**Sedimentology and depositional environments of
Murihiku Supergroup sediments exposed in the Southland
Syncline, New Zealand: implications for reservoir potential
in the Great South Basin**

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Abstract

A considerable amount is known about the biostratigraphy and organic geochemistry of the Murihiku Supergroup sediments exposed in coastal outcrops of the Southland Syncline, New Zealand. Much less work has been undertaken on the sedimentology of these strata, or understanding their depositional environments and depositional trends through time. What these implications are for reservoir prospectivity in the adjacent Great South Basin, has also had little study focused on it.

This thesis addresses these issues by undertaking outcrop-based sedimentological and facies interpretations of these rocks, thin-section based petrographic composition and provenance analysis, augmented by X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM), as well as porosity and permeability measurements from outcrop core plugs. Petroleum industry seismic data has additionally enabled seismic facies mapping of Murihiku rocks in the offshore Great South Basin.

Outcrop observations point to a progressive change in depositional setting, from shelf / upper slope settings during the Late Triassic, to base of slope turbidite deposition in the Early Jurassic. This transgression is followed by regression into fluvial settings in the youngest outcropping Murihiku rocks in the study of Middle Jurassic age. Petrographically the sandstones are feldspathic and lithic arenites and feldspathic and lithic wackes. Provenance suggests derivation from an evolving, intermediate arc that was becoming more siliceous through Late Triassic and Middle Jurassic time. Diagenesis is characterised by early calcite and chlorite precipitation which have almost completely destroyed any primary porosity. Any secondary micro porosity has subsequently been infilled through dissolution of framework grains and zeolitization. SEM and core plug porosity and permeability measurements corroborate the diagenetic changes observed petrographically, with only fluvial facies of Middle Jurassic (Upper Temaikan) age showing any measureable porosity or permeability.

As a result, reservoir potential for the Late Triassic to Middle Jurassic, Murihiku Supergroup rocks analysed in this study is low. Younger Murihiku sandstones which are postulated to occur offshore in the Great South Basin are likely to be less influenced by burial diagenesis. As shown from North Island occurrences, these younger successions hold some potential.

The reservoir potential for these youngest portions of the Murihiku succession therefore remains positive, both in the Great South Basin, as well as other frontier areas of Zealandia, and continue to provide an exploration target for the petroleum industry

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Chapter 1

1.1 Introduction

1.1.1 General introduction

New Zealand's basement geology comprises 12 distinct tectonostratigraphic terranes, reflecting a varied and complex, pre - Cenozoic geology. The terranes range in geological age from the Cambrian – Early Cretaceous, part of the Austral Superprovince of Mortimer et al. (2014). The Superprovince can further be divided into Eastern and Western Provinces (Figure 1-1) (Landis & Coombs, 1967; Turnbull & Allibone, 2003), and represents the

Figure 1-1 New Zealand's basement terranes.

Inset box displays the Murihiku Terrane of the Southland Syncline, (grey). (After Turnbull & Allibone, 2003).

acoustic (seismic) basement to Zealandia's sedimentary basins. These two provinces are separated from each other by the igneous, Median Batholith (Figure 1-1). The Western Province comprises the Takaka and Buller terranes and the Tuhua Intrusives. The Eastern Province comprises the Drumduan, Brook Street, Murihiku, Dun-Mountain and Caples terranes, as well as the Waipapa and Torlesse composite terranes and their metamorphosed equivalent called the Haast (Otago) Schist (Figure 1-1) (Mortimer et al., 2014).

The focus for this thesis is to undertake detailed petrographical, sedimentological and facies interpretations of the Late Triassic to Middle Jurassic Murihiku Supergroup exposed in the Southland Syncline, of South Otago and Southland, New Zealand. The Supergroup also crops out in a fault-controlled section of the Nelson region (Figure 1 1). Murihiku Supergroup rocks also underlie regions of on/offshore Northland and Taranaki basins in the North Island, and outcrop in the Kawhia Syncline. The two South Island locations of Murihiku outcrops have been offset by Neogene displacement on the Alpine Fault.

1.1.2 General geological setting

The Murihiku Supergroup is a >10km thick succession consisting of a broad range of

lithological facies, mostly comprising weakly metamorphosed (zeolite facies) volcanoclastic sediments, interspersed with tuffs and rare volcanic rocks (Campbell et al., 2003b; Turnbull & Allibone, 2003). These sediments comprise thick successions of mudstone, siltstone and sandstone units that

Figure 1-2 Mesozoic Murihiku Terrane depositional setting. Deposition occurred off the Gondwana margin and adjacent to an active volcanic arc. Here the terrane (Dark Grey) is depicted in a fore-arc setting. (After Briggs et al., 2004).

include fossiliferous, carbonaceous or coaly horizons with occasional conglomerates. The northern contact of the Murihiku terrane in the Southland Syncline area is delineated by the Hillfoot Fault, a fault that separates the supergroup in the south from the Dun Mountain-Matai Terrane to the north (Figure 1-1 & Figure 3-1). The southern boundary in the Murihiku rocks in the coastal Catlins area is not exposed, but further north toward Fiordland, is in fault contact with the Brook Street Terrane. In the offshore, this southern boundary of the terrane is delineated by the Letham Thrust Fault (Ghisetti, 2010).

The Murihiku Supergroup represents long-lived deposition from Permian to Early Cretaceous time, with the younger age constrained by detrital zircon dating of 143, 141 and 139 Ma for sandstone formations in the south Auckland area (G Browne, pers. comm. October 2016). Deposition may have continued into the mid-Cretaceous (Cook et al., 1999b).

Within the North Island succession of the Murihiku Supergroup, Black et al. (1993) analysed clay minerals (chlorite, smectite and vermiculite) and determined a temperature range of 60-150 °C for Murihiku sandstones of Jurassic age and nearer 200 °C for Triassic age rocks. In the South Island, the Hokonui Hills succession records a maximum burial temperature for the Triassic Murihiku rocks outcropping there of c. 230 °C (Boles & Coombs, 1975).

Apatite fission track investigations by Kamp and Liddell (2000) reveal that the geothermal gradient of the Murihiku Terrane until Late Jurassic was low, at c. 15 °C km⁻¹. This gradient is suitable for the roughly 10 km of sedimentary thickness deposited by the Late Jurassic. It wasn't until the initiation of eastern Gondwana rifting (~105 Ma) that the gradient probably started to increase to normal continental levels as the disappearance of the subducting

Period	Epoch	NZ Stages	Basaltic andesite	Andesite	Dacite	Rhyolite
Jurassic	Late	Kh-Op				
	Middle	Hu-Kt				
	Early	Bw-Ha				
Triassic	Late	Br-Bm				
	Middle	Ge-Gk				
	Early	Gn-Gm				

Figure 1-3 Variations in volcanoclastic provenance with time.

New Zealand stages, Nelsonian-Puaroan (see Figure 2-2). Modified from Briggs et al. (2004).

margin ceased to have an effect on the regional geotherm (Kamp & Liddell, 2000). By 85 ± 10 Ma, the gradient is recorded as reaching c. 30°C km^{-1} suggesting that it was then exposed to mantle heating (Kamp & Liddell, 2000). This stabilised geotherm would require an additional ~ 6 km of sediment deposition, to account for annealing of the Jurassic sediments analysed by Kamp and Liddell (2000). This additional sediment cover would therefore allow for the sufficient burial metamorphism needed for zeolite facies to occur within the youngest Jurassic rocks. Whilst onshore successions no longer retain this thickness, it is possible that the offshore successions of the Murihiku may still contain this much thicker sedimentary package of up to ~ 16 km and which may extend into the mid-Cretaceous (Kamp & Liddell, 2000).

Structural deformation of the Murihiku Supergroup rocks is relatively limited, with the rocks folded into broad antiform and synform structures, with localised weak cleavage and simple jointing. Overall, the Murihiku rocks represent the least deformed of New Zealand's basement terranes.

1.1.3 Tectonic setting

The standard depositional model of the Murihiku Terrane represents sedimentation along the eastern margin of Gondwana in a forearc basin above a westward dipping subduction zone (Figure 1-2) (Campbell & Coombs, 1966; Carter et al., 1978; Ballance & Campbell, 1993; Grant-Mackie et al., 2000; Briggs et al., 2004; Pole, 2004).

Coombs et al. (1996) proposed an alternative model, suggesting that the presence of the high potassium, Park Volcanics in Southland, is evidence of a back-arc setting (Figure 1-4). They go on to suggest that rather than a westerly dipping subduction zone, the margin setting would in fact have been an eastwardly dipping subduction zone. Furthermore, Coombs et al. (1996) point to the little deformed nature of the Murihiku sediments, stating that it would be remarkable if such a structural style were preserved in a forearc setting, at least during the time of emplacement for the Park Volcanics (Late Triassic – Early Jurassic).

A third tectonic setting has been proposed by Briggs et al. (2004) who suggest that the two present day geographically separate regions (Kawhia Harbour and Southland Syncline) may have occupied both a forearc and a backarc setting, with one setting reflecting the North Island succession and one the South Island succession respectively, thus meaning the two

regions represent different depositional basins. This hypothesis is further supported by the earlier work of Howell (1980), who suggested that the Murihiku Terrane was situated in an intra-arc setting.

Geochemical analysis by Roser et al. (2002) identified variations in provenance for the Murihiku Supergroup occur throughout the period of Park volcanism (Figure 1-3). They showed that these changes were evident over the geographical extent of the proto volcanic arc, from the depocentre responsible for Southland to the basin responsible for North Island deposition.

Whilst the modern day position of Murihiku Terrane adjoins the Permian to early Mesozoic Brook Street Terrane, neodymium isotope analysis undertaken by Frost and Coombs (1989) indicated that this terrane was not the major source of the sediment to the Murihiku depocentre. The absence of any pillow lavas or pyroclastic deposits within the Supergroup, indicates that the basin was situated some distance from the volcanic arc itself.

Briggs et al. (2004), identified that rhyolitic tuffs are present in the North Island occurrences and when combined with petrographic analysis of rock fragments, determined that intermediate-felsic igneous lithics dominate the composition of the sandstones in the Kawhia Harbour region. These findings support earlier works by Coombs et al. (1992), who suggest the volcanogenic composition of the Murihiku Supergroup is derived from the distal terrane boundary volcanism (Figure 1-4), which changed composition from andesitic

Figure 1-4 Backarc tectonic setting of the Murihiku Terrane

In this model, Coombs et al. (1996) speculate that the Murihiku basin is situated above an eastwardly dipping subduction zone, with sediment source from the west. The high K Park volcanics are emplaced to the west. Here the authors hypothesise that the future terrane boundary (FTB) along which Brook Street Terrane was later inserted, separates the Murihiku Terrane, from the Median Batholith (see Figure 1-1). (After Coombs et al., 1996).

in the Early Triassic, becoming more felsic by Middle Triassic time, and finally rhyolitic by the Late Triassic (Figure 1-3). These changes during the Mesozoic suggest that during the late Middle to Late Triassic and Early Jurassic, the source region was a volcanic belt underlain by continental crust, rather than an intra-oceanic island arc (Coombs et al., 1992).

Here it is suggested that the changing spatial and temporal depositional situation occurring throughout the long lived history the Murihiku sedimentary basin, may reflect both a backarc and a forearc setting (i.e. Coombs et al., 1996; Roser et al., 2002; Briggs et al., 2004).

1.1.4 Research aims and objectives

A significant amount is known about the biostratigraphy and metamorphic petrography of the long-lived, Permian to Cretaceous, Murihiku Supergroup of southern and western New Zealand. However, much less is known about the sedimentology and petrography of these rocks, or changes in the depositional environment through the Triassic and Jurassic.

- The primary aim of this thesis is to undertake detailed, sedimentological and facies interpretations of the exposed Late Triassic - Middle Jurassic Murihiku Supergroup in the Southland Syncline, New Zealand.

With renewed interest in the Great South Basin by the petroleum exploration industry, the relevance for this research is high. Murihiku Supergroup rocks have traditionally been seen as economic basement and have therefore not attracted much exploration attention. However, the petroleum system potential of Mesozoic rocks in New Zealand has long been hypothesized (Cook et al., 1998; Cook et al., 1999a; Cook et al., 1999b). Triassic – Cretaceous Murihiku Supergroup rocks are a potential petroleum source rock in New Zealand's sedimentary basins, based on its high organic content (Cook et al., 1999a; Cook et al., 1999b). During petroleum exploration drilling, the Murihiku Supergroup has been intersected several times in the North Island (Forder & Bennett, 1988; Shell Todd Oil Services Ltd, 1991; Milne & Quick, 1999), but to date has not been intersected in the South Island. During North Island scientific and petroleum exploration investigations, the reservoir potential of these rocks have not been addressed in any detail by previous workers.

- The second main aim is therefore to undertake a petrographic review of selected

samples to determine provenance and diagenetic history.

- This focus area will also include a porosity / permeability evaluation of these rocks, and link this to petrographic observations to assess what, if any reservoir potential the Murihiku Supergroup may have.
- The final main aim is to undertake a high level review of petroleum prospectivity of the Great South Basin and a review of Murihiku plays within this basin. This section will only assess existing knowledge in the basin in order to highlight the potential of the Murihiku in this region and help focus future research. As such, no reprocessing or significant reinterpretation of seismic data will be conducted as part of this thesis.

1.1.5 Thesis outline

Field work for this thesis was carried out during two field excursions between December 2014 and March 2015. Eleven locations were studied along the coast of South Otago / Southland in the coastal Catlins region. All but one of these locations represents shore platform and seacliff exposure, with the non-coastal outcrop located in a quarry highwall. Brief outlines of methods are included in subsequent relevant chapters (Figure 2-1).

Samples from these locations were prepared for petrographic, porosity / permeability, X-ray diffraction and scanning electron microscopy analysis. Thin section microscopy preparation and analysis was undertaken at Victoria University of Wellington. Preparation for the remaining analytical techniques and analyses were undertaken at GNS science by this author and with assistance from GNS Science technical staff.

Chapter 1 introduces the reader to the general tectonostratigraphic setting and general geological background of New Zealand's basement geology.

Chapter 2 outlines the various methodologies employed and introduces the reader to the geographical area of focus.

Chapter 3 presents the main body of work for this thesis and investigates outcrop lithology and sedimentology. Descriptions for each of the 11 locations are given and depositional facies are assigned to each location.

Chapter 4 presents the petrographic properties of selected samples acquired during outcrop mapping. This chapter also deals with the provenance and diagenetic history of

samples, utilising X-Ray diffraction and scanning electron microscopy imaging. Inferences on reservoir quality are also made in this chapter.

Chapter 5 gives a brief overview of geological evolution of the Great South Basin and looks at Murihiku occurrences within the basin, suggesting examples of trapping and play types.

Chapter 6 summarises the results and interpretations from chapters 3-5 and discusses these results and their implications.

Chapter 7 presents the conclusions from this study.

