5.29).

The ripple and horizontal lamination results from flows in the lower part of the lower flow regime. Occasional mudstone laminae indicates the transport of sand is intermittent. Bi-directional paleocurrents probably indicate a tidal influence in which case the mudstone laminae may record deposition during tidal still-stand. The ripples may represent both current and wave ripples. The relative lack of burrows in vertically adjacent beds of lithofacies MoSr may indicate fluctuating salinity or high sedimentation rates.

(vii) Lithofacies MoSZ1: Laminated Fine Sandstone And Siltstone, Lenticular And Wavy Bedding

Grey, hard, structureless muddy siltstones contain laminae and lenses of medium or fine sandstone which are usually millimetres thick, the shape in plan view and the internal cross stratification within the lenses is difficult to assess because of the two dimensional nature of the outcrop (Fig. 5.30). The larger ripples show load structures (Fig. 5.31). Surrounding muddy siltstone has risen diapirically around the ripples. The lithofacies is very minor and is thin (a few centimetres thick) and eroded into by overlying coarser lithofacies.



Figure 5.30
Monro Beach (Map 1: F36/091167) Tauperikaka Formation, Moeraki Member
(early to mid Haumurian). Lenticular and wavy bedding. Youngs bottom to
top. Lithofacies MoSZI.



Figure 5.31
Monro Beach (Map 1: F36/091167) Tauperikaka Formation, Moeraki Member
(early to mid Haumurian). Load-casted ripples. Youngs bottom to top.
Lithofacies MoSZI.

Lithofacies MoSZ1 represents long periods of vertical aggradation, in standing water, of silty mudstone. The cycle is occasionally interrupted by low kinetic energy currents depositing fine sandstone as bedload. Lenticular bedding is due to either current deposition or wave reworking. Load casted ripples indicates the muddy siltstone was over saturated with water.

The relative infrequency of lithofacies MoSZ1 in the Moeraki Member and the thinness of bedding may be a reflection of the relatively low preservation potential of the lithofacies within the environment of deposition.

(viii) Lithofacies MoMm: Structureless Mudstone

Thick beds of structureless, grey, hard, carbonaceous silty mudstones are up to 4.5m thick. The lateral geometry of the bed is not exposed.

The lithofacies represents long periods of undisturbed vertical aggradation from standing water. The preservation potential of the lithofacies is relatively high to preserve 4.5m which suggests the sediment accumulated in a protected environment below the base level of any migrating channels. The lithofacies could represent the infilling of abandoned channels, ox bow lakes or lagoonal type structures.

In Breccia Creek, beds up to 1m thick are highly carbonaceous and consist of silty mud. Small channels up to 1m deep cut into the top of the lithofacies. Concave downward lenses of coarse and medium sands are also contained within the lithofacies.

The Breccia Creek exposures represent semi-protected areas which supported vegetation, but too much sedimentation prevented accumulation of thick peat deposits. The back swamp was frequently dissected by small channels.

Concretions

Concretions are associated with the bottom and top contacts of lithofacies MoSe, MoSr and MoMl. The concretions are maroon, sideritic sandstones or siltstones, oval in shape and up to 30cm or 40cm along the longest axis, and occur together in bands parallel to bedding.

Composition of the Moeraki Member

The compositions of typical sandstones are shown in Table 5.3. Litharenites sub-litharenites and feldspathic litharenites are all represented in samples from the Moeraki Member (Fig. 5.15).

Quartz

The majority of sections studied are of medium to fine silty sandstones and quartz grains are predominantly monocrystalline.

Polycrystalline grains usually consist of 2 to 5 crystals with strongly sutured inter-crystalline boundaries. Some polycrystalline grains are made of up to 50 crystals (U.of C. 11986) and other grains show excessive elongation of quartz crystals (the latter grains are included under "rock fragments"). Polycrystalline grains with strongly sutured inter-crystalline boundaries, consisting entirely of slightly elongated quartz crystal with a bimodal size distribution (U.of C. 11981) are very similar to grains from a disintegrated gneiss (Blatt et. al. 1980, p.288). Undulatory extinction is apparent in 90% to 100% of quartz grains and in most samples is 5° or less.

A minority of monocrystalline grains show lines of vacuoles typical of vein quartz (U.of C. 11986) and occasionally, monocrystalline grains contain worms of mica (U.of C. 11986).

Table 5.3
 Modal analyses (in%) of typical sandstones from the Tauperikaka Formation
 Moeraki Member.

*¹ Alternates between laminae
 **² Biotite

SAMPLE NO. U. of C. D.S.I.R.	11966 F36/p27	11980 -----	11985 S87/p52	11986 S87/p54	11982 (AA69)	119891 (T2)	11987 S87/p71
APPARENT GRAINSIZE (mm)							
max.	0.41	0.25	0.70	2.21	3.35	2.70	1.05
mode(s).	0.20/0.15	0.10	0.22	0.9/0.6	2.20	0.5	0.35
min.	0.03	0.03	0.03	0.05	0.03	0.03	0.03
ROUNDNESS	v.a.-s.r.	v.a.-s.a.	a.-s.a.	v.a.-a.	a.-r.	a.-r.	v.a.-s.r.
SORTING	v.w.s.	w.s.	m.s.	m.s.	m.s.	m.s.	p.s.-m.s.
QUARTZ	50	45	40	60	50	40	60
mono.	--	98	95	60	50	95	80
poly.	--	2	5	40	50	5	20
undul.	--	95	95	95	100	99	95
MICROCLINE	6	10	3	5	:	5-15* ¹	:
other.ALK.F.	0	0	0	>1	-15	--	-2
PLAG.FELD	2	0	2	>1	:	0	:
ROCK FRAG	30	10	45	20	25	25	15
MICA	4	1	1	1	>1	2	1
H and O	>1	10	1	>1	>1	>1	>1
OTHER	>1	>1	>1		0	>1* ²	>1
MATRIX CEMENT:	>5	20	>5	4	5	18	13
QUARTZ	5	5	5	10	5	5	10
DOLOMITE	0	0	0	0	0	0	0
SIDERITE	5	0	0	0	0	0	0
LIMONITE							
STAIN	0	1	1	2	0	3	0
GLAUCONITE	0	0	0	0	2	0	0

The amount of rim cement, which usually falls between 5% and 10% of a whole rock composition, is difficult to estimate as parent grains are not usually outlined by impurities. Rim cement is apparent by its protruding nature into surrounding grains and the mutually interlocking grain boundaries. Overgrowths are angular and do not show any signs of rounding.

Feldspars

Feldspars are manifested in significant quantities in all the Moeraki Member samples studied. Alkali feldspar is predominant, with between 3% and 15% of a whole rock composition, of which microcline is the main constituent (Fig. 5.32). Orthoclase is apparent in some samples (U.of C. 11982 and 11981) and anorthoclase may be present in one sample (U.of C. 11986).

Plagioclase feldspar (albite where identifiable) is present in quantities less than 2% (U.of C. 11985; 11986; and 11987). Plagioclase feldspar also occurs combined with vein chlorite in rock fragments (U.of C. 11985).

Alkali feldspars are usually very fresh (samples U.of C. 11981 and 11985), but occasionally show signs of vacuolization and kaolinitization along cleavages (sample U.of C. 11982). Grains are usually angular to sub-angular but are occasionally both very angular and rounded (U.of C. 11982). Plagioclase is fresh or shows signs of kaolinitization (U.of C. 11985).

Rock Fragments

The percentage of rock fragments varies considerably from 45% to 10% which is reflected by the litharenite and sub-litharenite classification of Moeraki Member rocks (Fig. 5.15).

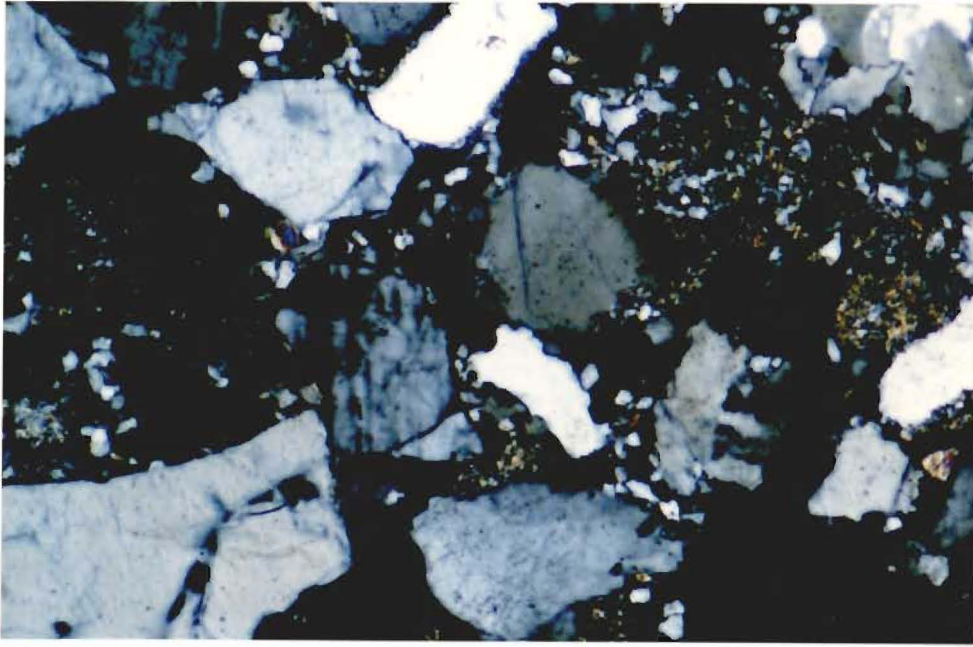


Figure 5.32 Microcline, quartz and sedimentary rock fragments, including chert (left).

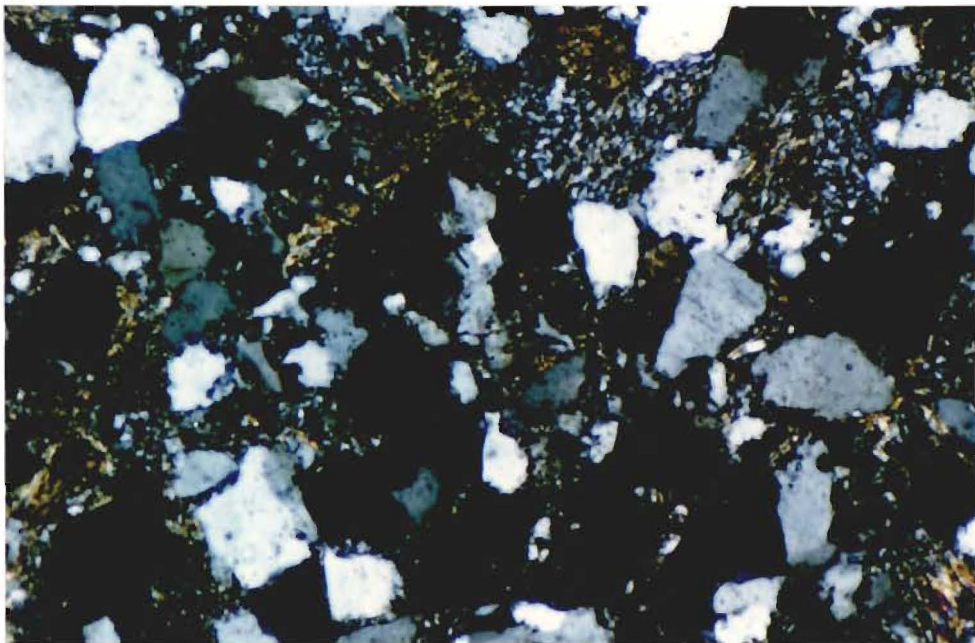


Figure 5.33
Rock fragments squeezed between more resistant quartz grains.

Rock fragments consist of chert, which is a major rock fragment component (Fig. 5.32), vein chlorite (antigarrite?) (U.of C. 11985), stretched polycrystalline grains (U.of C. 11985; 11987), and feldspars combined with vein chlorite and muscovite (U.of C. 11985 and 11981 respectively). The most abundant rock fragment is composed of silt sized quartz grains and oriented flecks, or continuous networks of mica. The latter rock fragments show varying degrees of deformation, and have been squeezed around more resistant quartz grains (Fig. 5.33) (sample U.of C. 11981). Some of the laminae contain matrix and no rock fragments and some contain rock fragments, which indicates rock fragments may have been broken down in the environment of deposition, before burial. Deformation of rock fragments after burial has formed a pseudomatrix in many samples (e.g. U.of C. 11986).

Samples from the base of the Lagoon Creek sequence (Sample U.of C. 11982) contain granules of Greenland Group lithologies (Fig. 5.34). The granules are composed of poorly sorted, angular, medium sand to coarse silt in an argillaceous matrix. The framework grains are quartz. The matrix contains a mass of oriented micas indicating low grade metamorphism. The edges of some of the granules have been squeezed to conform to the shape of the boundaries of surrounding quartz grains.

Polycrystalline grains show strongly sutured intercrystalline boundaries, elongation of quartz crystals, bimodal size distribution of crystals and veins of chert like material cutting through the grains (U.of C. 11981). Some samples (U.of C. 11988a, 11985) contain similar polycrystalline grains in which quartz crystals show pronounced elongation (Fig. 5.35). Examples in the latter two samples resemble mylonite lithologies (pers. comm. D. Shelly).

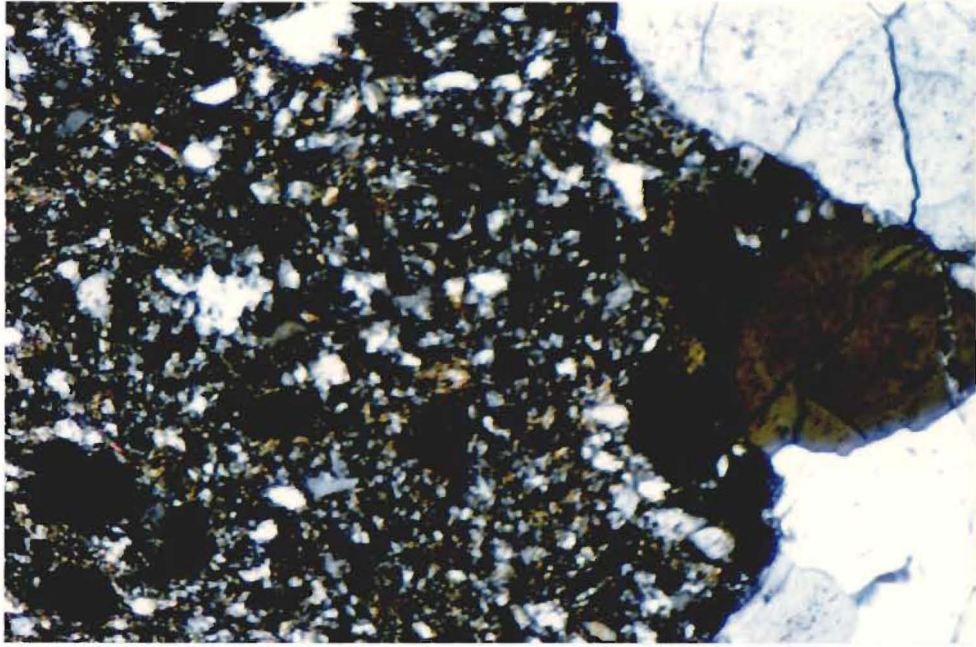


Figure 5.34
A granule derived from the Greenland Group (left) abuts against quartz granules (right).

