Geologic Setting,
Gravity Collapse and Hazard Assessment
of the Kongahu Fault Zone,
Westport.

A thesis
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of
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Kane Scott Inwood

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Abstract

The Buller Coalfield comprises the northern end of the Paparoa Trough, an elongate basin that began to subside in the mid Cretaceous. Subsidence occurred in response to mid Cretaceous extension, leading to crustal thinning, and culminating in opening of the Tasman Sea. The area underwent asymmetric subsidence between the mid-late Eocene and the late Oligocene, controlled by normal faulting, inferred to occupy the same position as the present day Kongahu Fault Zone. Inversion of the Paparoa Trough commenced in the late Oligocene, by reactivation of normal faults as reverse/thrust faults through a regional change from extension to shortening and establishment of the Alpine Fault as a new plate boundary. Positive inversion progressed through a number of phases over the last 25Ma producing the present day Buller Coalfield. Four sets of Quaternary coastal marine terraces are recognised within the Westport region. Preservation and tilting of this terrace sequence is indicative of progressive regional uplift continuing through to the present day.

Large scale gravitational collapse structures (forming the Kongahu Fault Zone Failure Complex, with a surface area of approximately 18km²) have formed over several hundred thousand years, along the escarpment separating Tertiary units on Denniston Plateau from Quaternary deposits along the coastal plain. Landslide materials of the Kongahu Fault Zone failure are very complex and have been subdivided into four zones based on slide geology and surface morphology. Six separate deformation phases have been identified based on interpretations of geomorphic evolution of the failure complex. Initial failure is inferred to have taken place along unfavourably oriented rockmass defects, such as bedding planes, joint sets and faults, with destabilisation initiated through head loading (caused by tectonic uplift) and removal of toe support through erosion of Late Tertiary units. Preservation of Caledonian Formation marine terraces and associated deposits, on the landslide complex, places this event beyond 334 000 years BP. Later phases of reactivation of the landslide complex are related to interglacial high stands in sea-level and ongoing fluviatile erosion, removing toe area support. The initial rupture surface is inferred to have propagated along bedding planes within the Brunner Coal Measures, but as the failure complex evolved the rupture surface propagated into sheared granitic basement, forming large-scale, deep-seated
collapse. Preservation of coastal marine terraces in the toe area of the main failure complex, formed during the last interglacial period are indicative of stability of the main failure complex since approximately 58-72 000 years BP. However, interpretation of geomorphic features upon the coastal plain indicate extremely slow deep-seated activity within the central "Mt Rochfort Failure".

A seismic hazard assessment of the main Kongahu Fault Zone failure complex indicates that it is inherently stable and unlikely to undergo large scale reactivation through high intensity ground shaking. Seismically triggered local rock falls, rock avalanches and rapid soil flows form the dominant hazard associated with earthquake triggered failure. Only one section of the failure complex, the "Mt Rochfort failure", is considered to still be active although inferred to be failing as extremely slow, deep creep. Localised recent failures are primarily related to antecedent pore water conditions and triggered by intense or prolonged rainfall and seismic events. These create a low level hazard due to lack of human interaction in areas where the failures occur. Reactivation of debris within fluvial channels leading to avulsion onto fan surfaces along the coastal plain forms the dominant hazard.

Lake Rochfort is a landslide formed lake (approximately 320 000m³), 460m above the coastal plain, located within the active Mt Rochfort Failure. By comparison with the (1981) Ram Creek Dam burst, it has been concluded that catastrophic failure of Lake Rochfort would destroy property and services with the potential for causing serious injury and loss of life on the coastal plain.
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Chapter 1

Introduction

1.1. Scope and Objectives of this Study

The elevated Dennistion and Stockton Plateaux of the Buller District are separated from the wide coastal plain by a major escarpment. Over the years two opposing schools of thought have developed, to explain the structurally controlled nature of this escarpment:

a) Laird (1968) interpreted fault displacement being taken up as a large scale monoclinal fold or flexure; and

b) Cave (1983b) inferred displacement across a clearly defined fault plane.

Large-scale landslides/gravitational collapse structures were identified prior to this study, but their extent and genesis were not understood and have not been studied in detail. Early workers such as Morgan and Bartrum labelled the structurally controlled escarpment the "Lower Buller Fault" but this nomenclature is not retained here with more recent classification as the "Kongahu Fault Zone" favoured.

Subdivision of farmland into new 2-5 hectare lifestyle blocks is occurring along the coastal plain and the question arose as to whether tectonic activity on the Kongahu Fault Zone or remobilization of large scale landslides/gravitational collapse structures pose any hazards with respect to the development. As a result the principle objectives of this study are defined as follows:

a) regional engineering geomorphological mapping at 1:10,000 scale (including more detailed mapping and logging of specific locations) to document bedrock and surficial features;

b) evaluation of the Kongahu Fault Zone by detailing the monocline/warp structure and assessing possible Quaternary fault activity;

c) landslide assessment to determine the triggering mechanisms, types of failure and deposits formed by landslide complexes within the Kongahu Fault Zone; and

d) landslide and tectonic hazard assessment of the Kongahu Monocline (including Lake Rochfort), from the Orowaiti River to Waimangaroa.
1.2. Study Area

1.2.1. Location

The study area lies within the Buller Coalfield, north of Westport, and includes much of the Denniston Sector, on the West Coast of the South Island, New Zealand (Figure 1.1). The total area studied is approximately 80 km$^2$ with exact boundaries defined by:

• North eastern boundary; Waimangaroa River.
• South eastern boundary; Headwaters of the Cascade River.
• South western boundary; Orowaiti River.
• North western boundary; The Tasman Sea.

Access to the western sector of the field area was by provincial State Highway 67, Westport-Seddonville. The Waimangaroa to Denniston road allowed access onto the Denniston Plateau and a network of old mining, exploration and Electrics tracks which provided walking access to the central part of the Denniston Sector. A four wheel drive service road for the Mt Rochfort transmitter allowed walking access to the south-eastern part of the study area.

1.2.2. Physiography

Landforms reflect the influence of bedrock geology. Broad, flat-lying Quaternary fans and prograded postglacial shoreline deposits form the coastal plain extending from the base of the escarpment to present day shoreline (Figure 1.2.) The Denniston Plateau forms an extensive and locally dissected dip slope rising 600-1000 m.a.s.l. and gently plunges seaward. The dip slope is formed on erosion resistant coal measure sandstones cut by fault scarps and present-day fluvial systems, some of which are deeply incised. In contrast, the underlying Hawks Crag Breccia and Greenland Group erode to form steep-sided v-shaped valleys typified by the head waters of the Cascade and Orowaiti Rivers. An escarpment reaching almost to sea-level, associated with the Kongahu Fault Zone, forms the north-west boundary of the plateau. Both the Orowaiti and Waimangaroa Rivers are deeply incised gorges forming natural northeast and southwest boundaries to the study area. Massive cliffs (300m+) face eastward from Mt Rochfort (1040m), into the deeply incised headwaters of the Cascade River (Figure 1.3.).
Figure 1.2. View looking north from below Mt Rochfort across the Denniston Plateau and Holocene coastal plain, separated by the escarpment formed by the Kongahu Fault Zone. Note the gently northwest dipping plateau (Structural Domain 3) and abrupt truncation by the escarpment (Structural Domain 2) and flat lying coastal plain (Structural Domain 1). See text in chapter 2 for structural domain interpretation.
Figure 1.3. Massive east facing cliffs, below Mt Rochfort, within massive beds of Brunner Coal Measure basal conglomerates. Note the 40m high transmitting tower in the background for scale. The photograph is taken looking south immediately north of Mt Rochfort (GR, K29 062359).
1.2.3. Vegetation

Very little of the Denniston Plateau or Mt Rochfort areas are vegetated except for small alpine mosses, lichens, tussocks and shrubs. Stunted larger beech and alpine tree communities can be found in some of the more sheltered gullies and shaded areas where a greater thickness of soil has formed (Alarcon, 1997). Large mature beech forests characterise the steep sided Waimangaroa, Cascade, Orowaiti Rivers and the escarpment where Tertiary strata (Kaiata Mudstone, Blue Bottom Group) and underlying basement rocks are exposed. Much of the escarpment is underlain by the Brunner Coal Measures and derived colluvial material which will only support stunted native trees and scrub. Pinus radiata forestry was attempted on these deposits in the late 1970’s-early 1980’s but most trees died or have struggled to survive. The coastal strip is farmed although much of the poorer land is being redeveloped for lifestyle blocks as the population of Westport and the surrounding area continues to grow.

1.2.4. Mining History

Coal was first discovered in the Buller Coalfield in 1859 by explorer John Rochfort (cited in Morgan and Bartrum, 1915). Following his discovery a more detailed investigation was carried out in 1860 by geologist Julius von Haast and colliery engineer James Burnett (Meyer, 1971). Large-scale mining began in the Denniston sector in 1878 with commissioning of the Denniston incline to service the plateau mines. Production reached a peak of between 7-800 000 tons/year from 1908 to 1916 (Barry and MacFarlan, 1988). Through to 1967, when the Denniston Incline was decommissioned, it is estimated to have transported some 13 million tonnes of coal down the escarpment (Todd, 1989a). All coal haulage since has been by truck with only three small privately owned mines currently operating.

A gold-rush began in 1867 but was short-lived, mining alluvial gold contained within “blacksand leads” preserved in old marine terraces (McPherson, 1978). Marine blacksand leads resulted from the heavy mineral concentration along shorelines. Deposition occurred during interglacial and post-glacial sea-level rises, with landward shoreline migration slowed by increasing cliff heights and/or slowing of sea-level rise. Consequently greatest gold concentrations occurred close to the foot of cliffs cut at time of maximum sea-level (Suggate, 1996). Areas of blacksand leads worked for gold...
within the study area were divided into low lying (0-12 m.a.s.l.) Holocene deposits and high level (20-140 m.a.s.l.) interglacial marine terraces, as shown in Figure 1.4.

a) Low lying pakihi swamp (Fairdown Beach Lead and scattered low level workings); and

b) high-level alluvial terraces overlying blacksand ore bodies (German Terrace, Giles Terrace, Rochfort Terrace, Hatters Terrace, Christmas Terrace, Greenhill Terrace and Fairdown Terrace).

Figure 1.4. Westport historical northern alluvial mining district showing approximate distribution of mining claims over blacksand leads (Adapted from McPherson, 1978).
1.2.5. Climate

The characteristically extreme climate on the Denniston Plateau and Buller Coalfield result from pronounced orographic effects superimposed upon regional patterns. Prevailing moist westerly oceanic air streams ascend the north-westerly escarpment with consequent cooling, condensation and increased wind speeds. As a result the rainfall frequency and intensity are greater in the Mt Rochfort, Denniston areas than on the adjacent coastal plain. Wind velocities also increase up the escarpment, particularly at the crest (N.Z. Coal Resources Survey, 1987; Todd, 1989a).

Mean annual rainfall at Westport Airport is 2192 mm/yr and increases markedly inland towards the mountain ranges (Mew and Ross, 1991). Although detailed climatic records for the Mt Rochfort and Denniston areas do not exist, annual rainfall is estimated to be between 5000 and 7000mm with monthly variations of 120 to 500mm (Alarcon pers comm, 1997). Surface runoff during storm events tends to occur very rapidly resulting in high stream flow rates that drop rapidly over short periods of time. The wettest months are from November to February while the winter months can be quite dry (Todd, 1989a). Due to the high relief light short-lived snowfalls occur from autumn to spring, as well as low cloud and fog throughout the year. Such conditions became a major controlling factor for conducting field work, especially on the Mt Rochfort and Plateau sectors.
1.3. Geologic Setting

The South Island of New Zealand is divided into two Provinces separated by a complex belt of dismembered arcs known as the Median Tectonic Zone (MTZ) (Figure 1.4) (Bradshaw, 1993). Miocene to recent displacement along the Alpine Fault has lead to the separation of the two crustal blocks by nearly 480km (Bradshaw, 1989). The Western Province consists of the Buller and Takaka terranes, separated by the Anatoki Thrust. The basement of the Buller Terrane comprises a relatively uniform suite of Ordovician quartz-rich turbidites (Greenland Group), cut by Palaeozoic and Cretaceous granites (Cooper and Tulloch, 1992). Charleston Metamorphic Group and Gneiss are considered to represent highly metamorphosed equivalents of these rocks (Tulloch and Kimbrough, 1989; Ireland, 1992).

New Zealand forms a largely submerged micro-continent, situated astride the obliquely convergent Pacific-Australia plate boundary in the southwest Pacific (Pettinga, 1997; Berryman and Beanland, 1991). Relative plate motion varies from 53±1 mm/year, north of New Zealand to 42±1 mm/yr in the northern South Island with convergence becoming increasingly oblique to the southwest (Figure 1.6) (DeMets et al, 1990). Tectonics of the present day plate boundary represent the change from opposite dipping and obliquely convergent subduction zones in the north and south of New Zealand. These are separated into three main elements (Pettinga, 1997; Berryman and Beanland, 1991):

a) the northwest dipping Hikurangi Margin oblique subduction zone along the eastern side of the North Island;
b) Alpine Fault System composing of the North Island shear belt, forming a series of strike slip faults northwest of the Hikurangi margin, extending south through the Marlborough Transfer Zone into the east dipping oblique dextral Alpine Fault; and
c) the southeast dipping Puysegur oblique subduction zone in the far southwest of the South Island.

A major accretionary prism and imbricate thrust system has developed off the eastern North Island, where oceanic crust of the Pacific Plate subducts beneath continental crust of the Australian Plate, with associated magmatic arc and back arc extension within the Central Volcanic Region (Bishop et al, 1995; Berryman and Beanland, 1991). The Alpine Fault forms the most prominent element in the Alpine Fault System, forming a linear extension some 400km long, through the central western portion of the South...
Figure 1.5. Summary of regional geology of the Western Province (From Waight, 1995).
Figure 1.6. Location of the West Coast area of South Island with respect to the present plate tectonic setting of New Zealand. Tectonic provinces shown by dashed boundaries are based on faulting style (Adapted from Berryman and Beanland, 1991). Filled arrows represent relative rates of movement in mm/year between the Australian and Pacific plates (DeMets et al., 1990).
Island. Passing northward into the Marlborough Transfer Zone there is a transition from subduction to continental collision, associated with tectonic shortening, crustal thickening and uplift across the rapidly widening Australia-Pacific plate boundary (Pettinga, 1997). To accommodate the westward dipping boundary of the Hikurangi Trench, the eastward dipping Alpine Fault changes into a series of lesser dextral strike-slip faults, striking near parallel to the plate vector (Pettinga, 1997). Tectonic shortening within the Marlborough Transfer Zone has lead to reactivation of reverse faults (such as the Kongahu Fault Zone), within Northwest Nelson and Buller.

In its present form the West Coast Region can be divided into two main tectonic units: the West Coast Basin and Range Province and the Western Platform (Figure 1.7.) The Western Platform covers a large tectonically stable offshore area west of the South Westland fault zone and Cape Foulwind fault zone, comprising of little deformed flat-lying to gently dipping latest Cretaceous to Cenozoic sequence. Sediment thickness is approximately 2-3000m (north of Ross), increasing southwards and gradually thinning westward beyond the continental margin (Nathan et al, 1986).

In contrast, the Buller Coalfield lies within the tectonically unstable West Coast Basin and Range Province. Uplifted to the east and highly deformed the Buller Coalfield has been characterised by subsidence and uplift since the Late Cretaceous (Nathan et al, 1986). Extension at this time is thought to have developed in relation to continental rifting associated with opening of the Tasman Sea (Nathan, et al, 1986, Laird, 1994). A strong north to north-northeast structural trend overprints the province reflected by block faulting and rapid Quaternary uplift, controlling the position of mountain ranges and inter-montane depressions, and giving rise to present day topography (Nathan et al, 1986).

The Buller Coalfield is bounded by two north to north-northeast trending faults, the Kongahu and Glasgow Faults, forming a discrete latest Cretaceous to Miocene sedimentary basin ("Paparoa Trough") in which the coal measures of the Buller Coalfield were laid down, buried and subsequently inverted (Webster, 1992, Kamp et al 1996).
Figure 1.7. Sketch map and cross-section illustrating major structural elements of the West Coast (Adapted from Nathan et al 1986).
1.4. Previous Geological Studies

Julius von Haast, in 1860, was the first geologist to explore the Buller District and discover the coalfield between Mt William and Mt Rochfort (later named “Buller Coalfield”). Subsequent explorers were then sent to further investigate the Buller District with most initial investigations concentrating on the Buller Coalfield. Detailed mining and geological investigations of much of the Buller Coalfield for the following 54 years are summarised in Morgan and Bartrum (1915). Morgan and Bartrum’s 1915 survey recognised the complexity in the structure of the Kongahu Fault, and that it was distributed over a zone of some width. From Waimangaroa South it becomes further complicated by folding of the Brunner Coal Measures, with repeated curving of the faults strike and increasing throw as it passes southward (Morgan and Bartrum, 1915).

Regional mapping has since been carried out by Gage (1946), Suggate (1950), Wellman (1950b), Bowen (1964), Laird (1968), Nathan (1980 and 1996). Of these, only Nathan (1980, 1996) supply much detail on the Denniston area. Nathan et al (1986) has also published a general but comprehensive account of Cretaceous to Cenozoic geology of the West Coast region.

The structural geology of the Buller Coalfield has been assessed by Laird (1968), Laird and Hope (1968), Cave (1983a,b) and more recently by Nathan (1996). A chronology of subsidence and uplift has also been presented by Kamp et al (1996) based on fission track dating and coal rank studies.

A New Zealand Coal Resources Survey (NZCRS) was instigated during the early 1970’s in response to energy shortages and in order to define New Zealand’s national coal resources. A period of intense exploration within the Buller Coalfield followed, involving geological mapping, over 250 exploration drillholes, and preparation of detailed reports (Nathan, 1996). Most of the results of the NZCRS within the Buller Coalfield are summarised by Barry et al (1994: p31-39). Other publications and theses by Todd (1989), Titheridge (1988 and 1992) and Webster (1992) include useful summaries of work conducted within the Buller Coalfield.

Only a small amount of literature is available on the coastal strip between Westport and Waimangaroa. Nathan (1976) produced a detailed 1: 25 000 scale map of the Cape Foulwind Area identifying and correlating many of the late Quaternary coastal deposits. McPherson (1978) published detailed work on Westport’s ilmenite deposits which had formed the basis Nathan’s (1976) late Quaternary stratigraphy. Mew and Ross
(1991) conducted a detailed soil survey and review of the Westport district based on changing agricultural requirements in the region.

Considerable amounts of time and effort have been spent on geological investigations within the Buller Coalfield, but with far less emphasis on the Kongahu Fault Zone and coastal plain. It has only been in very recent work by Nathan (1996) that large-scale landslide collapse features affecting the escarpment, west of Mt Rochfort and the Denniston Plateau, have been recognised.

1.5. Investigation Methodology

1.5.1. Field Procedure

Approximately 18 weeks of field work was conducted for this study. Field work commenced in early May (1996) and ended late April (1997). Mapping was performed by a combination of field work and aerial photo interpretation. Field mapping was carried out on 1:10 000 base maps (with 20m contour intervals) and laser copied aerial photographs at approximately 1:8 000 scale. Creeks, streams, gullies, ridges, spurs, cliffs and road cuts were systematically mapped. For each outcrop (where possible) lithology, bedding (strike/dip), faults, shears, fault gauge, folding and any rock mass deformation characteristics (whether in situ, degree of displacement). Due to continual thick cloud cover accurate positioning on base maps became difficult. An older Geographical Positioning System (GPS) unit was tried as a means of location but steep topography, size and inherent uncertainties made it's use unsatisfactory.

On the Denniston Plateau bedrock geology is quite well exposed because of a lack of vegetation and soil cover. Over the escarpment sector however, the vegetation cover, soil and slope debris result in poor outcrop exposure. Many other areas were not readily accessible due to the steep and broken terrain, particularly in the headwaters of streams and creeks flowing from the Mt Rochfort and Plateau sectors. These creeks and streams tended to be choked with large blocks of Brunner Coal Measures, which obscured in-situ outcrop and limited access (Figure 1.8.). Consequently, exposure of suitable outcrop was generally poor and discontinuous, resulting in poor field relationships between rock units. Considerable inference had to be applied between physiography and geology. Cliffs and bluffs, especially in the Mt Rochfort sector, provided favourable exposure. However, even with the aid of ropes it was far too
dangerous to conduct more than brief geological investigations (Figure 1.9.). Accurate regular measurements were possible in limited areas, such as new road cuts, the Denniston Plateau and some stream sections where outcrop was relatively continuous.

Figure 1.8. View of a typical rugged stream section within the study area. Large blocks of Brunner Coal Measure derived conglomerate, grit and sandstone choke the stream bed obscuring bedrock exposure. Note the pack and A3 map board for scale (GR, K29 073405).
Figure 1.9. View looking down a extremely steep, very rugged section of stream bed in the headwaters of the Cascade River. Such conditions frequently prevented access or required the use of climbing equipment (GR, K29 051354).
1.5.2. Map Compilation

A 1:10 000 scale base map was generated by scanning the New Zealand 25 000 scale topographical maps (topo plot sheets K29B and K29D) and importing them into ACAD R12 Tracer. This allowed a 1:10 000 base map to be generated as an ACAD drawing. Cultural and geomorphic information, such as roads, river and power lines, were digitised on at a later date off the same 1:25 000 scale topographical maps.

Five sets of aerial photographs were used during this study and are listed in Appendix 1. These were laser copied at a scale of approximately 1:8000 and laminated with original field work recorded on transparent mylar overlays. All discernible geomorphic features such as; river and sea cut terraces, landslide scarps, fans, dune systems and scour channels were marked onto another set of overlay sheets. Information from the New Zealand Soil Bureau map (SB6-Westport)(Mew and Ross, 1991b) was also used for interpreting land forms along the narrow coastal strip. Photo overlays were then photo reduced to 1:10 000 and hand drafted onto 4 A1 transparencies of the reverse printed base map. These in turn were digitised back into ACAD version R13. Final map drafting and editing were conducted and colour copies prepared.

1.6. Thesis Format

Chapter two is predominantly a literature review looking at the geological development of the West Coast and the pre-Quaternary stratigraphy. Structural Domains are recognised and related to the Kongahu Fault Zone.

Chapter three reviews Quaternary geology, allowing correlation of marine terraces and Holocene deposits within the study area and providing a time frame for escarpment collapse evolution.

Chapter four investigates the extent, initiation and episodes of failure, within the "Kongahu Fault Zone Failure Complex", in conjunction with the development of failure models.

Chapter five reviews and assesses the hazard associated with the Kongahu Fault Zone and failure complex, including the stability of Lake Rochfort.

Chapter six presents a brief summary, with conclusions and recommendations for future research.
2.1 Geological Development of the West Coast

a) Introduction

Evidence for three pre-Miocene tectonic events are recorded in Western Province rocks of the West Coast, with extensional and compressional phases identified:

- Late Middle to Early Cambrian Haupiri Disturbance (Cooper, 1979; Brathwaite, 1989);
- Late Ordovician or Early Silurian Greenland Tectonic Event (Cooper, 1979, 1989; Cooper and Tulloch, 1992); and
- Mid Palaeozoic Tuhua Orogeny (Cooper, 1979, 1989; Brathwaite, 1989).