Chapter 2

2.1 Methodology

2.1.1 Introduction

The aims of this thesis are to undertake sedimentological observations and petrographic analysis of Murihiku Supergroup rocks along the south Otago / Southland coastline (Figure 2-1). Field samples were taken and catalogued before representative samples were prepared for petrographic thin section analysis following the method of Dickinson (1985). Porosity / permeability testing of samples was also undertaken using core plugs and analysed in a Hoek Triaxial Cell at GNS Science, Lower Hutt. Thin section petrography, supplemented with the use of a JEOL JCM-6000 desktop scanning electron microscope (SEM), and X-ray diffraction (XRD), were used to determine diagenetic effects and implications for reservoir quality.

Figure 2-1 Field work locations, South Otago / Southland.

Eleven sample locations within the Southland Syncline (Figure 2-1) were chosen as representative locations for field work observations and collections. These locations are of the Late Triassic - Middle Jurassic age (Speden, 1971; Noda et al., 2002; Pole, 2004) (Figure 2-2) and reflect the spectrum of depositional environments present within the Murihiku

Supergroup rocks of the Southland Syncline. A total of 57 field samples from all locations were collected for laboratory analysis. Of these, 33 were prepared for thin section microscopy and 22 tested for porosity / permeability. An additional 18 samples were imaged using the SEM and of these nine samples were prepared for quantitative XRD analysis (Appendix 1).

Figure 2-2 Field locations by age.

Timescale is the 2015 New Zealand Geological Timescale showing international Periods, Epochs, Ages and New Zealand Series and Stages. Ages are given in millions of years. Abbreviations for New Zealand stages are given in brackets. (After Raine et al., 2015).

Outcrop samples were collected from four lithostratigraphic groups, as defined by Campbell et al (2003a) for the Murihiku Supergroup units in New Zealand. The groups consist predominantly of thick-bedded sandstones and conglomerates with interbedded siltstone and mudstone successions (Figure 2-3).

Period	Epoch	NZ Stage		Facies	Location	Murihiku Supergroup Names	Formation	Lithology	
Jurassic	Middle	Kt	U	Fluvial	False Islet	Mataura	False Islet Fm
					Dummy's Beach	Ferndale			
					Curio Bay				
					Shades Beach				
					Waikawa Harbour				
			M	Paralic	Owaka Heads	Tuhawiki Fm	Pounawea Fm
				Shallow Water	Cannibal Bay
								Ratanui Fm
								Tucks Bay Fm
	L		Fluvial	Cathedral Caves	Purakauiti Fm
			Shallow Water	Warnock Rd
	Early	Hu	U	Base of Slope	Sandy Bay	Diamond Peak	Otekura Fm
			L						
		Ha	U						
			L						
Triassic		Late	Bo				Taringatura		
			Bw						
	Bm								
	Br								
				Slope	Roaring Bay		Maitai Fm?

Figure 2-3 Generalised stratigraphic column.

Ages from left to right refer to International periods, epochs with New Zealand stage abbreviations given. U, M and L refer to Upper, Middle and Lower respectively (Figure 2.2). Locations refer to locations sampled during this thesis, Murihiku Supergroup Names follow the nomenclature of Campbell et al.(2003a). Formation names follow those prescribed by Speden (1971).

2.1.2 Field sampling

At each location, detailed lithological logging, and representative sampling of outcrops was undertaken. Each sample was assigned a unique field identification number and photographed prior to removal of the sample. World Geodetic System 84 (WGS84) GPS coordinates were captured at each location with hand-held GPS, enabling spatial plotting of data (Appendix 1). All in text references to GPS coordinates are given as the above datum and referred to as decimal degree latitude and longitude.

At all locations, special care was taken not to disturb yellow eye penguin rookeries or other wildlife, such as the New Zealand fur seal. At Curio Bay, all sampling was undertaken outside of the scientific reserve area, and was done with the approval of the Department of Conservation, who were consulted prior to sampling.

Lithological, stratigraphic and sedimentological observations gathered at each outcrop location enabled inferences about the depositional environment to be made. Paleocurrent data from fossilised logs, lineations, flutes and sole marks additionally allowed inferences about paleoflow direction. These measurements were undertaken by following the technique of Andrews (1982).

Stratigraphic columns for each location were created using Royal Holloway University of London's SedLog software www.sedlog.com. Lithological symbols for all stratigraphic columns are represented in Figure 3-2.

2.1.3 Porosity & permeability

Samples were prepared for porosity and permeability analysis at GNS Science, Lower Hutt, by drilling 21.5mm diameter x 45mm long core plugs from large field samples, with the core plugs orientated perpendicular to depositional bedding. Each drilled sample was measured and weighed before and after drying in a rock lab oven at 120 °C for 12 hours to determine the pore volume and bulk volume of the sample, thus allowing porosities to be calculated (Appendix 2). Permeability of the samples was measured using CO₂ injection whilst contained within a Hoek triaxial cell. Increasing confining pressures of 5, 10, 15 and 20 MPa were utilised to simulate pressure at various depths

2.1.4 Thin Section preparation

Thin sections were prepared at Victoria University of Wellington, following the method of Dickinson (1985) with additional blue dye staining to assist in the visual identification of porosity. Slides were also dipped in hydrofluoric acid to enable differentiation of feldspars and easier identification of carbonate minerals, following the method of Houghton (1980).

Grain identification and percentages were undertaken following the Gazzi-Dickinson point-counting method (Ingersoll et al., 1984). 300 counts were made per slide and plotted on ternary quartz, feldspar, lithic (QFL) diagrams, to display their normalised quartz, feldspar and lithic content, enabling provenance to also be determined (Appendix 3).

Use of the Gazzi-Dickinson method minimizes variation of composition with grain size, thus allowing the assignment of sand sized crystals and grains within larger fragments to the category of the crystal or grain, rather than to the category of the larger fragment (Ingersoll et al., 1984).

2.1.5 Scanning electron microscope (SEM)

Scanning electron microscope (SEM) work was undertaken at GNS Science, Lower Hutt, using a JOEL NeoScope bench top SEM JCM-6000. Sample stubs were cut and prepared before being coated

Figure 2-4 JEOL smart coater. Used during sample preparation prior to SEM imaging.

with a thin film of conductive gold spatter using a JEOL smart coater (Figure 2-4), to avoid charging of non-conductive surfaces. Each stub was coated for six minutes before being placed in the SEM. All photographs were taken using 15kv settings, with both back-scatter and secondary images taken at 50x 100x and 500x zoom levels (six images per sample). This range of zoom allowed the microstructures of samples to be viewed at various scales, enabling diagenetic effects to be analysed.

2.1.6 X-ray diffraction analysis (XRD)

Quantitative XRD analysis was undertaken by the New Zealand Geothermal Analytical Laboratory at GNS Science, Taupo. The samples were initially prepared by chipping and crushing. They were then spiked with 10% zinc oxide and analysed using a Philips X'Pert Pro

instrument, utilising CoK α radiation and the following operating conditions:

Start Position [°2Th.]	2
End Position [°2Th.]	80
Step Size [°2Th.]	0.05
Scan Step Time [s]	1
Generator Settings	40 kV, 35 mA

The mineralogy of the samples was determined using PANalytical interpretive software *X'Pert High Score* and data plotted and labelled as shown in Chapter 4 (Appendix 4). Quantitative mineral percentages were determined using *Sietronics Pty Ltd* software, *Siroquant*.

2.1.7 Seismic interpretation

2D seismic reflection data from the DUN06 survey, shot on behalf of the New Zealand Government by Multiwave Geophysical in 2006, was used to identify potential Murihiku reservoir facies in the offshore Great South Basin (GSB) area along strike from the outcrop. Seismic line DUN06-09 was used for interpretation.

IHS Kingdom software was used to view and interpret seismic data. No reprocessing of data was undertaken during this study as this was out of scope of the thesis.

Seismic facies mapping was undertaken following the method defined by Sangree and Widmier (1977). This method allows the identification of three dimensional seismic reflection packages which contain specific characteristics that differentiate it from surrounding patterns.

The results of this analysis work will be discussed further in Chapter 5

Chapter 3

3.1 Outcrop descriptions

3.1.1 Introduction

The study area extends from Roaring Bay in South Otago to Curio Bay in Southland (Figure 3-1). Eleven locations were identified as being suitable for outcrop mapping and sampling of Murihiku Supergroup rocks in this region (Figure 2-1).

Deposition of these sediments of Late Triassic to Middle Jurassic age represent significant variation of depositional environment. These environments range from deep marine, outer shelf / slope and base of slope facies in the Late Triassic and Early Jurassic sections, measured at Roaring and Sandy bays respectively (Figure 2-3). Following this deepest depositional setting recorded for Murihiku Supergroup rocks in the Southland Syncline, the depositional environment observed in outcrop shallowed from Early Jurassic time,

Figure 3-1 Simplified geological map and cross section of the Southland Syncline. Modified from Noda et al. (2002).

becoming paralic and finally terrestrial in the Middle Jurassic. This was observed in the youngest outcropping rocks of the Murihiku Supergroup rocks occurring at False Islet, and located within the fold axis of the NW to SE-trending Southland Syncline (Figure 2-1, Figure 3-1 & Figure 6-1). Within the southern limb of the Southland Syncline all outcrops studied during this thesis are representative of terrestrial depositional environments.

The following chapter describes the rocks at these outcrop locations, and is arranged in geographical sequence from north to south (see Figure 2-1).

Figure 3-2 Stratigraphic column symbols.

Symbols are outputted from SedLog software, SE Asia Research Group, Department of Earth Sciences, Royal Holloway University of London.

3.1.2 Roaring Bay – Late Triassic (Oretian)

3.1.2.1 Introduction

Roaring Bay is situated on the southern side of Nugget Point 25 km south of Balclutha (Figure 2-1). The bay is a southward-facing embayment on the northern limb of the Southland Syncline and presents a well exposed sea cliff and narrow wavecut platform outcrop extending south along the coast (Figure 3-3). Access is from the end of the Nugget Road Esplanade, via a small, unmarked walking track cutting through vegetation. This track passes through a yellow-eyed penguin rookery and has restricted access to the public. The Late Triassic succession at Roaring Bay has been well studied geologically over the past 150 years, following initial characterisation by Lindsay (1862) who first identified the rocks as belonging to the Triassic period. Hutton et al. (1875) assigned the beds to the Maitai Formation, although this name appears to have been lost in the literature and does not appear in any recent texts.

Later Park (1904) published the first detailed stratigraphic section at this location. Trechmann (1917) collected and identified numerous fossils from Roaring Bay, confirming

Figure 3-3 Roaring Bay looking south.

Red arrow shows conglomerate outcrop location. Blue arrow indicates younging direction to the SW. Yellow arrow designates the Triassic / Jurassic age boundary.

a late Triassic age (Oretian - Otapirian). Mackie (1935), undertook detailed stratigraphic work as part of his wider geological investigations into the Glenomaru survey region. Speden and McKellar (1958), completed important geological work defining the Triassic-Jurassic age boundary at the southern end of Roaring Bay (Figure 3-3), whilst mapping the coastal region between Roaring Bay and Catlins River mouth, some 6 km further to the south (Speden, 1971).

Six highly indurated samples were taken from this location (Appendix 1). Of these, three were prepared for thin section and two tested for porosity and permeability and also SEM imagery, with one of these analysed by XRD (Chapter 4 , Appendix 4).

3.1.2.2 Sedimentary description

The measured section is 62m in stratigraphic thickness (Figure 3-11), extending south-west from the prominent conglomerate outcrop highlighted by the red arrow in Figure 3-3, GPS: -46.446093, 169.800420. Bedding dips steeply 84°SW and represents a general fining-up succession as the section youngs to the south. The base of the measured section starts in a seven metre thick, matrix-supported conglomerate (Figure 3-4) that grades into repeating decimetre thick sandstone units with minor siltstone beds, with sharp basal contacts (Figure 3-11). Thin conglomerate beds <2 m thick also occur in this succession.

Sandstone comprises about 80% of the measured section, with the remainder consisting of siltstone and conglomerate. A strike-slip fault (S/D: 260°/78°/NE) intersects the top of the measured section; reliable offset was unable to be determined due to

Figure 3-4 Matrix supported conglomerate, Roaring Bay.
Field of view is roughly 70cm with younging direction to the left of image.

vegetation and gravel cover.

The matrix-supported conglomerate consists of moderately sorted, rounded to sub-rounded, granitic, andesitic, greywacke and chert clasts up to 15cm in diameter (Figure 3-4). Mackie (1935) undertook petrographic analysis of the granitic clasts and described them as soda-rich, composed mostly of oligoclase feldspar, 60-70%, with 20-25% quartz, 5-10% orthoclase feldspar and 5% biotite mica. The conglomerate matrix is comprised of medium to coarse sandstone displaying moderate sorting, rounded to sub-rounded, volcanoclastic grains. The basal contact displays rip up clasts from the underlying unit, indicating an erosional contact.

Sandstone beds are light grey to dark grey-green, ranging from coarse at the base of the measured section to very fine at the top (Figure 3-11).

These beds display alternating massive, planar and convolute bedding (Figure 3-5 & Figure 3-7), with basal contacts tending to be either sharp or erosive.

Figure 3-5 Alternating medium-fine sandstone displaying Tb planar laminations, Roaring Bay. Note zeolite filled jointing to left of image, red arrow. Younging direction is to top of image. Pencil for scale.

Figure 3-6 Typical shore platform outcrop at Roaring Bay.

Section comprises steeply dipping (80 SW, towards the right of this picture) fining-up sequence of interbedded sandstone and siltstone units. Vertical jointing is common, such as to right of photo. Metre ruler for scale. (Photo taken looking east).

Figure 3-7 Thinly bedded planar Tb and convolute Tc bedding in fine grained sandstone, Roaring Bay. Red arrow indicates bioturbation. Pencil for scale. Younging to top of image.

Figure 3-8 Mollusc fossil Roaring Bay.
Fossil contained within fine grained sandstone pencil for scale.

Interestingly, although macroscopic marine fossils were identified (Figure 3-8), plant fossils were also observed (Figure 3-9). The presence of the conglomerate beds at intervals throughout the measured section and the evidence of terrestrial material in these fine grained units (which are hypothesised to represent a slope facies), suggests transportation occurred through channelised flow. These channels would act to funnel coarser sediments and terrestrial material to deep water (Shepard & Dill, 1966).

Towards the middle of the measured section, significant vertical jointing perpendicular to strike is present and is often zeolite cemented (Figure 3-6). The prevalence of this cementation increases towards the top of the mapped section, and is inferred to result from proximity to the aforementioned high angle strike slip fault.

Figure 3-9 Plant fossil in fine grained sandstone, Roaring Bay.
Pencil for scale.

3.1.2.3 Interpretation of depositional environment

The presence of repeating successions of graded sandy deposits with sharp basal contacts and internal structures displaying massive, planar and convolute bedding reflects deposition as a series of Bouma divisions within turbidite flows (Bouma et al.,

1962). These classic sedimentary structures are comprised of five divisions and represent the idealised sedimentary structures that form during deposition of a turbidity current (Figure 3-10). Bouma divisions are named in descending stratigraphic order: Te, Td, Tc, Tb, Ta. These internal structures reflect a decreasing internal shear stress as the turbidite is deposited allowing normal grading of the unit. Often turbidites will not contain all divisions.