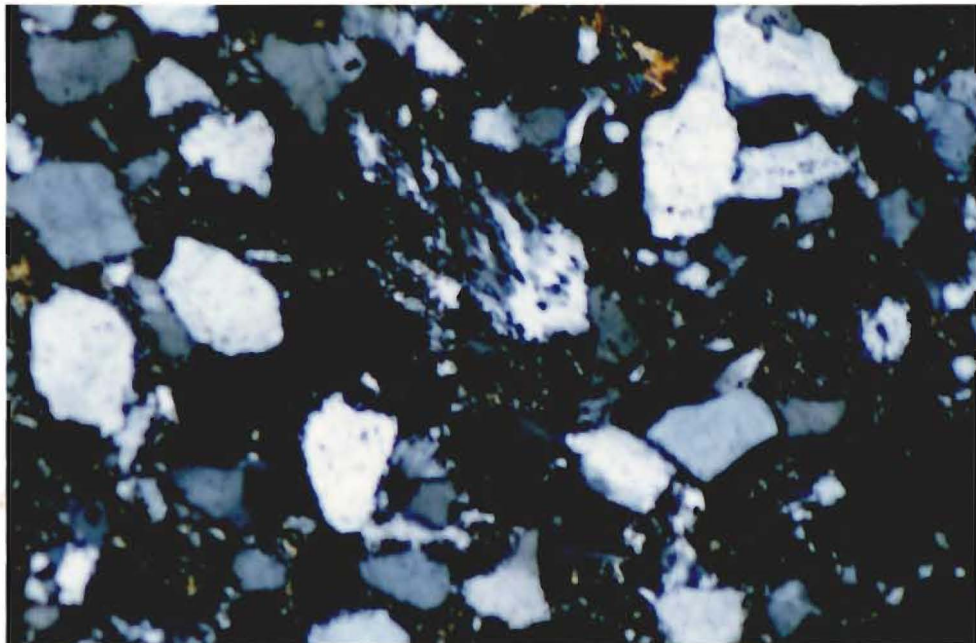


Figure 5.35
A polycrystalline grain in which quartz crystals show pronounced elongation (middle).

Heavy Minerals

The most abundant heavy minerals are ilmenite (e.g. U.of C. 11986) and leucoxene (U.of C. 11981), and zircon and tourmaline (U.of C. 11980) are present in most samples. Leucoxene is present in all but one of the samples from the Moeraki Member. A large amount of diagenetic material including siderite or ankerite? and pyrite is also present (U.of C. 11966). In addition to the latter minerals, apatite has been noted in a sample from the lower part of the Tauperikaka Formation (D. Smale pers. comm. Geological Survey, Canterbury). Tourmaline is the brown variety and is sub-rounded to rounded. Zircons are euhedral or sub-rounded.

Glauconite

Glauconite appears towards the top of the Moeraki Member exposed on Monro Beach and throughout the Moeraki Member exposed in Lagoon Creek.

The glauconite in Lagoon Creek samples is interstitial material (U.of C. 11982). The individual green pellets, comprising 2% of the total rock composition, have succumbed to compaction and have squeezed around more resistant framework grains.

Matrix And Cement

The proportion of matrix is occasionally as high as 27% (U.of C. 11981) but is more usually less than 5% and occasionally 10% of a whole rock composition.

The term matrix is used to describe interstitial material which is not conclusively pseudomatrix. The fine line between pseudomatrix, a discontinuous interstitial paste formed by the deformation of weak framework grains (Lewis 1982), and primary matrix, an interstitial fine clastic mineral matter which was deposited in the environment of sedimentation penecontemporaneously with the framework grains (Lewis 1982), is often difficult to estimate. Pseu-

domatrix is included with the framework grain population.

The matrix consists of quartz and sericite which lacks orientation and may be primary or diagenetic. In some samples (U. of C. 11981) laminae containing matrix are probably derived from the break down of rock fragments in the environment of deposition (see discussion under rock fragments).

The Moeraki Member samples show cementation by silica cement (see discussion under quartz). Carbonate cements are generally lacking in the Moeraki Member. Occasionally thin beds or layers of concretions contain red rhombic crystals which may be siderite or ankerite. The colour is due to oxidation of the crystal surfaces producing limonitic coatings. A minor amount of iron staining (5%) is present within the matrix of approximately half of the sections studied.

Interpretation of Composition

The abundance of fine grained sedimentary rock fragments, cherts, sub-rounded zircon and tourmaline and abundant leucoxene indicates a sedimentary source. A low rank metamorphic provenance is supported by textures in a large proportion of siltstone fragments containing mica. Granules and pebbles clearly indicate the Greenland Group sediments as a source rock. The Greenland Group, which contains an abundance of leucoxene, zircon and tourmaline, is thermally metamorphosed in areas surrounding granite plutons. Plagioclase feldspar may have been derived from the Greenland Group sediments of low metamorphic rank.

The abundance of microcline in association with coarse quartz grains indicates an acid igneous source. The Tuhua Group granites contain high proportions of the latter minerals. The coarse size of quartz grains indicates the Tuhua Group as a source rock as the Greenland Group sediments are predominantly medium and fine sandstones. Grains

derived from veins may be from either of the latter mentioned source rocks. A gneissic source is also indicated by some polycrystalline grains. Rock fragments which may be derived from a mylonite source, indicate proximity to a great zone of tectonic dislocation.

Coarse textures and fluctuations in the number of feldspars between samples is probably as much a function of proximity to granite plutons as well as sediment transportation mechanisms. The transport mechanism and distance to the depositional site will determine the amount of rounding of feldspar grains. The small degree of alteration of the majority of angular feldspars probably indicates relatively rapid sedimentation. Koalinitization of some grains may be a result of weathering before burial or diagenetic alteration.

The high proportion of leucoxene may be derived from the Greenland Group sediments, or underlying sediments, or perhaps an alteration product of ilmenite which could be derived from the Greenland Group sediments or from granite.

A proportion of the deformed rock fragments probably represent perigenic clasts and clasts derived from underlying formations. Separation of structurally deformed Greenland Group derived clasts from soft perigenic grains is not possible.

Pyrite is a diagenetic feature. The weathering of the pyrite gives the Moeraki Member sandstone the distinctive yellow and brown colours.

Lithofacies Sequences and Environments of Deposition

The four areas of Moeraki Member outcrop are: (a) the Monro Beach section; (b) the Breccia Creek and Bullock Creek tributary sections; (c) the Lagoon Creek Sequence. Each has a characteristic lithofacies sequence.

(a) Monro Beach Section.

At Monro Beach, in the basal part of the section, lithofacies MoSe is repeated in the fining upward cycles and eventually grades to MoMm (Fig. 5.36). The sequence probably indicates the deposition of point bars belonging to a migrating fluvial channel prior to channel abandonment. Barwis (1978) described features of tidal creek point bars that clearly distinguish them from fluvial point bars. The features include bimodal bedform distributions, flaser bedding on bar crests, intense bioturbation on bar crests and spartina rooted muds forming a dense mat capping the sequence. As none of the latter features are present (Fig 5.36) a fluvial origin is envisaged.

The stacked sequences of lithofacies MoSh, MoZl and MoMm suggest repeated storm/flood events. The finer sediment deposited in intervening periods may have been removed by the initial scour phase of the following high energy event. The fine sediment was not suitable for colonization by fauna, which may suggest fluctuating salinity in the inactive tract. An inter-channel area protected by poorly developed levees, that may be a marine influenced inter-distributary bay protected from the sea, is envisaged. The flood events may be localised crevasse splays, or larger storm events covering the flood plain with sediment once channel areas have been filled. Floods might also be radiating from incision points where streams leave mountain fronts or fault scarps.

The stacked MoSp and minor MoSZl and MoMm lithofacies indicate the periodic migration of lower flow regime bedforms in one dominant direction, alternating with periods of standing water. Higher in the column, a marine tidal influence becomes evident with the appearance of bi-directional currents, frequent slack water periods, increased burrowing and the appearance of substantial quantities of the mineral glauconite. Lithofacies MoSr was influenced by both fluvial and marine processes. The upper part of the sequence is therefore interpreted as an environment with a sheltered

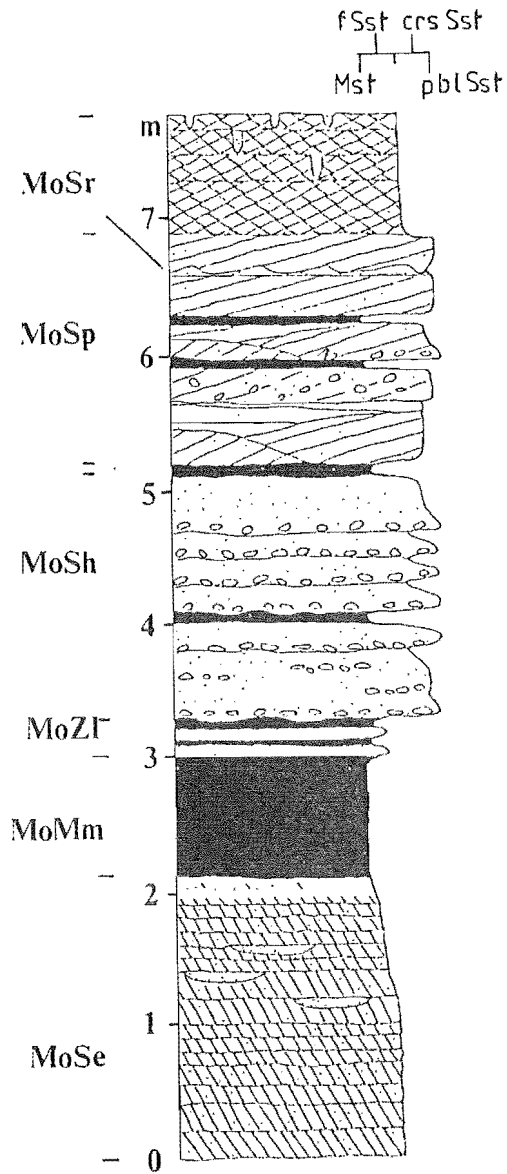


Figure 5.36
Lithofacies sequence, Tauperikaka Formation, Moeraki Member (early to mid Haumurian), Monro Beach, South Westland.

embayment, protected by a barrier, near the estuary of one or more small tidal creeks. Sand is probably provided by periodic floods from tidal estuaries and then reworked by tidal and/or wave currents. The marine transgression may be due to coastal subsidence, a rise in sea level or a combination of both. Where subsidence rates are high relative to the rate of the shore face erosion, a relatively thick and complete transgressive sequence will be preserved, but where subsidence rates are low, the sequence will be incomplete (Reading 1978). The transgression may have removed much of the sediments representing transitional environments between the fluvial and the marine bay environments. A laterally continuous layer of pebbles, cobbles and boulders on an undulatory surface at the base of the Paringa Member (see Section 5.3.2), in the type section on Monro Beach, may equate to the erosion surface, which in transgressive sequences is often included at the base of the lower shore-face facies.

During a marine transgression where streams are delivering a large amount of sediment into a sheltered area, where tides are not free to remove the sediment, stream channels must silt up to keep pace with the rise in the water table. Inactive tracts will be subjected to repeated flooding. The channels are also likely to continuously move laterally to lower lying areas. In order to preserve fine overbank facies, a combination of high sinuosity streams and overall subsidence is required. Low sinuosity streams tend to comb their flood plains (Allen 1965) and without net subsidence multiple stacked erosion surfaces in coarser sediment result as the preservation potential of finer overbank facies is lowered (Reading 1978). Taking these observations on modern environmental settings into consideration, the Moeraki Member on Monro Beach (Fig. 5.36) seems to represent a coastal flood plain, during a marine transgression, across which low sinuosity streams moved laterally back and forth, and which was also subject to repeated flooding. Back swamps are not represented due to their low preservation potential.

(b) Breccia Creek and Bullock Creek tributary Sections

In Breccia and Wells Creeks, stacked sequences of lithofacies MoC; MoSt; MoSp and MoSh (Fig 5.37), indicating channel processes, lack marine indicators and the sequences only contain a minor amount of fine grained flood plain sediments. The finer grained lithofacies that crop out contain lenses of coarser material and upper contacts are undulatory with concave downward scour surfaces of up to 1m deep filled with coarse pebbly granules. The sequence probably represents a sandy fan with laterally migrating or braided shallow channels. Lithofacies MoMm may represent a back swamp protected by a levee, an abandoned channel or a lagoon.

There is a lack of coal seams in the Moeraki Member sequence. At the top of Bishop's Folly, small lenses of coal measuring tens of centimetres thick in width, crop out between coarse grained lithofacies. The coal indicates swamps with favourable conditions for peat accumulation existed (Section 6.3.3). The lenses are remnants of seams eroded by migrating channels represented in the overlying coarse lithofacies. The low preservation potential of coal swamp deposits is probably due to the type of fluvial regime in combination with the local tectonic regime.

(c) Lagoon Creek Section.

The Moeraki Member sequence (Fig. 5.38) crops out at the base of Lagoon Creek. The processes and the unidirectional nature of the cross-bedding can be interpreted as the product of in-channel deposition within a fluvial regime. However, unless a nearby source rock is providing fresh glauconite, the environment must have had a marine influence. A similar succession is described by Kelling and George (1971, in Reading 1978) which is interpreted as a fluvial distributary channel sequence (Fig. 5.39). An alternative explanation, which may account for the glauconite, is that the sequence represents channel bottom deposits at the base of an estuarine channel sand. The glauco-

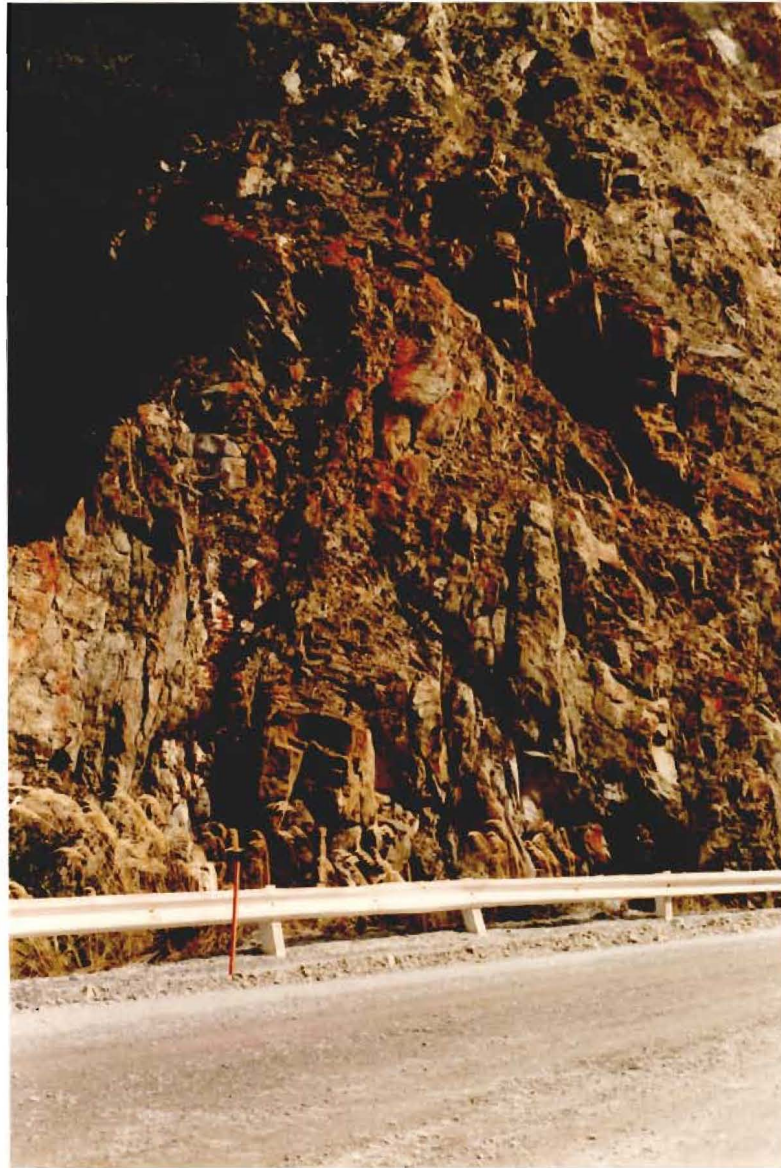


Figure 5.37
Breccia Creek (Map 1: F36/042124) Tauperikaka Formation, Moeraki
Member (early to mid Haumurian). Sequence of stacked lithofacies MoC;
MoSt; MoSp and MoSh. Concave scour surfaces suggest channel processes.