During the Permian to the early Cretaceous, New Zealand’s Western Province formed part of an extensive arc system located on the SW Pacific margin of Gondwana (Muir et. al., 1995). At this time the tectonic regime was characterised by convergence along a westerly-dipping subduction zone. This subduction zone formed New Zealand’s Median Tectonic Zone (MTZ) consisting of; magmatic arcs, forearc basins, trench slope basins and accretionary complexes. The compressional regime culminated in the Early Cretaceous, through deformation, metamorphism, uplift and erosion of the Rangitata Orogeny (Bradshaw, 1989). The Separation Point Batholith represents the final stages of magmatism associated with subduction, resulting in partial melting of a basaltic underplate and uplift of the thickened arc (Muir et. al., 1995).

During the mid-Cretaceous (105 +/- 5Ma) the tectonic regime changed, with the cessation of convergence and the onset of extension. The change from compression to extension has been attributed to the collision of the Pacific-Phoenix spreading ridge with the subduction zone on the Gondwana margin (Bradshaw, 1989). Laid (1993) summarises the evidence for four separate phases of extension on the New Zealand margin of the Tasman Sea from the mid to late Cretaceous. The abrupt change to an extensional regime lead to crustal thinning, culminating in the opening of the Tasman
Table 2.1. Summary of main depositional and tectonic periods of the West Coast, post-Late Mesozoic (Adapted from McNee, 1997).

<table>
<thead>
<tr>
<th>Period</th>
<th>Depositional Events</th>
<th>Tectonic Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miocene - Pliocene</td>
<td>Blue Bottom Group</td>
<td>Uplift, erosion of the Southern Alps due to transpressional Alpine Fault. Reactivation of normal faults leading to Basin Inversion</td>
</tr>
<tr>
<td></td>
<td>Influx of terrigenous clastics into basinal areas</td>
<td></td>
</tr>
<tr>
<td>Late Eocene - Oligocene</td>
<td>Kaiata M.S. and Torea Breccia</td>
<td>Renewed extension with gradual transgression</td>
</tr>
<tr>
<td></td>
<td>Marine transgression and clastics debris flows into basinal areas</td>
<td>Propagation of rift zone northwards from SE Indian Ridge into South Island</td>
</tr>
<tr>
<td>Middle Eocene</td>
<td>Brunner Coal Measures to Millerton sandstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fluvial to shallow marine</td>
<td></td>
</tr>
<tr>
<td>Late Paleocene to Early Eocene</td>
<td>Brunner Coal Measures</td>
<td>Cessation of Tasman Sea rifting</td>
</tr>
<tr>
<td></td>
<td>Penepplanation, fluvial sedimentation of Brunner proximal to Paparoa trough axis</td>
<td></td>
</tr>
<tr>
<td>Late Cretaceous to Early Paleocene</td>
<td>Paparoa Coal Measures</td>
<td>Extensional basin associated with Tasman Sea rifting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Formation Paparoa Trough</td>
</tr>
<tr>
<td>Late Campanian</td>
<td>Regional Unconformity</td>
<td>Onset of Tasman Sea spreading (break up)</td>
</tr>
<tr>
<td>Middle - Late Cretaceous</td>
<td>Pororari Group</td>
<td>Rifting resulting from NNE-SSW extension</td>
</tr>
<tr>
<td></td>
<td>Coarse alluvial Hawks Crag Breccia</td>
<td>WNW-ESE trending basins</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Formation of the Paparoa Metamorphic Core Complex</td>
</tr>
<tr>
<td>Regional Unconformity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early Cretaceous</td>
<td>Berlins Porphyry (Rahu Suite)</td>
<td>Cessation of subduction leading to partial melting of crust</td>
</tr>
<tr>
<td>Carboniferous - Permian</td>
<td>Karamea Batholith</td>
<td>Plutonism associated with subduction on the Gondwana margin</td>
</tr>
<tr>
<td>Ordovician</td>
<td>Greenland Group</td>
<td></td>
</tr>
</tbody>
</table>
Sea and Southern Ocean, as New Zealand rifted away from Australia and Antarctica (Bradshaw, 1989). However, seafloor spreading did not commence until approximately 82Ma, approximately 20-25Ma after initial rifting occurred (Laird, 1994).

Mid-Cretaceous extension resulted in the formation of a rift system throughout the western part of New Zealand (Kamp, 1986). Throughout the North Westland region north-northeast to south-southwest extension induced rifting, resulting in the widespread development of narrow, elongate half grabens (Laird, 1994). The most significant of these depressions recognised on the West Coast is known as the “Paparoa Trough” (Nathan et. al., 1986) or the “Paparoa Tectonic Zone” (Laird, 1968). Evidence for extension is seen as an unconformity observed over much of New Zealand, separating Rangitata Orogen rocks from younger, less deformed strata (Laird, 1981). Within the Buller region, evidence for Tasman Sea rifting is also seen in the Paparoa Tectonic Zone as lamprophyre dykes emplacement, magnetic anomalies and alkaline basaltic volcanism (at approximately 68 Ma) (Hunt and Nathan, 1976; Sewell et. al., 1988) Laird (1981) interpreted the Westland region as an area of incipient continental separation and a “failed arm” of the triple junction of a rift system. West-northwest to east-southeast trending grabens formed parallel to the future spreading axis of the Tasman Sea, filled with non-marine Pororari Group (Laird, 1993, 1994, 1995), consisting of up to 4500m alluvial fan, (Hawks Crag Breccia) and 600m of distal fluvial-lacustrine sediments of the Ohika Formation (Nathan, 1978a; Topp, 1996).

**b) Paparoa Metamorphic Core Complex Model**

Synchronous with, and partially post dating the middle Cretaceous graben development, was the formation of the Paparoa Metamorphic Core Complex, situated in the locality now occupied by the Paparoa Ranges. This model was first proposed by Tulloch and Kimbrough (1989) in order to explain the juxtaposition of high grade metamorphic and deformed granite basement rocks, beneath low grade metasedimentary rocks and undeformed granites (Figure 2.1.) by uplift on low angle detachment faults, with subsequent sedimentation in associated fault bounded sedimentary basins (Laird, 1995). Intrusion of Cretaceous granitoids near Charleston, and specifically the Buckland Granite near the core complex in the Paparoa Range, are likely to have facilitated ductile extension and uplift through input of intrusive heat (Tulloch and Kimbrough, 1989; Lewthwaite, 1995; Topp, 1996).
Figure 2.1. Map and cross-sectional view of the Paparoa Metamorphic Core Complex showing the distribution of basement units, the Ohika Detachment Fault (OF) and the Pike Stream Detachment Fault (From Tulloch and Kimbrough, 1989).
In Webster (1992), Block and Royden (1990) describe a core complex as “the exposure of mid-crustal normal detachment faults, uplifted to the surface by thinning and extension of hanging wall rocks”. This results in ductile, medium to high grade, mid crustal metamorphic units, juxtaposed with low grade brittle or unmetamorphosed upper level crustal rocks. Isostatic compensation can typically cause the metamorphic core to form an antiformal structure. The simple model they proposed involved thinning of the hanging wall (possibly by either erosion or extension), reducing load on underlying rocks. With sufficient reduction, a horizontal pressure gradient will develop in the underlying rock, initiating lateral flow to the incipient core complex with related updoming and eventual exposure of the core (Figure 2.2.). Other models described in the literature have been well summarised by Lewthwaite (1995).

Lewthwaite (1995) conducted a detailed study of structures and kinematic indicators in lower plate mylonites, which lead to the proposal of a two stage model for the development of the Paparoa Metamorphic Core Complex (Figure 2.3.). The first stage involved the formation of regional conjugate listric normal faults. The second stage envisages growth and eventual dominance of the Pike Detachment Fault, overprinting earlier fabrics. Doming of the core complex and ductile deformation of the lower crust was probably initiated by plutonic intrusion, but continued after intrusion by tectonic denudation. However, initiation of extension may have occurred as result of over thickening of the crust during the preceding period of subduction (Lewthwaite, 1995). According to the model proposed by Lewthwaite (1995), the Greenland Group cover slid off the Pike and Ohika Detachment Faults, forming half grabens which were subsequently infilled with Pororari Group sediments. It was concluded that the development of the Paparoa Metamorphic Core Complex did not fit the commonly advocated models for core complex development, such as uniform simple shear or pure shear (Lewthwaite, 1995).
Figure 2.2. Simplified formation of a core complex initiated by extension on mid-crustal detachment fault (A) where the underlying crust is strong, (B) or weak (Block and Royden, 1990; In Webster, 1992).
Figure 2.3. Schematic drawing of a two stage development model for the Paparoa Metamorphic Core Complex (not to scale) (From Lewthwaite, 1995).

PF=Pike Detachment Fault, OF=Ohika Detachment Fault, RJG=Red Jacket Granite, CA=Charleston Arch, PHA=Parsons Hill Arch, CFG=Cape Foulwind Granitoids, GG=Greenland Group, whc=White Horse Creek Fault, sense of shear indicated by arrows,


STAGE 2. Further development and eventual dominance of the conjugate PF and associated overprinting of shear fabrics.
c) Paparoa Trough

Sedimentation in the southern part of the Paparoa Trough began in the late Cretaceous (Titheridge, 1988), when onset of seafloor spreading in the proto-Tasman Sea (at approximately 82 Ma) caused a second phase of extension and reactivation of the west-northwest to east-southeast graben system (Laird, 1993). Syndepositional faulting led to the deposition of up to 2000m of Paparoa Coal Measures, consisting of alluvial fan, axial valley and lake deposits (Newman, 1985).

Slowing and final cessation of spreading in the Tasman Sea at about 60Ma is reflected by Early Palaeocene slowing of subsidence in New Zealand’s western basins (Laird, 1992), and followed by a period of tectonic quiescence (late Paleocene to early Eocene) and wide-spread peneplanation (McNee, 1997). This in turn resulted in a regional unconformity separating basement from the Brunner Coal Measures (Todd, 1989). Over this period, the Brunner Coal Measures had only accumulated locally along the central axis of the Paparoa Trough (McNee, 1997). Basement topography at this time was characterised by low hills and broad open valleys (Todd, 1989), with prolonged chemical weathering and frequent resorting of a limited supply of waste producing quartz-rich residuum (Titheridge, 1988).

Fluvial deposition initiated by relative rise in base level, during localised subsidence and early stages of a marine transgression, lead to the formation and preservation of the Brunner Coal Measures (Todd, 1989). Thickness variations are primarily due to localised rapid subsidence, superimposed on regional subsidence and in association with a marine transgression. Thickest occurrences tending to be preserved at sites of formerly localised active subsidence (Titheridge, 1988), such as at Mt Rochfort where they overlie Hawks Crag Breccia. These very thick sequences tend to be dominated by sandstone and conglomerates which are largely devoid of coal (Todd, 1989).

Regional subsidence and marine transgression commenced in the south, proceeding northwards up the Paparoa Trough, as Brunner Coal Measure are early to middle Eocene in the Greymouth area and middle to late Eocene in the Buller Coalfield (Titheridge, 1988). Kamp (1986) suggested this occurred in response to propagation of a rift zone northwards from the south-east Indian Ridge into the South Island region, combined with renewed extension. The marine transgression continued through until the middle Oligocene (Nathan et. al., 1986), with the Brunner Coal Measures grading
upwards into the shallow marine Kaiata Formation. Continued subsidence at the northern end of the Paparoa Trough resulted in accumulation of a thick sequence of Kaiata Formation (Todd, 1989). Faulting and uplift along the Paparoa Tectonic Zone produced locally thick marine breccias and conglomerates, interbedded with the Kaiata mudstone. In the Buller Coalfield they were derived from the west (probably from exhumed basement) forming the Torea Breccia Member. Further marine transgression, in conjunction with reduced subsidence during the Oligocene, led to local deposition of calcareous sediments and limestones on basin margins (Todd, 1989). Recent fission track and coal rank work by Kamp et. al. (1996) has indicated that up to 6km of these Tertiary sediments accumulated above the Brunner Coal Measures, within parts of the Buller Coalfield. Large lateral changes in coal rank within the coalfield, over distances of 10-15km, reflects the dip of the hanging wall blocks (Titheridge, 1992).

d) Inversion

The Paparoa Trough and many other early Tertiary basins, persistent from late Cretaceous to Oligocene, ceased to exist at the end of the Oligocene with uplift controlled by north to north-northeast trending faults (Nathan et. al., 1986). This occurred through a regional shift from oblique extension to oblique compression across the Indian-Pacific plate boundary, with resultant propagation of the Alpine Fault System (Nathan et. al., 1986; Webster, 1992).

Anderson et. al., (1993) proposed a possible geologic evolution for the Alpine Fault, illustrated schematically in Figure 2.4. Initially all the plate motion was accommodated along the Alpine Fault trace, but since inception of the fault as a transform structure, the pole of rotation (describing relative motion of the Australian and Pacific Plates) has shifted south, with an increasing component of convergence. Buoyant material of the Chatham Rise prevented convergence being taken up near the margin. Consequently leading to pre-existing normal faults in the Buller Region, reactivated as reverse faults to accommodate the increasing compressional component. The strike slip component is left to be taken up on the Alpine Fault, which then began to migrate northwest, forming the bend. As the strike-slip faults are transported northwest they become less active. The strike-slip component of motion is transferred to newer faults in the southeast, in an attempt to keep the Alpine Fault in the central South Island as a through-going structure.
The dominantly compressive regime resulted in uplift of the Paparoa Trough to above sea-level, and the formation of further sedimentary basins offshore (Barry and MacFarlan, 1988). Uplift of these basins is referred to as positive inversion, referring to a switch in tectonic mode from extension to contraction and generally involving the reactivation of extensional faults so they undergo reverse slip (McClay, 1995). One of the most striking changes to paleogeography at this time was the apparent emergence of large areas of land, including most of south Westland and the area immediately west of Nelson (Nathan et al., 1986).

Three phases of basin uplift have been identified over the past 25 Ma. Two Miocene compressional phases (24-19 Ma and 13-8 Ma) (possibly connected with the formation of the sub-Waiauan Unconformity), and a third further phase (Quaternary) of inversion that formed the present topography (Kamp et al., 1996; Webster, 1992). Miocene to Pliocene uplift of the Paparoa Trough along the Kongahu Fault Zone, was associated with erosion and deposition in troughs to the east and west (Titheridge, 1988). Consequently by the end of the Pliocene the North Westland area consisted of eroded blocks which were raised during the Miocene, alternating with sedimentary troughs, such as the Grey Valley Basin (Nathan et al., 1986). The most recent phase of uplift has continued through to the present day, forming the Paparoa-Papahaua Range (formerly the site of the Paparoa Trough) and supplying detritus to the actively subsiding Grey and Inangahua Valleys (Titheridge, 1988).
Figure 2.4. Proposed possible geologic evolution for the Alpine Fault (From Anderson et. al., 1993).
2.2. Stratigraphy

The stratigraphic nomenclature in the West Coast is complex, but an excellent review has been provided by Nathan et al., (1986). A generalised stratigraphic column for the study area is shown in Figure 2.5.

2.2.1. Basement

a) Greenland Group

The Greenland Group constitutes the oldest rocks found within the Buller Coalfield and are thought to be latest Cambrian to Early Ordovician (Roser et al., 1996). They consist of greenish-grey quartzose greywackes and argillites with a distinctive modal composition. Greywacke beds contain abundant detrital quartz (35-50%) and only minor amounts (<6%) of sodic plagioclase and fine grained rock fragments (Nathan, 1976). They are generally 0.2 - 1.2m thick, are commonly graded and thought to represent deep water turbidite deposits (Nathan, 1978a). The sequence is strongly folded and bedding is cut by penetrative cleavage in most outcrop exposures (Nathan, 1978a). Body fossils have only been found from a single locality near Reefton, indicating earliest Ordovician age, for Greenland Group rocks of that area (Cooper, 1979). Sedimentology has been described by Laird (1972) and geochemistry by Nathan (1976).

A belt of granitic plutons, ranging in age from mid Palaeozoic (Karamea Suite) to Cretaceous (Rahu and Separation Point Suites), intrude the Greenland Group, which is locally metamorphosed to biotite hornfels and schist close to these plutons (Webster, 1992, Muir et al., 1996, Nathan, 1996). Near intrusive contacts the Greenland Group loses its distinctive green colour and becomes dark brown to black, associated with the contact metamorphic growth of biotite (Waight, 1995). Within the headwaters of the Cascade River, relatively unaltered Greenland Group sandstones and mudstones are observed. However, emplacement of the Britannia Granite has lead to Greenland Group exposed in the Waimangaroa River to become altered to biotite zone and spotted slate zone (Figure 2.6a.) on the Denniston Plateau (Kutsukake, 1988). In the Orowaiti River catchment small outcrops of Greenland Group have become locally altered to chlorite schist (Figure 2.6b.).
<table>
<thead>
<tr>
<th>Lithology</th>
<th>Stratigraphy</th>
<th>Age</th>
<th>Depositional Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>River gravel, marine sand and gravel</td>
<td>Late Pleistocene to Recent</td>
<td>Terrestrial and marine</td>
<td></td>
</tr>
<tr>
<td>Blue Bottom Group</td>
<td>Siltstone, sandstone and calcareous mudstone</td>
<td>Miocene</td>
<td>Marine</td>
</tr>
<tr>
<td>Whitecliffs Formation</td>
<td>(Calcareous mudstones and limestones in the east only)</td>
<td>Miocene</td>
<td>Marine</td>
</tr>
<tr>
<td>Kaiata Formation</td>
<td>Dark micaceous siltstone with sandy interbeds near base</td>
<td>Late Eocene</td>
<td>Marine</td>
</tr>
<tr>
<td>Brunner Coal Measures</td>
<td>Early Eocene</td>
<td>Terrestrial</td>
<td></td>
</tr>
<tr>
<td>Hawks Crag Breccia</td>
<td>Mid Cretaceous</td>
<td>Terrestrial</td>
<td></td>
</tr>
<tr>
<td>Greenland Group basement with intrusive granitoids (Karamea Batholith)</td>
<td>Ordovician and Carboniferous to Cretaceous</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.5. Simplified stratigraphic column for the Buller coalfield (Adapted from Barry et. al., 1994)
b) Karamea Batholith

Granitic plutons ranging from mid Palaeozoic to Cretaceous in age intrude the Greenland Group, collectively making up the Karamea Batholith (Nathan, 1978a, 1996). Ion microprobe dating is summarised by Muir et al., (1996) and has been used to subdivide this belt into Cretaceous (Rahu, Separation Point Suites) and Palaeozoic (Karamea Suite) granitoids. Summaries by Topp (1995) and Waight (1995) have identified the S-type Karamea Suite, I-type Separation Point Suite and the intermediate I/S-type Rahu Suite granitoids. Within the field area it has not been possible to identify all granitoid bodies as belonging to previously identified plutons, so most have been mapped as undifferentiated granite (belonging to the Karamea Batholith), or where possible (Rahu Suite) Berlins Porphyry.

- Berlins Porphyry

The Berlins Porphyry consists of a series of high level plutons with similar phenocryst mineralogy and total rock composition (Figure 2.7.)(Nathan, 1978a). Suggate (1978) suggested the whole unit to be a near surface representation of a single large batholith preserved in a down faulted block but, the lack of short wave magnetic anomalies indicate the plutons are rootless and probably do not extend much more than one kilometre (Hunt and Nathan, 1976). It is found exposed in the north of the field area, within the Waimanaroa River gorge, as grey to pink biotite microgranodiorite (Figure 2.7.)(Nathan, 1996). Nathan (1974) produced a detailed study on the chemistry and petrography of the Berlins Porphyry.
Figure 2.6. Hand specimens of Greenland Group altered by granitoid emplacement to spotted slate (a) and chlorite schist (b).

Figure 2.7. Polished hand specimen of the Berlins biotite microgranodiorite.
c) Pororari Group

Bowen (1964) first proposed the name Pororari Group for Cretaceous non-marine sediments within the Buller District. In the Lower Buller Gorge the Group is dominated by alluvial fan breccia, breccia conglomerate (Hawks Crag Breccia Member) overlying and grading laterally into more varied fluvial and lacustrine deposits of the Ohika Formation (Nathan, et al., 1986). Dipping fairly uniformly to the west to southwest, the Hawks Crag Breccia unconformably overlies all older lithologies, except in the basal part of the sequence where it locally interbeds with the Berlins Porphyry (Nathan, 1978a). The Pororari Group is covered in more detail by Laird, 1995; Topp, 1996; Nathan, 1966; 1978; Nathan et. al., 1986.

• Hawks Crag Breccia

Only the Hawks Crag Breccia Member of the Pororari Group is found within the field area, outcropping in the headwaters of the Orowaiti and Cascade Rivers. McKay (1883) first introduced the name Hawks Crag Breccia when describing a coarse-grained breccia located in the Lower Buller Gorge. Within the map area it has not been possible to differentiate between individual members and it has been mapped as a single unit (Figure 2.8.).

Four differing members, based on dominant clast lithologies, were identified by Beck et. al., (1958) as belonging to the Hawks Crag Breccia (Trig C Member, Dee Point Member, Tiroroa Member, Blackwater Member). Each member has been interpreted as a different overlapping alluvial fan, belonging to separate rapidly eroding source areas, (as shown in Figure 2.8.) where either Greenland Group or a mixture of Greenland Group and Granites were eroded (Nathan, et. al., 1986). Thickness is inferred by Nathan, (1978a) and Nathan et. al., (1986) to range from 150-4500m. It is unfaulted and in steeply dipping contact with many older formations. Deposition probably occurred against existing hills or against temporarily inactive fault scarps during the late Motuan to earliest Ngaterian (Nathan, 1978a; Nathan et. al., 1986; Webster, 1992).
Figure 2.8. Typical view of coarse grained Hawks Crag Breccia in the field. Note variable clast composition of granite, greywacke and chert (GR, K29 033347).

Figure 2.9. Block diagram showing envisaged paleoenvironment for the Lower Buller Gorge during deposition of the Pororari Group. Hawks Crag Breccia represents tanglemerte from a series of overlapping alluvial fans with varying composition in source areas (Nathan et. al., 1986).
Recent petrological and geochemical work by Topp (1996) on the breccia clasts, has been useful in identifying multiple sources of compositionally varying basement rock, and are far more complicated than originally postulated. Imbrication directions within the Lower Buller Gorge indicate a southeast source consisting of Greenland Group, Karamea and Blackwater Granite, Steele Granodiorite and Okari Granite Gneiss (Topp, 1996).

2.2.2. Mawheranui Group (Brunner Coal Measures)

The Mawheranui Group is represented in the Buller Coalfield by the Brunner Coal Measures. Previous workers within the Buller Coalfield have generalised the stratigraphy by identifying and mapping four separate lithological units, based on sedimentological and paleogeographic reconstruction (Figure 2.10.). Complex lateral variations in the lithological units, disruption (due to gravitational collapse) and poor outcrop exposure, did not make it possible to subdivide this unit.

The Brunner Coal Measures are interpreted to represent fluvial to marginal marine sediments, deposited in meandering streams and peat swamps and developed on a surface of low relief during a period of relative tectonic quiescence (Figure 2.11.) (Nathan et al., 1986, Laird, 1988). The coal measures are early Eocene age, unconformably overlying Greenland Group, Karamea Batholith, Berlins Porphyry and Hawks Crag Breccia. Penetrative weathering to approximately 8m depth has occurred below the unconformity within the Karamea Batholith and is clearly observed in figure 2.12. They comprise a relatively simple succession of basal conglomerate, overlain by grit and a thick laterally persistent coal seam, and in places comprised of two or more splits. Uppermost assemblage consists of tabular sandstone and mudstone units with rare thin coal seams (Titheridge, 1988, 1992). In the northern sector, the Brunner Coal Measures are overlain by a bioturbated sandstone (Millerton Sandstone), which has been completely removed by erosion in the Denniston sector (Titheridge, 1988). For a more detailed analysis of stratigraphy and paleogeographic reconstruction it is recommended to refer to Flores and Sykes (1996).