High density flows representative of thick, coarsely grained deposits will often develop Ta, Tb beds but not Tc-Te, often due to the overlying units being eroded by subsequent flows. Conversely low density flows tend to produce thin, finer-grained turbidites and may develop units Tc-Te but not have enough bed stress develop Ta and Tb units (Boggs, 2001). The Bouma sequences identified at Roaring Bay are only partial sequences.

The notable conglomerate beds (Figure 3-11) and sandy nature of the Bouma sequences suggest that depositional elements represent both confined channelised flows (represented by the conglomerate beds), and less-confined turbidite flows, perhaps as flows which spilled out from these channels.

Figure 3-10 Idealised Bouma sequence. Divisions are given on left of diagram with associated grain size sedimentary structures on the right. (After Jobe, 2012).

The presence of conglomerates indicates that deposition occurred as a series of high density, slope-channel gravity flow deposits, possibly related to periods of increased sediment supply. The rhythmic, generally fining-upward and sandy nature of the turbidites and the low proportion of silty interbeds within the channels suggest they represent waning flow conditions, perhaps related to the preceding channel deposits, rather than as overbank deposits where a greater proportion of fine-grained units would expect to be observed (Arnott, 2010).

While not observed in the outcrop during this study, the identification of *Zoophycos* at Roaring Bay supports a deeper water depositional environment (Cave, 1982). Furthermore, the inclusion of terrestrial plant material (Figure 3-9) indicates that deposition was part of a larger channel system with established shelf channels transporting material from the terrestrial and shallow marine environments into deeper waters.

Figure 3-11 Roaring Bay stratigraphic column.

3.1.3 Sandy Bay - Early Jurassic (Ururoan Stage)

3.1.3.1 Introduction

The outcrop location at Sandy Bay, Otago is situated in a remote, eastward-facing embayment located on the northern limb of the Southland Syncline, at the end of Ahuriri Flat Road. It is accessed via the farm land of Mr Steven Harrison. At this location, three sections were measured (Figure 3-12), one at the northern end of the beach covering 138 m of stratigraphic section nominated as Sandy Bay Section 1 (SS1; -46.453232, 169.782189) and two parallel 41 m thick sections located in the centre of the beach, Sandy Bay Section 2 & 3 (SS2 & SS3; -46.454880, 169.780105) (Figure 3-12). Note, only the full stratigraphic column for SS1 is shown in text, with reduced columns for SS2 & SS3 shown. Full versions of SS2 & SS3 are attached in the appendices (Appendix 5).

Early geological mapping work at this locality was undertaken by Hutton et al. (1875); McKay (1877); Park (1886). The age-diagnostic marine fossil *Pseudaucella marshalli* was discovered by (Marshall, 1912), and later identified by Trechmann (1923), providing an Early Jurassic (Ururoan) age for the succession. Mackie (1935) and later Speden (1971) and (Carter, 1979) defined this location as being the type locality for the Otekura Formation, Glenomaru Group. This lithostratigraphic group was later revised by Campbell et al. (2003a) who included it as part of the Diamond Peak Group (Figure 2-3).

Small-scale normal faults are present at several locations in the bay (Figure 3-13), and offset on faults is difficult to determine due to vegetation and sand cover. Calcite veining is evident across fault planes and associated jointing, with average fault strike and dip being 320°/50°/NE.

Figure 3-12 Panoramic shot looking southeast down onto Sandy Bay, Otago. Note wavecut outcrops, with steeply dipping bedding (73°S) and younging direction to the SW (red arrow). Blue arrow indicates length of SS1 exposed in seacliff parallel to this line. Green arrows indicate SS2 & SS3 respectively.

The base of section 1 (SS1) at Sandy Bay is estimated to be approximately 1400 m stratigraphically above the top of the measured section in Roaring Bay, based on this author's measurements and those of Mackie (1935).

Figure 3-13 Sandy bay, normal fault. Displacement is around 3 m, Yellow lines indicate top of offset bed. Beds young to the SW (left of image). Metre ruler for scale.

Outcrops comprise wave cut platforms and sea cliff exposures, with varying degrees of sand and vegetation cover and are separated by areas of no exposure. Sea cliff exposures tend to be highly weathered, making identification of structures difficult.

3.1.3.2 Sedimentary description

Observations for this locality cover three logged sections. The longest, Sandy Bay Section 1 (SS1, Figure 3-21), was measured from the northern end of the beach and includes the coastal cliff before being obscured by vegetation cover and sand. Sandy Bay sections 2 and 3 (SS2 & SS3, Figure 3-25 & Appendix 5) represent shore platform

exposure and are located at the southern end of the bay. These sections were measured parallel to each other to determine lateral continuity of bedding. SS2 starts at -46.454789S, 169.779980E and SS3 starts at -46.454907S, 169.780189E and cover 41 m stratigraphic thickness. The horizontal distance between SS2 and SS3 is 23 m.

Bedding across all sections comprises millimetre to decimetre scale repeating Bouma Ta-Tc sequences, with massive (Ta), planar laminated (Tb) and convolute (Tc) bedding intervals evident. Beds comprise interbedded light brown massive mudstone, light blue - grey laminated siltstone, very fine sandstone and rare medium sandstone beds, and rare light brown / white tuffaceous horizons. The succession comprises up to 20% sandstone with this percentage increasing towards the centre of the measured sections (north, to the left of green arrows Figure 3-12). Basal contacts of individual beds tend to be sharp or gradational over a maximum of 5 cm. Base of beds often display fine scale laminations, with

Figure 3-14 Base of measured section 1 (SS1), Sandy Bay. Section displays lateral continuity of steeply dipping (73°S) bedding. Younging direction to South (right of image). Red arrow indicates very fine sandstone bedding.

siltstone units displaying a fissile, heavily jointed appearance. This characteristic has led to preferential weathering of these units (Figure 3-14). Occasional siltstone clasts up to 20 cm are present in coarser units.

The basal 30 m of SS1 (Figure 3-14 & Figure 3-21) consists of steeply dipping (73°S), millimetre to centimetre scale interbedded massive mudstones - dark green-grey siltstone with occasional very fine sandstone beds displaying lateral continuity over ~ 30 m (Figure 3-14). Basal contacts tend to be sharp with occasional flame structures evident (Figure 3-15). Present in this interval and sporadically throughout the outcrop,

light brown tuffaceous beds up to 10 cm thick are present (Carter, 1979).

The upper 70 m of SS1 displays a similar interbedded nature as the basal section, with bed thickness increasing up to 50 cm thick (Figure 3-16 & Figure 3-21). Sedimentary features

Figure 3-15 Flame structures in fine grained sandstone. Note light brown tuff at base of image. Pencil for scale.

become more difficult to identify due to the weathered nature of the sea cliff outcrop, with finer beds continuing to display a fissile texture. Basal contacts are predominantly sharp with occasional erosive contacts displaying rip-up clasts.

This section displays repetitive fining up cycles

Figure 3-16 Typical sea cliff exposure of S1, Sandy Bay. Low angle normal fault dipping 50° NE (right of image), with about 2m offset. Section youngs to the south (left of image) and displays a series of fining up cycles (yellow triangles) with mudstone beds at the top of successions displaying preferential weathering. Note metre ruler (circled in red) for scale.

with overlying mudstone beds more subject to erosion (Figure 3-16). The fining up cycles are up to 10 m overall thickness and contain zeolitic ovoid concretions and are up to 10 cm

Figure 3-17 Ovoid zeolitic concretions in steeply dipping beds, Sandy Bay. Note medium brown mudstone to right of hammer. Younging direction to left of image. Hammer for scale.

in thickness and 1.2 m in length (Figure 3-17).

SS2 and SS3 (Figure 3-12 & Figure 3-25) display bedding dipping at 74°S and comprise centimetre to decimetre thick, interbedded dark grey siltstone and very fine light brown sandstone beds. Sandstone bedding displays parallel and cross bedding with individual beds up to 230 cm thick. Siltstone beds are up to 113 cm thick. Overall, sandstone comprises ~30% of the outcrop.

Similar to SS1, basal contacts in SS2 and SS3 display either sharp or erosive contacts with small scale rip-up clasts

Figure 3-18 Laterally discontinuous bedding, Sandy Bay. SS2 displaying compensating geometry. Red lines highlight pinching of bedding. Younging direction to the top of this image. Metre ruler for scale.

evident at erosional surfaces. Rare 20 cm thick siltstone clasts are present in fine sandstone units with clast orientation east-west. Beds vary between being laterally continuous over the outcrop width (~75 m) or laterally discontinuous (Figure 3-18), with compensation style bedding in places (Figure 3-19). This compensation-style bedding is the result of sand deposition on the seafloor creating small topographic highs. As subsequent flows deposit material, these younger flows will seek to fill the adjacent lower areas on the seafloor and be deposited in these troughs. The result is variances in sand deposition with interbedded sand

Figure 3-19 Compensation bedding, Sandy Bay. SS3 section displays repeated fine sandstone (thicker units) and siltstone bedding (darker units). Note preferential weathering of siltstone units. Metre ruler for scale. Younging direction to the SW (right of picture).

Figure 3-20 Slumped sandstone unit (light grey) with siltstone infill, Sandy Bay. SS2 displaying internal deformation due to shearing within the moving flow. Younging direction towards top of image. 50 cm ruler for scale with 10 cm divisions.

bodies separated by shale beds (Slatt, 2013) (Figure 3-19).

Lateral continuity of bedding is determined for several beds, however the discovery of a small scale fault with offset of about 50 cm striking through the middle of the two sections, made comparison difficult.

Sand cover precludes continuous section mapping, however at the southern end of the beach a 6 m thick section of very thinly bedded sandstone and siltstone (Figure 3-23) is present and represents the top of the Otekura Formation (Speden, 1971). Adjacent to this location are groove casts exposed in a sea cliff section (-46.455029, 169.779097) (Figure 3-22), which indicate a paleo-flow in a NNW-SSE orientation. These sole marks represent infilled scouring and are up to 1 m in length. A uni-directional flow direction is unable to be determined from these sole marks, although Carter (1979) indicates a paleo-current direction from the S-SSW to N-NNE.

Figure 3-21 Sandy Bay section 1 stratigraphic section.

3.1.3.3 Interpretation of depositional environment

The distinctive Bouma divisions observed within the sandstone beds (Figure 3-24), together with the hydroplastic deformation of bedding and normal grading are indicative of deposition by turbidity flows. The presence of flame structures and slumping of coarser units is representative of rapid dewatering as beds were deposited, and some primary depositional slope (Figure 3-20) (Boggs, 2001). Furthermore, the evidence of sharp bases, fine scale internal structure and clear evidence for sole marks at the base of some beds would support the turbidite interpretation.

Mudstone beds, where associated with turbidite sandstone beds beneath, were likely deposited as a fine-grained tail of such turbidity flows. Intervals of thicker siltstone-dominated deposition (such as illustrated in Figure 3-23), represent periods of more quiescent deposition with less frequent sandy turbidite sedimentation. This situation might occur on an area flanking, or on the margin of

turbidite deposition such as a levee.

The presence of well-defined bounding surfaces (Figure 3-23), indicates that sediment supply must have stopped, or at least been restricted at certain times suggesting periodic abandonment of the sandstone deposition. This might be expected in a sandstone lobe setting such as a submarine fan, basin floor fan or slope fan.

These pulsating sandstone and mudstone events present as a series of intermittent sheet-like deposits, suggesting deposition occurred in an overbank setting (Arnott, 2010). Compensation style bedding further indicates that the deposition of sand

Figure 3-23 Flysch bedding, Sandy Bay.

Siltstone bedding representative of the top of the Otekura Formation, Southern end of Sand Bay, as identified by Speden (1971). Note the prominent bedding planes (red arrows) that may represent a hiatus in sediment supply. Metre ruler for scale. Younging direction to the right of this image.

Figure 3-22 Lenticular basal groove casts, Sandy Bay. Paleo-current direction from the NNW-SSE. Hammer for scale.

flows were at least in part controlled by the distribution of earlier-formed sandstone beds, characteristic of slope fans or basin floor fan settings (Boggs, 2001). Furthermore, the presence of slumping indicates that deposition occurred on an inclined surface (e.g. on the flanks of channels or levee margins etc) or perhaps as co-seismic events.

Whilst lateral continuity of some individual beds has been restricted due to slumping and pinch out of units (Figure 3-18, Figure 3-19 & Figure 3-20), overall the general sheet-like nature of bedding suggests that deposition occurred

outboard of the terminus of the feeder channels, becoming unconfined to form a distal apron of thin, finely bedded turbidites (Arnott, 2010).

Additional evidence to support this facies interpretation is the total lack of any terrestrial or coarser material that may have been deposited through channelised transportation.

Figure 3-24 Bouma Tb-Tc fining up cycles, Sandy Bay.

Small scale turbidite cycles in light brown sandstone and dark grey siltstone. Note the sharp and wavy basal contact (red arrow) at base of Tb bed. 50 cm ruler for scale, with 10 cm divisions. Photo credit Greg Browne.

It is therefore this author's interpretation, and in agreement with previous authors, that the Otekura Formation section at Sandy Bay was deposited as a deep marine, base of slope lobe or overbank facies.

This interpretation would support the work of Carter (1979) and Speden (1971), who both identify the section at Sandy Bay as representing muddy flysch overbank turbidite deposits.

Figure 3-25 Comparison of lateral continuity between Sandy Bay section SS2 & SS3. Horizontal distance between measured sections is 23 m. Total outcrop width is ~75 m.

3.1.4 Cannibal Bay –Middle Jurassic (Upper Temaikan)

3.1.4.1 Introduction

Outcrop at this location is a small wave-cut platform exposed at the north end of Cannibal Bay, South Otago. Access to the outcrop is via beach access at the end of Cannibal Bay Road. The measured section represents the contact between the Sweetwater and overlying Pounaweia Formations (Figure 3-26) on the northern limb of the Southland Syncline (Speden, 1971). The section is located roughly 2.2 km stratigraphically higher than the top of the SS2 & SS3 measured sections at Sandy Bay. Only one sample was obtained from this section due to the fissile and highly jointed nature of the outcrop making sampling problematic. This sample was prepared for porosity / permeability, petrographic analysis and SEM imagery (Chapter 4).

Figure 3-26 Type section of the Pounaweia Formation, Cannibal Bay. Typical outcrop, note cliff to the right of picture represents the Boundary between the Sweetwater and Pounaweia Formations (red arrow). Younging direction is to the south (left of image). Metre ruler for scale, highlighted in red.

Extensive paleontological and sedimentological work has previously been undertaken on this shore platform. Early work was carried out by McKay (1877) and later by Hector (1884), both of whom collected samples of *Haastina haastina*, with the latter naming this section as the Cannibal Bay Beds. Other 20th century geologists, notably Mackie (1935) and Marwick (1953) undertook considerable paleontological work through the area and were able to determine that the

age of the these rocks is Middle Jurassic (Temaikan) in age.

Speden (1971) built on his regional mapping work (Speden, 1961), and assigned the Cannibal Bay beds and associated units to the Pounawea Formation, Middle Jurassic (Upper Temaikan), assigning them as the type section for the Pounawea Formation. Campbell et al. (2003a), later redefined the Catlins Group as the Ferndale Group (Figure 2-3).