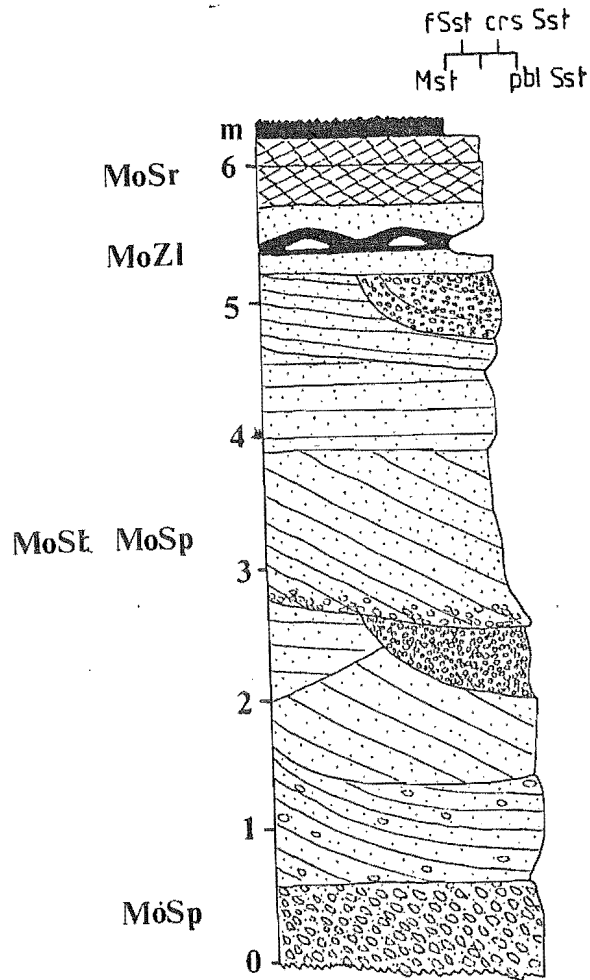


Figure 5.38
Lithofacies sequence, Tauperikaka Formation, Moeraki Member (early to mid Haumurian) Lagoon Creek, South Westland.

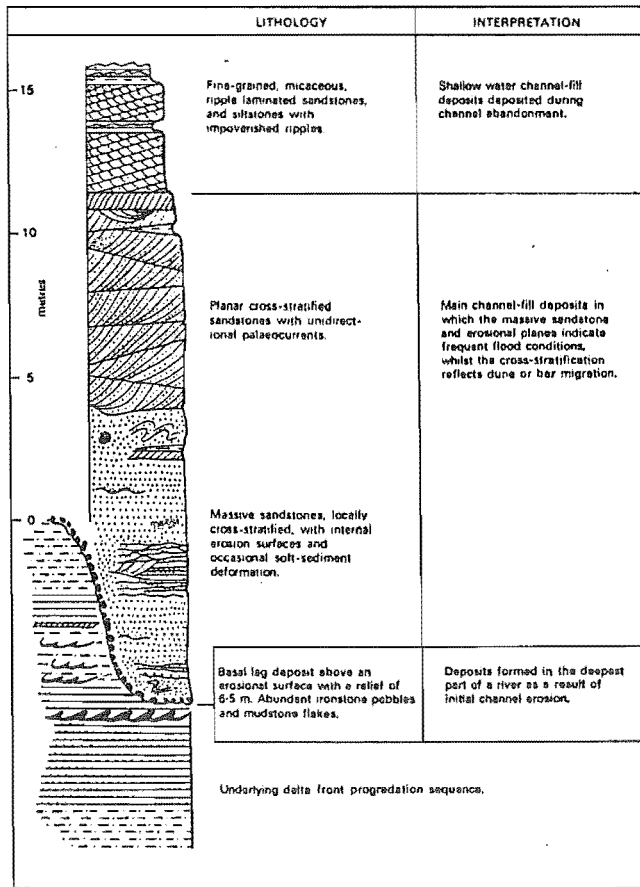


Figure 5.39
 A carboniferous fluvial distributary channel sequence in south-west Wales (Kelling and George 1971, in Reading 1978).

nite is likely to have been washed into the environment by tidal currents during periods of low stream flow.

Lithofacies MoSr and MoZl at the top of the Lagoon Creek lithofacies sequence together indicate a drop off in energy of depositing currents, and tidal processes are evident. The sequence probably represents channel abandonment and shallow water tidal and wave re-working of sands.

Textural immaturity of the Moeraki Member sediments, throughout the study area, combined with the abundance of rock fragments indicates the sediment has not undergone a rigorous mechanical breakdown or been transported over long distances and the sediment source is, therefore, relatively local.

5.3.2 Paringa Member
Sedimentary Structures and Textures

Introduction

The Paringa Member is divided into eight lithofacies which are based on combinations of characteristic sedimentary structures and textures. Each lithofacies has been assigned a code, for the sake of brevity during references to a lithofacies in the text. The codes are explained in Appendix 2 but briefly the codes are: PaC; PaSa; PaSf; PaSt; PaSp; PaSb; PaSr; PaSZ1; PaSm.

(i) Lithofacies PaC: Basal Conglomerate lag

A conglomerate layer crops out along strike for at least 35m at the base of the Paringa member type section on Monro Beach. Lithofacies PaC has not been seen elsewhere.

The conglomerate layer is approximately 20cm thick, but the thickness varies along strike, and consists of angular to sub-rounded sandstone clasts, occasionally up to 15cm in length, quartz clasts up to 20cm in length, and mudstone rip-up clasts. The average clast is the size of a pebble (Figs 5.40 and 5.29). Sandstone pebbles are more rounded than the sub-angular quartz pebbles. The conglomerate grades upward from small boulders, cobbles and pebbles to pebbles in some places and does not show imbrication. The clast supported conglomerate has a glauconitic sandstone matrix. The conglomerate layer rests on a 2cm thick, highly glauconitic, burrowed, fine grained green sand, and in some places a siltstone in which load structures are apparent. The fine sandstone and siltstone shows intense burrowing and/or a layer of oval maroon sideritic? concretions which are up to 20cm in diameter.

The concentration of glauconite and intense burrowing which occur together may represent a minor hiatus.



Figure 5.40
Monro Beach (Map 1: F36/091168) Tauperikaka Formation, contact between the Moeraki and Paringa Members (both early to mid Haumurian). Conglomerate layer (see also Figure 5.29). Youngs in direction of hammer handle. Lithofacies PaC.



Figure 5.41
Monro Beach (Map 1: F36/091168) Tauperikaka Formation, Paringa Member (early to mid Haumurian). Large scale planar tabular cross-bedding (tidal bundles) overlying ripple laminated sandstone/siltstone. Photo oriented to young from bottom to top. Lithofacies PaSa.

(ii) Lithofacies PaSa: Large Scale Planar Tabular Cross-Bedding.

Lithofacies PaSa crops out on Monro Beach and in Lagoon Creek. The lithofacies consists of large scale planar tabular cross-beds up to 1m thick, comprising tangential "avalanche" forsets (Figs. 5.41 & 5.42). Forsets dip at a maximum angle of 20° . The forsets pinch out upward and downward. Each forset is composed of white, very well sorted coarse or medium sand bordered by dark streaks of brown mud. Coarse grained forsets are 2cm - 3.5cm thick. Medium sand grained forsets are 0.5cm - 2cm thick. The upper surface of each forset is usually flat but occasionally is wavy on a small ripple scale. Forsets lack internal structure and do not show grading. Sub-rounded quartz pebbles and occasional burrows are scattered throughout the lithofacies.

Where bottom sets are apparent, each forset descends with a decreasing angle of rest, (to approximately 5° from bedding) to sand and mud wavy bedded ripple couplets (Figs. 5.43a and b). Top sets are not usually preserved. The upper contact of the lithofacies is sharp.

The lithofacies is laterally continuous for the length of the outcrop (up to 20m). However, transitional lithofacies which fall between PaSa and PaSf end members are apparent. The transition lithofacies consists of forsets dipping from 10° down to 5° from bedding. Forsets show a lateral decrease in their angle of repose until forsets become indistinguishable and large scale ripple flaser bedding (Lithofacies PaSf) replaces the forset bedding. Large (order of metres) shallow concave downward scour surfaces, on the upper surface of lithofacies PaSa are usually overlain by lithofacies PaSf.

Small scale faulting associated with soft sediment deformation displaces forset beds by a few centimetres (Fig 5.44). Some faults have associated water expulsion structures.



Figure 5.42 (above)
Monro Beach
(Map 1: F36/091168)
Tauperikaka Formation,
Paringa Member (early to
mid Haumurian). Large
scale planar tabular cross
bedding with mudstone
drapes on tangential
foresets. Interbedded with
flaser bedded sandstone.
Younging right to left.
Lithofacies PaSa and PaSf.

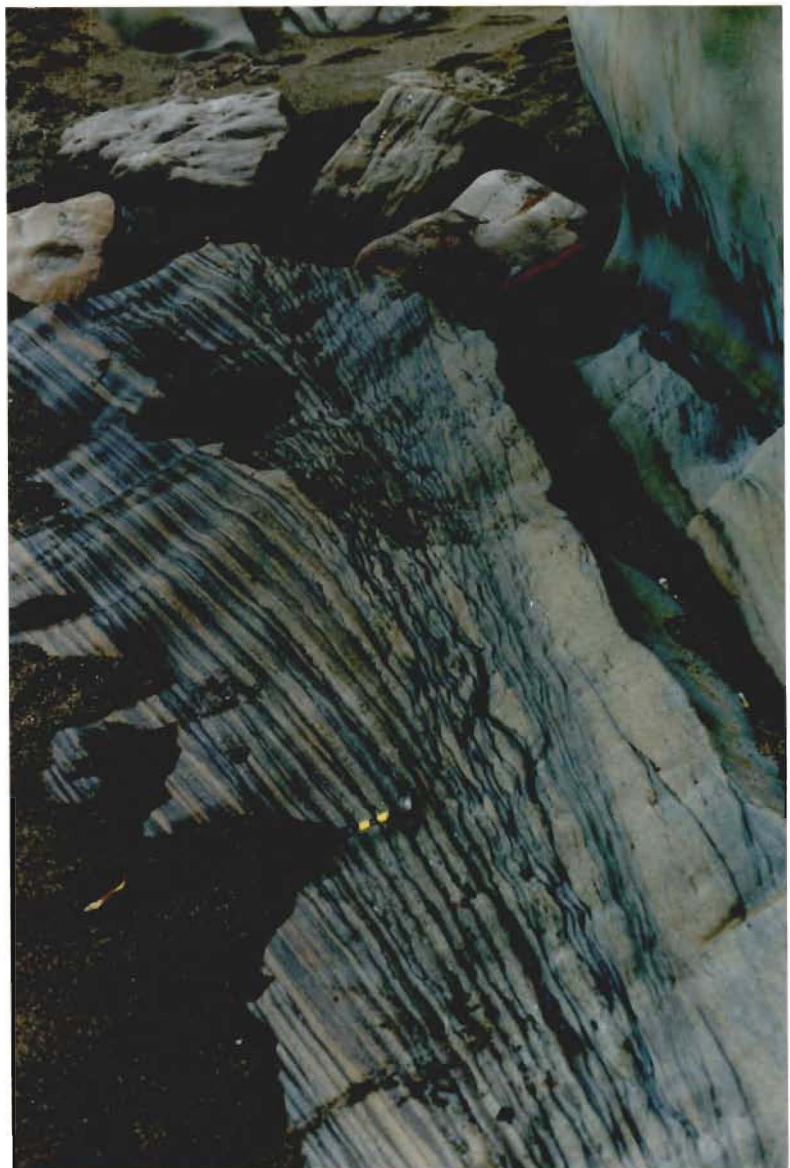
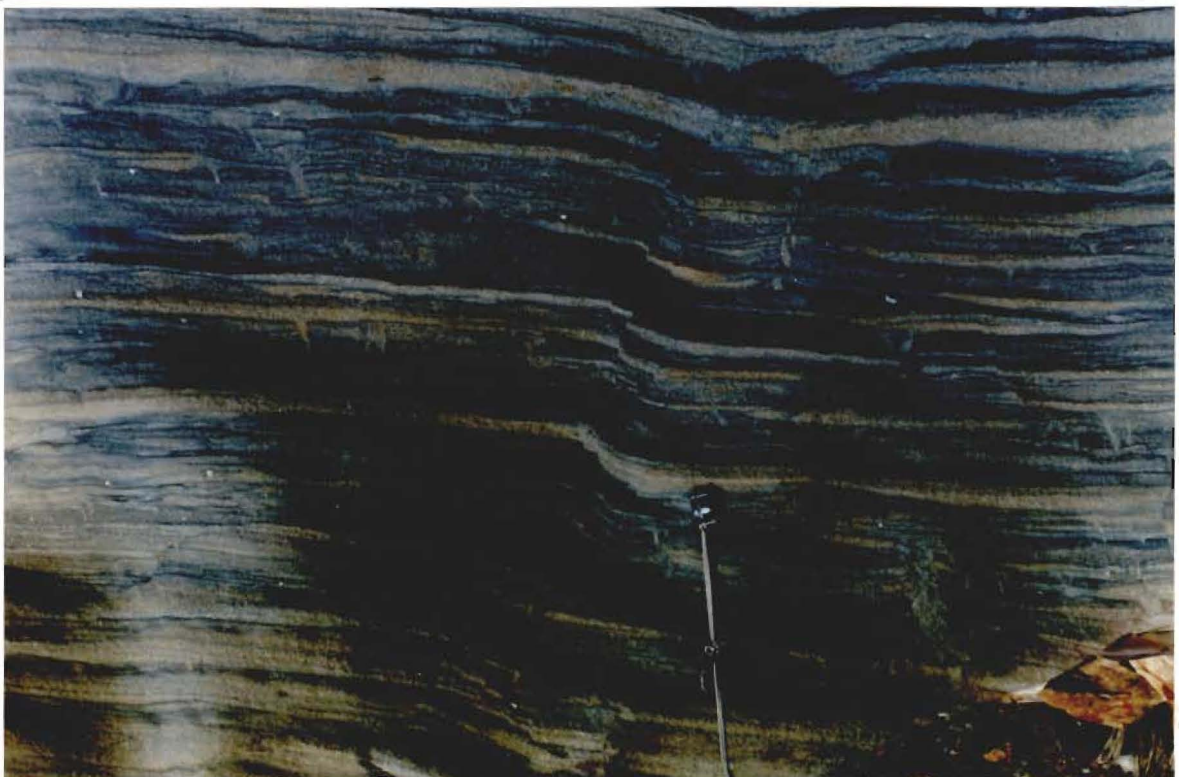


Figure 5.43a(right)
Monro Beach
(Map 1: F36/091168)
Tauperikaka Formation,
Paringa Member (early to
mid Haumurian). Bottom
sets on "tidal bundles"
showing foresets
descending to wavy
bedded sandstone and
siltstone couplets.
Younging right to left
(bedding dips near
vertical). Lithofacies
PaSa.

Figure 5.43b (right)
Monro Beach
(Map 1: F36/091168)
Tauperikaka Formation,
Paringa Member (early
to mid Haumurian).
Close up photo of
ripple couplets.
Younging left to right.
Lithofacies PaSa.



Figure 5.44 (below)
Otumotu Beach
(Map 1: F36/093169)
Tauperikaka Formation,
Paringa Member (early
to mid Haumurian).
Small scale faulting
associated with soft
sediment deformation.
(Photo oriented to
young from bottom to
top.)



Visser (1980) and Van den Berg (1982) described large scale cross-bedded sets with mud drapes similar to the sedimentary structures that form an important part of the Par-
inga Member. Visser described the large scale forsets as lateral bundle sequences, a descriptive term which has been changed to tidal bundle sequences in recent descriptions by several authors working on Holocene sediments in S.W. Netherlands. The structures are deposited by high energy bi-directional tidal currents in channelised parts of tidal estuaries or embayments and are related to the migration of megaripples. The term "megaripple" is used here descriptively for a large-scale (height above 0.04m), asymmetrical bedform with an avalanche face (after Mowbray et.al. 1984).

(iii) Lithofacies PaSf: Bi-directional Large Scale Ripple Flaser Bedded Medium Sandstones.

Cosets of planar and wedge shape sets are from 20cm to 2m thick. Sets consist of flaser bedded and wavy bedded very well sorted to moderately sorted medium sandstones and mudstones (Fig. 5.45). Mudstone laminae are up to 2mm thick and form shallow troughs, wavy convex crests which bifurcate.