Thickness of the coal measures is variable but typically varies from 30 to 100m over the most of the Buller Coalfield (Titheridge, 1992). Within the Denniston sector they range from approximately 40m (near Denniston township), lensing out against subaerial paleo-highs near the Old Sullivan Mine, to a maximum of approximately 370m at Mt Rochfort.
Figure 2.10. Schematic stratigraphic cross-section showing generalised stratigraphy of the Brunner Coal Measures (Adapted from Barry and MacFarlan, 1988).

Figure 2.11. Generalised depositional model of a retrograding fluvioparalic system that developed in the Buller Coalfield during deposition of the Brunner Coal Measures (From Flores and Sykes, 1995).
Figure 2.12. Photograph displaying the contact between the Karamea Batholith and overlying Brunner Coal Measures. Note the pervasively weathered nature of the underlying brownish yellow granite (GR, k29 042375).
**Basal Conglomerate and Grit**

Conglomerate dominated sequence occurs at the base of the Brunner succession, consists of clast supported sub-rounded to rounded pebbles, cobbles and boulders of quartz, granite and metamorphic and sedimentary origin (sandstone, siltstone and mudstone) in a sand-granule matrix. Conglomeratic sandstones are also present which may contain dispersed or discrete lenses of pebbles and cobbles (Figure 2.13.). Over much of the Denniston sector this is overlain and interfingered with thick grit sandstone beds (Figure 2.14.).

The lower-most conglomerate dominates the sequence in the vicinity of Mt Rochfort as massive thick beds (totalling approximately 370m thick) and have been interpreted by Titheridge (1988) as slightly older than the rest of the Brunner sequence. Here, fluvial conglomerates are interbeded with minor fluvial channel sandstones with minor overbank-floodplain siltstone, mudstone, carbonaceous mudstone and shale. Paleocurrent data from these fluvial channel sandstones indicate a northeast paleo-flow direction (Figure 2.15.). This could in part be due to syndepositional faulting with the thick conglomerates reflecting the location of the major paleochannel; or through a secondary alluvial supply from a higher westward source, feeding coarse sediment onto the peneplane, where thick peat swamps later developed.

The conglomeratic sequence around Mt Rochfort is polymitic with a gradual upward transition to quartzose clasts (Titheridge, 1993). This upward increase in quartz content reflects increasing mineralogical maturity, in turn reflecting time, intermittency of transport and distance from source. General fining upwards of the sequence also suggests the source became more distal. Conglomerates in the Mt Rochfort area are inferred to have been deposited in an almost continually subsiding half-graben system (with approximate east to north east orientation), while most of the Buller Coalfield remained stationary and acted as an area of bypass (Titheridge, 1988). The thick conglomerate sequence at Mt Rochfort lenses northward over several kilometres, pinching out towards the Old Sullivan Mine. Limited thickness data suggest isopachs have a northwest orientation. Any relationship with deposition of these thick basal conglomerates to the Kongahu and Mt William Faults is unknown (Titheridge, 1988, 1992, 1993).
Figure 2.13. Basal conglomerates containing abundant, matrix supported, rounded pebble to boulder clasts interbedded with sandstone grit beds (GR, K29 066363).
Figure 2.14. Thick tabular grit sandstone beds overlying basal conglomerates over much of the Denniston sector. Note A3 map board for scale (GR, K29 074385).
Figure 2.15. Paleogeographic reconstruction of the Buller Coalfield in the West Coast during the Bortonian - Kaiatan. Bold black arrows show paleoflow direction of braided tributary systems and open arrow indicates where an eastern paleodrainage system may have been connected to a southern marine embayment (From Flores and Sykes, 1995).
**Buller Seam Member and intersplit clastics**

Overlying the conglomeratic lithofacies is a thick coal seam (main seam) and carbonaceous shale. Interbedded fluvial channel sandstone and floodplain mudstone, siltstone and crevasse splay sandstone, locally split the main. Locally, the Buller Seam Member may be up to 12m, grading laterally into dirty coal, carbonaceous mudstone or paleosol (Titheridge, 1988).

**Tabular Alternating Sandstone and Mudstone**

Above the main seam member, inter-beded siltstone, mudstone and carbonaceous shale pass laterally into fluvial channel sandstones. Paleocurrent analysis of these sandstones indicate a northeast, southeast and southwest paleoflow, which when compared to those around Mt Rochfort, indicate the possible presence of more than one major fluvial axis (Flores and Sykes, 1996). The succession is 20-30m thick with tabular sandstone units (2-4m thick), interbedded mudstone (0.5-2m thick) and sometimes containing thin (up to 0.5m) coal seams of limited lateral extent (Titheridge, 1988).

**2.2.3. Rapahoe Group (Kaiata Formation and Torea Breccia Member)**

During the late Eocene over 2000m of predominantly dark carbonaceous mudstone accumulated, forming the Rapahoe Group (Webster, 1992). Within the Buller Region this group consists of widespread Kaiata Formation and it's associated Torea Breccia Member.

**a) Kaiata Formation**

The Kaiata Formation is mainly dark brown to grey brown, micaceous, massive or laminated mudstone. Pyrite and calcareous concretions are common, with the former particularly prevalent in the lower parts of the formation (Nathan, 1978a; Nathan, et. al., 1986; Webster, 1992). Marine molluscs and foraminifera are commonly found within the mudstone, indicating fully marine conditions (Barry and MacFarlan, 1988). Nathan et. al. (1986) interpreted deposition as taking place in a shallow water marine basin.
(probably inner to middle shelf) with restricted circulation. The typical dark brown colour is attributed to the presence of finely disseminated organic carbon (averaging 1-2% and suggesting deposition under poorly oxygenated bottom conditions), which decreases upwards with an associated lightening of colour, increasing carbonate content and particle size (Nathan, 1978b; Nathan et. al., 1986).

To the east of the Kongahu Fault Zone in the Denniston Sector, the Kaiata Formation has been completely eroded and the underlying Brunner Coal Measures are exposed. It is not certain, due to poor exposure, whether at some localities along the escarpment the contact is sedimentological or faulted. Structural relationships along the escarpment suggest a tectonic contact, however at some localities to the east within the Buller Coalfield, Kaiata Mudstone conformably overlies Brunner Coal Measures. On the Denniston road, approximately 700m of the succession is exposed. However, this is a minimum thickness as the top is truncated by an unconformity with the overlying Blue Bottom Formation, and the base is obscured beneath landslide material related to development of the escarpment. Deformation of the Kaiata mudstone by the Kongahu Fault System (on the Denniston road section), has lead to complication of the stratigraphic sequence, in turn lessening the thickness of the succession observed.

Within the Whareatea River the basal contact is clearly faulted, with sheared and highly deformed Kaiata mudstone material discordantly truncating bedding in the Blue Bottom Group (Figures 2.16. and 2.17.). Shearing and brecciation have occurred almost entirely within the Kaiata mudstone, over a zone of approximately 100m in width, decreasing as passing upstream. Highly deformed intraclasts of megacrystic granite, coal and unidentifiable rock material, are present within the shear zone. Coal is sourced from the Brunner Coal Measures and megacrystic granite from the Torea Breccia, transported up the zone of brecciation through shearing. This is reliable evidence that indicates Brunner Coal Measures lie beneath the Kaiata mudstone within this section of the escarpment.
Figure 2.16. Highly sheared Kaiata mudstone near the Kaiata/Blue Bottom contact, within the Kongahu Fault Zone, Wharetea River. Sheared clasts from the Tereu Breccia, Brunner Coal Measures and basement are observed (GR, K29 054399).

Figure 2.17. Kaiata/Blue Bottom contact as observed in the Wharetea River, where sheared Kaiata mudstone truncates near vertically inclined Blue Bottom. Note hammer, marked by an arrow, for scale (GR, K29 054399).
b) Torea Breccia Member

The Torea Breccia Member consists of coarse sandstone, pebbly mudstone, breccia and conglomerate, and is confined to the western margin of the coalfield. Clasts are composed of granite, schist, gneiss, carbonaceous argillite, greywacke and quartz (Laird and Hope, 1968). It has been interpreted as a sediment gravity flow sequence originating from a nearby rising basement source (Figure 2.18.) (Laird and Nathan, 1988), composing about 10% of the total exposure of Kaiata at the type section on the Denniston access road (Webster, 1992). The total preserved thickness is in the order of 700m and has now been folded near vertical by deformation associated with the Kongahu Fault Zone.

Passing southward, from the Denniston access road, units of Torea Breccia interbedded with Kaiata mudstone tend to become thinner (1-4m down to 5-30cm) and clast size decreases (massive float blocks and bouldery gravel grade laterally to pebbly sandstone). At occasional localities, such as the Whareatea River, there is a sudden re-introduction of coarse material (Figure 1.19.) and thickening of the Torea Breccia beds. This maybe related to multiple sources from a rapidly eroding range front, uplifted along an active fault scarp to the west (S. Nathan. pers comm, 1997). Due to the near proximity of the uplifting range front there would have been no preservation of the Brunner Coal Measures immediately west of the Kongahu Fault Zone, as basement was eroded providing source for the Torea Breccia. Rare imbrication structures within the breccia, in conjunction with regional stratigraphy and outcrop patterns, support the theory that the breccia was sourced to the west (Laird and Hope, 1968; Laird and Nathan, 1998).
Figure 2.18. Restored, east to west cross-section across the Paparoa Trough, in the Westport area, indicating the relationships between the Kaiata mudstone and Torea Breccia at the end of the Eocene (From Nathan et. al., 1986).

Figure 2.19. View of massive (6m diameter) boulder of biotite, megacrystic granite sourced form the Torea Breccia, within the Wharenue River. Note geological hammer for scale (GR, K29 054398).
2.2.4. Blue Bottom Group (O'Keefe Formation)

Abundant Blue Bottom Group is exposed in the west of the study area and, based on offshore drilling, is interpreted to directly underlie all Quaternary deposits west of the Kongahu Fault Zone (Nathan et. al., 1986). In this study, Blue Bottom Group sediments consist of mainly greenish-brown to bluish-grey, fine to medium grained, well sorted, indurated, bioturbated (generally in the top 20cm of beds), micaceous sandstones with rare shell beds. These are mainly found on the sub-Waiauan unconformity, forming the sedimentary contact between Blue Bottom and Kaiata Mudstone. Thin conglomerate beds containing pebble to cobble sized, well-rounded granitoid, quartz (schistose and greywacke) and Greenland Group clasts are observed at some localities near the base of the sequence (Figure 2.20.). Although some previous workers (Laird 1988, Nathan 1996) have differentiated a number of members based on regional considerations, no such divisions are attempted here.

The Blue Bottom is Waitakian to Altonian in age (Nathan, 1978a), and is generally considered to represent outer shelf or deeper open water conditions. The influx of terrigenous sediments reflects the initiation of a marine regression and onset of Alpine Fault movement (Nathan et. al., 1986).

The erosional surface underlying the Blue Bottom Group is called the sub-Waiauan Unconformity, and is exposed in the Waimangaroa River and the Denniston access road. A slight angular disconformity, of 3-6° towards the east, marks the boundary between pre-Waiauan beds and the overlying O'Keefe formation. South of Ww stream (actual name) the surface contact becomes faulted with highly deformed and sheared Kaiata mudstone, thrust over steeply dipping Blue Bottom (Figure 2.17). Thin (2-15mm) greyish-blue silty clay seams cut through the rock mass, and are generally oriented along bedding surfaces (Figure 2.21.). These probably represent shearing caused by flexure folding within the Blue Bottom, however, they become more prevalent towards the faulted Kaiata Mudstone contact where they are no longer confined to bedding planes and become pervasive throughout the rock mass (Figure 2.22.).
Figure 2.20. Thin bed of pebble to cobble, well rounded, granite, schist, Greenland Group and chert conglomerate, within the Blue Bottom Group, located near the base of the sequence. Note vertical nature of bedding and bioturbation to the left of the hammer head, decreasing in intensity as pass left into the bed with the unit younging to the right (GR, K29 054400).
Figure 2.21. 2-15mm thick greyish blue silty clay seams oriented parallel to bedding within the Blue Bottom Group. These increase in frequency towards the Kaiata mudstone contact and are indicative of shearing on bedding planes (GR, K29 054400).

Figure 2.22. In the Whareatea and Orowaiti Rivers, thin greyish-blue silty clay seams cut pervasively through near vertical Blue Bottom, increasing in intensity as move towards the Kaiata contact (GR, K29 054399).
2.3. Structure

2.3.1 Inversion

Positive inversion refers to a switch in tectonic mode from extension to contraction, such that extensional basins are contracted and become regions of positive structural relief. This process generally involves reactivation of pre-existing extensional faults so they undergo reverse slip (McClay, 1995). Early work by Laird (1968) and Laird and Hope (1968) provided basic understanding to the mechanism of basin inversion on the West Coast, although in some cases it lead to incomplete understanding of the structural complexities particularly the geometry of some faults in the region (Bishop and Buchanan, 1995).

During the Eocene and Oligocene, oblique extension in the West Coast resulted from propagation of the Southeast Indian Ocean Ridge into southwestern South Island (Kamp, 1986). This was abruptly halted during the early Miocene by a shift to oblique compression, resulting in formation of the modern Australia Pacific plate boundary, with the Alpine Fault propagating through Southern New Zealand (Kamp, 1986; Nathan et al., 1986). This deformation produced a north-northwest to south-southwest trending basin and range province. Shortening was commonly partitioned into narrow zones along basin and range margins, leaving unreactivated extensional structures in-between (Bishop and Buchanan, 1995). Subsidence in the early Tertiary Paparoa Trough ceased and was subject to local uplift with positive inversion, probably along the reactivated northeast to north-northwest trending Kongahu Fault Zone thrust system.

Recent thermal history analysis by Webster (1992) and Kamp et al., (1996) has lead to the identification and restoration of three phases of inversion. Two Miocene compressional phases (24-19 Ma and 13-8 Ma) and a further Quaternary phase forming the present topography. The broad sequence of events is illustrated in Figure 2.23 and summarised in Kamp et al., (1996). The early Miocene phase of inversion (24-19 Ma) is related to inception of the modern Australia-Pacific plate boundary through New Zealand as a continuous structure. The middle to late Miocene event (13-9 Ma) relates to the inversion phase when the plate boundary (Alpine Fault) changed from oblique extension to oblique compression, and the Pacific plate crust began to overthrust the Australia plate across the Alpine Fault. Quaternary uplift has been referred to as the third phase of uplift, corresponding to a general South Island wide Pliocene-Pleistocene increase in tectonic uplift and denudation (Webster, 1992; Kamp et al., 1996).
Figure 2.23. Four palinspastic restorations for a NW-SE cross-section through the central portion of the Buller Coalfield. Cross-sections display inferred positions of sediment to basement contact at the end of the Oligocene (A), middle (B) to late Miocene (C) and Quaternary (D) phases of inversion. The cross-section drawn for the present shows approximately where the top of the late Oligocene would lie if there had been no denudation (From Kamp et al., 1996).
The two Miocene uplift events are related to the wider tectonic development of New Zealand, with a delayed response in the Buller Coalfield a direct relationship to the distance from the Alpine Fault (Webster, 1992). Presence of the Sub-Waiauan unconformity, resulting from the second phase of uplift, has provided valuable information on the mechanism of inversion. This is explained by a model of stick-slip behaviour for the major inversion structures. The faults are locked during the early stages of inversion, basin margins are uplifted and eroded, and in the later stage the faults unlock with basement overthrusting the adjacent basin. Such extreme inversion has lead to the removal of up to 6000m of original basin fill with only 0-300m of the original fill succession remaining (Kamp et al., 1996). Preservation of the lowest part of the basin fill is due to the highly indurated Brunner Coal Measure sandstone and grits, which have acted as an erosion resistant cap, thus preserving the up-thrust block. The Buller Coalfield is a highly developed case of extreme basin inversion, very rarely found preserved in the rock record.

2.3.2. Present Day Structure

Early work by Laird (1968) and Laird and Hope (1968) interpreted the Kongahu Fault Zone through the Denniston sector as the Papahaua Overfold. Subsequent detailed work by Cave (1983a,b), Todd (1989) and Nathan (1996) have displayed the Kongahu Fault Zone (Paparoa Fault Zone - after Laird and Hope, 1968) to be structurally more complicated than first realised.

Sections of slope having approximately similar structural characteristics are designated "structural domains" (Piteau and Associates, 1977). Three distinct structural domains were first recognised by Anon, (1986b) and used to identify generically different regions within the field area (Figure 2.24. and 1.2.):
- Domain 1 constitutes the coastal plain consisting of relatively flat-lying Tertiary to Quaternary sediments;
- Domain 2 is represented by a 1-3 km wide zone of moderately to highly deformed Tertiary and basement lithologies along the escarpment; and
- Domain 3 represent the relatively undeformed areas of the Denniston Plateau and Mt Rochfort, where flat lying Brunner Coal Measures rest directly upon basement.

Domain boundaries, over much of the field area, were obscured by Quaternary deposits on the coastal plain, and landslide material from escarpment collapse.
Figure 2.4. Map of Structural Domains identified within the study area. Domain 2 represents the region of structural deformation associated with propagation of the Kongahu Fault Zone. See text for detailed descriptions of each domain.
a) Domain 1

In the west, relatively undeformed, gently tilted to flat-lying late Tertiary (Blue Bottom) to Quaternary sediments comprise the prominent terraces (up to 140m topographical altitude) and generally low lying areas. A break in slope marking the eastern extent of these weakly consolidated sediments coincides with the inferred position of the Kongahu Fault Zone (Anon, 1986b,c). Outcrop exposure of Tertiary and Quaternary formations is limited by extensive alluvial fan formation from major fluvial systems and debris derived from gravitational collapse of the escarpment. Exposure is confined to larger creeks which have incised through recent beach and fluvial deposits.

Blue Bottom Group siltstone outcropping in the north between Waimangaroa and the Whareatea River, is found dipping uniformly to the northwest. Dip of bedding increases towards the escarpment, where some beds are locally overturned. The style of deformation appears to have altered adjacent to this section, with displacement on the Kongahu Fault Zone taken up as folding within the Blue Bottom siltstone. Deformation has occurred as flexure slip folding (with thin (5-10mm) blue/grey silty pug zones preserved), generated by shearing along bedding planes. Passing south and west within Domain 1, deformation decreases rapidly. In the lower reaches of the Orowaiti River, Blue Bottom Group siltstones dip uniformly westward at approximately 5°. An exploration drill hole along Fairdown Straight passed through over 600m of Blue Bottom before drilling was halted, indicating a relatively uniform, undeformed complete Tertiary sequence preserved west of Domain 2 (Laird, pers comm 1997).

b) Domain 2 (Kongahu Fault Zone)

East from Domain 1 lies the complex Kongahu Fault Zone, ranging from one to three kilometres in width. Basement and Tertiary cover sequence strata (Brunner Coal Measures, Kaiata mudstone, Blue Bottom) are complexly deformed by reverse and/or thrust fault deformation (Anon, 1986b,c). Domain 2 forms the western boundary of the Buller Coalfield. Laird (1968) and Laird and Hope (1968) interpreted the Kongahu Fault Zone as the northern extension of the Paparoa Tectonic Zone, with most deformation through the Denniston sector taken up in the form of the Papahaua Overfold. Subsequent and more detailed work by Cave (1983a,b), Nathan (1996) and Kamp et al.,
(1996) has demonstrated this model to be over simplified. The fault zone consists of a series of thrust fronts, with folding associated with the thrusting. Deformation along this zone has lead to vertical offset of the base of the Tertiary succession by over 2000m, down thrown to the west (Nathan, 1996). Passing north-eastwards from the study area, the Kongahu Fault Zone is a zone of steeply dipping reverse faults (Cave, 1983b) which transfer into the Kongahu thrust front (Lamplough Fault) north of the Ngakawau River.

Poor exposure and complex deformation history is further complicated by the gravitational collapse of the coal measures along the escarpment, so partially obscuring the Kongahu Fault Zone. Sheared and deformed basement granite is only observed within restricted exposures of Lake Stream and the Orowaiti River (Figure 2.25.). In the north, exposure along the Denniston road suggests a minimum thickness of 700m for the Kaiata mudstone, assuming the sequence to be fairly continuous. At this locality the sequence is separated from the overlying Blue Bottom by the sub-Waiauan unconformity, and is faulted against Brunner Coal Measures at its base. The Kaiata mudstone narrows to the south, eventually being faulted out altogether in the Orowaiti River. Dips for the Kaiata mudstone range dramatically, from 45° northwest to overturned at 30° southeast. Strike is typically to the northeast, although there is considerable local variation with a slight swing to a north-northeast orientation in the south of the study area. The contact with the underlying coal measures is obscured, but in many locations it can be defined to within 20m, The coal measures exhibit gentle to steeply overturned dips, and with strike relatively uniformly northeast. Field and structural relationships point to a series of acutely faulted and folded thrust wedges, in conjunction with broader large scale folding associated with the Kongahu Fault Zone.

South at the Orowaiti River, the equivalent deformed slice of Kaiata Formation is absent and Blue Bottom, flat lying and slightly deformed, is found within 100m of highly sheared basement granite. Most of the stratigraphic sequence has been removed by fault displacement at this locality, with deformation predominantly confined to a 200m wide zone of brecciated granite (Figure 2.25.) and mildly sheared Blue Bottom (Figure 2.20.). Refer to Supplementary Map Sheet A for geologic cross-sections across the Kongahu Fault Zone within the study area. Faulting occurs as defined imbricate thrust wedges along the Orowaiti River, and becomes more complicated through the Denniston Road section involving a mixture of faulting, shearing and flexure folding.
c) Domain 3

Structural Domain 3 lies to the northeast, encompassing the Denniston Plateau and is generally unaffected by the major deformation associated with the Kongahu Fault Zone. This region displays more subdued relief, with landforms dominated by eroded dip slopes (8-12° northwest), steepening towards the western boundary. These dip slopes have developed on the tilted and planed-off surface of the Brunner Coal Measures and basement (Anon, 1986b; Todd, 1989). Numerous north to northeast trending faults of lesser throw (up to 5m) have been mapped on the Denniston Plateau area. The Denniston Plateau forms the western limb of the Denniston Anticline which passes through Mt Rochfort and is coincident with the crest of the Papahaua Range (Titheridge, 1988). Towards the south, bedding orientations change, dipping away from Mt Rochfort. This may in part be due to the extremely thick (300+m) succession of conglomerates preserved at this locality, interpreted as being slightly older than most of the Brunner Coal Measures. These are overlain by; thick coal seams, sandstones, siltstones, and carbonaceous deposits.