The Pounawea Formation grades into a conglomerate at False Islet, some 1.1 km to the south of the measured section at Cannibal Bay (section 3.1.5). This coarsening of grain size is representative of an overall regressive trend in the Murihiku rocks in the Southland Syncline and will be discussed further in Chapter 6 .

3.1.4.2 Sedimentary description

The measured section (Figure 3-29) covers a 35 m thick interval starting at -46.467598, 169.760316, with finer units displaying a fissile character and also displaying preferential weathering, resulting in up to 1 m relief between beds on the shore platform (Figure 3-26).

The beds are steeply dipping (78°SW) and comprise centimetre-decimetre thick, dark blue-grey, massive siltstone and very fine, well sorted volcanogenic sandstone beds. Sandstone only makes up around 5% of the outcrop. Internal structures were very hard to observe due to the highly fretted nature of the outcrop, although occasional planar and convolute bedding was observed at the top of some beds. Basal contacts of sandstone beds tend to be sharp and undulating.

Figure 3-27 Burrows in siltstone, Cannibal Bay.
This view looks down onto the top of a 30 cm thick bed. Hammer for scale.

Whereas previous authors (McKay, 1877; Hector, 1884; Mackie, 1935; Fleming & Kear, 1960; Speden, 1971) identified abundant fossils within this outcrop, only occasional bivalve casts were evident at the top of the measured section (Figure 3-29). This interval also correlates with

a zone of abundant burrows, up to 30 mm wide (Figure 3-27). A single belemnite fossil was identified away from the measured section in an adjacent sea cliff exposure at, -46.467042, 169.758959 (Figure 3-28).

3.1.4.3 Interpretation of depositional environment

The generally fine grained nature of the Cannibal Bay outcrop, suggests deposition occurred in a low-energy environment, with only minor influxes of coarser material. The presence of occasional planar (Tb) and convolute (Tc) bedding suggests that influxes of additional material may have occurred as a series of low energy silty turbidite flows.

Figure 3-28 Belemnite fossil in very fine sandstone, Cannibal Bay. Note infilled burrow to right of pencil. Pencil for scale.

The massive nature of the siltstones and presence of pervasive burrows indicates that this section has been heavily reworked by benthic organisms which explains the general lack of internal structures over the outcrop.

Speden (1971) noted that other localities of the Pounawea Formation include conglomeratic units which could indicate channelised flow. An outcrop section of the Pounawea Formation at the north end of Jacks Bay, roughly 4.3km south west of the measured section at Cannibal Bay and on the south limb of the Southland Syncline, displays plant remains and

carbonaceous beds, indicating, that at times a portion of the Pounawea Formation may have been purely terrestrial (Speden, 1971) or at least represent a significant channel system being able to supply material from a nearby terrestrial source.

Within the measured section, the presence of burrows and a belemnite fossil as well as the other marine fossils identified by previous authors, indicates a shallow water to possibly

continental shelf facies as the depositional environment for the Cannibal Bay section (Boggs, 2001; Plint, 2010). This interpretation differs slightly from that of Speden (1971) who suggests that the wider Pounawea Formation was deposited in very shallow to

Figure 3-29 Cannibal Bay stratigraphic section.

estuarine environment. He identifies several localities throughout the region that are correlated to the formation as being purely terrestrial with plant beds identified. He also notes a general coarsening of beds in the upper half of the formation. This coarsening trend is in line with the regionally regressive nature of the Murihiku Supergroup within the Southland Syncline.

The generally fine grained nature of this outcrop therefore marks the transition on a regional scale, from sand-dominated Late Triassic to Early Jurassic deposition (at Roaring and Sandy bays), to the fine-grained deposits of Middle Jurassic age at Cannibal Bay (Figure 6-1). The base of slope facies at Sandy Bay is interpreted to reflect maximum marine transgression within the Late Triassic to Middle Jurassic rocks of the Southland Syncline. From that age, a regressive phase of deposition occurred and is reflected in the shallow marine deposits at Cannibal Bay and the wider Pounawea Formation (Speden, 1971).

3.1.5 False Islet –Middle Jurassic (Upper Temaikan)

3.1.5.1 Introduction

Located in the core of the Southland Syncline, the outcrop at False Islet, represents the youngest rocks of the Murihiku Supergroup exposed in the Southland Syncline. The outcrop is a medium to coarse grained sandstone, grading up into a highly carbonaceous and coaly section. The measured section is unconformably overlain by an indurated, clast supported conglomerate (Figure 3-32).

Figure 3-30 Outcrop location of False Islet Formation. Normal fault S/D: $28^{\circ}/56^{\circ}$ /NW. Green arrow indicates coaly and carbonaceous beds. Yellow arrow indicates measured section. Bedding youngs to the northeast (left of image). (Red circle shows metre ruler for scale).

Figure 3-31 Base of measured section, False Islet Formation. Medium to coarse grained sandstone with trough bedding and fossilised organic material throughout. Unit fines up to carbonaceous sequence (left of image). Metre ruler for scale.

The section was mapped in sea cliff exposures, on the southern limb of the syncline axis, 7.5 km south-east of Owaka, Otago.

The base of the measured section, -46.479578, 169.750032, is roughly 1.5 km south west of the section at Cannibal Bay and is accessed either from Cannibal Bay Road and then via beach access along Cannibal Bay beach from the north, or from Newhaven Road end, along Surat Bay beach from the west. Eight hand samples were taken from this location with six prepared for thin section work, three for porosity / permeability testing and one for XRD analysis (Appendix 1, Chapter 4).

The False Islet Formation stratigraphically overlies the Pounawea Formation, with uppermost Pounawea Formation beds present on the north side of False Islet headland, coarsening-up into the False Islet Formation. The basal contact of the False Islet Formation, whilst displaying minor scour features, does not indicate any evidence of an unconformity (Speden, 1971).

Park (1904) and Mackie (1935) both identified a fault within the logged section, describing

Figure 3-32 Top of measured section in the False Islet Formation. Carbonaceous beds truncated by a large offset fault dipping 56°NW (red dashed line). Shear zone of fault is roughly 5 m wide. Lower portion of conglomeratic unit is highly carbonaceous. Younging direction is to NW (the top left of image).

Figure 3-33 Carbonaceous ripple laminated sandstone, False Islet Formation.

Note zeolite veins and overall fining up nature of beds. Younging direction is towards top of image. Ruler has 10 cm increments for scale. Photo credit, Greg Browne.

it as a strike slip fault. Strike and dip measurements taken from the fault surface give a fault dip of 56°NW (Figure 3-32), however determination of fault movement was unable to be made due to the large offset of the fault and lack of slickensides. Without this evidence it is difficult to determine fault type, however fault movement is postulated by this author to reflect the north-east trending structure of the region and is therefore likely to have the same movement orientation as the other major faults in the region which are normal faults (Speden, 1971).

3.1.5.2 Sedimentary description

The 22 m thick measured section unconformably terminates against the normal fault at the base of the conglomeratic unit (Figure 3-32). Described units comprise a succession of fine-coarse grained sandstone, fining-up to siltstone, carbonaceous mudstone and thin coal beds. Each of these form a fining and thinning-upward cycle several metres thick (Figure 3-34). The outcrop is truncated by the aforementioned fault with offset of ~ 45 m (Speden, 1971). Sandstone comprises about 50% of the measured section. Bedding of these units

Figure 3-34 Fining-up depositional cycles, False Islet Formation at False Islet.

Yellow triangles indicate sequences of light grey, fine grained sandstone beds fining-up to carbonaceous mudstone beds with minor coal seams at their tops. Younging direction is to the left of image. Metre ruler for scale.

dips $138^{\circ}/48^{\circ}/\text{NE}$ indicating that this outcrop is on the southern limb of the Southland Syncline. The fold axis of this regional structure is ~ 350 m north east of the measured section.

Beds at the base of the measured section (Figure 3-31) display fining-up sequences, and are decimetre-metre scale, light grey, lithic rich sandstones; grains are sub-rounded and display medium sorting. Beds are trough cross-bedded, with sets up to 30 cm thick (Figure 3-37). Beds are carbonaceous and often contain channel lag deposits, with larger pebble clasts up to 3 cm diameter entrained in the lower portion of individual beds, and display sporadic fossilised organic material. Basal contacts tend to be sharp. Top of beds often comprise ripple laminated, light grey fine grained sandstone.

The top 14 m of the measured section comprises alternating, fine grained, light grey sandstone, carbonaceous siltstone and mudstone units, with coaly mudstone and minor coal beds present (Figure 3-34). Fine sandstones in this portion of the section display carbonaceous ripple laminations (Figure 3-33) and trough cross bedding. Similar to the

Figure 3-35 In-situ carbonised tree stump, False Islet Formation. Younging direction is towards top of image. Hammer for scale. Photo credit, Greg Browne.

underlying coarser beds, these sequences display a cyclic fining-up character. Coaly and carbonaceous beds show evidence of rootlets and in-situ tree stumps at basal contacts (Figure 3-35). Coals contain zeolite cementation on jointing surfaces.

Coals have been sampled from this location and returned vitrinite reflectance values of 0.8% and GOGI of 0.78, indicating that they have good hydrocarbon potential (Cook et al., 1999b).

Overlying the measured section a thick, ~70 m thick succession of pebble-cobble sized, clast and matrix supported conglomerate is present, with individual clasts up to 20 cm in diameter (left side of Figure 3-30 & Figure 3-32). The conglomerate contains very coarse sandstone – gravel conglomerate interbeds and lenses up to 2 m thick, with the maximum clast size of 4 cm (Figure 3-36). The entire conglomerate unit often displays fracturing due to the proximity to the fault, with jointing displaying calcite-zeolite-epidote cementation (Speden, 1971).

Faint imbrication was apparent in the measured section with a clast dip measuring

Figure 3-36 Pebble-cobble, clast support conglomerate, False Islet Formation. Very coarse sandstone - gravel lens pinching out to left of image. Hammer for scale.

315°NW. Speden (1971), identified in a paleo-seacliff outcrop of the False Islet Formation, 2.5 km inland to the west, and adjacent to New Haven, that the conglomerate showed strong imbrication in lenses of grit with a north-easterly flow direction.

Interestingly, the larger conglomerate clasts are often fractured and offset (<5 cm) by small parasitic faults. These fractures are then infilled by zeolite cement.

Mackie (1935), identified the majority of conglomerate clasts as being acidic in composition and comprised of granites, trondhjemites, pegmatites, granophyres, quartz and mica-porphyrates, quartz-mica-diorites, rhyolitic and andesitic rocks, albite dolerites, and a ceratophyre. Furthermore, Speden (1971) identifies that the composition of the conglomerate at False Islet is similar to the McPhee Cove conglomerate which crops out 29 km south-west of False Islet south of Tautuku Peninsula. Pole (2004), also made this comparison, linking the False Islet conglomerates of Speden's Papatowai Subdivision to the Brothers and Slope Point Block conglomerates at the southern extent of the Southland Syncline.

3.1.5.3 Interpretation of depositional environment

Speden (1971), postulated that deposition of the False Islet Formation is a continuation of the shallow-water estuarine to terrestrial depositional process through which the

underlying Pounawea Formation was deposited. Within the measured section at False Islet, the large volume of conglomeratic material the presence of coals, in-situ tree stumps and rootlets, and the lack of any marine fossils (Speden, 1971), indicates that the outcrop at False Islet was deposited in a terrestrial fluvial facies.

The coarse grained nature at the base of the measured section and subsequent fining up cycles suggest that deposition occurred in a sinuous channel setting, and that these fining upward cycles represent the progressive migration of the channel facies with time. This is most like the gravelly, high sinuosity river facies, (model 4) of Miall (1985). Carbonaceous units and coals were likely deposited through overbank sedimentation or through changes in channel confinement and channel avulsion, leaving abandonment deposits.

Figure 3-37 False Islet stratigraphic section.
Note, overlying conglomerate is not true measured thickness (total thickness of this unit was ~70 m).

The fault contact of the conglomerate at this location suggest that significant tectonic uplift occurred to change the flow regime. The abundance of clasts indicates a substantial source area existed for the supply of that material and that it consisted of a range of geological rock types as indicated by the varied clast types. The rounded nature of the clasts indicates some considerable transport distance was involved, as opposed to derivation from a local source area.

The False Islet Formation therefore marks the transition between fully marine deposition on the northern limb of the Southland Syncline to a terrestrially dominated depositional setting on the southern limb. Whilst there is a shift back to a paralic facies in the immediate underlying units on the southern limb of the Southland Syncline (section 3.1.6), the terrestrial facies predominates throughout the majority of the mapped southern sections.

3.1.6 Owaka Heads – Middle Jurassic (Upper Temaikan)

3.1.6.1 Introduction

The outcrop at Owaka Heads is located on the south side of the Catlins River mouth entrance, 1.1km north-east of Haywards Point, on the southern limb of the Southland Syncline. The outcrop is also situated on southern limb of the local, NW-SE trending Owaka Valley Anticline (Speden, 1959), resulting in variance in bed dip of between 15° - 48° S away from the axis of the local anticline (Figure 3-38). The mapped section is a well exposed shore platform and is accessed via the Hina Hina Road end, directly across the water from the New Haven settlement

The outcrop is also in close proximity to the NE-SW trending Pullars Creek Fault trace. Deformation within the measured section is minimal, whilst to the east of the section (in

Figure 3-38 Wave cut platform outcrop, Owaka Heads.

Section displays laterally continuous, interbedded fine sandstone and siltstone bedding, with variance in dip of between 15° - 48° S with distance from the axis of the Owaka Valley Anticline (left of image). This feature runs NW/SE, parallel to bedding. Younging direction is to the west, right of photo. Dashed red line designates approximate location of Pullars Creek Fault trace. Metre ruler for scale.

Figure 3-39 Abundant calcification of microfractures in medium grained sandstone.
Pencil for scale.

the distance of Figure 3-38), deformation is evident through abundant folding and fracturing and a series of smaller scale faults with throws of less than 5m. The Pullars Creek Fault has the same SW-NE orientation with the offshore Sisters Shear zone (Kula et al., 2009), discussed further in Chapter 5 .

Proximity to the measured section to the Pullars Creek fault has resulted in intense calcite infill of microfractures within the measured section (Figure 3-39).

The outcrop at Owaka Heads is part of the Tuhawaiki Formation and sits conformably below the Pounaweia Formation. Extensive work has been undertaken on the stratigraphy and

Figure 3-40 Light grey-brown medium sandstone lens in dark grey siltstone, Owaka Heads.
Note the ripple bedform at basal contact. Younging direction to top of image. 25 cm ruler for scale.

paleontology of the Tuhawaiki Formation. Early workers (Hector, 1877; McKay, 1877; Park, 1904) catalogued numerous marine fossils, including the important *Haastina haastina*. Marwick (1953), also undertook extensive paleontological work in the area, identifying numerous occurrences of *Ostrea* sp. B, *Haastina haastina* and *Tancredia allani*, among others.

Sedimentologic studies of the Tuhawaiki Formation and surrounding Murihiku rocks in the Papatowai subdivision was undertaken by Speden (1971).