Separate horizons within individual sets show opposing paleocurrent directions. The lower three quarters of a set will show cross-bedding in one direction, the upper quarter may show cross-bedding in the opposing direction. In the latter case, bedforms climb up an inclined surface, whereas in the former case, bedforms migrate down an inclined surface.

A basal lag, consisting of a few centimetres of quartz granules, is common, granules are also scattered throughout the lithofacies. Burrows are scattered and infrequent, but increase upwards within a set. The bottom set of a coset is sometimes deposited on a concave downward, broad and shallow scour surface. The top contact of a coset is either flat or undulatory showing ripple and megaripple



Figure 5.45
Monro Beach (Map 1: F36091168) Tauperikaka Formation, Paringa Member (early to mid Haumurian). Bi-directional mega-ripple flaser bedding. Burrow to left of camera lens. Youngs from bottom to top. Lithofacies PaSf.

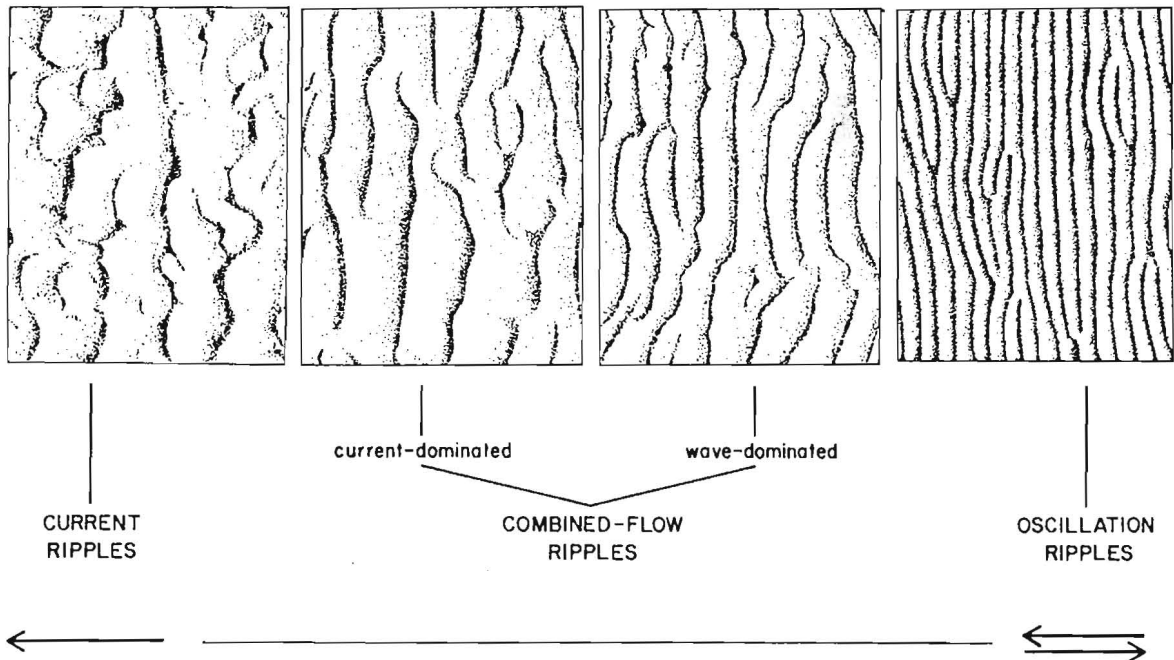


Figure 5.46
Plan view of ripples produced in 0.28mm sand by steady unidirectional flow, combined flow, and symmetrical purely oscillatory flow, showing variation in pattern of crests and troughs with relative importance of translatory and oscillatory flow components. Each box is 75cm across. (After Harms 1969 and Harms et al. 1982)

sized undulations.

Lithofacies PaSf was deposited by traction currents with flows in the middle to upper part of the lower flow regime. The bifurcation of flasers and distance between flasers indicates the migration of large ripples with sinuous crests. The ripple pattern equates to a steady unidirectional flow as opposed to an oscillatory flow and therefore relates to a current dominated rather than wave dominated current (Harms 1969) (Fig. 5.46). Deposition of suspended sediment in flasers indicates a current of fluctuating strength with periods of still stand. The latter factors combined with the bi-directional nature of the flow implies a tidal current. Mud drapes may be related to tidal rhythm or may be products of longer periods.

(iv) Lithofacies PaSt: Bi-directional Trough Cross-Bedded Medium Sandstones.

The two dimensional nature of the outcrop does not allow the direct differentiation of trough cross-bedding from planar cross-bedding in the majority of outcrops, but at Monro Beach an outcrop reveals trough cross-bedding. Each set measures 30cm to 40cm in width by 10cm -20cm in height with sharp and slightly convex downward lower contacts and sharp and erosional upper contacts, which also show small sandwave sized undulations. The sets consist of very well sorted medium sandstones with internal forsets that are bi-directional and coated with mudstone drapes.

Lithofacies PaSt was deposited by a traction flow in the middle to upper part of the lower flow regime. The bi-directional nature of the cross stratification and mudstone drapes indicate the currents are probably tidal, the mud drapes representing deposition from standing water during tidal still-stand.

(v) Lithofacies PaSp: Bi-directional Planar And Wedge Shaped Cross-Bedded Sandstone

Cosets of planar and wedge shaped tabular cross-bedding, are up to 2m thick containing sets from 10cm to 50cm thick, and are composed of very well sorted medium sandstones. Internal forsets indicate the presence of at least a bi-directional system. Siltstone and mudstone rip-up clasts are occasionally scattered throughout the lithofacies. Occasional scattered burrows are also present.

In the upper part of the Paringa member, beds become heavily bioturbated. Single wedge shaped or lensoidal sets 5m - 20m in length and 15cm - 20cm in height, pinching out laterally, are isolated in lithofacies PaSr or PaSZL (Fig. 5.47). At the south-western end of Monro Beach, the isolated sets are often sideritic and heavily burrowed or completely bioturbated.

Lithofacies PaSp was deposited by traction currents with flows in the middle part of the lower flow regime. The bi-directional nature of the cross stratification indicates the currents are probably tidal. Fine grained rip-up clasts indicate periods of scour at the expense of suspension deposits, deposited during calmer periods. A lack of burrows in cross stratified beds may indicate rapid continual sedimentation or a fresh-water influence causing fluctuating salinity.

(vi) Lithofacies PaSb: Stacked Non Erosive Lensoidal Sets

At Monro Beach and in Lagoon Creek lensoidal sets separated by continuous mudstone bands complement each other in the way they are stacked. Two laterally adjacent sets cause an overlying set to fill the intervening low and pinch out laterally on top of the previous sets. Sets are 2m long and up to 40cm high. Internal low angle forset stratification is unidirectional.

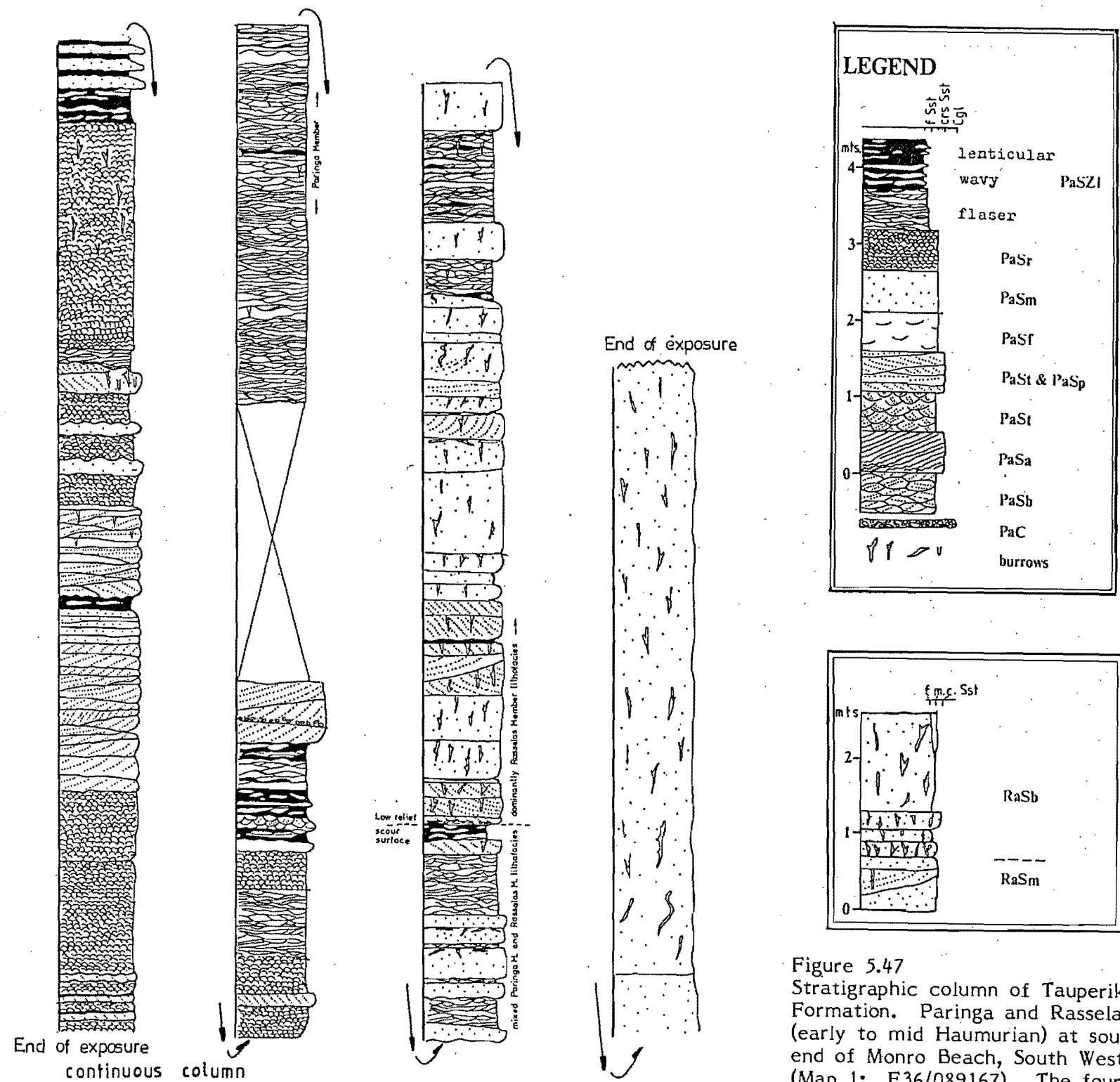


Figure 5.47
 Stratigraphic column of Tauperikaka Formation. Paringa and Rasselas Members (early to mid Haumurian) at south-west end of Monro Beach, South Westland. (Map 1: F36/089167). The four columns represent one continuous stratigraphic column (see arrows).

As intervening mudstone bands are continuous between sets, erosive currents are lacking. The current is just strong enough to move sand into the depression between existing sets the individual set resemble sand banks and may result from re-working of sand by a dominant ebb flow or flood flow current. Mudstone is deposited during periods of low energy by suspension.

(vii) Lithofacies PaSr: Ripple Bedded Sandstone

Ripple laminated coarse and medium grained sandstone are in beds up to 3m thick and contain very little finer grained sediment. Ripples are 0.5cm - 2cm in height and bi-directional, symmetrical and asymmetrical. The two dimensional nature of the outcrop on Monro Beach does not yield crest-line patterns. However, along the coast west of the Moeraki River, ripple crest lines, preserved in a mudstone layer, are slightly wavy, continuous and in phase. Ripples show load cast soft sediment deformation structures. Occasional laminae of mudstone have diapirically risen between overlying sinking ripples.

In Lagoon creek outcrop, ripples are slightly asymmetric and unidirectional. Crest-lines are sinuous, out of phase and broken. Crest lines are rounded. A subordinate ripple type has a peaked crest, and very disjointed crest-lines which are sinuous and out of phase, the disjointed nature producing a complex interference pattern.

Within the Lagoon Creek sequence burrows are randomly dispersed and rippled surfaces display abundant grooves - trail marks (Fig. 5.48).

The asymmetrical ripples with broken sinuous crest-lines in Lagoon Creek probably indicate a unidirectional current with a flow in the lower part of the lower flow regime. The current may be stream flow or a dominant ebb or flood flow tidal current.



Figure 5.48 (above)
Lagoon Creek
(Map 1: G36/238244)
Tauperikaka Formation,
Paringa Member (early
to mid Haumurian).
Trail marks on a rippled
surface.

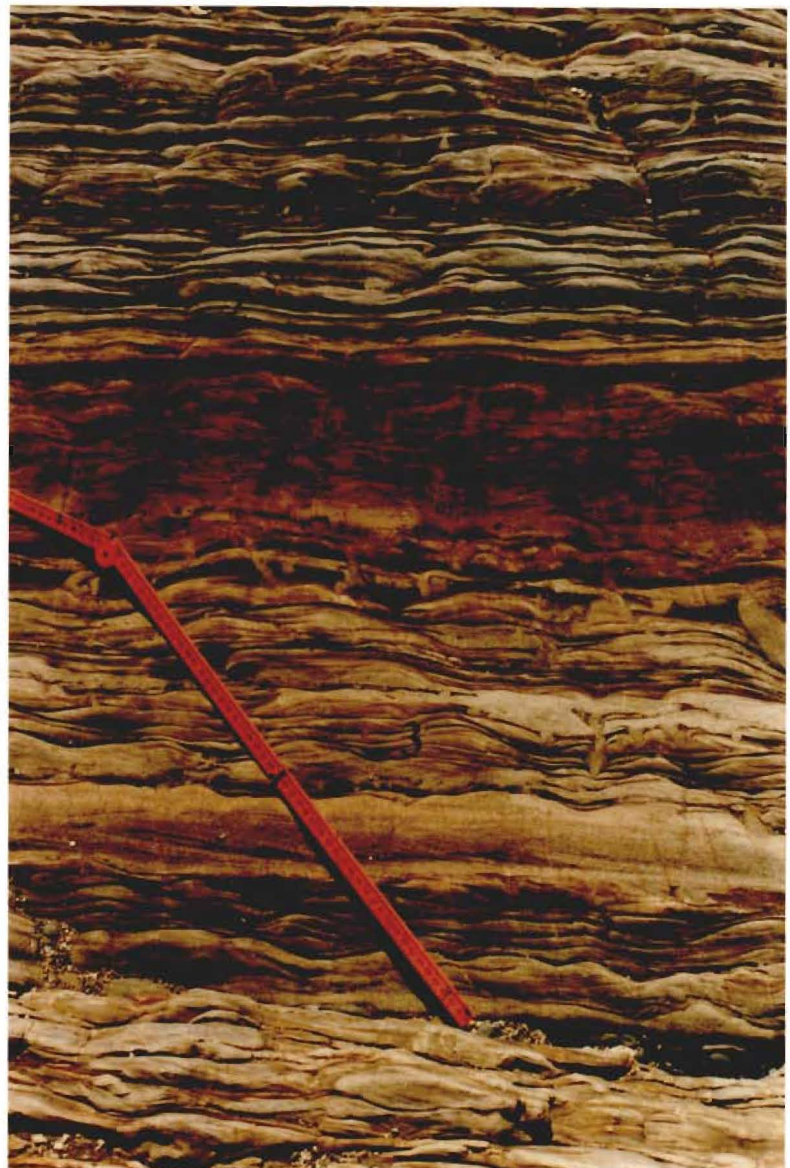


Figure 5.49 (right)
Monro Beach
(Map 1: F36/091168)
Tauperikaka Formation,
Paringa Member (early
to mid Haumurian).
(1) Lenticular bedding
(2) wavy bedding
(3) flaser bedding.

(viii) Lithofacies PaSZL: Lenticular Wavy and Flaser Bedded Sandstone, Siltstone and Mudstone

Lenticular wavy and flaser bedded sandstones, siltstone and mudstones are apparent in the Monro Beach type section and in the Lagoon Creek exposures. On Monro Beach, sequences of flaser bedding (Fig. 5.49), up to 4m thick, occur to the south, and to the north sequences of flaser bedding are generally less than 2m thick. (Fig. 5.50 Col.2). The flaser bedding shows wavy flaser bedding and bifurcated wavy flaser bedding (Fig. 5.49). Abundant reactivation surfaces are apparent and scattered burrows are up to 3cm long. A comparison with the various types of flaser bedding described by Reineck and Wunderlich (1968) (Fig. 5.51) indicates the flaser bedding is formed from small ripples with curved crests. Wavy and lenticular bedding (Fig. 5.51) grades up from flaser bedding at Monro Beach (Fig. 5.50 Col. 2) and occurs in beds up to 2.5m thick.