A series of large east to east-northeast normal faults, down-thrown to the north, are mapped near the headwaters of the Whareatea River and Mt Rochfort (Figure 2.26.). Displacement varies but some of the larger faults have been observed to display throws in the order of 50+m. Numerous north to northeast trending faults of lesser throw (up to 5m) have also been noted on the Denniston Plateau. These faults may have been initiated at any stage after deposition, or they may represent rejuvenated faults active during or prior to coal measure deposition (Titheridge, 1993). Bishop (1992) identified two major joint sets within the Brunner Coal Measures, mainly with strikes west-northwest and north-northeast. The west-northwest jointing is interpreted as a response to regional shortening during Neogene uplift of the Papahaua Range (Titheridge, 1993). Combined with regional deformation associated with the Kongahu Fault Zone, these may have influenced formation the large-scale gravitational collapse features located to the northwest of Mt Rochfort. Failure appears to have occurred along bedding planes, where weak carbonaceous mudstone and coal have facilitated failure. Similar failure mechanisms were recognised by Anon (1986c) during exploration of the Te Kuha block, immediately north of Mt Rochfort, to explain large scale collapse features observed.
Figure 2.25. Exposure of highly sheared and brecciated granitic basement, in the Kongahu Fault Zone, on the Orowaiti River. Shearing is oriented parallel to handle of geological hammer (GR, K29 022351).

Figure 2.26. An east-southeast trending normal fault, with an estimated throw of at least 50m, observed within the Brunner Coal Measures below Mt Rochfort. The geological hammer lies within the 30-40cm wide fault zone of light coloured fault breccia. Exfoliation, slacking and discoloration has occurred to carbonaceous units above and below the fault plane (GR, K29080372).
2.4. Overview

Most stratigraphic units are regionally extensive on the West Coast, with their stratigraphy and nomenclature well documented by previous workers. Early work by Morgan and Bartram (1915) identified most structures and stratigraphic units, however, structural complications were not always well understood. Stratigraphic correlation and dating have improved dramatically since these early workers. Presence of a complicated fault structure associated with the Lower Buller Fault and the Kongahu Fault was recognised at this time, although their significance in the regional development of New Zealand was not understood. Recent work by Nathan et al., (1986), Bradshaw (1989) and Laird (1988, 1992-95), have indicated the formation of the Kongahu Fault Zone, and the formation and preservation of the Buller Coalfield are related to the structural evolution of New Zealand's West Coast since Gondwana break up.

Evolution of the Buller Coalfield has been a very long and complicated process. Multiple stage uplift along the Kongahu Fault Zone is recognised as the final phase of development, creating a unique example of a very highly evolved basin of inversion. So far, only a very minor portion of the original sequence remains preserved near the original axis of the Paparoa Trough. Based on the work by Webster (1992) and Kamp et al., (1996) inversion involved approximately 7km of vertical uplift along the Kongahu Fault Zone. Uplift and deformation are still occurring through to the present day, although only one active Quaternary fault trace has been identified (Nathan, 1996) in relation to the Kongahu Fault Zone. This may be a result of the extreme nature of the topography (making such observations difficult), rather than an indication of little recent activity, as the West Coast region is one of the most tectonically active regions in New Zealand.
3.1. Quaternary Deposits

3.1.1. Introduction

Almost all the published work to date on coastal deposits in the Westport area is based on the work by McPherson (1967, 1978). Nathan, from 1975-1978 mapped much of the Westport district at 1:63 360 and 1:25 000 scales, with Quaternary stratigraphy based on units defined by McPherson. Since this time, little further work has been conducted other than a soil survey by Mew and Ross (1991) and regional glaciation correlation's by Suggate (1990 and 1992).

For this mapping project local nomenclature, developed by McPherson (1978), for the Quaternary coastal deposits at Westport is retained. Mapping of the Quaternary units is based on the necessity for a stratigraphic time frame to correlate and date landslide initiation and reactivation episodes off the escarpment.

3.1.2. Background to Correlation of Quaternary Terraces

New Zealand has abundant non-marine Quaternary strata, with glacial deposits found especially well preserved in the South Island. Quaternary marine strata are also widely preserved in uplifted basins and coastal terraces sequences (Pillans, 1991). In New Zealand, the most detailed terrestrial record over the past 300 000 years B.P. is found in Westland. Suggate (1990) identified four separate glaciations in the area, with Williams (1996) also identifying three individual advances during the last Otira glaciation. Unfortunately, inferences about individual glacial advances and the intervals between them are substantially subjective in many areas (Suggate, 1990). One of the main problems is correlating on land strata with the marine Oxygen Isotope record. This relies on simplistic assumptions of synchronous climate control (Pillans, 1991).

The coastal terraces of the West Coast reflect interactions between tectonism and climate change, expressed as sea-level fluctuations (Soons and Lee, 1983). Evidence of complex Late Quaternary history, including progressive regional uplift continuing
through to the present day, is displayed in dissected and tilted late Quaternary terraces on the western side of the Paparoa Range (Nathan, 1978, 1996). Many of the older terraces north of Westport have been removed by erosion, or buried beneath landslide material and cannot be easily correlated with the well documented sequences of McPherson (1978) and Suggate (1992) to the south.

Shoreline altitudes, due to differential uplift, become somewhat higher or lower than those anticipated from uniform regional uplift rates, leading to local preservation and removal of some sequences. Raised shoreline data, with well preserved sequences of terraces, between Westport and Hokitika show considerable breaks between sections of coast. This has resulted from substantial differential uplift (Suggate, 1992) caused by folding and faulting along the Paparoa Tectonic Zone. Consequently, gaps in continuity of the coastal glacial and interglacial marine formations have made the intra-regional correlations of local sequences uncertain. Higher uplift rates in southern Hokitika and Greymouth areas have lead to recognition of formations not separately distinguished in the northern Westport and Charleston areas (Suggate, 1992).

Surface weathering and soil development are not keys to correlation of terrace surfaces, as reworking of dune sands and other deposits commonly form surface materials much younger than the underlying units. Correlation depends on the altitudes of the tops of the marine formations at the former shorelines, usually adjacent to relic sea cliffs. Altitudes of the marine surfaces can not be used for correlation purposes, as marine and glacial deposits are lithostratigraphic units, where terraces form morphologic features of the same age along their length (Suggate, 1992).

3.1.3. Quaternary Stratigraphy of the Westport District

Well sorted shallow marine and beach sands were deposited during successive interglacial high stands, with dunes forming close to the coast and rivers aggrading rapidly to the new base level. Terraces formed during these periods underwent continual regional uplift so they were not submerged by preceding transgressions, resulting in marine terrace sequence preservation at successively higher elevations (Nathan, 1976, 1996; Laird, 1988). Equivalent aggradational river terraces were formed inland as rivers aggraded rapidly to higher interglacial base levels. During glacial periods the rivers cut down to new lower base levels, with sediments deposited during these periods buried during succeeding interglacials (Nathan, 1976; Laird, 1988).
Five Quaternary formations are described by McPherson (1978), along the coastal plain between the Paparoa Range and the present coast in the Westport region. Deposition and preservation relates to the last interglacial episodes and postglacial (Holocene) marine progradation. More recent work including Suggate (1992) and Nathan (1996) has in part lead to a revision of the nomenclature for interglacials on the West Coast. Both the Waites and Virgin Flat Formations are now interpreted to represent both older and younger parts of the last Kaihinu interglacial (Table 3.1.) (Nathan, pers comm 1997). Standard age terminations for each oxygen isotope stage are displayed in Table 3.2.

Each interglacial formation rests on a wave cut bench, formed during the interglacial rise in sea-level. Position of the inner margin and altitude range of each bench being unique to that formation. Marine sands and gravel deposited on the bench may in turn be capped by delta fan or progradational gravels (Figure 3.1.) (McPherson, 1978). Marine, eolian and alluvial deposits are represented by a member within the appropriate formation and interpreted as interglacial. Dominantly, marine and dune sands are composed of quartz and feldspar. Estuarine and fluviatile sands are particularly micaceous and arkosic, and derived directly from hinterland ranges (McPherson, 1978). There is no difficulty defining the interglacial formation capping each terrace where the altitude between successive wave cut platforms form strong geomorphic features such as a cliff, such as those observed (north of the Orowaiti River) on the seaward edge of "Giles Terrace". Elsewhere, however, adjacent wave cut platforms differ in altitude by only a few meters, making formation definition difficult (McPherson, 1978).

Sand and gravel forming three distinct sets of coastal marine terraces, ranging in altitude from 15 to 130 m.a.s.l., are thought to have been deposited during interglacial high stands of sea-level. One small local marine terrace is preserved near Waimangaroa at an elevation of 145m, but it is not clear as to which glacial high stand this relates to. However, only terraces formed during the last interglacial (Waites Formation) and the un-named interglacial at 279-334 000 years B.P. (Caledonian Formation) are found well preserved (such as "Giles Terrace"). They are underlain by fluvial gravels, which are thought to have been deposited during major glaciations when erosion was accelerated and considerable aggradation occurred (Nathan, 1996). Most other terrace deposits are largely eroded, displaced and buried by landslide material, or locally covered by younger alluvial fans.
Table 3.1. Sequence of glaciations and interglacials in the Westport region (Adapted from Nathan, 1996).

<table>
<thead>
<tr>
<th>Westport Quaternary Formations</th>
<th>Oxygen Isotope Stage</th>
<th>New Zealand Climate Zone</th>
<th>New Zealand Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nine Mile</td>
<td>1</td>
<td>Aranui (postglacial)</td>
<td></td>
</tr>
<tr>
<td>Speargrass</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Otira (glacial)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waites</td>
<td>5</td>
<td>Kaihinu (interglacial)</td>
<td>Haweran</td>
</tr>
<tr>
<td>Virgin Flat</td>
<td>6</td>
<td>Waimea (glacial)</td>
<td></td>
</tr>
<tr>
<td>Addison</td>
<td>7</td>
<td>Karoro (interglacial)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Waimaunga (glacial)</td>
<td></td>
</tr>
<tr>
<td>Caledonian</td>
<td>9</td>
<td>un-named interglacial</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>uncertain</td>
<td></td>
</tr>
</tbody>
</table>


Table 3.2. Estimated ages of oxygen isotope stage boundaries and terminations (Bradley, 1985).

<table>
<thead>
<tr>
<th>Oxygen Isotope Stage Boundary</th>
<th>Estimated Ages (x10^3 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>11</td>
</tr>
<tr>
<td>2-3</td>
<td>27</td>
</tr>
<tr>
<td>3-4</td>
<td>58</td>
</tr>
<tr>
<td>4-5</td>
<td>72</td>
</tr>
<tr>
<td>5-6</td>
<td>128</td>
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<td>6-7</td>
<td>188</td>
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<tr>
<td>7-8</td>
<td>244</td>
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<tr>
<td>8-9</td>
<td>279</td>
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<tr>
<td>9-10</td>
<td>334</td>
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<tr>
<td>10-11</td>
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</tr>
<tr>
<td>11-12</td>
<td>421</td>
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<tr>
<td>12-13</td>
<td>475</td>
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<td>13-14</td>
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<td>579</td>
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<td>16-17</td>
<td>608</td>
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<tr>
<td>17-18</td>
<td>671</td>
</tr>
<tr>
<td>18-19</td>
<td>724</td>
</tr>
</tbody>
</table>
Figure 3.1. Schematic idealised cross-section displaying the distribution of the Westport Quaternary sequence between the Okari and Totara Rivers (Adapted from McPherson, 1978).

Each interglacial formation rests on a wave cut bench (b) into underlying Tertiary "Blue Bottom" Formation, separated by sea cliffs, formed during interglacial sea-level rises. Position of the inner margin and altitude range of each bench is unique to that formation. Marine sands and gravel (1) deposited on the bench may in turn be capped by fluviatile sediments (2) of delta fan or progradational gravels.
Aggradational surfaces on the coastal plain, adjacent to the Waimangaroa and Whareatea Rivers, formed during the last glaciation when the supply of material was much greater than at present. During intervening interglacial periods, when the supply of material dwindled, the rivers cut down through the previously formed surfaces. Some aggradational terraces can be traced down the Upper Buller Valley as far as the Inangahua Valley (with some degree of certainty). Unfortunately, due to complex differential uplift and erosion of sequences, it has not been possible to correlate these terraces with the interglacial terraces on the western side of the Paparoa Range (Nathan, 1978).

a) Caledonian Formation (Nathan, 1976; McPherson, 1978)

This late Pleistocene interglacial marine and fluviatile gravel sequence is divided into:

- Caroline Member (fluviatile), and
- Kynnersleys Member (marine).

However, only the fluviatile Caroline Member is observed in the study area. Caledonian Formation was deposited during an un-named interglacial at 279-334,000 years B.P. (oxygen isotope stage 9) (Nathan, 1996).

- Caroline Member (Cc)

Recent erosion of the edge of Giles Terrace into the Orowaiti River has exposed a 50m high face, containing 12-20m of poorly sorted slightly stratified fluviatile gravel with arkosic sand lenses (Figure 3.2. and 3.3.). Clasts are well rounded, moderately weathered, pebble to boulder size, in a gritty medium sand, composed of Greenland Group, coarse muscovite granite, chert, Brunner Coal Measure conglomerate and sandstone/grit.

The exposure indicates that the fluviatile Caroline Member (ranging from 12-20m thickness and 100-130m in altitude) rests directly on a wave cut bench in the Blue Bottom Group. This is unusual, as a more standard stratigraphic relationship of a wave cut bench would be marine sand and gravel in turn capped by fluviatile alluvium. Deposition probably resulted through a very thick cover head of fluviatile gravel spread over the surface, during or following final emergence, replacing rather than over topping marine and sand deposits (McPherson, 1978). McPherson (1978) inferred more than one
marine incursion is represented by these deposits but due to limited knowledge and poor exposure, division was not attempted.

Figure 3.2. Caledonian Formation fluviatile gravels with arkosic sand lenses on the edge of Giles Terrace. Note A3 map board for scale (GR, K29 013358).
b) Addison Formation

Deposition is related to the Karoro Interglacial (Nathan, 1996) at 188-244 000 years B.P., but was not observed within the study area implying that it was probably removed by erosion during preceding interglacials.

c) Virgin Flat Formation (Vo) (Nathan, 1976; McPherson, 1978)

Late Pleistocene Virgin Flat interglacial marine and fluviatile gravel sequence is related to an early phase of the Kaihinu Interglacial (Nathan, 1996) and subdivided into:

- O'Malley Member (eolian),
- Gillows Member (fluvial), and
- Gallaghers Member (marine and lagoonal).

It has not been possible to differentiate individual members due to poor exposure and lack of preservation of a continuous interglacial sequence. South of the Buller River, river mouth bars, beach and lagoonal deposits are found preserved (McPherson, 1978). Virgin Flat formation is preserved as high level, minor beach terrace remnants of marine gravels between Rapid Creek and Ww Stream. The Virgin Flat Formation is composed of; partly cemented, clast supported, moderately well rounded, pebble to cobble, in a moderately poorly sorted ilmenite-rich sand matrix. Marine gravels of the Virgin Flat Formation are found lying directly on a wave cut bench in Blue Bottom, but are also observed directly overlying Brunner Coal Measure derived fluviatile deposits (Figure 3.4.). These are observed to directly overly Brunner Coal Measure derived landslide talus material, deposited during escarpment collapse. This provides a time frame for periods of reactivity of sections within the landslide failure complex.
d) **Waites Formation** (Nathan, 1976; McPherson, 1978)

Late Pleistocene interglacial sequence of the Waites Formation is related to a late phase of the Kaihinu Interglacial (Nathan, 1996) and can be subdivided into:

- Pipeline Member (eolian),
- Bradshaws Member (fluvial and estuarine), and
- Wilsons Member (marine and lagoonal).

No eolian component of the Waites Formation was observed within the terrace sequence. Maximum thickness of the Waites Formation is between 8-12m, with a wave cut basal surface lying 13-25 m.a.s.l. Reworking of the initial marine surface is believed to have occurred during final withdrawal of the interglacial sea (McPherson, 1978). A complex series of marine cliffs and terraces has been formed (Figure 3.5) by dissection of the initial marine surface at 35-45m (Wb1) during retreat of the sea, with formation of recessional surfaces at 27-32m (Wb2) and 18-24m (Wb3) respectively (Nathan, 1976, 1978).

The age of the Waites Formation, based on C\textsuperscript{14} dating has been discussed by both Nathan (1976) and McPherson (1978). Wood and peat resting on the wave cut platform at the base of the sequence has been dated, but contamination lead to highly variable conflicting ages, some beyond the age of carbon dating. Thus, the true age of the Waites Formation is probably beyond 45 000 years B.P. (Nathan, 1976). Retesting using more advanced, modern C\textsuperscript{14} testing techniques, identifying and removing sources of contamination, may more accurately date deposition of this formation. Dates oxygen isotopes place this at stage 5 (Nathan, 1996; Suggate, 1992) which gives 75 000 years B.P. as a minimum age, indicating considerable inaccuracy is involved in attempting to date these sequences.

- **Wilsongs Member** (Ww)

Wilson Member is composed of marine sand and gravel. Marine wave cut postglacial shoreline cliffs, following the section of road cut between Lake Stream and the Whareatea River, clearly display marine sand of the Wilson Member lying directly on a wave cut bench in the Blue Bottom. Coarse lag deposits are preserved on the bench cut, which in turn are overlain by marine sand and gravel (Figure 3.6).
Figure 3.5. Aerial oblique view (looking south, between the Whareatea River and Lake Stream) of a Waites Formation Terrace (Wb3), overlying talus material from the landslide failure complex. The gravel Electrics road runs on the surface of the marine terrace and State Highway 67 follows a low sea cut cliff formed between the Wb3 surface and Holocene formed surface (L. Homer, IGNS, CN 31109).
Figure 3.6. Road cut along S.H. 67, showing the wave cut bench in Blue Bottom with coarse Greenland Group and Granite boulder lag deposits overlain by the marine Wilsons Member (GR. K29 047401).

- Bradshaws Member (Wb)

Bradshaws Member consists of granitic river gravel and sand. Between Deadmans creek and Christmas creek marine Wilsons Member is exposed overlain by fluviatile Bradshaws Member.

e) Speargrass Formation

The Speargrass Formation represents local river aggradation terraces (h1, h2 and h3) which formed during the last glaciation (Otira Glaciation), at about 18 000 years B.P. The Speargrass surface is first recognised close to Lake Rotoiti but is only preserved as scattered remnants through much of the Buller Gorge (Suggate, 1988). This formation has been tentatively identified on the eastern side of the coastal plain near the Whareatea and Waimangaroa rivers, overlain by younger Holocene deposits.
3.1.3. Holocene Deposits

Lithological units deposited since the Otira Glaciation have been assigned to the Nine Mile Formation. These recent deposits are predominantly stream alluvium and dune deposits, with swamp and lagoonal deposits constituting a relatively minor component of the stratigraphy.

*a) Nine Mile Formation* (Nathan, 1976; McPherson, 1978)

Gibb (1986) produced a Holocene eustatic sea-level curve for New Zealand, indicating sea-level rising to its present height after the last glaciation at approximately 6.5±0.1 ka. Therefore, formation and preservation of the last post-glacial cliff at Westport, at 15m.a.s.l., is an indicator of continuing tectonic uplift. Recent deposits of the Nine Mile Formation between the last postglacial shoreline cliff and present shoreline, deposited during progradation of the present coastline, are subdivided into four formations based on generic origin:

- **Ferry Member (nf)**
  Outer belt of younger wind blown sand, capping beach deposits. Formation occurred through progradation of present day beaches, depositing 5-9m high dunes and low linear berms.

- **Okari Member (no)**
  Inner belt of older dunes, not related to the present day beach, banked against the postglacial cliff and swamp deposits to a height of approximately 15m.

- **Westport Member (nw and nq)**
  Granite, Greenland Group, Brunner Coal Measure and Hawks Crag Breccia derived sand and gravel, deposited by rivers and creeks draining the Papahaua Range. Stream beds and banks are commonly choked with unconsolidated boulders derived from landslide material and rapid down-cutting of streams in the steep slopes of the area. Most of the member is gravel (nw), but the top 2-5m usually consists of recent interbedded mud and peat (nq)(Nathan, 1976).
nq - represents modern swamp deposits
nw - composed of recent river gravel, sand and minor mud

• Shetland Member (ns)

The Shetland Member represent lagoonal and marine beach deposits along the coast, between high and low water marks, constituting marine sand and minor gravel with lagoonal swamp deposits.

3.1.4. Discussion

Photogrammetric work conducted by McPherson (1978), between the Totara and Buller Rivers, indicated tilting of the Waites Formation and older interglacial deposits. The initial surfaces of the Waites Formation show a northwards loss in height of about 6m over 10kms. This slight tilt is in accordance with the northward tilt observed in the high-level terraces (McPherson, 1978).

Variation in terrace heights (of Caledonian, Virgin and Waites Formations), observed in the field tends to be somewhat greater than those observed by Nathan (1976). This could in part be due to tectonic deformation of the terrace sequence when deposition occurred adjacent to the Kongahu Fault Zone. The nature of the Kongahu Fault Zone changes through the section, between the Whareatea and Waimangaroa Rivers, from discrete thrust wedges (south of the Whareatea River) to displacement taken up throughout the Tertiary units. Deformation is observed as recumbent folding within the Blue Bottom Group along this section, and this may have resulted in greater rates of local uplift and displacement of the marine terraces. This is observed as increasing primary terrace height and larger differences in elevation of individual terrace sets of the Waites Formation between the Whareatea and Waimangaroa Rivers. Assuming such deformation, it maybe possible to infer that the interglacial terrace above Waimangaroa (at 140-150m and dipping at 5° northwest), belongs to the Caledonian Formation.
3.2. Stream-Gradient Index Analysis

3.2.1. Introduction

The link between bedrock geology and geomorphic expression is well documented. More recently, a considerable amount of effort has been applied to the link between active tectonics and geomorphological features (Litchfield, 1995). The drainage pattern of rivers contains unique information about the past and present tectonic regime (Seeber and Gornitz, 1983). Stream-gradient interpretation provides a recognisable technique for aiding the structural interpretation of large regions. It can be applied rapidly to isolate smaller areas for more detailed work, in theory allowing rapid evaluation of large regions (Keller, 1986).

The stream-gradient index is particularly sensitive to five external factors (Litchfield, 1995):

a) tectonic uplift,

b) resistant lithologies,

c) entry of large tributaries,

d) changes in sediment load, and

e) climate.

By eliminating or taking into account the effects of factors b)-e), tectonic uplift can be evaluated and interpreted. The effect of resistant lithologies are easily taken into account by direct comparison with the geological map, although within the study area the most significant tectonic boundary is inferred to have occurred between resistant Brunner Coal Measures and soft Kaiata mudstone. As there are no major creeks, streams or rivers joining in the study area, the entry of large tributaries does not have a major affect. Changes in sediment load are fairly minimal, except for some creeks such as Lake Stream, where there has been remobilization of landslide material within the bed load. Climate maybe a factor, as knickpoints can develop from eustatic lowering of the base level, such as at the end of the last glaciation (at approximately 6.5±0.1ka) when the sea-level paused briefly at a slightly higher level than today. This steepens the gradient in the newly exposed level of the river and increases the amount of down cutting there. Resultant high gradients are unstable and will migrate upstream by headward erosion and disappear as the river regrades to the lower base level (Seeber and Gornitz, 1983).
3.2.2. Longitudinal Valley Floor Profile

The longitudinal profile of a river is sensitive to the ongoing process of uplift and can be used to recognise active structures. A stream not affected by listed external factors is in equilibrium with both discharge and load, and is found to possess a concave form due to progressive increase of downstream discharge (Litchfield, 1995; Bull and Knuepfer, 1987). In a steady-state system erosion keeps pace with uplift. River gradients (which determine the rate of erosion), are adjusted so differential rates of uplift are matched by differential rates of erosion, thus producing reaches that are steeper or more gentle. These departures from the idealised form are defined as knick-points, and relate to sudden increased concavity or appearance of convexity (Figure 3.7.). Consequently, abrupt changes in slope along river profiles may indicate active faults crossing these rivers (Seeber and Gornitz, 1983).