3.1.6.2 Sedimentary description

Total stratigraphic thickness of the measured section at Owaka Heads is 20 m (Figure 3-44). This section comprises a series of inter-bedded dark grey siltstone beds and very fine, light grey, moderately sorted sandstone beds with occasional medium sandstone lenses towards the top of the section (Figure 3-40). Sandstone makes up roughly 80% of the outcrop section.

Bedding displays a fining-up character with the top of individual beds tending to be intensely burrowed. This has resulted in there being few internal structures evident, although some fine scale planar laminations are present in basal beds. Elsewhere in the formation, sedimentary structures are more widespread with parallel and cross laminations, contorted and chaotic bedding, intra-formational brecciation and scour-and-fill structures evident (Speden, 1971).

To the immediate east of the measured section, on the downthrown side of the Pullars Creek Fault, packages of parallel, cross and ripple laminated bedding

Figure 3-41 Rafted fossilised log, Owaka Heads. Hammer for scale.

Figure 3-42 Extensive bioturbation in silty tuff, Owaka Heads.

Note, this section of outcrop was located 100 m SE of the measured section. Pencil for scale.

surfaces are evident, (Wood, 1956). Basal contacts within the measured section tend to be sharp, although some ripple bedforms were identified at the base of sandstone lenses (Figure 3-40). These structures are prevalent around rafted logs and are presumed to be caused by turbulence in flow around these structures. In adjacent sea cliff exposures (-46.485497, 169.715795), a light cream coloured silty tuff displays extensive bioturbation (Figure 3-42).

Abundant fossil logs are evident throughout the logged section and display no consistent orientation (Figure 3-41 & Figure 3-44). Also present are conspicuous, well rounded iron-sulphide nodules up to 15 cm in diameter (Figure 3-43). These are hypothesised by this author to have been rafted in the roots of organic material.

Near the top of the measured section a distinct fossil bearing zone, (-46.484146S, 169.711128E), rich in *Antarctica ampliforma* (J.S. Crampton, pers. comm. October 2016), *Ostrea* sp. B, *Haastina haastina* and *Tancredia allani* (Speden, 1971) is present.

Figure 3-43 Well rounded iron-sulphide pebble-cobble clasts in dark grey siltstone, Owaka Heads. Hammer for scale.

Interestingly, at the base of the measured section a 15 cm thick carbonaceous mudstone bed occurs (Figure 3-44).

3.1.6.3 Interpretation of depositional environment

The general fine grained nature of the outcrop, the presence of marine fossils, fossilised organic material, isolated pebble to cobble-sized iron sulphide clasts and ripple bedforms, together with abundant bioturbation, all indicate that the measured section of the Tuhawaiki Formation was deposited in a low energy marine environment.

Conspicuous fossiliferous beds suggest that at times, deposition may have been in an enclosed marine embayment allowing deposition of shells in a mudflat setting. The presence of rare carbonaceous beds further supports this changing environment. The presence of logs suggests that the area may have been close to a shoreline or river mouth.

This interpretation is consistent with that of Speden (1971), who identified the Tuhawaiki Formation as being a conformable continuation of the underlying Ratanui Formation which is also identified as a shallow marine facies.

By way of analogue, the environment of deposition may have been similar to the present day Catlins River estuary.

Figure 3-44 Owaka Heads stratigraphic column.

3.1.7 Warnock Road Quarry – Middle Jurassic (Lower Temaikan)

3.1.7.1 Introduction

The outcrop section is exposed in the highwall of the active Warnock Road Quarry, situated 8.5 km southwest of Owaka, Otago, -46.507182, 169.579163. Access to the quarry is via Warnock Road and site access was attained through the permission of quarry owners, Blackhead Quarries Ltd.

The outcrop (Figure 3-45) represents the upper contact of the Purakauiti Formation and is situated on the northern limb of the NE-SW trending Tarara Anticline (Speden, 1959). This formation is a 1200 m thick sedimentary package of mudstones and fine to medium grained sandstones with thin conglomeratic horizons at the top of the formation. The formation sits conformably between the underlying McPhee Cove Conglomerate and the overlying

Figure 3-45 Mapped section at Warnock Road Quarry. Younging direction is to the north east (left of image). Yellow line represents the measured section. Red arrow indicates highly fossiliferous siltstone bed. Red dashed line designates the gradational formation contact between the Purakauiti and overlying Tucks Bay Formations. Bedding dips 20°NE. Person for scale.

Figure 3-46 *Pleuromya milleformis* shell bed contained in light grey sandstone, Warnock Rd Quarry.

Note sample is not in-situ. Pencil for scale.

Tucks Bay Formation and is situated on the southern limb of the Southland Syncline.

Speden (1971) undertook a detailed sedimentological description of the Purakaiti Formation in the Papatowai Subdivision. At this location, the conformable, gradational formation contact represents a marine transgressive phase with early deposition of the overlying Tucks Bay Formation occurring in slightly deeper water depths than the underlying formation (Speden, 1971; Gardner & Campbell, 2002).

Paleontological work by Gardner and Campbell (1997) who sampled the fossil assemblages at the quarry, constraining the age of the upper Purakaiti Formation to Middle Temaikan. Later work by Adams et al. (2007) determined $^{206}\text{Pb} / ^{238}\text{U}$ detrital zircon ages, dating the outcrop at Warnock Road Quarry as $176 \text{ Ma} \pm 2$, Early Jurassic (lowermost Temaikan). Speden (1971), in his initial work also confined the top of the succession was Lower Temaikan, identifying *Pleuromya milleformis* at the very top of the formation (Figure 3-46).

Two samples were taken from this location, both prepared for thin section work and one prepared and tested for porosity and permeability, SEM and XRD analysis (Appendix 1).

3.1.7.2 Sedimentary description

The outcrop at Warnock Road Quarry provides excellent exposure of a ~50 m thick section of the upper Puakaiti Formation. However, due to highwall safety and inability to access

Figure 3-47 Bioturbation in fine grained sandstone, Warnock Rd Quarry.
Note, sample is not in-situ. Pencil for scale.

the higher reaches of the outcrop, only a 6.5 m section of the uppermost Purakauiti Formation was logged (Figure 3-45 & Figure 3-51).

The measured section at -46.507114, 169.579238 (Figure 3-45), comprises a sedimentary succession dipping gently 20°NE. The lithology includes interbedded fine grained, light grey, moderately sorted sandstone and occasional carbonaceous sandstone with rare coaly lenses up to 600 mm x 20 mm thick. A highly fossiliferous mudstone and severely weathered limonite enriched medium sandstone beds occur at the top of the measured section (Figure 3-45).

Sporadically within the light grey sandstone, both in the measured section and in blasted blocks on the quarry floor, burrows and abundant marine fossils are evident and include: *Grammatodon*; *Retroceramus inconditus*; *Meleagrinnella* cf. *echinata*; *Pleuromya milleformis*; *Astarte* sp. A; *Tancredia* sp. A (Speden, 1971; Gardner & Campbell, 1997) (Figure 3-46 & Figure 3-47). Of note in the measured section is a 60 cm thick highly fossiliferous and carbonaceous, dark grey, fine grained sandstone bed, with well-preserved bivalves evident, including: *Isocyprina* sp., *Neocrassina*(s.l.) sp., *Vaugonia*, *Grammatodon*

Figure 3-48 Planar laminations in fine grained sandstone, Warnock Rd Quarry. Red arrow indicates small scale cross bedding. Scale shows centimetre divisions. Note sample is not in-situ.

(*I.*) *implicates* (Gardner & Campbell), *Tetorimya* sp., *Pleuromya milleformis*; *Tancredia allani*; *Thracia* sp., *Retroceramus inconditus* (Marwick), *Meleagrinella* cf. (Smith), *Liostrea* sp., *Pinna* sp., and *Camptonectes* sp. (Gardner & Campbell, 1997) (Figure 3-49).

Internal structures are rare in the lower portion of the measured unit and unidentifiable in the highly weathered upper portions. However, in some blasted blocks lying on the quarry floor, planar laminations with rare cross bedding and climbing ripples evident (Figure 3-48). Basal contacts of sandstone beds tend to be sharp with some units displaying ripple bedforms, with wavelengths of up to 25 cm (Figure 3-50).

3.1.7.3 Interpretation of depositional environment

Within the measured section at Warnock Road Quarry, the overall fine grained nature of the outcrop; the occurrence of shell beds (and the abundance of marine fossils in the wider quarry setting), combined with the presence of coaly lenses and carbonaceous units, and the presence of ripple bedforms on the base of sandstone beds, suggests that deposition

Figure 3-49 Highly fossiliferous, carbonaceous fine grained sandstone, Warnock Rd Quarry.

Younging direction is towards top of image. Pencil for scale

Figure 3-50 Massive limonite rich medium sandstone bed, Warnock Rd Quarry.

Top of image displays limonite rich bed with erosional lower contact with wavelengths up to 25 cm. Bedding dips NE towards camera. Ruler with 10 cm markings for scale. (Photo credit: Greg Browne).

occurred in a shallow marine environment that may have included shore face (Boggs, 2001; Plint, 2010).

Further evidence of a shore face transition can be seen in the low angle planar cross bedding (Figure 3-48) and shell beds present in the wider quarry setting. This interpretation is consistent with that of Speden (1971) who interpreted the Purakaiti Formation as a shallow water-estuarine facies.

The top of the measured section represents the boundary between the Purakaiti and overlying Tucks Bay Formations (Figure 3-51). This conformable transition to a shelfal facies of the mudstone dominated Tucks Bay Formation is hypothesised by previous authors

(Speden, 1971; Gardner & Campbell, 1997, 2002) to represent a sequence of marine transgressive – regressive phases occurring during that time.

The measured section at Warnock Road Quarry is therefore consistent with the wider Purakaiti Formation representing a shallow water and at times shoreface facies (Speden, 1971).

Figure 3-51 Warnock Rd quarry stratigraphic section.

3.1.8 Cathedral Caves – Middle Jurassic (Lower Temaikan)

3.1.8.1 Introduction

Cathedral Caves, South Otago, is situated on the southern limb of the Southland Syncline and at the core of the local NW-SE-trending Fortification Syncline (Figure 3-66). This proximity to the axis of the local syncline is reflected in the gentle dip of beds at 005° NE.

A 12 m thick stratigraphic section was measured in the cliff face exposure at the north end of Waipati Beach, -46.608337, 169.381156 (Figure 3-52). Access to the outcrop is off the Chaslands Highway, via the Pratt Rd carpark and Waipati Beach access track. Permission was gained from local Iwi who manage the Tautuku Block X Section 3C Trust, in which Cathedral Caves is located.

Two samples were taken from this location, both were prepared for thin section, porosity / permeability analysis and SEM imagery with one also prepared for XRD analysis (Appendix 1)

Figure 3-52 Typical outcrop at Cathedral Caves.

Outcrop displays interbedded sandstone, siltstone and coal beds. Red arrow indicates tree stump cast. Note the wavy bedding which is prominent in much of the outcrop (yellow arrow). Bedding dips 005° NE (away from viewer). Metre ruler for scale.

Figure 3-53 Fine scale climbing ripples, Cathedral Caves.

Ripples indicate a paleo flow direction towards the southwest (left of image). Strike and dip of cross bedding: $150^{\circ}/40^{\circ}\text{NE}$. Younging direction towards top of image. Pencil for scale.

Figure 3-54 Fluid escape structure in interbedded sandstone, Cathedral Caves.

Vertical chimney and slumped beds. Note the distinct upward deflection of individual beds at chimney interface. Metre ruler for scale.

To date, little work has been undertaken on the stratigraphy or paleontology at the Cathedral Caves outcrop. During investigations into the geology of the Papatowai subdivision, Speden (1971) included this section in the Purakauiti Formation, and identified the age as Lower Temaikan. Identification and mapping of the local Fortification Syncline was also made by Speden (1959) during his regional mapping campaign.

3.1.8.2 Sedimentary description

The measured section at Cathedral Caves consists of a gently dipping (005°NE),

Figure 3-55 Nested cross bedded stratification in fine grained sandstone, Cathedral Caves. Cross beds are 3 m wide by 70 cm deep. Hammer for scale.

Figure 3-56 Carbonised, in-situ tree stump, Cathedral Caves. Note intact root system still visible, red arrow. Metre ruler for scale.

decimetre to metre interbedded succession, comprising of thin siltstone beds and graded, fine to medium sandstone beds. Sandstone comprises almost 90% of the outcrop. Laterally discontinuous coal beds up to 20 cm thick, abundant woody fragments and coaly lenses are also present in the section.

Internal structures in sandstones include small scale planar and cross laminations, with the latter indicating a paleo-flow direction towards the SW (Figure 3-53).

Sandstone units are light brown, volcanoclastic, moderately sorted, with basal contacts being sharp or erosive, occasionally

Figure 3-57 Cathedral Caves stratigraphic section.

displaying flame structures. Beds often display either trough cross bedding or planar bedding. Four metres below the top of the measured section (Figure 3-57), a fine sandstone unit displays nested trough cross bedded sandstone that incise into the underlying unit. Troughs are 3 m wide by 70 cm deep (Figure 3-55). A carbonised in-situ tree stump is present in the underlying unit with the root system still visible (Figure 3-56).

Impressive soft sediment deformation also occurs, displaying dewatering / degassing escape chimneys and slumped units (Figure 3-54). The chimneys are near vertical with the largest example extending over a 4 m vertical interval,

penetrating multiple overlying beds. The width of each pipe is up to 15 cm and clearly displays upwards warping of the host beds. The observed chimneys originate in two sandstone units within the measured section (Figure 3-57).

These sandstone intervals displayed numerous escape events, all with similar morphology to that illustrated in (Figure 3-54).

3.1.8.3 Interpretation of depositional environment

The Purakauti Formation has previously been interpreted to represent a constantly fluctuating shallow – water marine to estuarine depositional environment (Speden, 1971). However, the presence of in-situ tree stumps, abundant woody fragments and coal seams, suggest the section represented at Cathedral Caves was deposited in a purely terrestrial setting. The lack of any coarse units suggest that deposition occurred some distance from source, though sufficiently high energy to produce the trough cross bedding.

Figure 3-58 Typical distal plain fluvial environment model, prone to ephemeral flooding. This model reflects deposition in regions where ephemeral run-off forms a network of shallow, interlacing, poorly defined channels (After Miall, 1985).

Also of note in the outcrop is the general sheet like nature of bedding and the presence of laterally discontinuous coal seams. These structures are consistent with a broad coastal plain setting, characterised by fluvial sandstone distributary channels and associated overbank architecture. This type of deposit is consistent with a landscape that was prone to ephemeral runoff, causing flash floods with rapid sediment deposition of which the dewatering structures maybe indicative (Figure 3-58).

The dewatering events are especially notable and formed after deposition of the overlying interbedded unit. These chimneys possibly resulted from a co-seismic event or through rapid sediment loading of the still unconsolidated, water saturated underlying unit. Loading may have caused the underlying unit to dewater, thus creating these chimneys. Further evidence of this delayed dewatering can be seen in the thickness of the overlying interbedded unit deformed by the dewatering (some 4 m). It is likely that these chimneys would have also created an extrusive sand volcano at the top of the structure, although this feature was not observed, and is assumed to have been eroded.