Wavy and lenticular bedded fine glauconitic sandstone and siltstone also crops out in Lagoon creek. Lenticular bedding is both connected and disconnected but siltstone is predominant. Burrows are occasionally present, one of which is a vertical burrow resembling a structure from Seilachers (1967) skolithos-facies example "a" (Fig. 5.52). The other burrow resembles example "i" from the Cruziana facies (Fig. 5.52).

The bedding implies that both sand and mud are available and that periods of activity alternate with periods of quiescence. Sand is transported during current activity. During the following quiescent period the finer material held in suspension is deposited, mainly in the troughs. Current activity may then erode ripple crests, removing the finer material or only partly or insignificantly removing the finer material (Reineck and Singh 1980). Lenticular bedding indicates the environmental conditions were more favorable for the deposition and preservation of mud than for sand. The flaser and lenticular bedding may result from both tidal currents and wave induced currents.

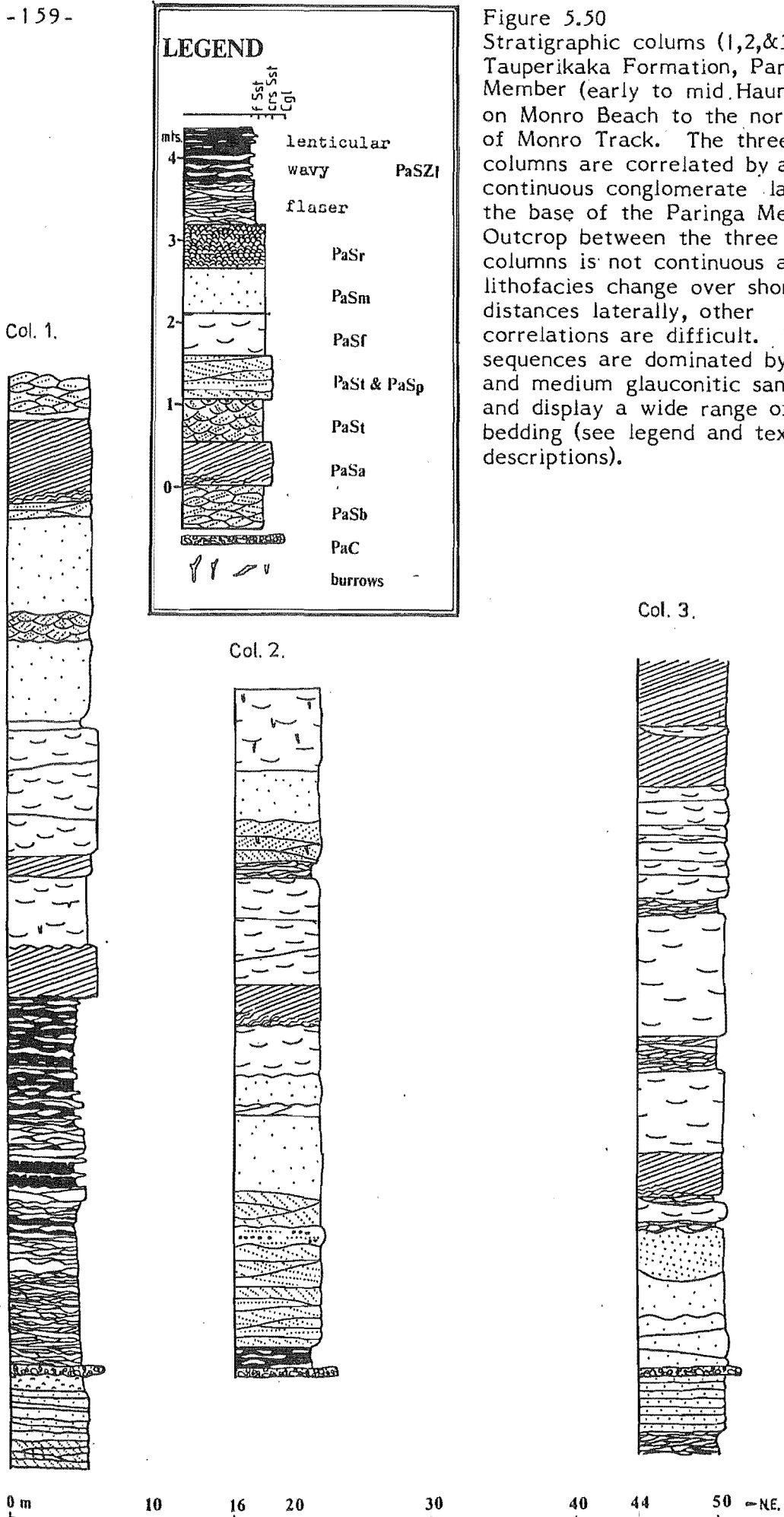
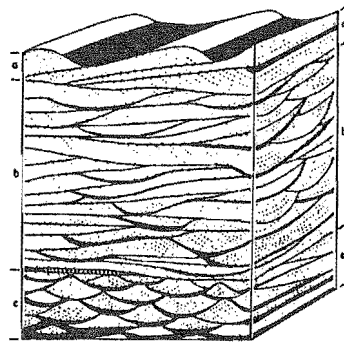
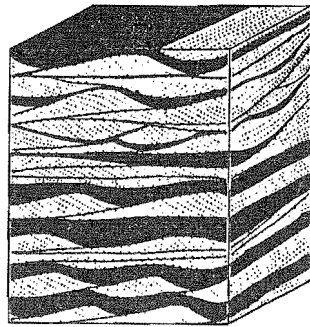


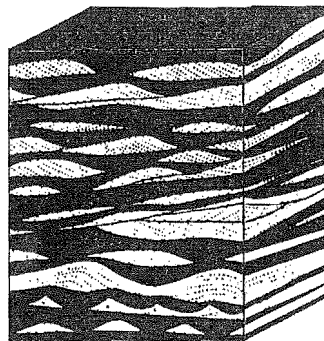
Figure 5.50
 Stratigraphic columns (1,2,&3) of
 Tauperikaka Formation, Paringa
 Member (early to mid Haumurian)
 on Monro Beach to the north-east
 of Monro Track. The three
 columns are correlated by a
 continuous conglomerate layer at
 the base of the Paringa Member.
 Outcrop between the three
 columns is not continuous and as
 lithofacies change over short
 distances laterally, other
 correlations are difficult. The
 sequences are dominated by coarse
 and medium glauconitic sandstone
 and display a wide range of cross-
 bedding (see legend and text for
 descriptions).



(a) Flaser bedding



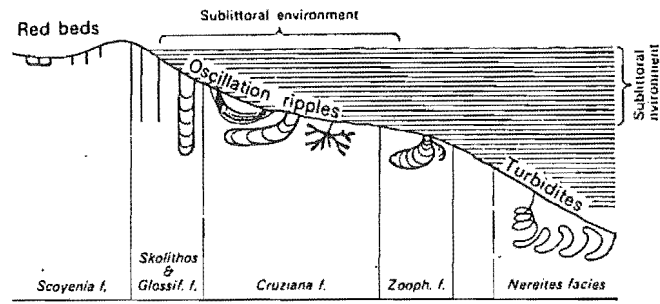
(b) Wavy bedding



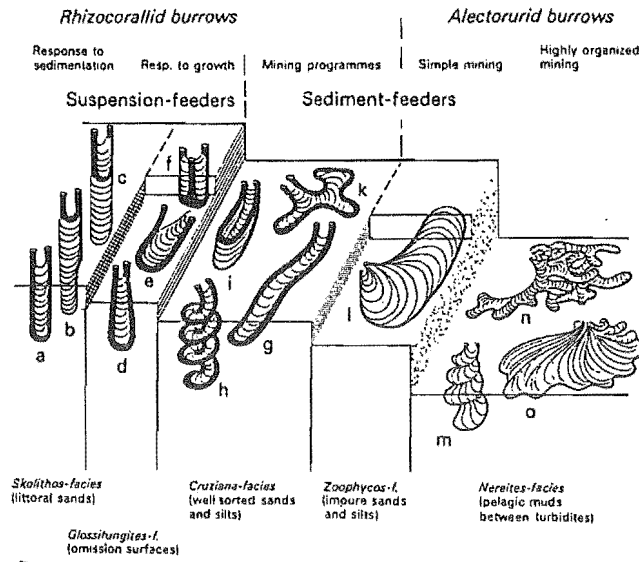
(c) Lenticular bedding

Figure 5.51

Flaser, wavy, and lenticular bedding. (After Reineck and Wunderlich 1968a.) In each diagram, the upper part is drawn for current ripples and the lower part for oscillation ripples. (a) Flaser bedding : i formed from current ripples with straight crests, ii formed from current ripples with curved crests, iii formed from oscillation ripples: (b) Wavy bedding. (c) Lenticular bedding. (Blatt et al. 1980)



A



B

Figure 5.52

Types and distribution of trace fossil communities in the sublittoral environment: A. generalised bathymetric distribution of the major trace fossil communities, and B. bathymetric zonation of fossil spreite burrows indicating the predominance of suspension feeders in the shallow water high-energy zone, which are gradually replaced in the deeper water lower energy environments by increasingly elaborate sediment feeders. (Seilacher 1967, from Reading 1978)

(ix) Lithofacies PaSm: Structureless Well Sorted Medium Sandstones

Structureless sandstones in beds up to 1m thick and in sequences up to 2.5m thick lie on flat or gently undulating lower contacts and are overlain by broad (20m) shallow flat bottomed scour surfaces, sharp contacts or straight or wavy contacts (Fig. 5.53).

The sandstone is medium grained, very well sorted and glauconitic. The beds do not contain pebbles, burrows or any other internal structure. Lithofacies below, within, and above lithofacies PaSm are very well preserved and reveal excellent sedimentary structures. Therefore, the structureless nature is not a product of weathering as opposed to the beds at the base of column 4 (Fig. 5.50) which lack internal structure due to weathering of the outcrop.

The structureless nature might be a primary sedimentary feature. The sand may have been deposited quickly from suspension where clasts were dispersed by fluid turbulence as in a sediment gravity flow and/or the sand may have been completely homogenised by escaping pore fluids after deposition and before burial by further sedimentation.

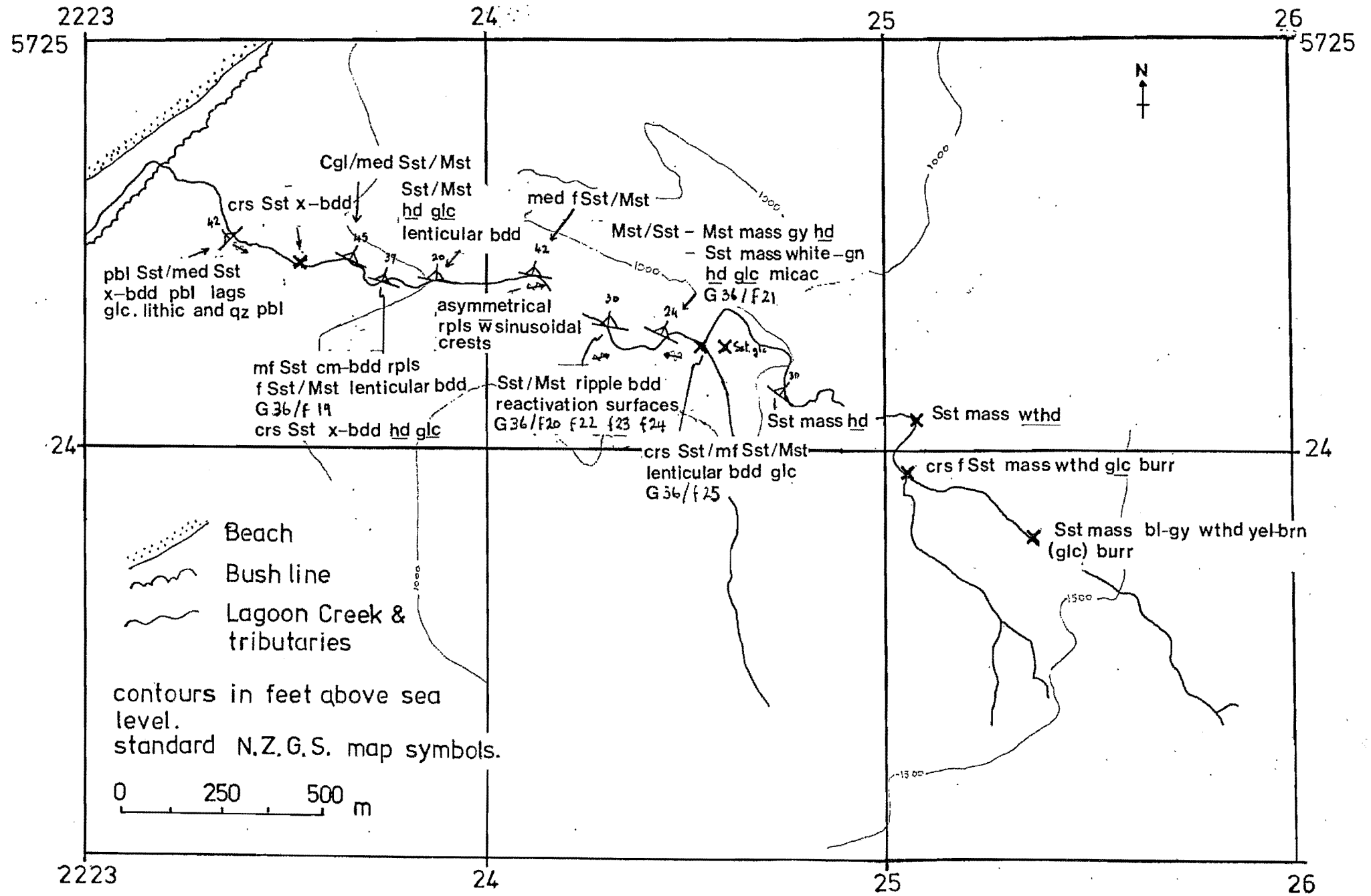
Paleocurrents

In Lagoon Creek (Fig. 5.54) paleocurrent directions were resolved back to the horizontal using a hinged carpenter's rule as described in Andrews (1982). This method is only recommended for simply tilted sequences. Therefore, the results can only be regarded as rough indicators. Much of the outcrop in creeks and along the coast is two-dimensional, restricting paleocurrent measurement. The sequence is also severely deformed (see Section 7.0) which prevents the reconstruction of paleocurrent directions with certainty and hinders comparison of measurements between outcrops.



Figure 5.53
Monro Beach (Map 1: F36/091168) Tauperikaka Formation, Paringa Member
(early to mid Haumurian). Structureless sandstone interbedded with cross-
bedded and laminated sandstone. Youngs left to right. Lithofacies PaSm.

Figure 5.54 MAP OF LAGOON CREEK SHOWING SELECTED OUT-CROP AND POLLEN SAMPLE DATA.



In Lagoon Creek cross-bedded channel sandstones (lithofacies MoSt) gave south-easterly flow directions and ripple crest-lines either pointed east or west. Where cross-bedded sandstones are interbedded with ripple laminated sandstones, often in shallow concave scour surfaces, the cross-bedding appears to have an opposite paleocurrent direction.

Paleocurrent directions could not be ascertained in the overturned beds exposed in two dimensional outcrop along the coast south of Otumotu Point.

Reactivation surfaces

Reactivation surfaces in the megaripple "tidal bundles" produced by megaripple overtaking (Fig. 5.55) were not exposed. Most of the tidal bundles contained well defined foresets with mudstone drapes indicating that very little erosion by the subordinate current has occurred (Fig. 5.55). The lack of reactivation surfaces is probably due to a relatively weak subordinate current compared to the dominant current.