This technique provides the most visual estimate for studying sudden changes in slope and the types of profile patterns produced. Profiles are very subjective, particularly in proportion to the scale of the plots (which are directly proportional to the length of the streams). Computer generated plots are generally of the same length and this results in varying amounts of vertical exaggeration. To overcome this problem, the Stream-Gradient Index is used to calculate quantitative values for individual reaches (Litchfield, 1995).

3.2.3. Stream-Gradient Index

The formula for the Stream-Gradient Index (SL) of a reach of river was defined by Hack (1973) as:

\[ SL = \frac{\Delta H \times L}{\Delta L} \]  

(1)

where \( \Delta H \) is the drop in elevation of the reach, \( \Delta L \) is a measure of the length of reach and \( L \) is the total channel length from the drainage divide to the centre of the reach, measured along the channel as in Figure 3.8. (Keller, 1986). When values are measured for every stream segment (between successive topographic contours following the general concave form of the longitudinal valley floor profile), sudden large changes from the general increase of downstream values can identify displacements away from the overall concave form of the profile (Litchfield, 1995).
<table>
<thead>
<tr>
<th>Types of profile patterns produced (and symbol)</th>
<th>Classification</th>
<th>Gradient index relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="predicted concave profile" /></td>
<td>predicted concave profile</td>
<td>general and steady increase in GI values</td>
</tr>
<tr>
<td><img src="image" alt="convex bulge" /></td>
<td>convex bulge</td>
<td>GI values steadily increase and then either decrease of increase at a slower rate, before eventually increasing again</td>
</tr>
<tr>
<td><img src="image" alt="step-type knick point" /></td>
<td>step-type knick point</td>
<td>sudden increase in GI, followed by a sudden decrease</td>
</tr>
<tr>
<td><img src="image" alt="step-type knick point (2)" /></td>
<td>step-type knick point (2)</td>
<td>sudden decrease in GI</td>
</tr>
<tr>
<td><img src="image" alt="cusp-type knick point" /></td>
<td>cusp-type knick point</td>
<td>sudden increase in GI, which slowly returns to normal values</td>
</tr>
</tbody>
</table>

**Figure 3.7.** Classification and interpretation of knick-points observed along longitudinal valley profiles in terms of physical appearance and gradient index values (From Litchfield, 1995).
SL values are then compared to a simple idealised logarithmic graph of the longitudinal valley floor profile. Most natural streams however, do not form a natural logarithmic profile over their entire length. Instead they form a series of connecting segments of various lengths, each logarithmic in form where SL is then redefined as (Hack, 1973):

\[
SL = \frac{\Delta H}{\log_e L_2 - \log_e L_1}
\]

(also shown in Figure 3.8.) The stream gradient index can also be recalculated in terms of the entire stream profile \(k\) where:

\[
k = \frac{H_i - H_b}{\log_e L_i - \log_e L_b}
\]

(also defined in Figure 3.8.). The SL/k values will steadily increase downstream, following the general increase in downstream gradient index values, from values slightly less than one to slightly greater than one. Changes in the longitudinal valley floor profile will be reflected in sudden changes of the SL/k values and provide some indication to the relative significance of these changes (Litchfield, 1995).

\[\text{Figure 3.8. Definitions of symbols used in equations 1, 2, and 3 (redrafted from Hack, 1973).}\]
3.2.4. Methodology

Most streams within the study area drain the Papahaua Range perpendicular to the coast. As a result it was not necessary to define catchments or divide streams with respect to order, as most flow parallel to each other with each stream defining its own catchment and distinct zone of drainage. A representative sample of streams from along the Papahaua Range front were chosen, generally perpendicular to the overall structural trend, corresponding to the major fluvial channels within each catchment (Map 2A).

Streams in the Te Kuha Block were also included in the survey and compared to the coalfield map of Anon (1986c). The original field area had been larger than that mapped by the end of the project and stream profile information had already been compiled, so it was decided to retain this data (Map 2A).

The SL index and plotting of logarithmic valley floor profiles were computed from 1:25 000 scale topographic maps (20m contour intervals) for the 23 streams chosen. A standard digitiser and a simple program, written by Yousif (1987), for generating longitudinal stream profiles and stream-gradient indices was used. This program simply required values of the highest and lowest topographic contours, followed by digitising the head of the stream and relative topographic contours along the stream length. Tables of SL, k, and SL/k were produced and imported into Microsoft Excel 7.0, where logarithmic valley profiles with fixed length x-axis were generated.

3.2.5. Results

"Knick-points" and convex portions were identified according to Litchfield (1995), where streams display relatively large changes in values of SL/k (generally > 0.5) along each of the stream profiles (Appendix 4) which in turn were transferred back to the map (Map 2B) using symbols shown in Figure 3.7. Interpretation was conducted by first removing effects of lithology by superimposing major lithological units, faults and folds on the profile plots. A direct comparison of their effects upon the profiles was made and then remaining anomalies were considered in terms of structure (Map 2C).
Substantial correlation exist between all types of anomalies and bedrock. This in part reflects the nature of the Kongahu Fault Zone, as much of the fault deformation appears to be concentrated near or along the contacts between lithological units. A series of "cusp"-type knick-points occur along the western margin of the Denniston Plateau and appear to correlate to the head zone of escarpment gravitational collapse. Through this same section these "cusp"-type knick-points also seem to correlate to the toe and downslope extent of displaced Brunner Coal Measure derived failure material. Between the Whareatea and Orowaiti Rivers the reliability of this technique decreases, due to the immense supply of Brunner Coal Measure landslide talus material and large displaced blocks derived from the vicinity of Mt Rochfort. Within Quaternary gravel units the stream-gradient index displays no effects of faulting.

South of the study area, within the Te Kuha Block, stream-gradient profiles show clear cusp-type knick point anomalies which correlate well with faults identified by Anon (1986c). These represent the southern extension of the Kongahu Fault Zone as it transfers into the Paparoa Tectonic Zone. Nomenclature places this boundary at the mouth of the Buller Gorge where early workers (Morgan and Bartrum, 1915) identified the Lower Buller Fault.

3.2.6. Synthesis

It has been found that longitudinal valley profiles are more useful than the SI index, which is effectively the logarithmic profile for a given reach. Normalising the logarithmic profile to total stream length and total stream fall, allows more ready comparison between streams of different sizes (Bull and Knuepfer, 1987).

Stream gradient index analysis has been found to be a useful preliminary investigative tool which can be applied to more than just faulting. Three sets of structures were identified from the study of gradient indexes consisting of the Kongahu Fault Zone, smaller scale faulting within the Mt Rochfort and Denniston Sectors, and delineation of gravitation collapse structures. Landslide debris, combined with the fact that displacement appears to occur upon a broadly disseminated zone within the Kaiata Mudstone, made identification of the Kongahu Fault difficult. The Kaiata mudstone unit is readily eroded, consequently, it does not support marked gradient contrasts identified using the stream-gradient index.
Head-scars and toe areas of the large scale gravitational collapse structures can be quite well constrained. This technique was more effective in the smaller creeks and streams. They do not have the erosive power of the larger rivers, and therefore lack the ability to cut through the Brunner Coal Measure derived failure material. Only minor faulting was identified within the vicinity of Conglomerate, V70 and V72 Streams, trending perpendicular to the Kongahu Fault zone. It is unclear whether these faults are resultant of Quaternary fault, activity or formed and preserved since initiation of inversion.

Care needs to be taken when applying stream-gradient indices, as lithologically resistant units are dramatically over emphasised. The majority of knick-point determined trends are situated some metres back from the mapped trace and are interpreted as a function of upstream migration (Litchfield, 1995). Sensitivity of the method is only as good as the base map from which profiles are derived, with knick points only positioned to the nearest 20m topographic contour. Large amounts of landslide material limited the effectiveness of this technique for interpreting the Kongahu Fault Zone. Although locations in the Whareata and Orowaiti Rivers, where the major fault traces were identified by field mapping, the stream-gradient index did not recognise these locations. This maybe as result of; Little recent fault activity, deformation spread over a broad zone with only subtle deformation features, or lithological and geomorphic effects obscuring structural features.
Chapter 4

Escarpment Gravitational Collapse and Landslides

4.1. Introduction

In this study "landslide" is used to denote "the downward and outward movement of slope forming materials composed of natural rock, soils, artificial fills, or combinations of these materials (Cleaves, 1961)". Nomenclature and classification of slope movement processes and deposits are based on those by Cruden and Varnes (1996) as shown in Appendix 5.

Gravitational collapse of the Kongahu Fault Zone escarpment has formed the largest known mass movement in the Buller Region, with a failure complex surface area of approximately 18 km² (Figure 4.1.). Collapse extends from the coastal plain (at RL 20m) to the top of Mt Rochfort (at RL 1040m), including the north-western margin of the Denniston Plateau (at RL 520m to RL 540m). Almost the entire north-west facing hillslope of the Papahaua Range, between the Orowaiti and Waimangaroa Rivers, is incorporated into the failure complex (Figure 4.2.). Boundaries are defined by a series of prominent scarps along the edge of the Denniston Plateau and ridge line, in the vicinity of Mt Rochfort head area. Topographic changes and appearance of in situ basement in the Waimangaroa and Orowaiti Rivers delineates the lateral extent of instability, with toe areas more variable. North of the Whareatea River, collapse appears on a smaller scale, and failure debris does not extend onto the coastal plain, This is primarily controlled by the change in nature of the underlying Kongahu Fault Zone through this sector. Failure is predominantly confined to bedrock and debris movements, as there is little material present that could be classified as earth, mainly due to weathering resistant nature of the Brunner Coal Measures.
Figure 4.1. Map of the study area, delineating the extent of the Kongahu Fault Zone Failure Complex. Collapse extends from the coastal plain, to the top of Mt Rochfort, and the northwestern margin of the Deanston Plateau, covering approximately 18 km$^2$. 
Figure 4.2. Aerial oblique view of Mt Rochfort, Lake Rochfort and the Mt Rochfort failure. Almost the entire hillslope viewed within this photograph consists of displaced Brunner Coal Measures of the Kongahu Fault Zone failure complex. Six separate evolutionary phases of deformation have been identified and these are discussed within the text. The numbers on the figure relate to each phase of evolution, which have been correlated from the present geomorphology, and delineated as mappable Zones (in Figure 4.8.) within the failure complex. Note the prominent lateral scarps of the Mt Rochfort landslide and the large alluvial fans that have developed, on the coastal plain, from both Lake Stream and Rapid Creek (L. Homer, IGNS, CN31114).
4.2. Slide Description

Slope modification of the escarpment is most noticeable below Mt Rochfort, where Tertiary Brunner Coal Measure sediments on the west face of the Buller Coalfield, have collapsed onto the coastal plain. Most of the slope failures in the Brunner Coal Measures and granitic basement are considered creeping translational, rock and chaotic debris slides, developed along bedding planes, fault crush, shear zones and joints. A wide range of coal measure and granite derived landslide materials have developed as part of the mass-movement process. A unique combination of geologic and morphologic features identify mappable mass movement deposits which are broken into: in situ, disturbed, displaced, blocky debris, chaotic debris, and outwash gravel (fan alluvium) which are displayed in Map 3. Descriptions have been adapted from those used by Gillon and Hancox (1991), Johnson (1986), Macfarlane et al. (1991) and Beetham et al. (1991) of schist landslide stabilisation studies during the Clyde Power Project in the Cromwell Gorge (Table 4.1.). Photographs 4.3. to 4.7. show typical exposures of some of the slope debris units.

Division of the failure complex surface into mappable mass movement deposits has proven a valuable technique and has enabled:

a) delineation of distinctive zones on the surface of the failure complex,
b) development of an improved understanding of subsurface geology and movement history of each slide zone within the failure complex.

Failure material of many tens of metres thick is found overlying gravitationally displaced granitic bedrock, underlain by a basal shear zone within the central section of the failure complex. Surface morphology of the failure complex is highly variable ranging from smooth vegetated slopes to rough, irregular, boulder littered surfaces. Numerous talus cones are common in the head zone of the slide complex, sourced from in situ and disturbed Brunner Coal Measures along main and secondary head scarps.
Table 4.1. Classification of mappable mass movement deposits of the Brunner Coal Measures.

<table>
<thead>
<tr>
<th>Term</th>
<th>Map Symbol</th>
<th>Mass Description</th>
<th>Surface Morphology</th>
<th>Comment on Soil and Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ</td>
<td>ins</td>
<td>Relatively undisturbed rock mass with closed defects.</td>
<td>Prominent dip slope bedding planes deeply incised by fluvial channels.</td>
<td>Thin to non-existent soil cover with moss and poor stunted vegetation cover.</td>
</tr>
<tr>
<td>Disturbed</td>
<td>dst</td>
<td>Relaxed rock mass with partly open bedding and defects due to stress release near failure crown area and below failure surface.</td>
<td>Forms prominent outcrops similar to undisturbed coal measures.</td>
<td>Thin to non-existent soil cover with moss and poor stunted vegetation cover.</td>
</tr>
<tr>
<td>Displaced</td>
<td>dsp</td>
<td>Very large coal measure blocks up to 10,000(+) m³ within slide mass. Joints open with bedding attitudes often rotated.</td>
<td>Blocks form prominent ridges, laterally persistent breaks in slope, flanked by fluvial channels.</td>
<td>Poor soil cover with moss and scattered scrub.</td>
</tr>
<tr>
<td>Blocky Debris</td>
<td>bld</td>
<td>2 to 1000(+) m³ blocks and boulders rafted in the slide mass. Highly relaxed open joints with numerous internal shear zones, formed as the block has been displaced down slope. Small to large boulders with minor fines support the debris.</td>
<td>Irregular sharp surface littered with angular boulders and small talus cones. Slope failures (&lt;200 m³) common in steeper slopes.</td>
<td>Poor soil cover, vegetation varying from scattered scrub to 10 m tall trees.</td>
</tr>
<tr>
<td>Chaotic Debris</td>
<td>chd</td>
<td>Gradation from large component of rock blocks to angular boulders supported within a matrix of angular coarse silty to coarse sand and rock fragments (commonly intensely sheared and crushed).</td>
<td>Highly variable rough to smooth, with scattered boulders on surface. Small slope failures common in steeper slopes.</td>
<td>Poor soil cover, vegetation varying from scattered scrub to 10(+) m mature beach forest.</td>
</tr>
<tr>
<td>Outwash Gravels</td>
<td>otw</td>
<td>Fan alluvium.</td>
<td>Relatively smooth surface radiating out from slope toe.</td>
<td>Thin to good soil cover supporting mature beach forest or cleared as farm land.</td>
</tr>
</tbody>
</table>
Figure 4.3. Disturbed rock mass within the crown area of the failure complex. Photo is taken looking south at Mt Rochfort with the main head scarp (delineated by arrows) featured in the extreme right.

Figure 4.4. Surface morphology of extremely large tilted blocks of Brunner Coal Measures, forming laterally persistent ridges (separated by normal faults), incised by V70 Stream. The photograph is taken looking north from Mt Rochfort.
Figure 4.5. A section of road cut clearly displaying blocky debris within the failure complex. Four lines indicated bedding within highly related blocks and weathering horizons, in a zone of brecciated material, between individual blocks. Note finger and spade for scale (GR, K24075171).
Figure 4.6. Chaotic debris with highly variable, rough to smooth surface morphology with boulders scattered upon the surface (GR, K29 032375).

Figure 4.7. Small local failure within structureless chaotic debris displaying angular boulders within a matrix of coarse sand and rock fragments which are susceptible to local remobilisation (GR, K29 036384).
4.3. Slope Movements

The Mount Rochfort failure complex has evolved over the last several hundred thousand years, with different sections becoming active and reactivated in response to external influences, such as:

a) loading of the head area through continued tectonic deformation and uplift;
b) removal of basal support through stream down cutting and cliffing (during interglacial high stands) within the toe area; and
c) antecedent weather conditions affecting interstitial pore water pressures.

It is uncertain whether large earthquakes associated with the Kongahu Fault Zone have had significant effects on failure or were the initial triggering mechanism. No Holocene fault activity has been identified within the study area, and only one Quaternary fault trace has been identified (by Nathan, 1996) within the Kongahu Fault Zone between the Whareatea and Mokihinui Rivers. The age of this fault trace is uncertain, but it is no older than the Caledonian Formation and maybe as young as deposits of the last interglacial.

Slide displacements have not been monitored, consequently, directions and rates of slide movements are not known. Much of the failure complex is inferred to be inactive/quasi-stable, based on 300 000+ year old sea terraces preserved across the toe region. Reactivation is assumed to have occurred during sea-level high stands with toe erosion of the slide mass initiating destabilisation and progressive reactivation in the head zone. Chaotic failure debris on the Denniston Road buries a paleosol horizon containing wood fragments and moderately weathered conglomerate (possibly representative of old fluviatile deposits). Unfortunately C14 dating is not possible as there would be sample contamination from coal measure C13. However, the age of much of the slide complex is beyond the limit of C14 dating.

Geologic and geomorphic description of the Kongahu Fault Zone failure complex has indicated six different zones (based on mappable mass movement deposits), related to phases of activation and reactivation during geomorphic evolution (Figure 4.8.). Each phase of failure is discussed in detail within section 4.5. Present day active slope failure is occurring within zones five and six. Rapid surficial rock fall and debris slide failures (initiated by intense rainfall and inferred seismic events), are observed in zone six (within Brunner Coal Measures derived talus material), between the Whareatea and Orowaiti Rivers. Zone five involves the "Mt Rochfort Failure"
Figure 4.8. Six Zones (1-6) of the Konshu Fault Zone Failure Complex are identified, and superimposed upon a 1:50,000 scale Digital Terrane Model of the study area. Zones (1-6) correlate to successive phases of collapse during geomorphic evolution of the failure complex. See text for detailed explanation of failure during each phase of collapse (Digital Terrane Model data courtesy of IGSN, 1997).
displaying a prominent head scarp south of Mt Rochfort, lateral scarps north of Lake Rochfort, in conjunction with deformed sheared granite basement within Lake Stream (Map 1 and 3), indicative of deep-seated, extremely slow (Appendix 5a) failure.

4.4. Subsurface Interpretation

Failure complex subsurface interpretation is based on surface observations only, with cross sections representing schematic models of subsurface slide geology displayed within supplementary map sheet B. Inferred failure surface geometry and depths are only depicted.

Section AA' is drawn through Zone 2a (near the Denniston Road) where failure material has buried the contact between the Kaiata Mudstone and Brunner Coal Measures. The cross-section shows relaxation within the crown area, large displaced Brunner Coal Measure blocks, immediately below the head scarp, which are failing upon a coal seam. Passing downslope, the failure material grades into blocky debris which in turn grades into chaotic debris, reflecting an increasing amount of internal deformation within the slide. The toe of the surface of rupture has formed where bedding within the coal measures has become steeply dipping, with failure propagating onto the ground surface.

Sections BB' and EE' display similar failure cross-sections passing through Zones 1, 2b, 3 and 6, with slope debris totally obscuring the Kongahu Fault Zone. Head scarp separates disturbed, relaxed coal measures from displaced blocks within Zone 1 of section BB' (Figure 4.9.), as this section has been eroded away within section EE' by the headwaters of the Orowaiti River. This passes into Zone 2b of blocky debris which has experienced greater internal deformation, and is separated from Zone 3 of chaotic debris by a large internal scarp. Translational failure has occurred upon coal bedding planes as indicated by Figure 4.10., which views from the south into Zone 3 of section BB'. Toe areas of these failures lie within Zone 6, where there are small shallow debris failures within the chaotic debris.
Figure 4.9. The main head-scarp of Kongahu Fault Zone Failure Complex (as indicated by arrows) within the Brunner Coal Measures. This separates disturbed debris (to the left) and displaced blocks (of Zone 1) to the right, buried beneath debris derived from head-scarp degradation. Photograph is taken looking south at Mt Rochfort.
Figure 4.10. Photo is taken looking north at a small failure that has exposed a cross-section through Zone 3 in failure the complex above Lake Stream. Note disturbed Bassen Coal Measures at the base truncated by a band of highly sheared chertaceous material forming the failure plane, overlain by chaotic debris (GR K29 043374).
Section CC' passes through the main head scarp (shown in Figure 4.9.), separating disturbed Brunner Coal Measures from displaced blocks of Zone 1. Zone 4 forms a small internal failure of blocky debris, where the rupture surface has propagated into granitic basement, which is exposed in Lake Stream. The toe of the rupture surface is inferred to have propagated up a blind thrust beneath Zone 3, which forms a small monoclinal fold in disturbed coal measures overlain by chaotic surface debris.

Section DD' dissects the "Mt Rochfort Failure" (Figure 4.2.), lying entirely within Zone 5. Disturbed coal measures form the crown area, with large displaced blocks separated by minor internal scarps. Internal deformation increases down the failure with blocky debris forming the main failure boy. The rupture surface propagates down bedding planes of thick coal measure basal conglomerates into granitic basement, forming a deep seated failure with less internal shearing than surface deposits in Zones 2 and 3.

Across the width of the escarpment, within the failure complex, the inferred subsurface geology displays the following distinct changes:
1) the location and type of basal rupture surface within each failure zone, is controlled by; tectonic deformation associated with the Kongahu Fault Zone, geomorphic development history and the thickness of overlying debris;
2) north of the Whareatea River, failure dominantly occurs sub-parallel to bedding and is inferred to occur through weaker carbonaceous lithologies within the Brunner Coal Measures. South, below Mt Rochfort, more complicated stratigraphy has lead to a more complex failure history. Failure has propagated through the coal measures and into granitic basement, which has been sheared and altered by deformation along the Kongahu Fault Zone; and
3) variations in underlying modes of failure are reflected by morphological changes between different surface zones.
4.5. Geomorphic Evolution of Kongahu Fault Zone Failure Complex.

Initiation and evolution of collapse is intricate and complicated with six separate phases of collapse recognised within the failure complex (Figure 4.11.). Each phase of evolution is correlated to the present geomorphology, and delineated as mappable Zones which have been identified within Figure 4.8. Age and evolution of the failure complex has been estimated by preservation of interglacial marine cliffs and terraces across the toe area. Progressive failure occurred, between the Whareatea and Orowaiti Rivers, prior to interglacial deposition of the Caledonian Formation (279-334 000 years BP). Evolution is related to removal of toe support through marine transgression during interglacial sea-level high stands, minor stream incision and prolonged tectonic uplift along the Kongahu Fault Zone creating surficial instability.

• Phase One

Initial failure is inferred to have occurred along coal (Figure 4.12.) and carbonaceous bedding planes within the coal measures, with rotational slumping in the head zone and translational displacement through the main body of the slide. The crown area has encroached towards Mt Rochfort through progressive failure and regression of the head zone (Figure 4.11.).

• Phase Two

The second phase of displacement also occurred prior to deposition of the Caledonian Formation (279-344 000 years BP) which is found overlying failure debris in the vicinity of Deadmans Creek (Map 1). This episode is separated into two generic zones, north (2a) and south (2b) of the Whareatea River (Figure 4.11.). Separation is based on failure complex evolution, as location of the head scarp is inferred to be controlled by an active blind thrust/reverse fault, beneath the coal measures. This inference is based on stream gradient profiles and the linear nature of the head scarp for the zone of failure.