Another possible mechanism for these structures are that they formed as a result of gas injection into a fluidised unit (Frey et al., 2009; Hilbert-Wolf et al., 2016; Sherrod et al., 2016). Frey et al. (2009), suggest that there is a significant morphological difference between water escape and gas escape structures. They suggest that water-escape structures are bounded by downwards-warping of beds before vertical expulsion of fluids. In their experiments, they found that injection of gas into a fluidised unit resulted in the intra-formational fluid becoming unstable and resulted in subsequent upward expulsion of this fluid. This expulsion created unique morphological upward deflection of bedding and

the associated creation of escape chimneys into the overlying units. Specifically in the gas injection results, no initial downward deflection of bedding occurs (as seen in purely water escape features) (Frey et al., 2009).

As seen in Figure 3-54, the purely upward deflection of the individual beds suggests that observed chimneys at Cathedral Caves are a result of the upward movement of gas through the sedimentary interval. Although the underlying unit (origin of chimney) is a sandstone, it is possible that this gas could have migrated into the unit during the period after deposition and before degassing. The source of this gas is hypothesized by this author to be one of the inter-formational coal seams (assumed to be peat at the time of formation).

3.1.9 Dummy's Beach – Middle Jurassic (Upper Temaikan)

3.1.9.1 Introduction

Dummy's Beach, Southland is situated on the southern limb of the Southland Syncline. Access to the beach is via the Progress Valley Road end and accessed through the farm land of Mr Alan Smith. Two, well exposed shore platform sections were measured (Figure 3-59). The northern section (Dummy's Section 1 (DS1): -46.632608, 169.256896), measured 56 m total stratigraphic thickness and stratigraphically overlies Dummy's Section 2 (DS2) (-

Figure 3-59 Typical shore platform at Dummy's Beach.

Outcrop represents base of measured section 1 (DS1). Bedding dips $118^{\circ}/48^{\circ}\text{N}$, younging direction to left of image. Person for scale.

46.632836, 169.256024). The base of DS2 is situated 69 m southwest of the base of DS1 and has a total stratigraphic thickness of 19.5 m. Four samples were taken from these two sections, two were prepared for thin section, porosity / permeability analysis and SEM imagery and one of those samples was analysed by XRD (Appendix 4).

Similar to the measured section at Cathedral Caves, little sedimentological or paleontological work has been undertaken on the outcrop at Dummy's Beach. Early investigations on the geology of the wider Catlins region were undertaken by Park (1886);

Figure 3-60 In-situ petrified tree stump, Dummy's Beach. Younging direction is towards the top of image. Hammer for scale.

(Park, 1904). Building on this work, Speden (1959) undertook further analysis and interpretation on the alignment of fold axes in the region. During this work he identified that the axial trace of the Progress Valley Anticline intersects the coast some 1.2 km SW of DS2 in Teahimate Bay (Figure 3-66), which would account for the steeply northward dipping beds at this location.

Noda et al. (2002), updated the stratigraphy and sedimentology in the Waikawa district, (contiguous to the SW with the Dummy's Beach section). Pole (2004), also carried out detailed geological

investigations on the Fortrose-Chaslands region of the Catlins coast, extending the work undertaken by Speden (1971) in the Papatowai subdivision to the north, to encompass the area towards the southern boundary of the Southland Syncline (Figure 3-62).

Pole (2004) divided the region into two tectonic blocks, the Slope Point Block and the Brothers Block, separated from each other by major NW-SE trending faults. These are the inferred Porpoise Bay Fault and a new shear zone which he proposed as the Waiparau Tectonic Zone (WTZ) (Figure 3-62), with the latter providing surface expression through Long Beach, immediately to the north of the DS1. The proximity to the WTZ could account for the abundance of calcite veining and the sheared nature of the outcrop at the top of that section.

Whilst undertaking his work, Pole (2004) proposed new names for several conglomeratic units belonging to the False Islet Formation in the region: the White Head Conglomerate, Black Bluff Conglomerate, Hoiho Conglomerate and the Slope Point Conglomerate (Figure 3-62). He further identified an additional five conglomeratic units belonging to the Slope

Figure 3-61 Dummy's Beach stratigraphic section 1 (DS1).

Point conglomerate (Figure 3-62).

In an attempt to correlate the lithology of the Slope Point and Brothers Block's to the Papatowai Subdivision, Pole (2004), suggests that all purely terrestrial sediments within the Papatowai Subdivision be placed into the False Islet Formation of Speden (1971). He goes on to suggest that the units within the Brothers Block are Early Jurassic in age. This contrasts with the palynological data presented by Noda et al. (2002) for the nearby Shades Beach (section 3.1.10), which suggests an age of Middle Jurassic (Upper Temaikan). Pole's assertion of an Early Jurassic age would imply that the False Islet Formation covers a much wider chronostratigraphic age range than constrained by Speden (1971) and Noda et al. (2002).

For the purpose of this study, and consistent with proximal outcrop locations, a Middle Jurassic (Upper Temaikan) age is assigned.

3.1.9.2 Sedimentary description

The outcrop measured in DS1 comprises a series of interbedded, centimetre to decimetre scale, dark grey siltstone to fine grained, light grey sandstone beds at the base of the section. Beds thicken to metre scale medium to coarse sandstone beds towards the top of succession. These are overlain by a very coarse to pebbly sandstone unit displaying abundant crossbedding and rare boulder sized clasts up to 1.2 m diameter

Figure 3-62 Map of Waikawa District, southern area of study.

Area shows location of the major conglomerates (lines of schematic cobbles) and outcrop locations. Hatched areas show inferred zones of major tectonic breaks. Note dashed area to east of map showing most southerly mapped extent of Speden (1971). Map modified from Pole (2004).

Figure 3-63 Disorganised pebble-boulder conglomerate, base of section 2, Dummy's Beach.

Conglomerate is matrix and clast supported with coarse sandstone lenses throughout (metre ruler for scale). Younging direction is towards right of image.

(Figure 3-61). It is inferred that these would have been eroded from the underlying conglomeratic units situated upstream of the paleoflow (see base of DS2, Figure 3-65). This uppermost section often displays calcite veining and is likely associated with the WTZ (Pole, 2004).

Carbonaceous mudstone horizons are common throughout the lower 4m of the section (Figure 3-61). These horizons often have in-situ tree stumps with root systems visible (Figure 3-60) and can be considered as paleosols. These horizons often grade-up from a minor coaly horizon. Coaly lenses occur throughout the lower portion of the measured section as do occasional rafted fossil logs. Fossilised organic

Figure 3-64 Fractured conglomerate clasts, Dummy's Beach. Metre ruler for scale.

material is abundant throughout the both measured sections.

Medium to coarse sandstone units display moderate to poor sorting, with grains up to 2 mm entrained in coarser beds. Medium sandstones are massive with no internal structures evident, whereas finer units display planar laminations. A paleoflow direction was able to be measured from cross bedding (Figure 3-61), giving an orientation towards the north east.

Basal contacts of beds throughout the section tend to be sharp.

The second measured section (DS2) is located 69 m south west of the base of DS1 and consists of a disorganised pebble-boulder, matrix and clast supported conglomerate with coarse sandstone lenses (Figure 3-63, Figure 3-64 & Figure 3-65). Strike and dip of bedding is: $118^{\circ}/52^{\circ}/N$. The measured section starts in a 7 cm thick coal and carbonaceous clay horizon and is identified as a paleosol by Pole (2004), who states that this represents the most northerly indicator of subaerial deposition in the Brothers Block. However, the carbonaceous mudstone bed with in-situ tree stumps from DS1 is an additional 74 m stratigraphically above this horizon, and can therefore redefine this most northerly extent.

Clasts within DS2 are up to 60 cm in diameter (Figure 3-63) and are well rounded to sub-rounded and moderate to poorly sorted. Granite, andesite, chert and minor sandstone clasts make up the majority of the conglomerate with some clasts showing evidence of fracturing (Figure 3-64), indicating significant post depositional stress to fracture the clasts.

There are no obvious signs of imbrication within the conglomeratic portion of the outcrop. Internal structures are generally absent, apart from within a four metre-thick medium

Figure 3-65 Dummy's Beach stratigraphic column 2 (DS2).

sandstone bed, which displays abundant cross bedding, giving a paleocurrent direction towards the north east (Figure 3-65). The measured section grades up to a medium-coarse sandstone with occasional finer units displaying carbonaceous lenses. Basal contacts tend to be sharp.

3.1.9.3 Interpretation of depositional environment

The presence of in-situ, fossilised tree stumps and abundant organic material indicates that deposition was terrestrial. The presence of conglomeratic units and graded successions terminating in paleosols at the tops of these cycles, with the addition of abundant cross bedding in coarser units, suggests a sinuous fluvial, channelised facies (Miall, 1985).

This interpretation supports Pole (2004) who inferred that deposition at this location was on a broad alluvial plain. The presence of abundant cross bedding at the top of DS1, combined with the presence of boulder clasts, suggest that the environment included high energy but fluctuating discharge events. Furthermore, the well-rounded nature of the conglomerate clasts indicates they were transported, some distance from source by the rivers.

This interpretation correlates to nearby locations (Cathedral Caves, Curio Bay), where a broad floodplain environment that was prone to widespread flooding is inferred.

3.1.10 Shades Beach – Middle Jurassic (Upper Temaikan)

3.1.10.1 Introduction

Shades Beach, Southland is located on the southern limb of the Southland Syncline and is 1.8 km geographically south west of DS2 at Dummy's Beach. Access to Shades Beach is via the Progress Valley Road and then across farm land and 4WD track of Mr Alan Smith to gain access to the beach. The outcrop is exposed in shore platform and coastal cliff exposures at the southern end of the beach and covers a 26 m thick stratigraphic section at - 46.641660, 169.235813.

The measured section is situated on the northern limb of the local WNW-ESE trending Waikawa Syncline, and around 1000 m south of the fold axis of the NW-SE trending, Progress Valley Anticline (Speden, 1959; Noda et al., 2002; Pole, 2004) (Figure 3-66). The strike and dip at this location is $115^{\circ}/25^{\circ}/S$. Three samples were taken from this location, all prepared for thin section and porosity / permeability analysis, with two selected for SEM imagery and one for XRD analysis (Appendix 1). Similar to the other mapped sections investigated during this thesis project, early geological investigations were undertaken by

Figure 3-66 Regional map of Waikawa District, Southland showing anticline and syncline orientations.

Park (1886, 1904), with Watters et al. (1968), mapping the area for his regional 1:250,000 scale map. Noda et al. (2002) undertook lithostratigraphic and sedimentological mapping of the Waikawa district over a three-year period. They proposed four lithofacies associations for the region, A, B, C & D, based on their distinctive lithologies, assigning this outcrop location to their lithofacies C which they described as characterised by repetitions of fining/thinning-upward conglomerate-sandstone sequences. During their investigations

Figure 3-67 In-situ carbonised tree stump and paleosol, Shades Beach. Note the lighter coloured erosional trough bedded, medium grained sandstone, incising into the top of the carbonaceous unit. Hammer for scale.

they identified palynological evidence to support an Upper Tertiary age. Mapping of the wider Fortrose-Chaslands region was undertaken by Pole (1999, 2001); Pole (2004).

3.1.10.2 Sedimentary description

The measured outcrop section replicates 'section 9' of Noda et al. (2002). The section represents a series of fining-up successions (with a general fining towards the top of the

measured section), comprising thick, metre scale, light grey, medium to coarse grained, moderately sorted, trough bedded sandstone units with carbonaceous material throughout (Figure 3-70). Fining-upwards cycles are up to 2.3 m thick with basal contacts often incising into underlying carbonaceous units (Figure 3-67). Sandstones grade up into laterally continuous coal seams up to 20 cm thick and medium brown carbonaceous mudstone paleosols, with in-situ tree stumps (Figure 3-67).

Abundant sedimentary structures are evident throughout the measured

Figure 3-68 Normal fault at top of measured section, Shades Beach.

Strike and dip: $218^{\circ}/78^{\circ}/SE$, offset of 70 cm. Red triangle designates fining up cycle. Hammer for scale.

Figure 3-69 Fossiliferous siltstone beds, Shades Beach.

A) Plant macrofossils in grey mudstone. Pencil for scale. B) Well preserved plant fossils (*Cladophlebis indica*) in light grey mudstone. Hammer for scale. Note, these specimens were not in-situ and had recently been exposed due to a slip in the adjacent cliff face; the origin of beds correlates to the upper 10 m of the measured section.

Figure 3-70 Shades Beach stratigraphic column.
Red triangles indicate fining-up sequences.

section. These present as planar, convolute and cross bedding with sets up to 80cm thick and an inferred paleoflow from the SW (Figure 3-70). This is in contrast to Noda et al. (2002), who had a flow direction for this section towards the south east.

A few erosive basal contacts display rip up clasts, up to 10 cm in diameter, with the majority of other basal contacts tending to be sharp and planar.

A normal fault (S/D: $218^{\circ}/78^{\circ}/SE$), offsets the upper portion of measured section by 70 cm and likely reflects the regional structural trend (Figure 3-68) and the associated offshore NE-SW trending Sisters Shear Zone (Kula et al., 2009).

Immediately adjacent to the measured section, a recent seaciff landslide had exposed and transported fresh rock to the beach. This material was from a section correlating to the top 10m of the measured section and contained abundant plant fossils including, *Cladophlebis indica* (Figure 3-69).

3.1.10.3 Interpretation of depositional environment

The presence of in-situ carbonised tree stumps and the near-by presence of plant fossils,

combined with the total lack of any marine macrofossils, indicate that the section at Shades Beach was deposited in a terrestrial environment. This is similar to the majority of formations associated with the south-eastern Murihiku Supergroup in the Catlins region and to Dummys Beach just to the north (section 3.1.9).

The several metre-thick fining upward cycles terminating in paleosols, often with erosive trough bedding incising into the underlying unit, and the abundance of cross bedding, suggest that this section is consistent with a sinuous sandy fluvial facies, perhaps as series of meandering point bar sequences. The presence of pervasive coal seams indicates that deposition occurred in a low-relief floodplain of a sinuous river with well-developed channels, allowing the accumulation of significant amounts of organic material in overbank areas (Miall, 1985).

3.1.11 Waikawa Harbour – Middle Jurassic (Upper Temaikan)

3.1.11.1 Introduction

Situated at the entrance to Waikawa Harbour, Southland, this outcrop location consists of two measured sections. Waikawa Section 1 (WS1): (-46.632714, 169.152491, base of measured section) is a 43 m thick stratigraphic section located on the east side of the harbour. WS1 is located 1.8km geographically northeast from Waikawa Section 2 (WS2): -46.646468, 169.142160 (base of measured section). WS2 is a 180 m thick stratigraphic section located on the northern side of North Head (Figure 3-66). The sections are partial replications of sections 4 and 6 respectively of Noda et al. (2002).

Seven samples were collected over both sections, five prepared for petrographic work and three for porosity / permeability analysis. Of these, two were prepared for SEM imagery

Figure 3-71 Base of measured section 2 at North Head. Bedding dips at $140^{\circ}/50^{\circ}/\text{NE}$, towards the left of image. Note distinct contact between coarse grained sandstone (right of image) and overlying conglomerate (red arrow). Person for scale.