Composition of the Paringa Member

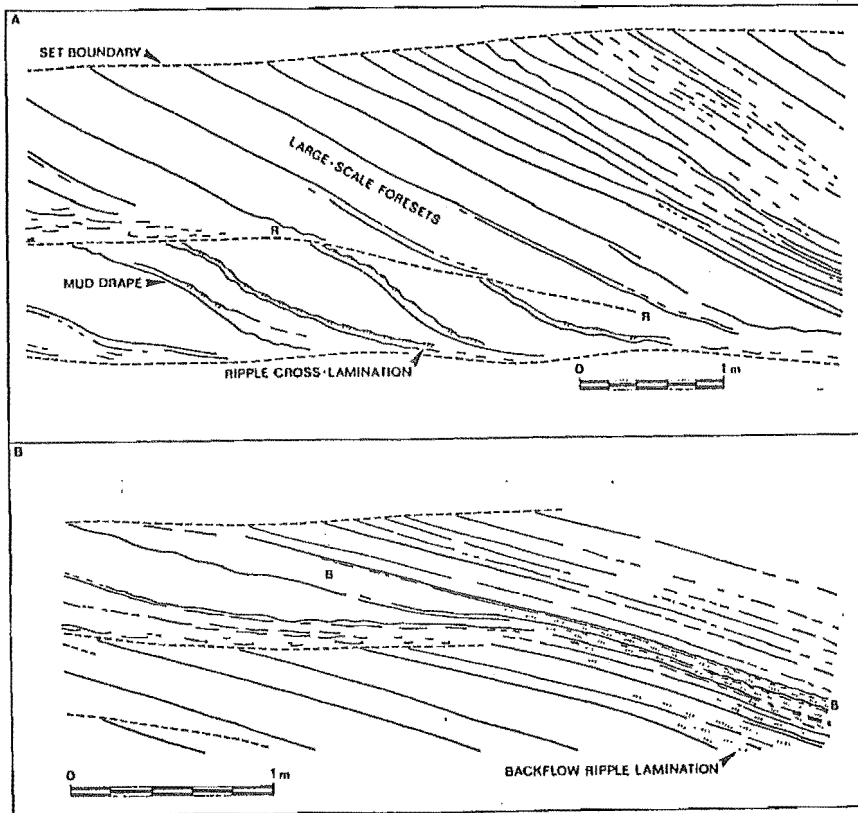
The composition of typical sandstone is shown in Table 5.4. Samples from the Paringa member (Fig. 5.15) are sub-feldsarenites and feldsarenites.

Quartz

The sections studied are composed of coarse to medium sandstones in which quartz grains are predominantly monocrystalline and 5% to 10% of grains are polycrystalline. Polycrystalline grains usually consist of between 10 and 50 crystals that show strongly sutured inter-crystalline boundaries. Undulatory extinction is evident in 95% quartz

Figure 5.55

Structures produced by mega-ripple overtaking. A) Overtaking during spring tides has produced a well developed reactivation surface, R-R, extending almost to the base of the set. That overtaking took place during spring tides can be established from the bundle sequence from the upper set. B) Overtaking during neap tides. The lower set (not shown in its entirety) is 1.5m high, the upper set is 0.6m high. There was no erosion associated with the overtaking process. (Mowbray et al. 1984)



Reactivation surfaces resulting from subordinate - current erosion in a bi-directional flow system. Successive diagrams show the effects of an increase in the strength of the subordinate current with respect to the dominant currents. (Mowbray et al. 1984)

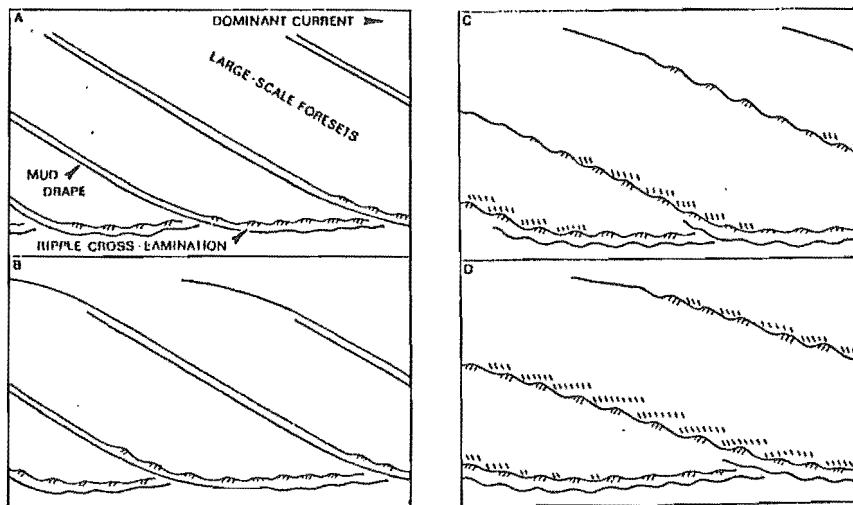


Table 5.4
 Modal analyses (in %) of typical sandstones from the Tauperikaka
 Formation, Paringa Member.

SAMPLE NO.	11967	11988	11989
U. of C.			
D.S.I.R.	F36/p29	S87/p70	F37/p5
APPARENT GRAINSIZE (mm)			
max.	1.32	0.63	8.16
mode(s).	0.69	0.30	0.66
min.	0.06	0.03	0.06
ROUNDNESS	s.a.-r.* ¹	v.a.-s.r.	s.a.-r.
SORTING	v.w.s.	w.s.-v.w.s.	p.-m.s.
QUARTZ	55	65	52
mono.	95	90	95
poly.	5	10	5
undul.	95	95	95
MICROCLINE	15-20	4	1
other.ALK.F.	1	0	1-20* ²
PLAG.FELD.	1	1	1
ROCK FRAG.	5	5	10
MICA	>1	>1	>1
H and O	0	>1	>1
OTHER	0	>1	>1
MATRIX	>2	>2	10
CEMENT:			
QUARTZ	5	10	5
DOLOMITE	20	0	0
SIDERITE	0	0	0
LIMONITE			
STAINING	0	0	0
GLAUCONITE	1	12	3

*¹ 90% of grains are sub-rounded to rounded (texturally very mature).

*² Feldspars do not show twinning and are kaolinitized and illitized. Therefore number estimates and differentiation is difficult.

grains. Rim cement makes up 5% to 10% of the whole rock composition and is apparent by its protruding nature into surrounding grains and mutually interlocking grain boundaries (Fig. 5.56).

Feldspars

Feldspars form up to 20% of the rock composite in which alkali feldspars are dominant with microcline accounting for 80% to 95% of the feldspar population. Albite and unidentifiable plagioclase feldspars are present in very minor quantities. Within the one section (U.of C. 11967) feldspars show a gradation in alteration from very fresh to completely altered. Feldspars totally altered to clays show a pseudo cleavage.

Rock Fragments

Rock fragments only form a minor component of the total composition (Table 5.4). The rock fragments are composed of silt sized particles and oriented micas, stretched polycrystalline grains, and cherts and vein chlorite (anti-garite?) is also present. Rock fragments have flowed between more competent quartz grains in a response to compaction and although some of the rock fragments may be perigenic, these clasts are no longer distinguishable from deformed rock fragments.

Heavy Minerals

There is a conspicuous lack of heavy minerals in the samples studied. Opaques are present in sample U.of C. 11988a. No heavy minerals were identified in sample U.of C. 11967

Glauconite

Glauconite occurs in rounded pellets, some of which have been squeezed between quartz grains. Glauconite is also replacing illitized feldspars.

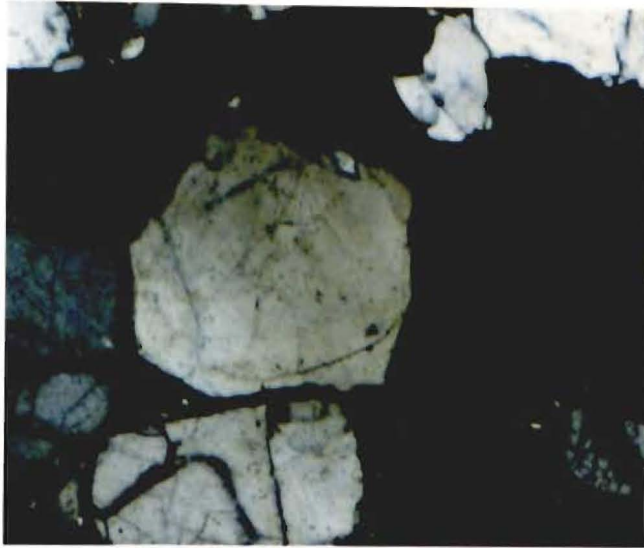


Figure 5.56
Well rounded quartz grain with rim cement. Sample U. of C. 11967.

Matrix and Cement

One sample (U.of C. 11967) contains an anhedral slightly pleochroic carbonate cement with a dark brown stain along well defined cleavages. The cement occurs in patches and surrounds framework grains. An analysis by X.R.D. indicates the cement is either dolomite or ankerite (Appendix 8, diffractogram 5).

Matrix is only present in a minor quantity, consisting of fine silt and clay, and is often difficult to distinguish from pseudo matrix formed from deformed rock fragments and highly altered feldspars.

Interpretation of Composition

The abundance of coarse and medium sand sized quartz grains combined with high percentages of microcline indicate an acid igneous source, probably the local Tuhua Group. The cherts and sedimentary rock fragments (characterised by oriented micas) indicate a sedimentary provenance with a low metamorphic grade. The local Greenland Group consists of fine sandstones predominantly composed of detrital quartz and is dominantly lower Greenschist facies. The Greenland Group probably contributed a large proportion of the finer grained quartz and vein chlorites which are a common feature of the Greenland Group rocks. The presence of abundant glauconite indicates a marine environment.

The textural maturity of samples (e.g. U.of C. 11967) suggests a large proportion of rock fragments may have been broken down and the finer residue carried away by powerful tidal currents or waves. The population of grains has been transported through the transition zone from non-marine to marine rocks and has been subjected to processes operating within the transition zone (such as high energy wave action and tidal currents) which mechanically break down the weaker framework grains. Therefore, the relative proportions of quartz and feldspar are likely to have increased at the

expense of the rock fragment sub-population. The importance of the Greenland Group as a source rock compared to the Tuhua Group is therefore difficult to assess and its importance has been under-estimated by previous authors. The source is unlikely to have differed significantly from the source of the Moeraki Member sediments, which has produced litharenites. In conclusion environmental factors are responsible for significantly modifying the original framework grain population, and the sub-feldsarenites of the Paringa Member are likely end products.

Lithofacies Sequences and Environments of Deposition

A marine environment is established for the Paringa member by a combination of several features including assemblages of trace fossils, glauconitic accessory mineralogy, and high textural maturity in some sandstones. Erosion surfaces are low relief and laterally continuous. Tidal currents are inferred from bi-directional formed sedimentary structures, the abundance of cross-bedding, reflecting dunes and sand waves, and mud drapes and reactivation surfaces in ripples.

(a) Monro Beach Section

The base of the sequence is marked by a minor erosional unconformity (Fig. 5.50). Walther (1894) stressed that an erosive contact may represent the passage of any number of environments whose products were subsequently removed.

Thick sequences of lithofacies PaSZL (Fig. 5.50 Col.1) indicate low energy tidal currents, with one dominant current transporting the ripples. The variability of the lithofacies reflects fluctuations in the intensity of hydrodynamic conditions and in the supply of sediment. Either the lithofacies was protected from high energy currents by distance from channel areas or the lithofacies is deposited

in the abandoned channels. The relative lack of burrowing may indicate fluctuating salinity. Van den Berg (1981) describes a similar sequence in an area within the Oosterschelde mouth in the Netherlands in which the alternating flaser and laminated members within an abandoned tidal channel represented winter and summer layers respectively (most of the flaser bedding belonged to the wavy flaser type). Pulses of higher energy deposits periodically interrupted rhythmic bedding in lithofacies PaSZL and these influxes of sand are interpreted as storm deposits.

The heterolithic facies is superceded in Col.1 (Fig. 5.50) by a lithofacies (lithofacies PaSa) which represents larger scale bedforms migrating along tidal channels in which the energy of the tidal current has been concentrated. Boersma (1969, 1971, 1981), Visser (1980), Van den Berg (1981, 1982) Yang and Nio (1985) all describe the large scale cross-bedded sets in Holocene deposits in the Netherlands as features preserved in channelised areas of estuaries or tidal embayments in which tidal currents are spatially separated into flood dominated and ebb dominated zones. The lithofacies has also been recognised in ancient sequences (e.g. Kreisa et. al. 1986). Within the large cross-bedded sets each foreset unit bounded by mud drapes is described as a single tidal bundle. Visser (1980) and Allen (1981) for example, have related each bundle to one tidal cycle in which four stages of a tidal cycle are recorded:

(1) a dominant current stage in which the movement of a bedform in a channel results in the deposition of a sandy foreset;

(2) a slack water period during which a mud drape is deposited from suspension;

(3) a subordinate, reverse, current stage during which a net period of erosion may result or a thin lamina of sandstone may be deposited;

(4) a slack water stage during which a second mud drape is deposited.

Bundles thicken and thin laterally reflecting neap-spring tide periods as well as daily fluctuations in cur-

rents and supply (Visser 1980; Allen 1981).

Protected hollows on the lee side of migrating bars are potential preservation sites for ripple laminated mudstone and sandstone. Ripples formed from flows in the lower part of the lower flow regime may be formed from eddies of currents moving perpendicular to forsets (Fig. 5.57) or formed during the reverse, subordinate, current stage during which small scale bedforms migrate back up the sandy forsets. However the lack of reactivation surfaces indicates the reverse subordinate current is not strong enough to deposit the ripples. Mudstone laminae are probably related to sedimentation during slack water periods between tidal current flows.

Fast lateral migration of tidal channels, caused by erosion along the outer margins of channels and accretion on the inner margins, is conducive to a high preservation potential for bedforms within the channels (Nio et. al. 1983).

Lithofacies PaSa merges laterally with lithofacies PaSf. The transition represents the change to migration of smaller bedforms under the influence of the same tidal currents, but of lower energy. The transition is interpreted to reflect the lateral change from bedforms (lithofacies PaSa) deposited in the channel thalweg, where the current energy is more concentrated, to bedforms deposited on channel margins (lithofacies PaSf) where the current energy is relatively lower. Van den Berg (1982), Nio et. al. (1983) and Yang et.al. (1985) have all made observations on modern environments which support this interpretation (Fig. 5.58).

The rapid alternation of lithofacies PaSa and PaSf in the upper parts of columns 2, 3 and 4 suggests an area in which channel migration has played an important role and as a consequence the preservation of the low energy heterolithic facies is poor.

Lithofacies PaSp and PaSt are interpreted on the products of migrating ripples, dunes and sandwaves across

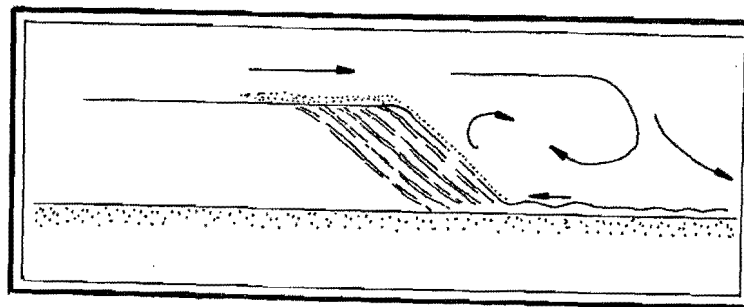


Figure 5.57
Diagram illustrating the movement of sand by a current to the lee face of a bedform where avalanching causes deposition of a sandy foreset. Turbulence and back eddies may also cause movement of sand in ripple form at the base of the avalanche foreset.