Zones 2a and 2b are shallow failures (approximately <50m thick) occurring upon bedding planes within the coal measures, initiated through tectonic evolution of the escarpment, leading to instability and resulting in collapse. Deep incision of the Whareatea River has resulted in both sections (2a and 2b) developing independently of each other. Zone 2b experienced a more complicated evolution, as initial failure would have loaded the head zone, in conjunction with removal of toe support through erosion. The presence of thick coal seams and carbonaceous mudstone in the south (absent or
Figure 4.11. Schematic cross-sections displaying successive phases of collapse for the Kogalnu Fault Zone Failure Complex. Each phase of failure is recognised as mappable Zones, as identified in Figure 4.8. Two separate generic zones are recognised north and south of the Whareata River, resulting in phase 2 of collapse being separated into 2a and 2b. See text for detailed explanation of failure during each phase of collapse.
Figure 4.12. a) 3-4m thick highly sheared coal seam located within Zone 1 of the failure complex. Shearing is inferred to have occurred by propagation of a failure surface through the weak coal seam.

Figure 4.12. b) Close up of the coal seam indicating the highly sheared and brecciated nature of the coal and immediately adjacent mudstone. Shearing has refracted into the coal seam, facilitated by the weak strength of the coal compared to surrounding mudstone and sandstone lithologies. The photo's are taken facing north in the headwaters of the Orowa River (GR. K29 040352).
areally less extensive in the north) may have also been a controlling influence on the scale of failure. Second phase failure may reflect underlying changes across the Kongahu Fault Zone as thrusting in the south occurs along discrete zones, where in the north deformation is taken up as shearing and folding across a very broad zone, as indicated by the structural domain map (Figure 2.24.).

• **Phase Three**

Phase three is limited to the area between the Whareatea River and Lake Stream, where reactivation of slope deposits has occurred through removal of the toe buttress by a sea-level high stand during the Kaihinu Interglacial (72-128 000 years BP) (Figure 4.11). Failure occurred as reactivation of pre-existing failure planes of carbonaceous material within the slide mass underlain by more intact, less deformed coal measures (Figure 4.10.). Carbonaceous material is inferred to represent coal and carbonaceous mudstones that phases one and two had already failed upon, creating a weak basal surface ideal for reactivation. Grabens and back-tilted blocks developed in the head and crown zone, but collapse ceased during the mid Kaihinu Interglacial, as Waites Formation deposits (Wb2) are preserved in the cliffed toe area.

• **Phase Four**

Phase four is only a minor component, but may relate to a small and less developed portion of the deep-seated failure that evolved as phase 5. Collapse occurred post episode 3 as the head area locally dissects the head scarp of phase 3 (Figure 4.11.). Failure may have been initiated by the removal of the toe buttress by Lake Stream, combined with continued tectonic deformation, steepening and destabilising the head area. Numerous tension fractures are preserved in the crown area, with initial failure probably occurring on basal coal measure conglomerate sequence, (steeply dipping northwest and lensing out onto basement) with shear surface then propagating into deformed granitic basement. The toe of this failure is observed within the head waters of Lake Stream (Figure 4.13.), with rupture propagating up along a shallow northeast dipping shear surface beneath a relatively intact float block of granite and coal measures. The toe area has been stabilised through buttressing by in situ coal measures, which are deformed into a monoclinal fold structure (Figure 4.14.). It is unclear whether this monoclinal folding has resulted through transfer of strain from buttressing of this phase of failure, or represents tectonic deformation associated with a blind thrust/reverse
Figure 4.13. Deformed shear zone of basement granite overlain by Brunner Coal Measures within Lake Stream. Note the 0.6m thick zone of sheared/breciated granite at the base of the exposure, inferred to represent the rupture surface of failure phase 4 and possibly a blind thrust associated with the Kongahu Fault Zone (GR K29 042375).
Figure 4.14. Folding within 2.5m thick carbonaceous and grit sandstone beds within disturbed Bremner Coal Measures. Folding may be induced through tectonic deformation, with coal measures draped over a blind thrust/reverse fault, or caused by internal deformation within the failure complex (GR. K29 942375).
fault associated with the Kongahu Fault Zone, which the basal failure surface has propagated up.

• **Phase Five**

Phase five represents the largest deep-seated failure (Figure 4.11.). The crown area and main head scarp are situated immediately south of Mt Rochfort, with the main body of failure extending onto the coastal plain. The rupture surface extends into basement (>100m depth), displacing extremely large granitic blocks (possibly >1x10⁶ m³) which appear as displaced, disrupted granite in the toe area, exposed in both Christmas Creek and Lake Stream (Figure 4.15.). Displaced, blocky and chaotic coal measure debris, dissected by numerous small internal debris slides, overlie displaced granite within this failure. The head zone has advanced through propagation of the main rupture surface through the crown area, creating graben structures between back tilted blocks. Lake Rochfort is preserved within a shallow depression in the main body of the collapse.

Geomorphic features and non-preservation of the Waites Formation in the toe area, infer collapse has proceeded since the end of the Kaihinu Interglacial and possibly through to the present day. Mature trees growing within the failure complex are not disturbed or affected by movement, which would typically be observed within shallow failures. However displacement maybe occurring as deep-seated discrete blocks which display little current internal rotation and deformation. Flanking the toe area are two large alluvial fans, sourced from Lake Stream and Christmas Creek, derived form this failure and indicative of the vast amount of mass wasting that has occurred. On the coastal plain these units bury the sea cliff formed at the end of the last glaciation, at approximately 6500 years BP (Gibb, 1986), indicating continuing rapid degradation of the failure mass.

• **Phase Six**

The most recent activity is confined to Phase 6 where limited surface remobilization within chaotic coal measure debris (in the toe area of the major collapse structure) has lead to small active toe failures (typically <500m³) (Figure 4.11.). Collapse occurs as rock fall and slump-earth flows are initiated by slope destabilisation through erosion and antecedent rainfall conditions. Slumping also occurs in failure debris on the southwest bank of the Whareatea River through erosion at the base, removing lateral support, and initiating collapse. Rock falls and topples are also active to the southeast of
Mt Rochfort, where steep high bluffs define the headwaters of the Cascade River catchment. Ongoing erosion and removal of lateral support leads to relaxation and opening of joint sets subparallel to the cliff face, allowing small graben structures to form, as large sheet-like slabs slowly rotate off the cliff face.

Figure 4.15. Highly sheared and deformed granite within the zone of accumulation for the Mt Rochfort Failure in Lake Stream. Note the highly brecciated nature of the rock mass and the numerous shear zones (indicated by arrows) directly above the pack and A3 map-board (GR, K29 041377).
4.6. Factors Influencing Failure

The influence of the Kongahu Fault Zone has been a dominant factor in the development of the failure complex, as geomorphic evolution of the gravitational collapse and local secondary slope failures, reflect changes in the underlying geologic structure. Failure is inferred to have been initiated through head loading caused by tectonic uplift (effect of basin inversion), and removal of toe support through erosion of the Tertiary Kaiata and Blue Bottom Formations (west of the Brunner Coal Measures), leading to slope destabilisation.

*Structure*

Change within underlying geologic structure of the fault zone is reflected by variations in geomorphic expression and failure development. Below Mt Rochfort the nature of the debris suggests weakness in the basement has influenced failure, allowing the rupture surface to propagate deep into granitic basement. Instability developed due to unfavourably oriented dislocation surfaces such as bedding within the coal measures, joints sets and faults (possibly a series of low lying (43-60°NE) thrusts and blind thrusts associated with the Kongahu Fault Zone).

Stream-gradient analysis of the headwaters of the Orowaiti River and Giles Creek suggest the presence of an active northeast-southwest fault structure in the vicinity of Mt Rochfort (Map 2C). This feature in conjunction with west-northwest and northwest trending normal faults north of Mt Rochfort, may have acted as head zone release structures for gravitational collapse. The resultant failure developed through deep-seated collapse, as massive blocks of deformed sheared granite overlain by translationally derived, thick coal measure talus and large relatively undeformed float blocks.

The orientation of bedding planes has an important effect on stability. Initial slope failure occurred as translational landslides, dominantly controlled by the distribution of on coal and carbonaceous units within the coal measure sequence. Extremely thick basal conglomerate and a grit sequence is present at the base of the Brunner succession in the vicinity of Mt Rochfort, lensing to the north and west (Titheridge, 1988) with bedding dipping at 15°-25° to the northwest. Initial slope displacements loaded and destabilised lower sections of the escarpment, allowing failure to propagate down these bedding planes and joints, through the basal conglomerate and
grit sequence, developing deep seated gravitational collapse within granitic basement (Figure 4.11. phases 1 and 2, and Section BB’, Supplementary Map Sheet B).

- **Toe Support**

  Stability conditions within the failure complex are likely to have varied greatly subsequent to the main episode of collapse. Interglacial sea-level high stands may have been a controlling influence. They resulted in the removal of Kaiata and Blue Bottom lithologies, which acted as basal support and limited propagation of the rupture surface. Sea-level high stands also raises ground water levels, increasing interstitial pore pressures within the slide mass, reducing shear strengths and increasing loading on the slope. Between the Whareatea River and Lake Stream, reactivation has developed through cliffting of the toe area. A complex debris slump, debris slide has developed, with large back tilted blocks, separated by graben structures, composed of coal measure derived destabilised chaotic debris material (Map 1). Virgin Flat and Waites Formations are preserved at the base of a large sea cliff cut into chaotic debris, inter-fingering with landslide deposits in the failure toe. Slumping in the head zone has lead to deposition of material in the zone of accumulation, reforming the toe buttress and restabilisation of the failure. To the north of the Whareatea River, collapse occurred on a smaller scale. Low hills of Kaiata mudstone are preserved, supporting the theory that these acted as toe support, controlling extent and depth of slope failure and preventing cliffting of the slide toe area during interglacial high stands.

- **Pore Water Pressures**

  Pore water pressures may also have a significant effect on initiation and reactivation of the slide complex. The pronounced orography effects results in rainfall frequency and intensities far greater on the Denniston Plateau and Mt Rochfort areas than on the adjacent coastal plain. Annual rainfall is estimated to be between 5000 and 7000mm with monthly variations of 120 to 500mm (Alarcon pers comm, 1997). Such high annual rainfall and intensity, in conjunction with the disrupted nature of the failure material, allow rapid infiltration and high pore water pressures to develop throughout the failure complex. Recent work by Gillon and Hancox (1991) and Gillon et al (1991) on large scale gravitational collapse in the Otago schist, highlight the effects of pore water pressures as the major controlling factor influencing slope failure.
Overall, the failure complex must be relatively stable as it is located within one of the more tectonically active regions in New Zealand, and would have experienced numerous high intensity earthquakes during its long term geomorphic evolution. These events may have triggered or influenced initiation and reactivation of the failure complex.

4.7. Discussion

Subdivision of the landslide material into mappable mass movement deposits, displays the degree of internal deformation within different sections of the failure complex. They also reflect variations in modes of failure between different surface zones, which in turn are governed by the changing underlying structure of the Kongahu Fault Zone. Collapse has been a long complex process, inherently related to head loading and destabilisation, through ongoing tectonic deformation and removal of toe support by fluvial down cutting and sea cliffing during interglacial high stands. Antecedent interstitial pore water pressures would have had a considerable effect on stability, but their distribution and effects were not considered within the context of this study. However, climate change and interglacial high stands of sea-level could have adversely affected stability through alteration of interstitial pore water pressures in the failure complex.

Initial failure occurred, prior to deposition of the Caledonian Formation, along unfavourably oriented dislocation surfaces such as bedding within the coal measures, joints sets and faults. As collapse evolved, below Mt Rochfort, the rupture surface propagated into granitic basement sheared and altered by the Kongahu Fault Zone, forming a deep seated, extremely slow creeping failure. Geomorphic interpretation of deposits upon the coastal plain indicate that this is still an actively evolving feature. Future detailed monitoring and investigation is required involving surveying, drilling and piezometers to more fully understand the mechanisms and influencing factors of this failure complex.
Chapter 5
Hazard Implications

5.1. Introduction

*Defining Hazard*

Throughout the literature numerous definitions with subtle variations in terminology have been applied to the term "natural hazard". McManus (1996) conducted a thorough, critical review of the concepts of "natural hazard" within the context of engineering geology, to clarify the confusion of definitions. However, McManus's hazard definition does not include harm to the environment, where IPENZ (1983) defines "hazard" as:

"A condition or situation which has the potential to create or increase harm to the people, property or the environment"

For the purpose of this study, McManus's definition of "natural hazard" has been adapted to incorporate natural process as having an effect upon activities of man and the environment. Thus "natural hazard" is defined as:

One or more natural or human induced landscape modification processes* of varying duration, which have potential to harm the environment, and/or cause loss of life, injury, or property/infrastructure damage within or adjacent to a given human community.

Natural hazards have a specific magnitude, return period and affected area.

The principle that "the past and present are keys to the future" is a long established and useful concept in geology. Natural slope failures in the future will most likely reoccur under geologic, geomorphic and hydrologic conditions similar to those that have lead to past and present failures (Varnes, 1984). Incorporated within this chapter is all the information presented in previous sections concerning geology, geomorphology and geotechnical characteristics of the field area. Hazards are assessed qualitatively in association with a particular geological process, and identifying the areas affected by the active process. Recent subdivision of farmland into life style blocks

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* Earthquakes, tsunami, erosion, volcanism and geothermal activity, landslip, subsidence, sedimentation, wind, drought, fire, flooding, rock fall and avalanche.
between Fairdown Straight and the escarpment, has increased the risk of the human community to the adverse effects of natural slope forming processes.

### 5.2. Nature of the Kongahu Fault Zone

#### 5.2.1. Introduction

The New Zealand seismicity catalogue for large earthquake events only spans the last 150 years, while the instrumental catalogue is much shorter. Current techniques to predict the location and probable magnitude of future seismic events is based on the understanding of earthquake mechanics and historical earthquake data, to generate "educated guesses". Historical seismicity provides valuable information on the frequency of smaller magnitude earthquakes, the intensity of shaking and the damage sustained. Long-term earthquake hazard analyses, independent of a time datum, provide estimates of geographical distribution of seismic hazard (Chamberlain, 1996).

Earthquakes are measured in terms of "magnitude" (M) and "intensity" (MM)(Modified Mercalli scale). Earthquake magnitude is instrumentally measured, reflecting the amount of energy released during the event. Intensity measures the effects felt on the ground surface in response to the earthquake and varies according to; proximity of the epicentre, engineering structures and local geology (Cowan and Pettinga 1990). It seems logical to assume that as the intensity of an earthquake decreases with distance from the epicentre, the area affected by landslides during an earthquake will be proportional to the earthquake magnitude (Keefer, 1984; Walker and Fell, 1987).

#### 5.2.2. Long Term Regional Seismicity

Seismicity within New Zealand has been recorded by the relatively widely spaced National Seismograph Unit (Figures 5.1. to 5.3.). These figures indicate high levels of seismic activity within the upper crust, in the West Coast of the South Island, with earthquake events dominantly located within the upper 15km. Mountainous terrain and dense forest cover over much of the West Coast make identification of active tectonic features difficult, with slip rates and recurrence intervals only derived from a few sites (Anderson et al, 1994).
Figure 5.1. Epicentres for earthquakes deeper than 15km and shallower than 40km for the period 1 January 1990 to 28 February 1993. The symbol size is scaled to magnitude unit steps of M_L (From Anderson and Webb, 1994).
Figure 5.2. Epicentres for earthquakes shallower than 15km for the period, 1 January 1990 to 28 February 1993. The geographic location of the Hawks Crag (HC) earthquake event is identified. The symbol size is scaled to magnitude unit steps of $M_L$ (From Anderson and Webb, 1994).
Figure 5.3. Epicentres for earthquakes shallower than 40km, in the Buller to Northwest Nelson region, for the period from, 1 January 1991 to 30 November 1996. There was a total of 503 events identified. 1 - 3 represent three events $M_L > 6$, 1 and 2 on the 28 January 1991 and 3 on 15 February 1991 (Adapted from B, Ferris, pers comm, 1997, IGNS).
Buller to Northwest Nelson, of the South Island, is historically one of the most seismically active areas in the New Zealand. Benn (1992) noted historical return periods for large earthquake events (over the last 150 yrs) is an order of magnitude greater than for the Marlborough Fault System and eastern North Island. He postulates that the order of magnitude difference for periodicity maybe due to accumulated strain released during a period of seismic activity, in quite rapid succession to large earthquakes, followed by a long period of quiescence. Therefore, the return period for earthshift at any one site on the surface is much longer than what may be indicated by the level of historical seismicity. Alternatively, historical seismicity maybe normal with accumulating strain released through many faults and folds.

Many of the large faults within the Buller district such as the; White Creek, Inangahua/Glasgow and Cape Foulwind Faults, have experienced strong seismic events during the last 70 years. The two largest historical events were the 16 June 1929 Murchison or Buller earthquake (surface wave magnitude = $M_s$) (White Creek Fault, $M_s$ 7.8) and the 23 May 1968 Inangahua earthquake (Inangahua/Glasgow Fault, $M_s$ 7.4). Also the 10 May 1962 Westport earthquake which was relatively small but was still strongly felt within the Buller region (Cape Foulwind Fault, $M_s$ 5.9) (Dowrick and Smith, 1990; Anderson et al, 1994). Figures 5.4. a)-c) display isoseismal maps of felt intensities using the Modified Mercalli (MM) scale for these three seismic events. The 9 March 1929 Arthur's Pass earthquake was also strongly felt within the Buller region, although relatively distant (Downes, 1995). All large earthquakes in the Buller region indicate almost pure reverse faulting. This is in contrast to the mechanisms observed to the east in the Marlborough Fault System (Anderson et al, 1993). All have been shallow events resulting in locally very high intensity ground shaking.
Figure 5.4. a-c) Isoseismal maps for three large earthquakes within the Buller Region. a), 1929 Buller or Murchison Earthquake (White Creek Fault rupture); b), 1962 Westport Earthquake (Cape Foulwind Fault Zone); and c), 1968 Inangahua Earthquake (Inangahua/Glasgow Fault) (Adapted from Downes, 1995).
5.2.3. Recent Seismicity within the Buller District

Three earthquakes with local magnitudes (\(M_L\)) close to 6 occurred approximately 15km southwest of Westport in 1991 (Figure 5.5.). These are referred to as the Hawks Crag Earthquakes (28th January), with two separate shock events and a later, third event on 15th February (Table 5.1.) (Anderson and Webb, 1994; Benn, 1992; Cousins et al, 1991). The focal mechanism for these events is reverse faulting (Anderson and Webb, 1994), similar to that observed in the 1968 Inangahua Earthquake (Anderson et al, 1993), and consistent with the structure observed within the Paparoa Tectonic Zone and the Buller region. These events are inferred to represent strain release along the southward extension of the Kongahu Fault Zone, and hence indicative of continued tectonic activity. Numerous small, shallow earthquakes within the Buller region have occurred throughout historic times to the present day, and are further indicative of ongoing tectonic deformation and evolution.

5.2.4. Earthquake Hazard Assessment

Integration of both seismicity records and geological data (fault segment slip rates) are required for earthquake hazard assessment. No surface rupture of the Kongahu Fault Zone have been identified within the field area, consequently, generation of earthquake hazard models based on paleoseismic information are beyond the immediate scope of this study. Distribution of recent surface deposits, based on the understanding of active geomorphic and geologic processes, are indicative of past slope forming processes and are useful for assessing areas at risk from events triggered by seismic activity. Within the study area MM scale shaking intensities of 7 or greater have been recorded four times from historical seismic events between 1840-1990. MM intensity patterns of the Hawks Crag earthquakes are not known, although from personal observation, it is likely it had a felt intensity within the Westport region of approximately MM VI-VII. Collection of earthquake data has improved dramatically in the last 50 years. However, nationally seismicity of larger events over the past 40 years has been noticeably low compared with the previous one hundred years (Downes, 1995).
Figure 5.5. Labels 1 and 2 mark the epicentres of magnitude 6.1 and 6.2 earthquakes on 28 January 1991 and 3 epicentre for magnitude 5.9 on 15 February 1991 (From Cousins et. al., 1991).

Table 5.1. Epicentral details for the three 1991, strong earthquake events (Cousins et. al., 1991).

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Universal Time</td>
<td>12h 58m 47.5s</td>
<td>18h 00m 53.6s</td>
<td>10h 48m 10.7s</td>
</tr>
<tr>
<td>Latitude</td>
<td>41.89S</td>
<td>41.90S</td>
<td>42.04S</td>
</tr>
<tr>
<td>Longitude</td>
<td>171.58E</td>
<td>171.67E</td>
<td>171.59E</td>
</tr>
<tr>
<td>Focal Depth</td>
<td>8.3km</td>
<td>13km</td>
<td>7km</td>
</tr>
<tr>
<td>Local Magnitude</td>
<td>6.1</td>
<td>6.2</td>
<td>5.9</td>
</tr>
</tbody>
</table>
5.2.5. Implications for Seismic Hazard

Keefer (1984) collected data from 40 historical world-wide earthquakes to determine the characteristics and hazards from landslides. This comprehensive study identified 14 types of landslide, including submarine slides. Rapid soil flows, rock avalanches and rockfalls cause at least 90% of all landslide related deaths. Rock avalanches and rapid soil flows are the two leading causes of death. They are capable of travelling several kilometres at high velocities on slopes of a few degrees, but are relatively uncommon during earthquake events. Rockfalls form the most abundant failure mechanism and are the third leading cause of death. Areas at risk are limited to the distance which boulders can roll once they reach the base of steep slopes (typically in the order of a few hundred metres) from which the falls originate.

Seismically triggered rockfalls and rock slides are the most common slope failure, occurring near actively incising streams, with little influence from lithology. However, studies of deep seated slumps and earthflow deposits indicate these deposits do not tend to be reactivated by weak seismic activity. This suggests failures of these types are mainly controlled by climatic factors or initiated by stronger ground shaking (Sidle et al, 1985; Keefer and Harp, 1990). Lateral spreads and debris flows require the greatest seismic activity (Sidle et al, 1985). Areas along the coastal strip (especially estuarine swamps) and those not buried beneath thick alluvial fans, will potentially suffer from liquefaction, especially areas of sand dunes overlain by shallow swamp deposits.

Preservation of marine terraces across the toe area of the main failure complex, are indicative of stability since the end of the Kaihinu interglacial (approximately 72 000years BP). Over this time period, numerous large earthquakes accompanied by strong ground shaking are inferred to have affected the study area. However, there is no evidence for reactivation of the landslide complex.
5.3. Landslide Stability Assessment

5.3.1. Introduction

It is possible to adequately explain failures after the event (by post event evaluation or hind casting), but is a very different problem forecasting future events with respect to magnitude, location and timing (Department of the Environment, 1994; Jones, 1992). However, landsliding is potentially one of the most predictable geological hazards (Leighton, 1976) and extremely high estimated potential (90%) for loss reduction with excellent cost-benefit ratios (Alfors et al, 1973). These statements specifically refer to small and medium scale events and depend on three basic assumption made by Varnes (1984):

a) Principal of uniformitarianism applies, in that conditions which lead to past and present slope instability will equally apply to the future. Thus estimation of future instability can be based on assessment of conditions that lead to past failure;

b) main conditions causing failure can be identified; and

c) where landsliding causes are identified it is usually possible to estimate relative significance of individual factors. This facilitates assessment of hazard by examining the number of mechanisms inducing failure present in any area.