Figure 3-72 Moderately sorted clast-supported cobble conglomerate, Waikawa Harbour. Outcrop is located at the base of section 1. Note the slight imbrication (red line). Metre ruler for scale.

and one for XRD analysis (Appendix 1). Access to the sections is via Yorke Road and then by foot along the beach.

The measured sections at Waikawa Harbour are located on the southern limb of the Southland Syncline and are also on the southern limb of the local NW-SE trending Waikawa Syncline (Park, 1886; Speden, 1959; Noda et al., 2002) (Figure 3-66).

WS1 is a poorly exposed seacliff, with portions of the section being obscured by vegetation. WS2 represents a well exposed outcrop of shore platform and seacliff (Figure 3-71).

Early fieldwork in the area was undertaken by Park (1886) who proposed that these strata be assigned to the Waikawa Harbour Beds. However, this name has not been widely adopted by subsequent workers and was not included in the publication on the Murihiku Supergroup by Campbell and Coombs (1966). Pole (2004), proposed the naming of four prominent conglomeratic units within the Slope Point and Brothers Blocks, as the White Head Conglomerate, Black Bluff Conglomerate, Hoiho Conglomerate and the Slope Point Conglomerate Members (the latter being comprised of five distinct subdivisions) (Figure 3-62).

Within the Waikawa District, extensive stratigraphic and lithological mapping was undertaken by Noda et al. (2002).

At the most southerly extent of the Brothers Block, the measured stratigraphic succession is separated from the Slope Point Block by the NW-SE Porpoise Bay Fault (Pole, 2004) (Figure 3-62). This fault separates the steeply dipping beds at North Head ($140^{\circ}/50^{\circ}/\text{NE}$), from the gently dipping ($098^{\circ}/12^{\circ}/\text{NE}$) beds at Curio Bay on the south side of the harbour. This observation contrasts with the regional mapping of Watters et al. (1968), who

Figure 3-73 Measured section 1 (WS1), Waikawa Harbour. This section mirrors the representative section of lithofacies association C of Noda et al. (2002). Red triangles represent fining-up cycles.

with sub-rounded to sub-angular grains. The measured section displays abundant internal structures, with trough, planar and cross bedding throughout, with sets up to 50 cm thick (Figure 3-73).

At the top of the section a highly micaceous medium sandstone bed is overlain by an organic rich, carbonaceous sandstone with abundant cross bedding and wood fragments up to 80 cm thick. Rare, pink tuffaceous beds occur at the top of the measured section.

proposed that the beds at Curio Bay continued under the harbour to sit conformably under those at North Head.

Based on palynological evidence (*Cladophlebis indica*) of Suggate et al. (1978), and bivalve fossil (*Neocrassina* sp.) of Noda et al. (2002), the units at Waikawa have been assigned a middle-Upper Temaikan (Bajocian-Callovian) age (Noda et al., 2002).

3.1.11.2 Sedimentary description

WS1 is a representative section of the lithofacies association C described by Noda et al. (2002) (Figure 3-73). The measured section consists of a series of fining-up successions of moderately sorted, pebble-boulder grade conglomerate, with clasts up to 3 m diameter (Figure 3-74). These grade-up into metre scale, light grey, moderately sorted, fine to medium sandstone beds,

Figure 3-74 Three distinct conglomeratic units from WS2, Waikawa Harbour.

A) Poorly sorted, cobble-boulder grade. Individual clasts up to 3 m. B) Moderately sorted, clast supported pebble-cobble grade. C) Moderately sorted, matrix supported pebble - cobble grade; note weak imbrication. Coarse poorly sorted sandstone lenses occur throughout all three lithofacies and also comprise the matrix. Hammer for scale in A, 25 cm ruler with 10 cm division for scale in B & C. (Photo B & C, credit Greg Browne).

Basal contacts of all beds tend to be gradational over <10 cm.

WS2 is a representative section of the lithofacies association A described by Noda et al. (2002). The section consists of a series of fining-up successions (Figure 3-75) with each comprised of one of three distinct sheet like conglomeratic units (Figure 3-74). These can be classified as: a poorly sorted, cobble-boulder grade conglomerate, with Individual clasts up to 3 m diameter; a moderately sorted, clast supported pebble-cobble grade conglomerate; and a moderately sorted, matrix supported pebble - cobble grade conglomerate (Figure 3-74). Clasts are well-rounded to sub-rounded, with clasts often highly fractured, indicating significant tectonic stress has occurred.

Clasts are predominantly granite, felsic and intermediate volcanic rocks and occasional sandstones. Coarse, poorly sorted volcanogenic sandstone lenses up to 30 cm thick occur

Figure 3-75 Measured section 2, Waikawa Harbour.
Representative section of Lithofacies association A of Noda et al. (2002). Red triangles represent fining-up cycles.

contacts.

The top 18 m of the measured section consists of an interbedded succession of medium-coarse grained, moderately sorted sandstone fining-upward to fine sandstone / siltstone units. Beds are 10-30 cm thick and heavily fretted. Occasional planar and cross bedding occurs in finer units and basal contacts tend to be sharp (Figure 3-75).

throughout all three units, and also comprise the matrix (Figure 3-76). Basal contacts for conglomeratic units are often sharp but can also display highly erosive scoured contacts with erosive reworking of underlying units represented by rip-up clasts. Poorly developed imbrication was evident in only one conglomeratic unit, 35 m below the top of the measured section (Figure 3-74).

Each of these conglomeratic units fines upward into light grey, moderately sorted, fine-medium grained sandstone beds up to 10 m thick. These units are organic rich and fossiliferous in part. Sandstone beds don't display any internal structures and tend to have sharp basal

Figure 3-76 Typical cobble conglomerate, WS2, Waikawa Harbour. Coarse sandstone lenses (red arrow) up to 30 cm thick, dipping 50°NE (left of image). Weak imbrication is evident (yellow arrow). Bag for scale.

3.1.11.3 Interpretation of depositional environment

Throughout the measured section, no marine fossils were observed, however Noda et al. (2002) identified bivalve fossils (*Neocrassina* sp.) and burrows in adjacent outcrops on the opposite (north west) side of the inlet.

Throughout both WS1 & WS2, abundant plant fossils were identified, i.e. *Cladophlebis indica* (Suggate et al., 1978), suggesting terrestrial or shallow marine deposition. Furthermore, this would imply that without any major unconformity separating the measured sections from those observed by Noda et al. (2002) on the western side of the Waikawa Harbour, that it is likely WS1 & WS2 were deposited in a terrestrial to shallow marine setting, such as a delta or fan delta facies.

The abundance of coarse clastic material with interbedded sandstone would be consistent with a fluvial delta or fan delta interpretation. Perhaps the rivers that fed this coarse clastic material to those delta settings consisted of large coarse-bedload braided rivers which were nearby to the Waikawa area, or reflected deposition at the confluence of two rivers.

The presence of carbonaceous and finer grained horizons further suggest that a floodplain was nearby to the delta / fan delta environment, allowing for the build-up and input of

organic material. This depositional environment would have been affected by fluctuations in sea level or sediment supply, which would have controlled development of the two facies. The aforementioned occurrence of marine fossils in adjacent areas further supports this variance in depositional environment.

The general lack of fossils in outcrop likely reflects the high energy deposition of sediments, such that fossils were unlikely to be preserved. This interpretation supports the findings of Noda et al. (2002) who interpreted the depositional environment at Waikawa Harbour as reflecting an environment influenced by rapid transgression and regression.

These changing depositional settings would therefore allow for the presence of boulder grade conglomerates with sparse internal structures in WS2 to be deposited through a high energy environment with rapid deposition. Whilst also allowing for more distal deposition of sediments in a floodplain environment and account for the presence of abundant internal structures observed in WS1.

The rounded nature and often pitted surface of the individual conglomerate clasts further indicates that the environment was high energy, with the clasts rounded by some considerable transport distance from their source areas.

3.1.12 Curio Bay –Middle Jurassic (Upper Temaikan)

3.1.12.1 Introduction

Curio Bay, Southland, is the southernmost outcrop location studied for this thesis work. Four sections (Figure 3-81) were logged along the seacliff exposure at Curio Bay, Section 1 (CS1): -46.661478, 169.108156 Section 2 (CS2): -46.662533, 169.104578 Section 3 (CS3): -46.661642, 169.097768, Section 4 (CS4): -46.662211, 169.101799.

Ten samples were taken over all sections. Of these, seven were prepared for thin section analysis and three were analysed for porosity / permeability testing and SEM imagery. Of those chosen for SEM imagery, one was prepared for XRD analysis (Appendix 1). All samples were gathered outside the scientific reserve area. Department of Conservation approval was gained for the sampling.

Figure 3-77 Representative outcrop section at Curio Bay.

Outcrop represents measured section CS4. Yellow arrow indicates 40 cm thick coal horizon; blue arrow indicates organic rich paleosol horizon. Both horizons have in-situ tree stumps with intact root systems. Overlying these intervals are interbedded medium sandstone-siltstone units representative of stacked overbank and channel-fill deposits. Red arrow indicates planar tabular bedding. Strike and dip of beds is $92^{\circ}/15^{\circ}$ /NE (towards right of image). Note laterally continuous nature of beds. Metre ruler for scale.

Figure 3-78 Curio Bay measured sections.

Inset shows location of field area with star designating Curio Bay location.

Access to the coastal section is via the Waikawa-Curio Bay Road end. The outcrop is of Upper Temaikan age and has been identified as belonging to the False Islet Formation (Pole, 2004; Tidwell et al., 2013).

The petrified forest at Curio Bay was first recorded by Park (1886). Since that time, extensive work has been undertaken on palynological data at Curio Bay by Raine and Pole (1988); Pole (1999, 2001); Thorn (2005), with Pole (2001) continuing from his earlier works

Figure 3-79 Curio Bay shore platform, showing extent of the petrified Forest.

Red arrows indicate fossil logs, orientation of logs are NW-SE. Bedding dips to the NE, bottom left of image. People on left for scale.

to describe the sedimentology of the outcrop. Pole (2004) further tied those interpretations into the region from Fortrose, Southland at the southernmost extent of the Southland Syncline (some 25 km SW of Curio Bay), to Chaslands Mistake (~20 km NE of Curio Bay and the southernmost mapped region of Speden (1971)).

3.1.12.2 Sedimentary description

Curio Bay is situated on the southern limb of the local Waikawa Syncline with bedding at Curio Bay dipping 15°NE (Figure 3-66). The four measured sections represent a combined 34 m thickness of outcrop and consist of a series of erosional channel-fill and overbank deposition (Figure 3-77).

Channel fill deposits dominate deposition and consist of fine to coarse sandstone, often displaying channel pebble lag deposits. Planar and trough cross bedding occurs sporadically throughout these deposits, with basal contacts often erosively scouring into underlying horizons.

Overbank deposits comprise interbedded sandstone and siltstone deposits with sharp bases. These horizons sometimes display tabular bedding and incise into the underlying unit. Fossilised tree stumps also often project through these deposits.

Throughout all measured sections the dominant lithology is fine to coarse-grained, volcaniclastic sandstone, with occasional pebble grade conglomerate beds. Laterally continuous lignite and carbonaceous horizons occur throughout the sections. In-situ petrified tree stumps with intact root systems, and fallen / rafted logs occur throughout all intervals (Figure 3-79 & Figure 3-80).

Figure 3-80 In-situ petrified tree stump in medium grained sandstone, Curio Bay. Metre ruler for scale.

Figure 3-81 Curio Bay measured sections. Clockwise from top left, stratigraphic sections are CS1, CS2, CS3 & CS4. Paleocurrent measurements are taken from fossilised logs and conglomerate imbrication. Log orientation is not unidirectional and is only somewhat indicative of flow direction.

Figure 3-82 CS3, showing major channel with cut margins and channel fill, Curio Bay. Red line indicates line of channel incision. Height of outcrop is ~15 m .

These organic rich horizons are inferred to be paleosols by this author and in agreement with previous workers (Raine & Pole, 1988; Pole, 2001). These horizons display preferential weathering in outcrop (Figure 3-77). Small scale reverse and normal faults are present, although offsets are generally less than 50 cm (Figure 3-83).

Fine scale sedimentary structures are generally lacking throughout all measured sections, however some beds do display small scale cross lamination (Figure 3-85). More prevalent

Figure 3-83 Measured section 1 (CS1) outcrop, showing massive channel fill deposits, Curio Bay. Note reverse fault (centre of image), Strike and dip: $110^{\circ}/40^{\circ}$ SE with 40 cm displacement, red dashed line. Metre ruler for scale.

are planar and trough bedding with sets up to 1 m thick (Figure 3-77).

Measured imbrication of channel lag conglomerate is also evident and gives a paleo-current orientation towards the southeast. This orientation is similar to that given by fossil log measurements (NW-SE), which, whilst somewhat unreliable due to the various depositional factors associated with flow (e.g. eddies, obstructions etc), support the lag orientation (Figure 3-81). Pebble conglomerates are moderately to poorly sorted, with clasts up to 10 mm in diameter, and often fine-up into a medium to coarse sandstone (Figure 3-84). These channel lag deposits occur at the base of channel structures. Sandstone beds are moderately – well sorted, often carbonaceous, lithic rich with sub-rounded to sub-angular grains. Basal contacts tend to be either gradational or sharp and erosive, often displaying rip-up clasts. Sandstone makes up virtually 100% of the non-coal lithologies, with very minor siltstone beds less than 5 cm thick occurring sporadically at the top of channel successions or overbank flood deposits.

Figure 3-84, Channel lag deposit, Curio Bay.

Shallow channel architecture displaying fining-up sequence of granule conglomerate-medium sandstone, overlain by mud drapes. Pebble clasts are up to 10 mm. Younging direction is towards top of image. Pencil for scale.

Figure 3-85 Cross bedding in medium grained sandstone, Curio Bay.
Younging direction is towards the top of image. 25 cm ruler for scale.

3.1.12.3 Interpretation of depositional environment

The abundance of medium-coarse grained, moderately – well sorted sediment, trough and planar tabular cross bedding, in-situ tree stumps, fallen / rafted logs and numerous paleosols at Curio Bay are all indicative of fluvial deposition. This is consistent with the terrestrial depositional facies described at other locations in the southern portion of the Southland Syncline.

Two main depositional modes are represented at Curio Bay; channel fill and overbank fill (Miall, 1985; Pole, 2001). By far the dominant process is channel fill which accounts for around 90% of the section thickness and can be seen at multiple intervals throughout the measured sections. Perhaps the best preserved channel fill is identified at CS3 where a channel margin incises into a thick section of underlying channel fill (Figure 3-82) and gives an indicated channel depth of around 7 m. This section likely represents the thalweg architecture of a meandering river system (Miall, 2010).

CS2 displays a stacked succession of both overbank and channel fill architecture. The channel fill succession contains interbedded medium sandstone beds displaying trough bedding and distinct fining-up cycles representative of laterally accreting deposition.

Figure 3-86 Overbank deposition, Curio Bay.
Interbedded fine sandstone-siltstone (section overlies coal horizon, depicted in Figure 3-77).
Light coloured intervals are tuff beds. Metre ruler for scale.