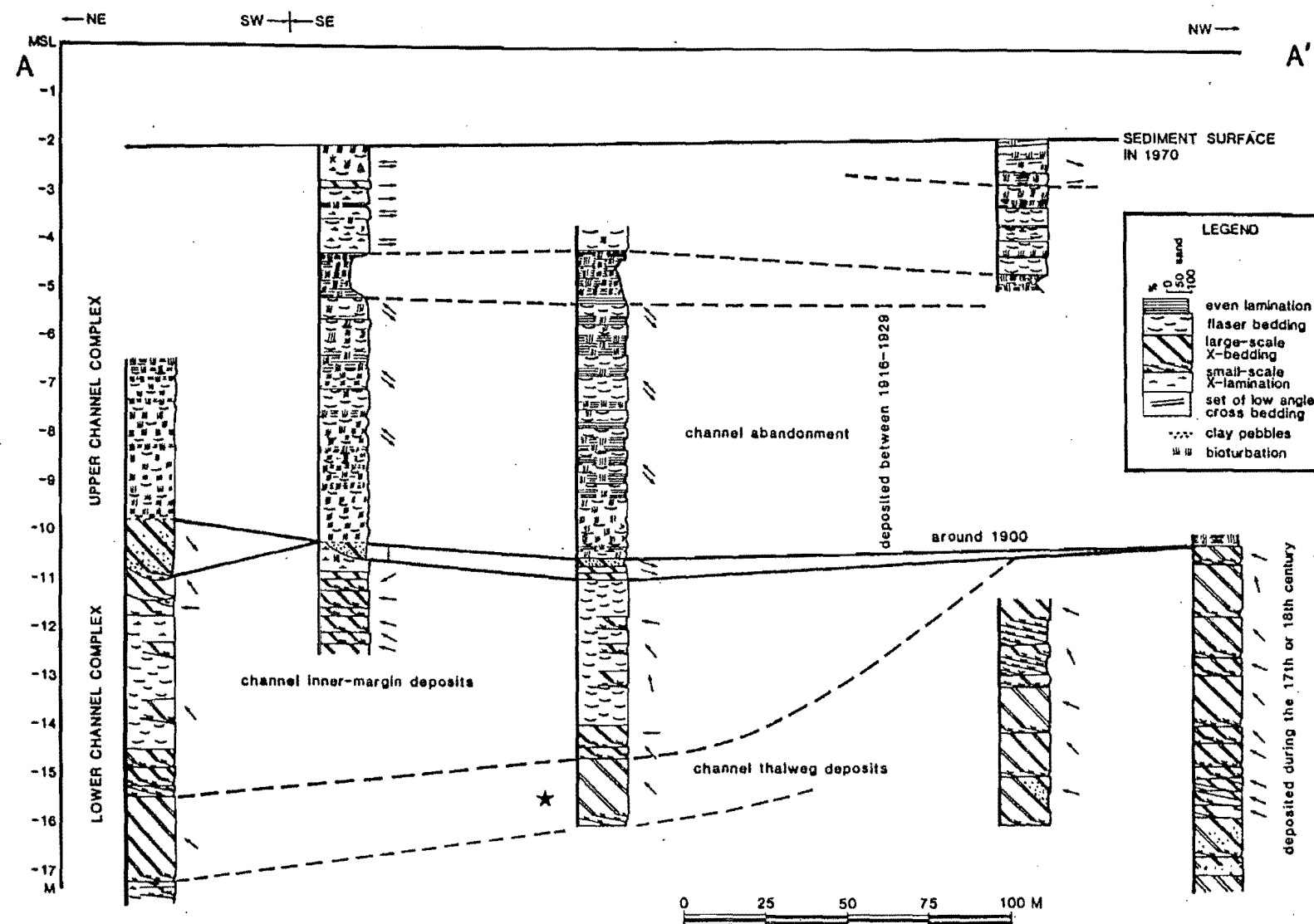


Figure 5.58
Stratigraphic columns in the Schaar construction pit, Oosterschelde basin, south-west Netherlands. The columns represent a Holocene sub-tidal environment and show the superposition of two tidal channel sequences. The large scale cross-bedded sets with tidal bundle sequences occur in the channel thalweg deposit unit (marked with an asterisk). (After Van Den Berg 1981, 1982 and Nio et al. 1983)

shoal areas. Periods where the ebb flow is dominant over the flood flow and visa versa are recorded.

To the south on Monro Beach, (Fig. 5.47) the tidal channel sandstone units (lithofacies PaSa and PaSf) are not represented. Relatively thick cross stratified sandstones are a lot further apart in the stratigraphic column than to the north-east and thick sequences of rippled bedded sandstone dominate the sequence. The sequence may reflect deposition in a shoal area away from the influence of tidal channels on which the migration of ripples (lithofacies PaSr) probably represents alternate wave dominated and tidal current dominated systems, and periods when larger bedforms cross the shoal area may reflect storms, or the approach of a tidal channel system providing "washover" deposits. Reversals in cross stratification direction upwards within the thicker, higher energy sandstones indicates one of two possibilities: (1) currents may have re-worked sand sheets deposited within the environment and ebb flow and flood flow or two or more long shore currents alternated in dominance; (2) the sand sheets are derived from opposing directions, which might suggest channel systems operating on both sides of the shoal area.

Terwindt (1970) described a similar subtidal estuarine sequence. The greater development of heterolithic sediments in one area was related to a protected area of shoal away from channels. A large scale group of cross-bedded sandstones increased in abundance towards channel areas. The whole sequence showed marked changes of facies laterally.

(b) Lagoon Creek Section

The paleoenvironment of the sediments in Lagoon Creek differs slightly from the Monro Beach model. A far thicker sequence of lithofacies PaSZ1 is exposed in which silty mudstone is dominant and lithofacies PaSf does not crop out. Minor channeling is evident. The abundance of glauconite supports marine influence and the bi-directional nature of

the currents reflects the effects of tides. The environment was more conducive to the deposition and preservation of silty mud, compared with the interpreted environment for the Monro Beach section, which suggests relatively more shelter from marine currents perhaps because of headlands or a sand barrier.

Two major paleocurrent directions, one in channels and one in the opposite direction in finer grained sediments of inter-channel areas, indicates large areas of shoal may have been swept by a flood flow current and ebb flow maybe concentrated into channels or visa versa. Sand deposited on the flank of channels by tidal currents or a fluvial regime is probably re-worked into sand banks by the ebb flow. The sparse distribution of burrows maybe a result of fluctuating salinity, caused by input of fresh water from a stream or river (which is indicated by exposures at the base of the Lagoon Creek sequence).

The sequence is interpreted as estuarine. The estuary consists of a system of shallow channels in which tidal currents are concentrated, and inter-channel shoal areas. The flood flow brings glauconite into the estuary. Silty mud is deposited during tidal still-stand on shoal areas which are partly exposed at low tide. Closer to channels the fluvial currents keep mud in suspension allowing a sand dominated ripple lithofacies. Areas where tidal currents and the fluvial current meet at oblique angles sets up a complex ripple interference pattern. A paleoenvironmental model interpreted from both the Monro Beach and Lagoon Creek sections is shown in Figure 5.59.

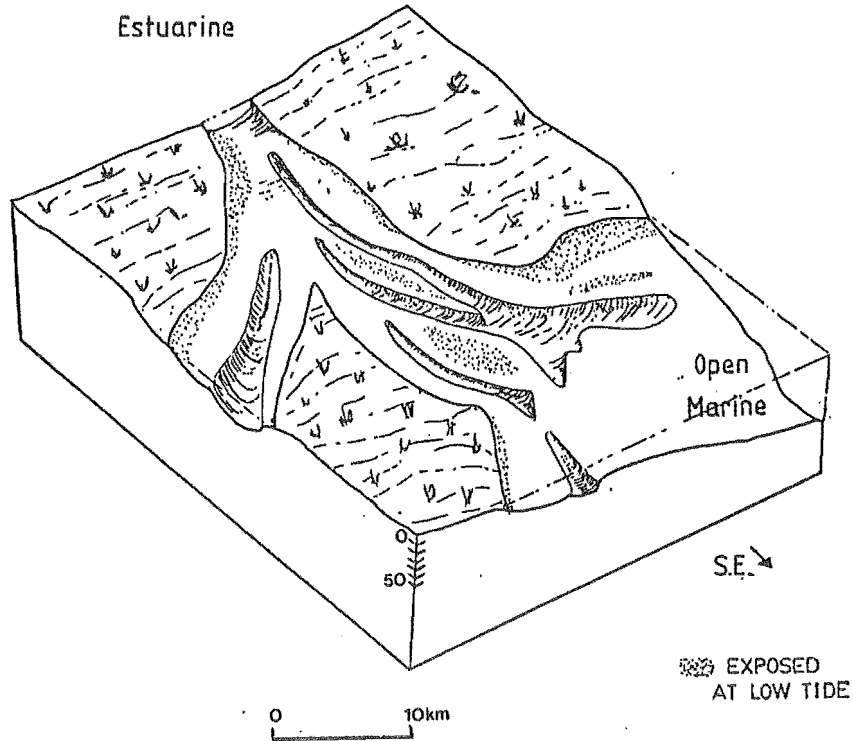


Figure 5.59
Paleoenvironmental model for the Tauperikaka Formation, Paringa Member (early to mid Haumurian) showing a tide dominated coast line during a marine transgression from the south-east. Tidal channel complex subtending from the coast inland to estuarine environments. The tidal channel complex consists of laterally migrating tidal channels, which either concentrate ebb flow or flood flow, and inter channel shoal areas. Abandoned channels aggrade with alternating flaser and laminated fine sandstone and silty mudstone.

5.3.3 Rasselas Member

Sedimentary Structures and Textures

Introduction

The Rasselas Member is divided into lithofacies which have been assigned codes for brevity of expression during reference. The codes are "RaSb" and "RaSm" and are explained in full in Appendix 2.

(i) Lithofacies RaSb: Burrowed Glauconitic Sandstone

In the type section of the Rasselas Member on Monro Beach, a bioturbated glauconitic, medium sandstone shows a high density of biogenic sedimentary structures (Fig. 5.60). In some places, discrete siltstone laminae are preserved between beds and intermittent laminae of siltstone preserved within beds, but the siltstone becomes mixed with sandstone towards the top of the Rasselas Member. Glauconite is concentrated over small scour surfaces and in burrows. Clastic grains are very angular to rounded and become very angular to well rounded higher in the sequence (rim cement obscures the original boundaries of some quartz grains and may be responsible for some errors in the estimation of grain roundness). The grain population is either moderately well sorted or well sorted.

Two major trends occur upwards within the stratigraphic column within lithofacies RaSb; 1) the sediment becomes finer and more poorly sorted and 2) the diversity and density of burrows decreases.

Characteristic types of biogenic sedimentary structures are briefly described, in note form, and divided into nine separate types for discussion purposes. Two or more of the types may have been created by the same organism.

Type 1. Gyrochorte sp.

Description: Straight burrows inclined at 20° to bedding in two opposed directions. Burrows up to 1cm in



Figure 5.60
Monro Beach (Map 1: F36/089167) Tauperikaka Formation, Rasselas
Member (early to mid Haumurian). Interbedded burrowed (RaSb) and
structureless (RaSm) beds.

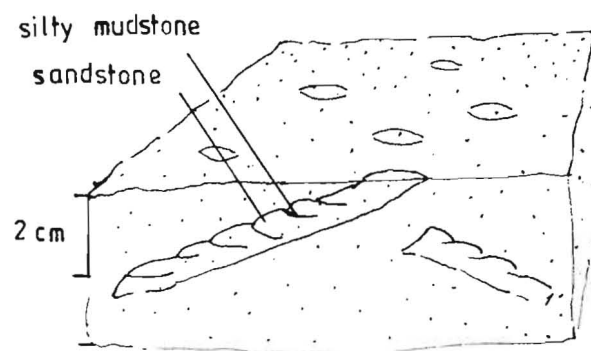


Figure 5.61
Diagram of Type 1: Gyrochorte sp. taken from a sketch made in the
field, Monro Beach (Map 1: F36/089167).

diameter and 30cm long. Oval in cross-section. Top surface shows a series of plat like structures marked by mudstone laminae, and the underside of the burrow is straight (Fig. 5.61).

Discussion: The burrow shape implies a sediment feeder undertaking a simple mining programme and falls within the Cruziana facies of Seilacher (1967). The tunneling probably is developed by a gastropod, crustacean or worm.

Type 2. Unknown Genus.

Description: Crescentric laminae dropping from a hinge point. 2cm - 4cm in depth and 4cm in length.

Discussion: The structure represents a sediment feeder undertaking a simple mining programme and falls within the Cruziana facies of Seilacher (1967).

Type 3. Unknown Genus.

Description: Bi-lobed meandering vertical burrow up to 4cm in diameter and at least 50cm deep. Probably extends to the base of the bed. No internal morphology. Infilled by sand from the surrounding bed. Small oval burrows (species 4) within burrow fill of genus 3 (Fig. 5.62).

Discussion: The structure implies a sediment feeder undertaking a simple mining programme and falls within the Cruziana facies of Seilacher (1967).

Type 4. Unknown Genus.

Description: Oval meandering vertical burrow up to 0.8cm in diameter. Lacks internal morphology.



Figure 5.62
Monro Beach (Map 1: F36/089167) Tauperikaka Formation, Rasselas
member (early to mid Haumurian). Burrow type 3: unknown genus.

Type 5. Unknown Genus.

Description: Oval straight trace along bedding planes. 1cm in diameter and up to 40cm long. No internal morphology.

Type 6. Unknown Genus.

Description: Round trace consisting of a series of coils (like a rope). Diameter is 2.5cm and each coil length 1.5cm. The trace is horizontal and lies on, and beneath bedding planes.

Type 7. Thalassanoides sp.

Description: Horizontal branching burrows 0.5cm to 1.5cm in diameter. Branches are Y shaped and filled with sandstone from surrounding bed.

Discussion: Thalassanoides is a common ichnogenus from Mesozoic and Tertiary rocks (Miller and Knox 1985) and is interpreted as a feeding or dwelling burrow of one or more crustaceans (Hantzschel 1975).

Type 8. Asteriacites sp.

Description: Star like traces up to 15cm in diameter consisting of five arms projecting outward from a central area. Surface texture knobby. Each are 2cm -2.5cm in diameter. Central ridges running down each arm. Angles between arms vary from 30° to 92°.

Discussion: The structure has been described by Seilacher (1953) and is thought to be produced by ophiuroids or slender asteroids.

Type 9. Polychaete sp.

Description: Tubes of polychaetes, 1mm in diameter and several millimetres long, are straight and circular. The tube has ridges running down the outside edge.

Discussion. Polychaete burrows share strong distributional similarities with the trace fossils, skolithos and monocraterion. The vertical tubes occur in a wide range of restricted and open marine conditions.

Species 1, 4, 7 and 9 occur throughout the Rasselas Member, the other species die out upwards within the Member, producing the effect of decreasing numbers and diversity of species upward in the stratigraphic column.

(ii) Lithofacies RaSm: Massive Glauconitic Sandstone And Silty Sandstone.

Beds up to 2m thick of structureless, green, glauconitic, medium sandstone contain occasional siltstone flecks which align with bedding planes. The lithofacies generally lacks burrows with the exception of type 3 - unknown genus, which penetrates the lithofacies vertically from above. The tops of beds often show a network of horizontal burrows including Thalassanoides sp. The lack of evidence of cross-bedding in coastal and road outcrops is probably due to weathering. Occasionally cross stratification can be inferred from concentrations of glauconite that appear to have accumulated in troughs although corresponding crests of bedforms are not discernable.

The lack of biogenic sedimentary structures, with the exception of the largest type (genus 3), indicates that the bed was deposited both quickly, so as to prevent organisms burrowing during sedimentation, and covered relatively quickly, to prevent the organisms burrowing down into the bed.

Composition of the Rasselas Member

The composition of typical sandstones is shown in Table 5.5. The samples from the Moeraki Member are feldsarenites, sub-feldsarenites and lithic feldsarenites (Fig. 5.15). The majority of thin sections studied are coarse to medium sands from the lower part of the Member and fine sands from the upper part.

Quartz

Between 90% and 99% of quartz grains are monocrystalline, the percentage increases with decreasing grain size from the lower to the upper part of the Member. In the lower part of the Member 99% of grains show undulatory extinction, in the upper part of the member 50% of quartz grains show undulatory extinction, which is probably size related.

The amount of rim cement is difficult to estimate, as parent grains are not usually outlined by impurities, but usually it falls between 5% and 10% of a whole rock composition. Rim cement is apparent by its protruding nature into surrounding grains and the mutually interlocking grain boundaries. Overgrowths are angular and do not show signs of rounding. The overgrowths on some grains may bias the roundness estimations towards the angular end of the spectrum.