There are, however, some very real problems with landslide hazard assessment. For example, the principal of uniformitarianism can only be applied in very general terms, and it is not always possible to assign relative levels of significance to landslide causes with a high degree of confidence, especially in complex situations (Department of the Environment, 1994; Jones, 1992). Vulnerability to landsliding has also been correlated to increase with velocity, as it can be expected that extremely rapid landslides cause greater loss of life and property than slower failures (Table 5.2.)(Cruden and Varnes, 1996).
Table 5.2. Definition of probable destructive significance of landslides of different velocity classes (From Cruden and Varnes, 1996).

<table>
<thead>
<tr>
<th>Landslide Velocity Class</th>
<th>Probable Destructive Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely</td>
</tr>
<tr>
<td>6</td>
<td>Some lives lost; velocity too great to permit all persons to escape</td>
</tr>
<tr>
<td>5</td>
<td>Escape evacuation possible; structures, possessions, and equipment destroyed</td>
</tr>
<tr>
<td>4</td>
<td>Some temporary and insensitive structures can be temporarily maintained</td>
</tr>
<tr>
<td>3</td>
<td>Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase</td>
</tr>
<tr>
<td>2</td>
<td>Some permanent structures undamaged by movement</td>
</tr>
<tr>
<td>1</td>
<td>Imperceptible without instruments; construction possible with precautions</td>
</tr>
</tbody>
</table>

5.3.2. Hazard from current active slope forming processes

A large range of landslide processes have been identified and classified by Varnes (1978) (Appendix 5a), however, only a small number of these mass movements were identified during geomorphic mapping and perceived as posing a hazard within the study area. The degree of hazard each poses to the community is a direct function of the location, speed and extent of failure. Mobilisation of slope forming material is recognised to fall within three major categories based on lithology and landslide process.
a) Primary Failure

Primary failure involves the collapse of previously insitu material and is separated into reactivation of the main failure complex and small scale recent failures.

• Large Scale KFZ Failure Complex

Much of the coastal plain is at risk from the large scale gravitational failure complex, although the hazard from large scale remobilisation of this structure is very low. Geomorphic interpretation suggests collapse occurred as very slow to extremely slow creep, with only occasional localised sections experiencing higher velocity failure. Correlation of marine terraces preserved in the vicinity of the toe area of the major collapse feature indicate substantial movement has not occurred since the last interglacial (approximately 72 000 years BP). Stabilisation of the main body of the failure complex can be inferred to extend back to prior deposition of the Caledonian Formation (pre 334 000 years BP). Only one section of the failure complex is inferred to be still active, and this is the "Mt Rochfort Failure", between Lake Stream and Christmas Creek. Here a very large fan complex has developed, burying the coastal cliff marking the last post glacial shoreline (approximately 6500 years BP). Failure is interpreted to occur as ongoing extremely slow creep, with minor periods of local failure where Lake Stream and Christmas Creek are deeply incised.

Following detailed study of preserved marine terrace sequences in the toe area of the main body of the failure complex, it has been inferred these collapse structures are relatively stable and, therefore, large scale landslide reactivation poses a low degree of hazard to the coastal plain. Initiation of failure is considered to have resulted from destabilisation through tectonic uplift, removal of basal support during interglacial high stands, possible high intensity seismic shaking and high pore water pressures. Predominantly the hazard, as indicated by preservation of marine terraces in the toe area, for large scale remobilisation of the failure complex is low. However, the hazard is much higher for localised second and third order remobilisation.
• Localised Recent Failures

Recent primary slope failure involves in situ bedrock and weathered regolith mantle. Regolith failure typically occurs as earthflows above the Kaiata Mudstone (Figure 5.6.) and earth slumps grading into earthflows above the Blue Bottom Group. Failures are typically up to 80m wide and 300m long, with some extending a short distance onto the coastal plain. Because of the slow nature of collapse, these failures only pose limited risk to the community, although they have resulted in realignment of the lower section of the Waimangaroa Denniston road. Complex slump-earthflow failures in the Blue Bottom Group pose a low degree of hazard for some residential properties within the township of Waimangaroa, where these back onto steep hill slopes within the zone of accumulation (run out zone). Triggering mechanism is inferred to be high interstitial pore pressures with removal of toe support by rivers and road cuts. However, concentration of water runoff through road construction, such as seen on the Waimangaroa Denniston Road, has further loaded and destabilised marginally stable slopes.

Active rockfalls (Figure 5.7.) and topples (Figure 5.8.) are widespread along the deeply incised fluvial channels and cliff sections within the Brunner Coal Measures, predominantly within the vicinity of Mt Rochfort (headwaters of the Cascade River) and the upper reaches of the Whareatea Gorge. Most failures are small, typically less than 100m$^3$ in volume. Some larger complex rock slide-rock topple collapses have occurred in the headwaters of the Whareatea River (Figure 5.9.) and are up to 200m wide and 200m long. Translational rock and block slides are also present, although fewer in occurrence and confined to areas where steeply dipping coal measures have had basal support removed through ongoing stream erosion. Complex failures of rockfall and debrisflow are also present, and can be observed on hillsides above the Waimangaroa River. These have destabilised sections of historical walking tracks. Extreme climate of the study area, high rainfall (intense weathering and high interstitial pore water pressures) and broad temperature ranges (slacking and frost heave), further weaken the rock mass. Periods of high intensity rainfall and seismic events trigger most collapses. Although all four failure types are relatively common, the hazard is low due to lack of human interaction in areas where these active slope failure processes occur.
Figure 5.6. Earthflow on the lower section of the Waimangaroa - Denniston Road. Earthflows have lead to realignment of this section of the road. Photo is taken looking northwest from above Sandstone Stream (GR, K29 073417).
Figure 5.7. A typical small rockfall from the cliffs of Brunner Coal Measures conglomerates below Mt Rochfort (GR, K29 057358).
Figure 5.8. A large toppling block (approximately 50m$^3$) of Brunner Coal Measures conglomerate looking out into the Cascade River catchment (Note the camera case, marked by arrow for scale)(K29 062359).
Figure 5.9. Large complex rock topple - rock slide collapse, 200m wide and 200m, long in the headwaters of the Whareatea River. Arrows indicate location of the main scarp. Photo is taken looking due west (GR, K29 085376).

b) **Second Order Remobilisation**

Second order remobilisation of the failure complex predominantly occurs as localised rotational slump, falls, flows and avalanches within previously failed debris material of the main failure complex. Most occur on steep slopes or where down-cutting streams have removed basal support leading to slope destabilisation. The main risk is to property and roads (cultural factors) immediately below the unstable slopes, involving burial and/or inundation by reactivated slope debris material. Some debris avalanches are capable of flowing at very high speeds across large distances of relatively flat lying topography, depending on the gradient, volume, nature of the failure material and water content. Debris falls, flows, rotational slumps and complex failures may also occur at high speeds, but typically do not occur as rapidly or involve long run-out distances (typically <200m). Failure is characteristically related to antecedent pore-water conditions and triggered by periods of intense or prolonged rainfall, causing increased interstitial pore pressures, reducing shear stress and loading the slope.
c) Third Order Remobilisation

Third order remobilisation involves reactivation of debris within fluvial systems. Undercutting causes material to collapses into the fluvial channel, partially blocking or damming the river channel, affecting the natural stream gradient profile. This results in rapid down cutting and stream bed remobilisation as debris flows during periods of high rainfall or dam burst. Within deeply incised river systems, debris is contained until it passes out onto the coastal plain, where if no natural levees or man made confinement structures are present, it will avulse onto the fan surface and/or coastal plain. Christmas Creek and Lake Stream are the most likely locations of such events, due to the high number of active collapse features within their deeply incised catchment areas and the large amounts of active bed load debris stored within each fluvial catchment. Both streams exit steep gorges at the head of a large active fan complex. These fans do not have natural head zone levees confining the fluvial channel, like those present at Ww Stream and the Whareata River. This is the only large fan complex formed on the coastal plain where the main fluvial channel, within the head zone, is not confined by incision of earlier aggradational surfaces. This is indicative of active slope forming processes within their catchment areas, leading to high stream bed load transportation. Most other fan complexes are incised within the head zone, denoting a drop in sediment supply. This is indicative of little or no current tectonic uplift or active slope failure within head areas of the river catchments.
5.4. Landslide Dammed Lakes

5.4.1. Lake Rochfort

a) Introduction

Lake Rochfort was originally a small (approximately 1.5 hectares) landslide bounded lake, located at the boundary between the zone of depletion and zone of accumulation within the Mt Rochfort failure. Embankment dams were constructed by "The General Exploration Company" between 1880 and 1900, to increase the depth and capacity of the lake to its present day size of approximately 5.3 hectares (Figures 4.2. and 5.10.). Water races were cut in the hill above the lake to divert water from nearby catchments, some of which are still operational (Figure 5.11.).

Initially Lake Rochfort was used to supply water for hydraulic gold mining but, because of the very high rainfall in the area and relative relief, in 1924 its potential was realised as a small power scheme (Buller Electric Power Board, 1958). In the morning and evenings this water was released into the headwaters of Christmas Creek, which had a diversion structure used to divert river flow into a water race running around the side of the hill (Hendricks pers comm, 1997). This in turn fed a pipeline which dropped 135m vertically to the powerhouse at the head of Powerhouse Rd (Figure 5.12.).

In 1954 high tension transmission lines connected Westport to the national grid, providing large quantities of cheap electricity to meet the Buller Regions ever increasing demand. Unfortunately by 1968 it was considered uneconomic to maintain the Fairdown Power Scheme, leading to it's decommission (Hendricks pers comm, 1997), although the lake and water diversion structures still remain.

b) Hazard

Lake Rochfort covers 5.3 hectares with an average depth of 6m (Buller Electric Power Board, 1958), equating to approximately 320 000m$^3$ of water situated at 480m above R.S.L. No plans remain, or possibly were ever drawn up, for design and construction of the embankment structures, so there is no way of assessing their stability, or deterioration in geotechnical conditions over time. The original lake before the embankment dams were built, was quite small (approximately 1.5 hectares), as can
Figure 5.11. An old operational water diversion structure used to redirect water into Lake Rochfort (GR, K29 040370).

Figure 5.10. A view looking due east across Lake Rochfort. Note the shed on piles at the south end of the lake (as indicated by arrow) housing controls for the outlet valve and tops of dead trees protruding from the frozen water surface near the centre of the lake (GR, K29 030273).
Figure 5.12. Plan of the Lake Rochfort Power Scheme displaying locations of water diversion structures.
be noted by the tops of trees protruding from the lake surface some 150m from shore (Figure 5.10.).

Currently, there is no monitoring of the lake level, which sits 0.2m below the level of the spillway cut into rock on the southern end of the lake. Some water is drained from the lake via a partially open control gate valve, which during prolonged dry periods lowers the lake level by up to 1m. Potentially, given time, this could become blocked resulting in the lake remaining at its maximum level. Due to frequent high intensity rainfall and rapid run off there is potential, during extreme events, for the spillway and embankment dams to be damaged, so adversely affecting their stability.

Past seismic activity indicates this structure has experienced at least five strong shaking events, with the last occurring in 1991. Events prior to this occurred while the power scheme was still operational, indicating there would have been some ongoing monitoring of the embankment structures. However, there is no way of knowing whether they have been damaged and/or destabilised by more recent events.

The Mt Rochfort landslide, in which the Lake Rochfort has formed, is interpreted as an active deep-seated creeping slope failure. Loading through formation of Lake Rochfort, removal of toe support through erosion in Christmas Creek and Lake Stream, and changes in pore water conditions, by prolonged intense rainfall, could result in reactivation of slope failure. Such reactivation could potentially alter geotechnical surrounding the lake adversely affecting stability of embankment dams.

Destabilisation of embankment dams, from any of the factors mentioned in the previous three paragraphs, could result in the catastrophic release of water contained within Lake Rochfort. Such a failure could occur down either Christmas Creek or Lake Stream destroying land, property, homes, services (HT power lines), roads, railway lines, with the potential for causing serious injury and loss of life.

c) Remedial Options

A number of options are available, with the most effective being to lessen the elements creating the hazard, in particular lowering of the lake level. Three simple steps are required:
1) Dismantle stream diversion structures, limiting water inflow into the lake; and
2) slowly lower the lake level to at least that before retention structures were erected by opening control gate valve; and
3) removal of at least part of the containment structures to allow natural drainage patterns to resume.

5.4.2. 1981 Ram Creek Dam Burst

The setting and size of the 1981 Ram Creek catastrophic dam burst is very similar to that of Lake Rochfort. Consequently, the triggering mechanisms and effects of this failure could be very similar to those perceived for catastrophic failure of Lake Rochfort. The dam in Ram Creek was located 7km due east from Inangahua Junction at the foot of the Brunner Range (Appendix 6 Figure 1.). The lake formed during the 1968 Inangahua Earthquake when a 600m long, 400m wide section of hillslope collapsed, damming Ram Creek with approximately $4 \times 10^6$ m$^3$ of debris. A lake formed (from personal observations), covering approximately 3 hectares with a maximum depth of 40m (Appendix 6, Figure 2.).

Intense rainfall initially resulted in severe flooding downstream of Ram Creek. This was followed by a cloud burst in the foot hills along the western margin of the Brunner Range, which triggered catastrophic breaching of the landslide dammed lake (Appendix 6 Figure 2.). The lake level was lowered by 30m in a period of less than 10 minutes, cutting a large v in the toe of the landslide, and releasing an estimated 700 000m$^3$ of water. The resultant debris flow plunged down 5.5km of narrow gorge, losing over 360m of altitude, washing out State Highway 6 and burying 60 hectares of farmland under 4-5m of logs and gravel (Appendix 6, Figures 3 and 4 a - b).

In contrast to this dam failure, Lake Rochfort contains an estimated 320 000m$^3$ of water, which is slightly under half that of Ram Creek dam. However, upon failure it would loose 440m of altitude in little over 1.5km, where as Ram Creek lost 360m of altitude in 5.5km. Consequently, despite the smaller volume of water involved, the greater altitude drop and higher stream gradient would probably result in very similar effects as those experienced in Ram Creek. The dam burst was confined to within the river catchment, which limited the damage incurred, however, Lake Rochfort would rapidly spread out onto the coastal plain, affecting a far greater area.
5.5. Hazard Reduction

Methods used to contain, control or mitigate landslide hazards can be subdivided into three categories:

a) restricting development in areas at risk to landsliding by planning controls;
b) monitoring slope conditions and changes; and
c) physical methods to control unstable slopes with engineering solutions.

In many circumstances the option of taking no action at all is adopted, either due to lack of knowledge and understanding, or financial constraints. However, measures such as development restrictions in landslide prone areas, are easily applied to future development and very cost effective. Hutchinson (1991) states the essential aim of landslide hazard assessment is to reduce human suffering and loss from landslides. Thus effective communication and co-operation with the public and decision-makers is of crucial importance.

5.5.1. Planning

The planning process serves disaster prevention in two ways (Office of the United Nations, 1978):

a) appraisal of physical conditions and develop guidelines for the community based on physical aspects and risks identified;
b) implementation of disaster prevention measures, which are not in conflict with planning goals, achieved by either direct government and local authority action or by indirectly influencing individual behaviour.

Zoning and subdivision controls are used to regulate activities in the private sector by placing locational restrictions and minimum standards on specific land-uses and activities. This can be interpreted as constraining future land use development, by measures such as placing a caveat upon the title, for the purpose of avoidance or mitigation of hazards along sections of the coastal plain at high risk from slope processes. It is also important to prevent development on the failure complex that could create future instability problems. Land-use planning operates to prevent the land market from developing at cross purposes to the public's interest (Office of the United Nations, 1978).
Education of the public body to raise the awareness of adverse effects on landslide stability, and how they maybe managed, is an inexpensive form of mitigation. Many people are not aware of potential problems but, once informed, will use this information during future decisions, which could effect individual development and associated risk.

Prior to future changes in land use upon the failure complex, it must be recommended to instigate detailed engineering geological site investigations, based upon the philosophy advocated by Bell and Pettinga (1983)(Appendix 7), to assess potential detrimental affects upon stability.

5.5.2. Monitoring

Monitoring is one of the least expensive options for hazard reduction. Instigation of a monitoring program, involving regular surveying of the more active sections of the failure complex, to build up a data base and background knowledge of its movement history is recommended. If, after a large seismic event or prolonged rainfall, there is failure remobilisation, data is available to assess deviations from the normal background activity. This is a low cost option for an ongoing program, involving six monthly checks to ensure no large landslides have dammed or collapsed into river catchments, and pre-existing failures remain stable. These could remobilise during high intensity rainfall events and lead to avulsion upon fan surfaces.

5.5.3. Engineering

A slope stabilisation program requires the interaction of a number of interrelated activities including; environmental and safety issues, geotechnical engineering as well as construction methods and costs (using stabilisation procedures appropriate for the particular conditions at each site ) (Wyllie and Norrish, 1996). Engineering solutions are generally expensive to implement, while planning is a more easily applied and cost effective measure. However, construction of stop banks along Lake Stream and Christmas Creek, where head zones of alluvial fans lack natural levees or degradation terraces, would lessen the potential effects of debris flows by confining and directing the area over which they spread. Other commonly adopted solutions, such as catch fences to limit the hazard of rockfall, would not be cost effective, as high risk locations are
generally remote and do not warrant remedial measures. Encouraging revegetation of the toe area of the main failure complex would lessen the risk of localised debris failures, as much of the main failure complex in the past was burnt for attempted forestry development.

5.6. Discussion

The preservation of marine terraces through the toe area of the main failure complex, is indicative of stability since the Kaihinu interglacial (approximately 72 000 years BP). Over this time period, numerous large seismic events would have applied severe shaking to the study area. As these events did not cause marked reactivation, it is unlikely these failures will be susceptible to future collapse induced through intense seismic shaking.

Current active slope processes are predominantly small localised failures, primarily related to antecedent pore water conditions and triggered by periods of intense or prolonged rainfall and seismic events. Hazard from these failure types is relatively low, due to lack of human interaction where these active slope collapses occur. Debris flows from Lake Stream and Christmas Creek form the greatest hazard, as neither of these catchments have natural degradation surfaces, reflecting high bed load transported by these catchments. A lack of natural degradation surfaces is also indicative of extremely slow, deep-seated creep within the Mt Rochfort failure, encouraging active down cutting of fluvial channels in the zone of accumulation. The presence of Lake Rochfort within the toe area of the Mt Rochfort failure is of concern as potential effects through rapid failure of the embankment dams would be catastrophic in areas immediately below both Lake Stream or Christmas Creek.

Zoning and subdivision controls would provide the most cost effective measure in reducing risk, as it seems unlikely money would be provided for ongoing monitoring or engineering works. Further detailed investigation of Lake Rochfort is recommended to further assess stability of the embankment dams and underlying landslide complex. However, this option would be more expensive and involved, than reducing the risk by draining the lake.
6.1. Introduction

Morgan and Bartrum (1915) first recognised complexity within the Kongahu Fault, south of the Waimangaroa River, with faulting distributed over a zone of some width and possible monoclinal folding within the Brunner Coal Measures. Today, the structure of the Kongahu Fault Zone is still not fully understood and this study has attempted to clarify the structural setting. Investigations also included delineating the aerial extent and failure mechanisms of large-scale gravitational collapse features present along the western boundary of the Buller Coalfield. Stability of these collapse features has been assessed quantitatively, in particular, to determine the hazard these pose to future development along the coastal plain.

6.2. Geological Setting

The Paparoa Trough formed in response to the mid Cretaceous change in tectonic regime from contraction to extension, leading to crustal thinning, and culminating in opening of the Tasman Sea as New Zealand rifted away from Gondwana. The trough is only one of a number of narrow, elongate half grabens throughout North Westland. Synchronous with graben development was formation of the Paparoa Metamorphic Core Complex, where mid-crustal high grade metamorphic rocks are exposed through extension on low-angle detachment faults, with subsequent sedimentation in associated fault bounded basins.

Sedimentation began in the northern end of the Paparoa trough during the late Paleocene - early Eocene, during a period of widespread peneplanation, accumulation only occurring along the central axis of the trough as the Mt Rochfort conglomerates. Sedimentation increased in conjunction with tectonic subsidence and marine transgression, resulting in formation and preservation of the Brunner Coal Measures. Marine transgression continued until the mid Oligocene with deposition changing from dominantly paralic to progressively marine. Local faulting and uplift within the Paparoa
Tectonic Zone lead to local thick marine breccias and conglomerates of the Torrea Breccia member.

Sedimentological evidence from outside the basin suggests that during the early Miocene the sense of movement on the western boundary fault, having previously controlled subsidence, was reversed. The style of faulting changed in response to a regional shift from extension to contraction, accompanying the progressive change to a more transpressive plate boundary setting in the upper Cenozoic. Positive inversion occurred through a number of phases over the last 25Ma, producing the present day Buller Coalfield with uplift and erosion exposing basement over a large part of the coalfield.

Five Quaternary stratigraphic units are recognised within the Westport region including four sets of coastal marine terraces and their associated deposits. These reflect the interaction between tectonic deformation, sea-level fluctuation during glacial and interglacial episodes, and postglacial Holocene marine progradation. Preservation and tilting of this terrace sequence is indicative of progressive regional uplift continuing through to the present day.

6.3. Structure

The Kongahu Fault Zone is interpreted to represent extensional normal faults reactivated as a reverse fault zone, accompanied by inversion of the Paparoa Trough. Two Miocene contractional phases (24-19Ma and 13-8Ma), and a further Quaternary phase, resulting in formation of the present day topography. The two Miocene phases relate to inception of the modern Australia-Pacific plate boundary as a continuous structure through New Zealand and the Alpine Fault changing from inferred oblique extension to oblique compression.

Three distinct structural domains were recognised and used to identify generically different regions within the study area. Domain 1 constitutes the coastal plain consisting of relatively flat-lying Tertiary and Quaternary sediments. Domain 2 is represented by a 1-3 km wide zone of moderately to highly deformed Tertiary and basement lithologies along the escarpment. Domain 3, represents the relatively undeformed areas of the Denniston Plateau and Mt Rochfort, where flat lying Brunner Coal Measures rest directly on basement.
6.4. Failure Development

Gravitational collapse of the Kongahu Fault Zone escarpment has been ongoing for several hundred thousand years, forming the largest known mass movement in the Buller region, with a surface area of approximately 18km². Landslide materials of the Kongahu Fault Zone failure are very complex and are subdivided into four distinct zones based on slide geology and surface morphology. The rupture surface is inferred to have propagated along unfavourably orientated bedding planes and rock mass defects.

Six separate deformation phases have been identified, based on interpretations of the geomorphic evolution of the failure complex. The Kongahu Fault Zone has been a dominant influence on development of the escarpment collapse, as the nature and evolution of slope failure reflects changes in underlying controlling structure. Initial failure probably occurred along unfavourably oriented dislocation surfaces, such as carbonaceous bedding planes within the Brunner Coal Measures, joint sets and faults. Slope destabilisation was initiated through head loading (caused by tectonic uplift) and removal of toe support through erosion of Late Tertiary units. A second phase of displacement occurred through continued tectonic deformation and erosion of a previously unstable slope. Deposits from this episode are found overlain by coastal marine terraces of the Caledonian Formation, placing this event beyond 334 000 years BP. Later phases of displacement are related to interglacial high stands in sea-level and ongoing fluvial erosion removing basal support. A rupture surface is inferred to have formed along bedding planes within the Brunner Coal Measures, but as the failure complex evolved, the rupture surface propagated into sheared granitic basement forming large-scale, deep-seated collapse.

Preservation of coastal marine terraces in the toe area of the main failure complex, formed during the last interglacial period (approximately 58-72 000 years BP), are indicative of underlying stability of the main landslide. However, interpretation of geomorphic features of the coastal plain indicate extremely slow deep-seated activity within the central Mt Rochfort failure.
6.5. Hazard Assessment

6.5.1. Seismic

Historically Buller-Northwest Nelson is one of the most seismically active regions in New Zealand. The Buller region lies within a region of reverse faulting which is capable of generating numerous strong intensity earthquakes. There are abundant potential sources but their recurrence intervals are inferred to be in the order of hundreds to thousands of years. Historical records extend over the last 150 years, and during this time Westport has experienced at least five earthquakes of MM VII or greater. Most earthquakes are shallow, occurring as pure dip-slip reverse mechanisms within the upper 15 km of the earth's crust. The typically shallow location of foci results in the potential for high intensity, localised ground shaking.

A history of regular strong seismicity indicates that the Kongahu Fault Zone Failure Complex would have experienced numerous strong intensity seismic events during its formation and evolution. As these events did not cause marked reactivation of the landslide complex, it is considered unlikely these failures will be susceptible to future activity induced through high intensity ground shaking. Only the strongest local seismic events associated with rupture of the Kongahu Fault Zone, and of probable long return periods, could potentially effect stability of the complex. It is concluded seismically triggered local rock falls, rock avalanches and rapid soil flows form the dominant hazard associated with earthquake triggered failure.
6.5.2. Landslide

Mobilisation of slope forming materials has been recognised to fall within three major categories based on lithology and landslide process. Primary failure is separated into reactivation of the large scale Kongahu Fault Zone failure complex and localised recent failures. Stabilisation of much of the failure complex is inferred to have occurred prior to deposition of the Caledonian Formation (pre 334 000 years BP) with localised reactivation during the Waimea glacial (pre 72 000 years BP). Only one section of the failure complex, the "Mt Rochfort failure", is considered to still be active, although considered to be extremely slow, deep creep.

Localised recent failures are primarily related to antecedent pore water conditions and are triggered by intense or prolonged rainfall and seismic events. Primary failures and second order remobilisation are typically small and are confined steep topography within the field area. Failures are relatively common although the degree of hazard is relatively low, due to lack of human interaction in areas where these active slope processes occur. A low degree of risk does exist where the run out zone of these failures extend onto roads, walking tracks and the coastal plain. Third order remobilisation involves debris flow reactivation within fluvial channels, leading to avulsion onto existing alluvial fan surfaces. This poses a significant hazard to development upon fan surfaces below Christmas Creek and Lake Stream, where no natural degradation scarps or levees are present to confine these debris flows.

6.5.3. Landslide Dammed Lakes

Lake Rochfort contains an estimated 320 000m$^3$ of water, and is located some 460m vertical meters above the coastal plain. Destabilisation of embankment dams due to deterioration over time, intense rainfall or seismic shaking, could result in catastrophic release of water contained within the lake. There is no way of knowing what effect weathering and past seismic shaking have had on geotechnical conditions of the confinement structures. Catastrophic failure of the landslide formed Ram Creek Dam has been compared with Lake Rochfort to estimate potential affects of failure. It has been concluded that catastrophic dam release would destroy property and services, with the potential for causing serious injury and loss of life on the coastal plain.
6.5.4. Recommendations

Planning involving zoning and subdivision controls would provide the most cost effective measure to reduce hazard from landslides within the study area. Annual monitoring of parts of the failure complex is recommended in order to assess potential future remobilisation. Engineering protection structures are generally expensive but stop banks would provide protection, below Lake Stream and Christmas Creek, from potential remobilisation of stream bed load and catchment debris in storage. Lake Rochfort is identified as a hazard, and lowering of the lake level to the original level, prior to construction of embankment dams, is recommended. The main failure complex is inferred to be stable except for minor local slope debris remobilisation, and the Mt Rochfort failure, which is interpreted to be extremely slow, deep-seated creep. Prior to any changes in land-use of the failure complex, detailed engineering geological site investigation and assessment is recommended.

6.6. Recommendations for Future Work

1) Geotechnical testing program in conjunction with drilling, trenching and more detailed field mapping to develop a greater understanding of geotechnical conditions within the failure complex.

2) Survey program monitoring slide movement in conjunction with rainfall and piezometric data to discern pore water pressure effects on stability.

3) Perform dating on beach terrace surfaces, although it has been demonstrated by previous workers that C\textsuperscript{14} dating is ineffective due to proximity of coal measures sourcing old carbon, to provide better constraints on individual phases of reactivation.
Acknowledgements

I would like to thank the numerous people who have generously put their time and effort into making this project possible.

I would like to thank Dr Jarg Pettinga for his enthusiastic support and guidance during the project. Reviews of drafts, along with many helpful comments and words of wisdom during thesis compilation. Dr Simon Nathan deserves great amounts of praise, for his assistance in many aspects of the project. Thank you for all the varied information and material you made accessible to me. For coming out into the field and looking with an open mind at what I had to say, even if sometimes it was a little far fetched. Also for the valuable guidance you provided during times of confusion. Thank you to Dave Bell for the introduction to the project and field area.

I would like to express my thanks to the people of the Westport district who allowed me onto their land, and shared an interest in what I was attempting to do. Also to Solid Energy who allowed me access to the restricted area of the Denniston Plateau.

Many thanks to my parents, Ruth and Warren Inwood, for their unwavering support and words of encouragement. Also for the use of their four wheel drive, which saved many weeks of walking. Not to mention all the free meals, as I passed through on my way between Westport and Christchurch.

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I commend Angeline Frayle who has spent many hours reading and proofing every chapter I have written, which would have been a very slow and tedious process. Also for sticking hundreds of little numbers on charts.

To the class of 1997, I extend my warmest appreciation, it is amazing we get on so well after all the stress and pressure we have been through together. As Matt would say "I just can't get stressed anymore". I will always remember the good times we have had together. To my room mates: Rob, may your spading be long and prosperous; Aaron, no I am not wrong; and Ed, don't work so bloody hard you make us all look lazy. You have all provided me with priceless technical support, and entertainment when it was most dearly required. Also to Charlie Palmer, who provided valuable climbing expertise and enjoyed grovelling around cliffs in the rain and snow.


Mew, G. and Ross, C.W., 1991b: New Zealand Soil Bureau map (LR301), Published by: DSIR Land Resources.


Appendix 1

List of Aerial Photographs
List of aerial photos used for generation of geomorphic/geological map of the study area.

1) “Buller Coalfield Survey”
   Flown: 26/5/43
   Run: 1280 (1-9).

2) “Buller Coalfield Survey”
   Flown: 25/3/46
   Runs: 1275 (1-5), 1276 (1-7), 1277 (1-7), 1278 (1-7), 1279 (1-9), 1281 (1-8), 1282 (1-7), 1283 (1-4).

3) “Westport-Reefton Survey”
   Flown: 1/11/47.
   Run: 1457 (4-10).

4) “Seddonville-Buller Survey”
   Flown: 7/10/59
   Runs: 2641 (5-6); 2642 (14-19).

5) “Buller Coalfield Survey”
   Flown: 19/10/82
   Runs: SN 8119 [(A1-6)(B1-7)(C3-9)].
Appendix 2

Interim New Zealand Geological Time Scale

a) Interim Cenozoic Time Scale

b) Interim Mesozoic Time Scale

c) Interim Palaeozoic Time Scale
a) Interim Cenozoic Time Scale (Crampton et al 1995)

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<tr>
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<td>Placenzian</td>
<td>Mangapanian</td>
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<tr>
<td></td>
<td>Zanclean</td>
<td>Weipipian</td>
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<tr>
<td></td>
<td>Mesozoic</td>
<td>Opotician</td>
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<tr>
<td></td>
<td>Tortonian</td>
<td>Kapitean</td>
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<td>Serravallian</td>
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<td>Langhian</td>
<td>Liliurnian</td>
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<td>Clilidenian</td>
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<td>Chattian</td>
<td>Panana</td>
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<td></td>
<td>Rupelian</td>
<td>Otaian</td>
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<td>Waitakian</td>
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<td>Bortonian</td>
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NB: change in scale
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</tr>
<tr>
<td>70</td>
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**b) Interim Mesozoic Time Scale (Crampton et al 1995)**
c) Interim Palaeozoic Time Scale (Crampton et al 1995)
Appendix 3

Rock and Soil Definitions

a) Engineering Geological Field Description for Rock Material (Bell and Pettinga, 1983)

b) Engineering Geological Field Description for Soil Material (Bell and Pettinga, 1983)
a) ENGINEERING GEOLOGICAL FIELD DESCRIPTION FOR ROCK MATERIAL

### WEATHERING

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<tr>
<th>TERM</th>
<th>GRADE</th>
<th>ROCK DESCRIPTION</th>
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<td>6: residual (RW)</td>
<td>VI</td>
<td>loss of original fabric, deeply weathered</td>
</tr>
<tr>
<td>5: completely</td>
<td>V</td>
<td>with a cap of loose debris or pieces of</td>
</tr>
<tr>
<td>weathered</td>
<td></td>
<td>rock, or an irregular surface of rock.</td>
</tr>
<tr>
<td>4: inky</td>
<td>IV</td>
<td>with some of the rock's structure remaining,</td>
</tr>
<tr>
<td>weathered</td>
<td></td>
<td>such as flaking or stained to a brown or</td>
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<tr>
<td>3: moderately</td>
<td>III</td>
<td>weathered, and some of the rock's structure</td>
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<tr>
<td>weathered</td>
<td></td>
<td>remaining, such as flaking or stained to a</td>
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<td>II</td>
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<tr>
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<td></td>
<td>remaining, such as flaking or stained to a</td>
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### STRENGTH

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<th>IGNEOUS</th>
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<td>CONGLOMERATE</td>
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<td>SEDIMENTARY</td>
<td>DUNITE</td>
<td>OTHERS</td>
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<td>4 to 7</td>
<td>FINE</td>
<td>SEDIMENTARY</td>
<td>GABBRO</td>
<td>OTHERS</td>
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<td>2 to 4</td>
<td>VERY FINE</td>
<td>SEDIMENTARY</td>
<td>GRANITE</td>
<td>OTHERS</td>
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<td>5: moderately weak</td>
<td>2 to 4</td>
<td>COARSE</td>
<td>SEDIMENTARY</td>
<td>MARBLE</td>
<td>OTHERS</td>
</tr>
<tr>
<td>6: weak</td>
<td>2 to 4</td>
<td>MEDIUM</td>
<td>SEDIMENTARY</td>
<td>DIORITE</td>
<td>OTHERS</td>
</tr>
<tr>
<td>7: very weak</td>
<td>2 to 4</td>
<td>FINE</td>
<td>SEDIMENTARY</td>
<td>DUNITE</td>
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### GEOLGICAL CLASSIFICATION

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<tr>
<td>MARBLE</td>
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<tr>
<td>QUARTZITE</td>
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</tbody>
</table>

### SIZE CORRECTION CHART

- **Key to using chart**
  - Step 1: Measure sample diameter (mm)
  - Step 2: Measure core size range (mm)
  - Step 3: Use size correction chart
  - Step 4: Apply correction

### POINT LOAD STRENGTH INDEX

- **Use of nomogram**
  - Step A: Measure point load strength index (MPa)
  - Step B: Apply correction
  - Step C: Use size correction chart
  - Step D: Apply final correction

### COLOUR

- **Key to using chart**
  - Step 1: Measure sample diameter (mm)
  - Step 2: Measure core size range (mm)
  - Step 3: Use size correction chart
  - Step 4: Apply correction

### FABRIC

- **Key to using chart**
  - Step 1: Measure sample diameter (mm)
  - Step 2: Measure core size range (mm)
  - Step 3: Use size correction chart
  - Step 4: Apply correction
Appendix 4

Stream-Gradient Index Analysis Results
1 Sandstone Stream-Gradient Profile
2 Rapid(a) Stream-Gradient Profile
3 Rapid(b) Stream-Gradient Profile
4 Ww Stream-Gradient Profile

Altitude (m)
Stream Length (m)
5 Whareatea River-Gradient Profile

Stream Length (m) vs. Altitude (m) graph for Whareatea River.
7 V70 Stream-Gradient Profile
8 Conglomerate Stream-Gradient Profile
9 Fairdown Stream-Gradient Profile

![Graph showing stream gradient profile with altitude on the y-axis and stream length on the x-axis. The profile line is decreasing from left to right, indicating a decrease in altitude as stream length increases.](image-url)
11 Christmas Creek-Gradient Profile
12 Myers Stream-Gradient Profile

![Graph showing the stream gradient profile with altitude (m) on the y-axis and stream length (m) on the x-axis. The graph includes data points at various stream lengths and corresponding altitudes.](image-url)
13 Deadmans Creek- Gradient Profile

Altitude (m)

Stream Length (m)
14 Orowaiti River-Gradient Profile

![Graph showing the Orowaiti River Gradient Profile with altitude on the y-axis and stream length on the x-axis. The graph includes data points and a trend line.]
15 Giles(a) Stream-Gradient Profile
16 Giles(b) Stream-Gradient Profile

Altitude (m) vs. Stream Length (m)
17 German Gully-Gradient Profile
18 Ballarat Stream-Gradient Profile
19 Coal(a) Creek- Gradient Profile

Altitude (m) vs. Stream Length (m)
20 Coal (b) Stream-Gradient Profile
21 Coal(c) Stream-Gradient Profile

Altitude (m)

Stream Length (m)
22 West Creek-Gradient Profile

Altitude (m) vs. Stream Length (m) plot.
23 Tekuha Stream-Gradient Profile

Stream Length (m) vs. Altitude (m) graph showing the gradient profile of the stream.
Appendix 5

Landslide Classification

a) Slope movement Terminology and Classification

b) Landslide Nomenclature

c) Classification for Velocity of Slope Movement
a) Slope movement Terminology and Classification (After: Cruden and Varnes, 1996; and Varnes, 1978)

<table>
<thead>
<tr>
<th>Type of Movement</th>
<th>Type of Material (before movement)</th>
<th>Engineering Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bedrock</td>
<td>Predominantly Coarse</td>
</tr>
<tr>
<td>Falls</td>
<td>Falls</td>
<td>Rock Fall</td>
</tr>
<tr>
<td></td>
<td>Free fall through the air, with leaping, bounding or rolling of fragments</td>
<td></td>
</tr>
<tr>
<td>Topples</td>
<td>Topples</td>
<td>Rock Topple</td>
</tr>
<tr>
<td></td>
<td>Pivotal rotation about centre of gravity resulting in fall or slide</td>
<td></td>
</tr>
<tr>
<td>Slides</td>
<td>Slides</td>
<td>Rock Slump</td>
</tr>
<tr>
<td></td>
<td>Shear displacement along one or several discrete surfaces or within a relatively narrow</td>
<td>a) Rotational</td>
</tr>
<tr>
<td></td>
<td>Lateral Spreads</td>
<td>Rock Spread</td>
</tr>
<tr>
<td></td>
<td>Lateral extensional movements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a) Without a basal shear surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b) Due to liquefaction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flows</td>
<td>Rock Flow</td>
</tr>
<tr>
<td></td>
<td>Extremely slow and non-accelerating movement in bedrock, slow to rapid viscous (fluid like) movement in soils</td>
<td>(deep creep)</td>
</tr>
<tr>
<td></td>
<td>Complex</td>
<td>Rock Fall - Debris Flow</td>
</tr>
<tr>
<td></td>
<td>Involves combination of two or more principal types of movement</td>
<td></td>
</tr>
</tbody>
</table>
b) Landslide Nomenclature (Cruden and Varnes, 1996)

Figure 1. Landslide features: upper portion, plan of typical landslide in which dashed line indicates trace of rupture surface on original ground surface; lower portion, section in which hatching indicates undisturbed ground and stippling shows extent of displaced material. Numbers refer to features defined in Appendix 5b) table 1 (From Cruden and Varnes, 1996).
### Table 1. Definitions of landslide features (From Cruden and Varnes, 1996).

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crown</td>
<td>Practically undisplaced material adjacent to highest parts of the scarp</td>
</tr>
<tr>
<td>2</td>
<td>Main scarp</td>
<td>Steep surface on undisturbed ground at upper edge of landslide caused by movement of displaced material (13, stippled area) away from undisturbed ground; it is visible part of surface rupture (10)</td>
</tr>
<tr>
<td>3</td>
<td>Top</td>
<td>Highest point of contact between displaced material (13) and main scarp (2)</td>
</tr>
<tr>
<td>4</td>
<td>Head</td>
<td>Upper parts of landslide along contact between displaced material and main scarp (2)</td>
</tr>
<tr>
<td>5</td>
<td>Minor scarp</td>
<td>Steep surface on displaced material of landslide produced by differential movements within displaced material</td>
</tr>
<tr>
<td>6</td>
<td>Main body</td>
<td>Part of displaced material of landslide that overlies surface of rupture between main scarp (2) and toe of surface of rupture (11)</td>
</tr>
<tr>
<td>7</td>
<td>Foot</td>
<td>Portion of landslide that has moved beyond toe of surface of rupture (11) and overlies original ground surface (20)</td>
</tr>
<tr>
<td>8</td>
<td>Tip</td>
<td>Point on toe (9) farthest from top (3) of landslide</td>
</tr>
<tr>
<td>9</td>
<td>Toe</td>
<td>Lower, usually curved margin of displaced material of a landslide, most distant from main scarp (2)</td>
</tr>
<tr>
<td>10</td>
<td>Surface of rupture</td>
<td>Surface that forms (or has formed) lower boundary of displaced material (13) below original ground surface (20); mechanical idealisation of surface of rupture is called slip surface</td>
</tr>
<tr>
<td>11</td>
<td>Toe of surface of rupture</td>
<td>Intersection (usually buried) between lower parts of surface rupture (10) of a landslide and original ground surface (20)</td>
</tr>
<tr>
<td>12</td>
<td>Surface of separation</td>
<td>Part of original ground surface (20) now overlain by foot (7) of landslide</td>
</tr>
<tr>
<td>13</td>
<td>Displaced material</td>
<td>Material displaced from its original position on a slope by movement in landslide; forms both depleted mass (17) and accumulation (18); it is stippled in Appendix 5b) Figure 1.</td>
</tr>
<tr>
<td>14</td>
<td>Zone of depletion</td>
<td>Area of landslide within which displaced material (13) lies below original ground surface (20)</td>
</tr>
<tr>
<td>15</td>
<td>Zone of accumulation</td>
<td>Area of landslide within which displaced material lies above original ground surface (20)</td>
</tr>
<tr>
<td>16</td>
<td>Depletion</td>
<td>Volume bounded by main scarp (2), depleted mass (17) and original ground surface (20)</td>
</tr>
<tr>
<td>17</td>
<td>Depleted mass</td>
<td>Volume of displaced material that overlies surface of rupture (10) but underlies original ground surface (20)</td>
</tr>
<tr>
<td>18</td>
<td>Accumulation</td>
<td>Volume of displaced material (13) that lies above original ground surface (20)</td>
</tr>
<tr>
<td>19</td>
<td>Flank</td>
<td>Undisplaced material adjacent to sides of surface of rupture; compass directions are preferable in describing flanks, but if left and right are used, they refer to flanks as viewed from the crown</td>
</tr>
<tr>
<td>20</td>
<td>Original ground surface</td>
<td>Surface of slope that existed before landslide too place</td>
</tr>
</tbody>
</table>
c) Velocity of Slope Movement (From International Union of Geological Sciences Working Group on Landslides, 1995)

<table>
<thead>
<tr>
<th>Velocity Class</th>
<th>Description of velocity</th>
<th>Velocity (mm/sec)</th>
<th>Typical Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Extremely Rapid</td>
<td>$5 \times 10^3$</td>
<td>5 m/sec</td>
</tr>
<tr>
<td>6</td>
<td>Very Rapid</td>
<td>50</td>
<td>3 m/min</td>
</tr>
<tr>
<td>5</td>
<td>Rapid</td>
<td>0.5</td>
<td>1.8 m/hour</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>$5 \times 10^{-3}$</td>
<td>13 m/month</td>
</tr>
<tr>
<td>3</td>
<td>Slow</td>
<td>$5 \times 10^{-5}$</td>
<td>1.6 m/year</td>
</tr>
<tr>
<td>2</td>
<td>Very Slow</td>
<td>$5 \times 10^{-7}$</td>
<td>16 mm/year</td>
</tr>
<tr>
<td>1</td>
<td>Extremely Slow</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 6

Ram Creek Landslide Formed Dam Burst
Figure 1. Location Map of the Ram Creek Dam and principal landmarks. Source: Dept of Survey and Land Information, 1:50 000 topographical map, NZMS 260 Sheet L.29 (Inangahua).
Figure 2 Aerial oblique photograph of the 1968 earthquake triggered landslide that dammed Ram Creek. Upon failure, the released water cut out the toe section of the landslide, creating a v shaped channel, estimated to be up to 50m deep and 400m long. A small remnant of the original lake is observed behind the landslide. The snow capped Brunner Range lies in the background. Ram Creek flows down the central portion of the photograph (L. Homer, IGNS, A9971a).
Figure 3. The flood created by the Ram Creek dam burst. A wall of water and debris 6-7m high swept across State Highway 6, destroying everything in its path, burying the road beneath 8-10m of water, logs and debris. The old road bridge and much of the road adjacent to the creek was destroyed. Note trucks in the background, as indicated by arrow, for scale (GR, L29 245273).
Figure 4 a) View looking south, from the west abutment of the old bridge, one week after dam failure. Previously grassy river flats are now buried beneath 3-5m of sand and gravel, with only a few large willow trees remaining. An abutment is being constructed for the installation of a temporary Bailey Bridge. Note timber piles in the bottom centre of the photograph, which are all that remains of the original bridge (GR, L29 243276).

Figure 4 b) View of typical logs and debris that was deposited over river flats beside Ram Creek (GR, L29 252268).
Appendix 7

Conceptual Approach to Site Investigations
Conceptual Approach to Site Investigations (Bell and Pettinga 1983).

<table>
<thead>
<tr>
<th>FUNCTION NO</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Define Project Objectives and ask relevant Questions</td>
</tr>
<tr>
<td>2</td>
<td>Collect &amp; Assess Existing Data Development of Tentative Geomechanical Site Model</td>
</tr>
<tr>
<td>3</td>
<td>Plan work to fill in Gaps Formulation of Appropriate Activity Chart</td>
</tr>
<tr>
<td>4</td>
<td>Prepare Cost Estimate for Investigation Programme</td>
</tr>
<tr>
<td>5</td>
<td>Carry out Activities to determine semi-quantitative engineering-geological site model</td>
</tr>
<tr>
<td>6</td>
<td>Quantify site model by appropriate field and/or laboratory testing</td>
</tr>
<tr>
<td>7</td>
<td>Analysis of all site data Answering of Initial Questions</td>
</tr>
</tbody>
</table>

NOTES: 

E = Engineering, G = Geological

Arrows indicate iterative feedback process to solve additional problems (or "questions") found during main investigation programme