Feldspars

Feldspars account for 25% of a rock mass in the lower part of the member, 20% - 25% in the middle part of the member and 10% - 15% in the upper part of the member. The decrease corresponds with decreasing grain size. Microcline is the major feldspathic component and albite is present in quantities up to 1% in sample U.of C. 11969.

The majority of feldspars from sediments in the lower part of the member are very fresh, and some feldspars show

Table 5.5
 Modal analyses (in %) of typical sandstones from the Tauperikaka
 Formation, Rasselas Member.

SAMPLE NO.	11983	11968	11969
U. of C.	-----	F36/p30	F36/p31
D.S.I.R.			
APPARENT GRAINSIZE			
max.	1.12	0.50	0.57
mode(s).	0.50	0.19	0.15
min.	0.03	0.03	0.03
ROUNDESS	v.a.-r.	v.a.-r* ¹	v.a.-w.r.
SORTING	m.w.s.	m.s.	w.s.
QUARTZ	50	42	60
mono.	95	90	99
poly.	5	10	1
undul.	99	95	50
MICROCLINE	25	1	10-15
other ALK.F.	--	1-20-25* ²	--
PLAG.FELD.	0	1	1
ROCK FRAG.	5	10	5
MICA	>1	1	>1
H ₂ AND O.	>1	>1	1* ³
OTHER	>1	1	>1* ⁴
MATRIX CEMENT:	10	3	5
QUARTZ	10	5	10
DOLOMITE	0	10	5
SIDERITE	0	>1	0
LIMONITE			
STAINING	0	0	0
GLAUCONITE	>1	8	3

*¹ Majority of grains are sub-
angular.

*² Microcline (major)+sanidine?
and albite? kaolinitization
and sericitization + glauconite
replacement along cleavages.

*³ Tourmaline (schorlite), zircon,
pyrite.

*⁴ Biotite.

vacuolisation and kaolinitisation alteration. In the middle part of the member, most feldspars show some alteration, some feldspars show replacement by glauconite along cleavage planes and a proportion have undergone illitization. One fresh grain is apparent in sample U.of C. 11969.

Rock Fragments

The percentage of rock fragments is low (5% - 10%). The primary rock fragment is chert and the other major rock fragment is composed of silt sized crystals and flecks and networks of oriented mica.

Micas

Micas are present in insignificant quantities. The matrix contains flecks of mica which may have been derived from disaggregated rock fragments. Occasional muscovites form part of the framework grain population.

Heavy Minerals and Opaques

Leucoxene, zircon and tourmaline (schorlite) are all present. Grains of tourmaline are rounded. Pyrite is also present.

Glauconite.

Glauconite is present in all samples in quantities up to 8%. In sample U.of C. 11983, the glauconite is interstitial and present in insignificant quantities. Glauconite in other samples forms part of the framework grain population and is sub-rounded to well rounded.

Matrix and Cement

A definition of matrix is given in Section 5.3.1 -Composition. Matrix is present in small quantities (5% -10%) and consists of silt sized quartz, sericite and glauconite. The Rasselas Member is cemented by silica cement

(see discussion under quartz). A brown carbonate cement, identified in an X.R.D. analysis as dolomite (or ankerite) (Appendix 8, diffractogram 5) is present in quantities up to 5% and occurs as occasional disseminated spherical shaped blebs that may be filling burrows. In sample U.of C. 11968 the cement is crystallising around and replacing a dark brown nucleus which may have been siderite or ankerite.

Interpretation of Composition

The abundance of microcline combined with quartz indicates an acid igneous source which suggests the Tuhua Group granites. The presence of rock fragments from a sedimentary source rock that appears to have a low metamorphic rank, combined with evidence that preceding members of the Tauperikaka Formation have a Greenland Group source, suggests a Greenland Group source.

The gradual increase in the amount of feldspar and rapid decline in the amount of rock fragments from the lower part of the Tauperikaka Formation to the middle part of the Rasselas Member may indicate the acid igneous source is becoming more prominent over the sedimentary source. However, the change is more likely to be environmentally related. Textures indicate sediments are becoming more mature upward within the Tauperikaka Formation. The gradual decrease in grain size upward within the Rasselas Member is also related to a decrease in the relative number of feldspars within the member, a decrease in polycrystalline quartz and quartz with undulatory extinction, and an increase in sorting and roundness of the sediments together with an increase in the amount of alteration of feldspars. The loss of sedimentary rock fragments is due to mechanical destruction by strong currents within the environment rather than changes in the source rock areas. A large part of the rock fragment residue can be accommodated in the silt sized component.

The relative maturity of the sediments combined with the glauconite accessory mineralogy indicates a marine environment or marginal marine environment.

Macrofossils

Three macrofossil specimens have been found in the Rasselas Member sediments and each are photographed and described in the appendix of Nathan (1977). The fossils are Inoceramus sp. and Kossmaticeras (Natalites) bensoni.

Environment of Deposition of the Rasselas Member

A marine environment is established for the Rasselas Member by Inoceramus sp. and Kossmaticeras (Natalites) bensoni supported by features including assemblages of trace fossils, glauconitic accessory mineralogy, high textural maturity and the presence of marine dinoflagellate cysts. Thalassanoides and Gyrochorte biogenic structures occur in shallow and deep water marine deposits. Asteriocites is usually reported from shallow marine or tidal flat deposits of presumed normal salinity (Miller and Knox 1985). Polychaetes are described from a variety of settings but usually occur in shallow marine, tidal estuaries and tidal lagoon sediments (e.g. Barwis 1985). The total assemblage of trace fossils is typical of the Cruziana facies and Glossifungites facies of Seilacher (1967) which together occupy the sublittoral environment.

The biogenic structures in lithofacies RaSb indicate the sediment water interface was relatively stable, probably for the length of the period between storms, as time was available for trace fossil communities to inhabit the lithofacies across and below a single bedding plane. Lithofacies RaSm lacks colonisation by all but a few of what were probably the deepest burrowing organisms and indicates one of two possible origins, either (1) a rapidly shifting substrate combined with sedimentation for relatively long periods of time or (2) reworked storm deposits in which any

evidence of former colonisation of the sediment has been erased. The bed thickness and abundance of biogenic sedimentary structures elsewhere within the sequence suggests the latter interpretation is more likely.

The increase in the maturity of the sediments upward within the Rasselas Member combined with relative adjustments in the composition and the higher degree of alteration of feldspars indicates the sediment is being exposed to reworking at the same site for longer periods of time before burial. The thick sequence of homogenised silty sand in the upper part of the Rasselas Member which contains a lesser degree of burrowing also suggests regular reworking of the sand sheets by storms. This evidence infers increasingly more open marine conditions during the Rasselas sedimentation, and a corresponding gradual shift in environment off-shore.

In stratigraphic columns to the south-west end of Monro Beach (Fig. 5.47), the jump from a protected environment, characterised by fine grained lithofacies and flaser bedding, to a relatively open unprotected environment, characterised by thick sequences of bioturbated and reworked homogenised sandstones, indicates a protective barrier was removed over a relatively short period of time. To the north-east of Monro Beach, stratigraphic columns show fluctuations between relatively protected environments and relatively more open environments which indicates the transgression there was more gradual.

The Rasselas Member sequence is similar to sediments on the modern shelf of the northwestern Gulf of Mexico where there is a decrease in diversity and abundance of burrows with increasing water depth across the shelf which also displays a decreasing grain size off-shore (Hill 1985). The outer shelf zone exhibits less bioturbation due to the presence of very few organisms and high sedimentation rates. The supply of sand to the shelf area is most likely to be from the tidal river mouths and through the tidal channels inferred for the Paringa Member depositional environment.

Transgressions also provide major sources of sand as beach, barrier and fluvial deltaic sediments are drowned and reworked by shoreline processes. Storms will also transport sand offshore, with the prerequisites for the accumulation of thick blanket sandstones being abundant sand supply, fluctuating sea level and strong tidal currents (Reading 1978).

5.4 LAW COAL MEASURES

Sedimentary Structures And Textures

Introduction

The outcrop in Coal Creek is very poor. Intermittent exposures, which are weathered and covered with vegetation and soil, usually reveal conglomerate or coal seams and associated underlying siltstones and mudstones but the exposures are difficult to correlate. For these reasons a detailed lithofacies analysis can not be undertaken and basic lithologies that crop out will be briefly described.

(i) Cobble to Pebble Conglomerate

Massive, green, hard, cobble conglomerates consist of lithic and quartz clasts which are very well rounded. Clasts are clast supported in a silty sandstone.

Imbricated conglomerate also grades up over 2m from well rounded, clast supported cobbles to well rounded, clast supported pebbles, with a granular sandstone matrix. The lower contact is undulatory and erosional, with concave downward scour surfaces, overlying coal seams in two outcrops.

The textural maturity of the clasts, the clast supported nature of the conglomerate and the imbrication indicates the conglomerate was transported a considerable distance from the source area and deposited by a traction current. The flow transported cobbles and therefore had a relatively high competence. The grading upwards in grain size may indicate a waning of energy.

(ii) Boulder to Pebble Conglomerate

Structureless, sandstone matrix supported, boulder to pebble conglomerate (Fig. 5.63) consisting of angular to sub angular boulders of Greenland Group lithologies (Fig. 5.64) and sub rounded to rounded chloritised dacitic and rhyolitic clasts (R. Sewell, pers. comm. N.Z.G.S.) (Fig. 5.65), is



Figure 5.63
Coal Creek (Map 5: 297350225450), Law Coal Measures (Kaiatan).
Boulder to pebble conglomerate. (Photo - M Aliprantis)



Figure 5.64
Coal Creek (Map 5: 297350225450), Law Coal Measures (Kaiatan).
Angular Greenland Group derived boulders and cobbles (both ends of
15cm marker). (Photo - M Aliprantis)



Figure 5.65
Coal Creek (Map 5: 297350225450), Law Coal Measures (Kaiatan).
Sub-rounded volcanic boulder (15cm marker). (Photo - M Aliprantis)

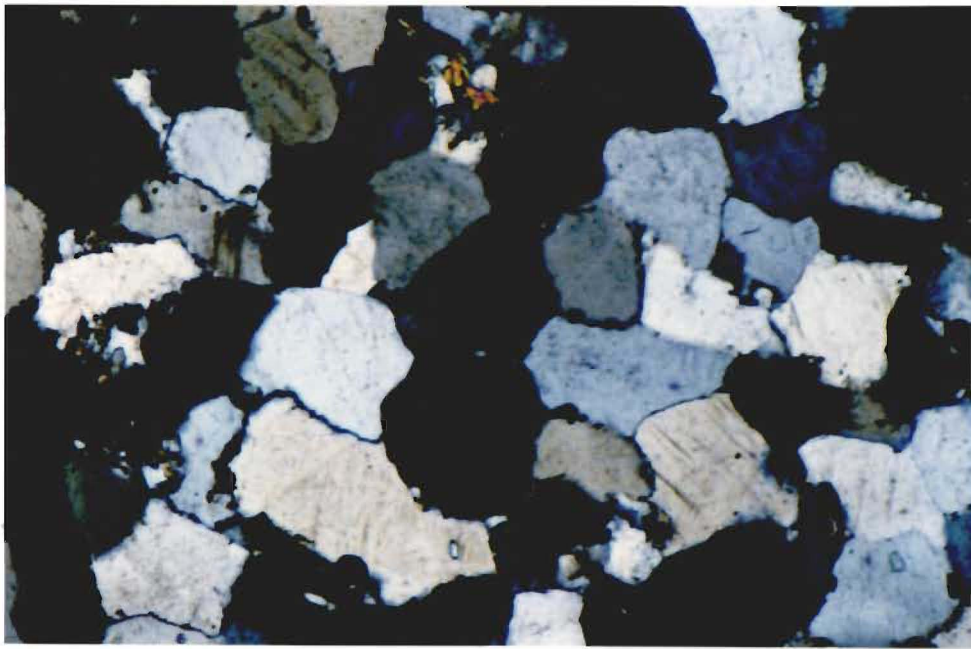


Figure 5.66
Quartz cemented quartz sandstone (sample no. U. of C. 11988).

exposed beneath interbedded quartzose sandstone and coal seams (see Section 4.5)

The poor sorting, angularity of Greenland Group derived boulders, structureless nature of the bed and matrix support, together suggest a gravity flow which could be sub-aerial or sub-aqueous.

(iii) Sandstone

Sandstones are green or grey, hard, moderately sorted, medium grained, micaceous, quartose, silica cemented sandstones with carbonaceous flecks. Green and grey sandstones overlie coal seams with undulose erosional contacts. The coal seams occasionally lie on black, carbonaceous, silty sandstones which grade up to siltstones and mudstones. Sedimentary structures are not apparent due to the poor nature of the exposures.

(iv) Carbonaceous Silty Mudstones and Mudstones

Structureless carbonaceous silty mudstones and mudstones usually up to 1m thick are associated with overlying or underlying coal seams and laterally lying coal seams. The mudstones usually contain abundant carbonaceous fragments.

The mudstone represents deposition from standing water over long periods of time. Where mudstone is grading up to coal seams the sequence probably represents dropping of relative water levels in the swamp to allow deposition of peat without the influx of mineral matter, coal seams grading up to or overlain by mudstone may represent cessation of the provision of plant material due to raised water levels in the swamp. Coal seams within the Law Coal Measures are composed of a distinctive coal type which is discussed in Section 6.3.

Composition of the Law Coal Measures

Visual estimations on the well rounded conglomerates interbedded with coal seams indicate 70% of cobble and pebble clasts are composed of medium to fine sandstones and siltstones with a minor proportion of black "argillaceous" clasts and 30% of clasts are quartz. A sample of sandstone (U. of C. 11988b) from the upper part of the coal measures in Coal Creek was thin sectioned and, with a visual estimation, revealed a texturally mature (very well sorted, sub-angular to well rounded) highly quartzose (90% quartz and silica rim cement) silica cemented medium sandstone (Fig 5.66) containing occasional well rounded sedimentary rock fragments and altered alkali feldspars, a small proportion of which are microcline, and a heavy mineral assemblage composed dominantly of tourmaline. The sedimentary rock fragments are composed of poorly sorted, angular, sandy quartz siltstones in a matrix of fine silt and clay containing aligned flecks and networks of sericite. A section of a lithic pebble (U. of C. 11990) from the well rounded conglomerates revealed a similar texture.

Interpretation

The conglomerate clasts and rock fragments in the sandstone indicate a sedimentary provenance which has been slightly metamorphosed and which texturally and compositionally resembles the sandstones and siltstones in the Greenland Group. Quartz may have been derived from quartz veins within the Greenland Group sediments or from a granitic source which is indicated by the presence of alkali feldspar in the sandstone.

Dacitic and rhyolitic boulders, cobbles and pebbles, which contain chlorite, are derived from an unknown volcanic source which has undergone incipient metamorphism.

Environments of Deposition

A complete lack of marine indicators such as dinoflagellate cysts, glauconite and characteristic trace fossil assemblages combined with the abundance of coal seams and carbonaceous matter in the sediments implies a non-marine environment. However the textural maturity of sandstones interbedded with coal seams in the upper part of the coal measures indicate high energy processes over a prolonged period of time which, combined with the evidence of marine rocks overlying the Law Coal Measures, requires that a marine influence in the upper part of the sequence cannot be discounted. Inactive tract sediment and the abundance of coal seams indicate areas of peat swamps and ponds or lakes which were protected from deposition of stream sediment for relatively long periods of time.

The relatively long distance from the source rock that the conglomerate has travelled, and the presence of erosional contacts characterised by scouring and channeling along the upper contacts of coal seams, indicates a fluvial system. Lateral sweeping of the flood plain by the channel system may be responsible for cessation of deposition of peat in the peat swamps.

Sandstones may be a product of in channel deposition, channel margin and levee deposition, or inactive tract flood deposits. The fluvial system may be braided, anastomosing or meandering, the restricted nature of the outcrop prohibits interpretation.

The source rocks are, the Greenland Group from a relatively long distance away from the depositional site, and the Tuhua Group or another granitic source. An unidentified slightly metamorphosed dacitic and rhyolitic source occurring near a Greenland Group source, that may be relatively close to the depositional site, is providing mass flows that lie either beneath or within the Law Coal Measures.