Overbank successions are represented by interbedded fine sandstone and siltstone units (Figure 3-77 & Figure 3-86), which unconformably overlie both coal and paleosol horizons with in-situ tree stumps protruding through the clastic deposits. This succession reflects deposition during one of the multiple flooding events at Curio Bay (Pole, 2001) and may have occurred as a crevasse splay deposition out of the channel fill facies and onto overbank intervals (Miall, 2010).

Pole (2001) identified 14 major scour surfaces present in the sea cliff exposures at Curio Bay, suggesting that the region experienced multiple high-discharge flooding events, interspersed with periods of lower energy deposition when peat swamps and paleosol

Figure 3-87 Schematic of Curio Bay flooding event cycle.

Schematic shows a standing forest (A), shallow channel formation during the early phases of flooding (B) and sheet like flooding as the levees are overtopped (C). Paleosol and forest formation would then form after flooding had subsided. (After Pole, 2001).

development were predominant. Channel facies were able to migrate across the flood plain area incising into previous fluvial deposits.

Pole (2001) interpreted deposition at Curio Bay to have occurred within a flash-flood prone, unconstrained distal braidplain environment (Figure 3-87) and points to the relatively small size of trees as indicating that the forest was relatively young when flooding events occurred (less than a few hundred years based on tree ring estimates (Pole, 2001)). He goes on to suggest that the fluvial facies is most similar to model 11 (distal braidplain) of Miall (1985: Figure 3-58).

However the relatively deep nature of the channel incision and obvious channel stacking (Figure 3-83, Figure 3-77, Figure 3-82 & Figure 3-84) suggests that the fluvial architecture was more similar to the classic sandy, mixed load meandering river facies (model 6 of Miall

(1985). The repeated flooding events were of a sufficient scale to either overtop the channel levees or create crevasse splays, felling trees and depositing sediment across a broad area of floodplain. The 'few hundred year' return period of these flood deposits, as suggested by Pole (2001) would subsequently allow the formation of organic rich paleosols to occur.

These features suggest a facies where actively migrating channel distributaries were able to migrate freely across a flood plain with adjacent areas of overbank deposition able to be variously colonised by tress.

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Chapter 4

4.1 Petrography

4.1.1 Introduction

The metamorphic petrology of Murihiku Supergroup rocks and the variations in their zeolite-grade metamorphism are well understood in the South Otago and Southland region (Coombs, 1954; Boles & Coombs, 1977; Coombs et al., 1992) with comparable work undertaken in the North Island on metamorphic petrology (Clark, 1982; Black et al., 1993). The detrital mineralogy and sedimentary petrography of the South Island units is however less well documented, with a relatively small number of publications (Dickinson, 1971; Speden, 1971; Boles, 1974; Cook et al., 1999b; Roser et al., 2002; Noda et al., 2004) and university theses (MacKinnon, 1980) addressing this aspect.

In the North Island, there has been a similarly limited number of studies into the sedimentary petrology of the Murihiku rocks, with work undertaken mainly on outcrop sections (Ballance et al., 1980) and also petroleum well completion reports such as Pluto-1 (Shell Todd Oil Services Ltd, 1991), Pukearuhe-1 (Forder & Bennett, 1988), and Waka Nui-1 (Milne & Quick, 1999). A number of student theses, notably Martin (1967) and Middleton (1993) have also been undertaken. Briggs et al. (2004) included the work of Middleton (1993) and described the geochemical and petrological aspects of the North Island sections and changes in sedimentary composition through time.

For the purpose of this thesis, 57 representative outcrop samples were collected from 11 locations along the South Otago / Southland coastline (Figure 2-1). Petrographic data determined from these samples are used to characterise the sedimentary petrography. To date, no petroleum exploration wells have intersected the Murihiku Supergroup in the offshore Great South Basin (GSB) so the outcrop samples are the best way to characterise the petrographic features which may occur in Murihiku rocks in the adjacent GSB. As aforementioned, in the North Island a small number of onshore and offshore wells have penetrated Murihiku rocks in the basement overthrust units in the Taranaki and Northland basins, allowing sampling of the Murihiku succession at depth (Figure 1-1).

Of the 57 samples collected during this work, 33 were prepared for thin section microscopy and 22 tested for porosity / permeability (with a total of 48 individual core plugs tested from these 22 samples). Of these, 22 samples, 18 were imaged using a SEM of which, nine were prepared and tested for quantitative XRD analysis (Appendix 2). The methodology and techniques for each of the above analyses is outlined in Chapter 2 . In this chapter, the sedimentary petrography of these selected sandstone samples is described.

Analysis of these samples has been undertaken to assess what, if any, reservoir potential the sampled sections may have and to determine the implications for the offshore Great South Basin. Parameters for this assessment include porosity and permeability analysis and what affects the associated burial history may have had on reservoir quality.

Point counting of thin sections used to determine modal compositions of analysed sandstones in this study, indicates that the samples are feldspathic and lithic arenites and feldspathic and lithic wackes (nomenclature for modal compositions for sandstones is after Williams et al. (1982)). This is consistent with Speden (1971) who identified the sandstones of the Southland Syncline as arenites and greywackes and also Noda et al. (2004) who identified the sandstones of the Waikawa District as poorly to moderately sorted, lithic–feldspathic wacke to arenite.

4.2 Petrography of thin sections

4.2.1 Introduction

Collected samples are representative of volcanogenic, very fine to coarse grained sandstones of the Murihiku Supergroup in the Southland Syncline. Samples range in age between Late Triassic (Oretian) to Middle Jurassic (Upper Temaikan) and are predominantly characterised by poor sorting, sub-angular to sub-rounded grain texture, and their lithic content. Depositional environments range from deep marine, base of slope fan turbidites to fluvial terrestrial facies (see Chapter 3.1 for detail). The volcanogenic sandstones sampled are characterised by the following constituents: 1) their generally low quartz content, 2) a high percentage of volcanic rock fragments, 3) an abundance of plagioclase feldspar, and 4) a high clay content.

All percentages in the following sections are given as a percentage of modal quartz, feldspar and lithic fragment as observed in the thin sections. Components are derived from point

Figure 4-1 Photomicrograph of sandstone sample FMJ-08 (False Islet – Middle Jurassic). Note trachytic lath texture of volcanic rock fragments (VRF). Euhedral to subhedral grains with embayment and dissolution of zoned feldspar (F). Disaggregation of feldspar (Dis F). Chlorite cementation (Cl). Zoom is 10x under cross polarisation.

counting of samples following the method of Ingersoll et al. (1984). Total quartz is given as the sum of monocrystalline and polycrystalline quartz. Total feldspar is given as the sum of plagioclase and potassium feldspar (although no potassium feldspar was observed in thin section). Total lithic fragments are given as the sum of volcanic, metamorphic and sedimentary rock fragments.

4.2.2 Quartz

Other than in one sample (sample BMJ-02, Figure 4-2) quartz is almost always subordinate to other framework grains sampled. Quartz percentages range from 0-74 modal percent, with the average being 10 modal percent across all samples. Both monocrystalline and polycrystalline grains are present with the former dominating and tending to be sub-angular to sub-rounded, often displaying embayment and occasionally displaying graphic

Figure 4-2 Photomicrograph of sandstone sample BMJ-02, Warnock Rd Quarry (Early Jurassic). Moderately poorly sorted fine quartz- and lithic-rich sandstone. Grains are sub angular to sub rounded, contacts tend to be arcuate. Iron stained clay particles around grain boundaries with carbonate and chlorite cementation. Zoom is 10x under cross polarisation.

Figure 4-3 Photomicrograph of sandstone sample RLT-05, Roaring Bay (Late Triassic). Graphic intergrowth of quartz and alkali feldspar nucleating on a subhedral feldspar grain (F) (myrmekitic texture). Zoom is 40x, under cross polarisation.

texture (Figure 4-3). In general, the finer grained and more poorly sorted samples contain a higher percentage of quartz (Figure 4-2).

Diagenesis of quartz grains occurs through grain crushing and pressure solution of grains, indicated by sutured grain boundaries and suggests significant depth of burial. Pressure solution would have allowed pores to become flushed with silica and then re-precipitated as grain rimming cement (Figure 4-6). Similar to feldspar grains, laumontite and also calcite, often replaces quartz.

4.2.3 Feldspars

Feldspar content ranges from 5-90 modal percent of framework grains within the analysed samples, with the average across all samples of 51 modal percent. Plagioclase feldspar is the dominant grain type. The composition of the plagioclase includes anorthite; labradorite; andesine and albite, with albite being the most common (see XRD plot, Appendix 4). No potassium feldspar was observed in thin section and Speden (1971) states

Figure 4-4 Photomicrograph of sandstone sample FMJ-10, Curio Bay (Middle Jurassic).

Feldspars display euhedral to subhedral texture with arcuate to sutured grain contacts. Thin section displays volcanic (VRF) and sedimentary rock fragments (SRF). Feldspars display laumontite replacement. Fracturing of rounded quartz grain (Q). Chlorite cementation (Cl). Zoom is 10x under plane polarisation.

that orthoclase is a very minor constituent of most rocks in the Southland Syncline. He does note however, that the presence of these feldspars in his samples indicates that not all of the plagioclase is of volcanic origin (Figure 4-10).

The percentage of feldspar in relation to quartz generally increases with grain size and is low where lithic content is high. Plagioclase grains occur as euhedral-subhedral shaped crystals and are sub-angular to sub-rounded (Figure 4-4).

Diagenetic alteration of feldspars is common and involves varying degrees of dissolution of the primary plagioclase grains by precipitation of pervasive laumontite (Black et al., 1993), grain crushing and dissolution of framework grains (Figure 4-4). XRD analysis indicates that laumontite cement can account for up to 11% of selected samples (Table 4-5).

4.2.4 Rock fragments

Rock fragments comprise an average 39 modal percent of all analysed slides with a range of 1% to 95% of samples examined (Sample DMJ-04). The overwhelming majority of the

Figure 4-5 Photomicrograph of sandstone sample OMJ-1, Owaka Heads (Middle Jurassic). Medium grained sandstone comprised predominantly of sub-angular to sub-rounded, containing subhedral feldspar and volcanic rock fragment grains in a fine grained matrix. Note fractured euhedral zircon (z)? middle right. Zoom is 10x, under cross polarisation.

lithic grains are represented by andesitic rock fragments with smaller percentages of sedimentary and rare metamorphic grains. Rock fragments tend to be more rounded than other framework grains, due to their ductile nature.

Volcanic rock fragments often display a trachytic lath texture (Figure 4-1) with individual clasts dominated by euhedral plagioclase and albite. Grain rims occasionally display haematite weathering (Sample WMJ-07) and are often suspended in a feldspathic or calcite rich matrix. Embayment and dissolution of grains is common (Figure 4-1).

Andesitic rock fragments have undergone significant diagenesis, with dissolution of grains widespread and replacement by chlorite, calcite and laumontite. Grain crushing has resulted in rock fragments tending to display grain contacts that are arcuate to sutured, indicating significant burial.

Figure 4-6 Photomicrograph of sandstone sample OMJ-1, Owaka Heads (Middle Jurassic). Quartz (Q) overgrowth bubbles (B) rimming rounded framework grains. Zoom 40x under plane polarisation.

The sedimentary rock fragments are comprised mainly of sub-angular to sub-rounded siltstone and fine sandstone, with chert clasts. These rock fragments tend to be present in coarser grained samples.

Groundmass tends to be a very fine clay or mud sized matrix. Grains are often haematite rimmed indicating exposure to weathering and exhibit embayment.

In general the analysed samples are dominated by andesitic volcanoclastic grains comprising up to 39 modal percent across all samples. This is roughly 25% less than the findings of Speden (1971) who identified that andesitic detritus averages 59 modal percent of analysed samples from the Catlins district. This is likely due to differences in point counting methods between the two studies.

4.2.5 Other minerals

Micas are present in most samples throughout the Catlins district, most commonly occurring as dark brown biotite grains which are often distorted by compaction (sample WMJ-07 Figure 4-8). Muscovite is less common, however its inclusion points to a plutonic

Figure 4-7 Photomicrograph of sandstone sample ShMJ-02, Shades Beach (Middle Jurassic). Abundant calcite cementation (C) in poorly sorted volcanogenic sandstone. Framework grains mostly display point contacts, reflecting the initial high intergranular porosity. Note metamorphic rock fragment (MRF) sutured against feldspar grain (F). Zoom 10x under cross polarisation.

or metamorphic terrane providing sediment input. Clinopyroxene is also present in some samples (Table 4-5). These accessory minerals suggest that sediment source was proximal to deposition (Boggs, 2001) as any significant transport distance is likely to have eroded these soft grains. Rare zircons are present in a few samples as euhedral grains with bright interference colours (Figure 4-5).

Pyrite occurs in minor amounts (up to 2 percent total rock), forming as small nodules, either isolated or in small clusters. Its formation is symptomatic of the diagenetic characteristics of the rock and will normally form under reducing conditions, although it may occur as replacement of framework grains.

Montmorillonite is identified from XRD analysis and is present in small quantities throughout the selected samples. It is thought to have formed through alteration of tuffaceous material (Folk, 1968).

Figure 4-8 Photomicrograph of sandstone sample WMJ-07, Waikawa Harbour (Middle Jurassic). Poorly sorted volcanogenic sandstone. Framework grains are predominantly quartz (Q) and feldspar (F) with minor rock fragments (VRF with arrow). Amygdaloidal textured chlorite with in-filled zeolite cementation fills pores (Cl + Z). Note smeared mica (M) between framework grains. Zoom is 10x under Cross polarisation.

4.2.6 Matrix and cement

Matrix comprises up to 38 percent of the total rock, although it is often absent due to replacement from cement. It is represented by clay and silt-size material of which chlorite and calcite can be determined optically, with laumontite and to a lesser extent heulandite identified by XRD analysis. Speden (1971) identified heulandite as forming only in the youngest rocks within the southern reaches of the Murihiku Supergroup.

Cementation in all samples is high (up to 76 percent of total rock), with both siliceous and carbonate cementation common. A micaceous mineral also commonly precipitates as a thin film around the rims of framework grains and is often associated with a zeolite cement which infills remaining pore space. Quartz precipitate rims occur as tiny bubbles around framework grains and are thought to be produced by pressure solution (Figure 4-6).

Calcite cementation often completely fills both primary and secondary pore space and is especially prevalent in fine grained samples (Figure 4-7), and may constitute up to 21 percent of the total rock.

Chlorite is the most common cementing mineral, with an amygdaloidal texture (Figure 4-1 & Figure 4-8) with what appears to be two generations of formation. The first is a fibrous cement choking the pore throats. Where this chlorite doesn't completely eliminate porosity, a second generation of chlorite crystals infills any remaining porosity (Figure 4-9). Alternatively, primary generation of chlorite may also be filled by secondary zeolite cementation (Figure 4-8).

Figure 4-9 Photomicrograph of sandstone sample CcEJ-02, Cathedral Caves (Middle Jurassic). Medium grained, volcanogenic sandstone. Framework grains are predominantly feldspar (F). Note amygdaloidal texture of pore filling, primary and secondary chlorite (Cl). Laumontite (La) cementation replacement of matrix is common through many of the coarser sandstones. Zoom is 40x under Cross polarisation.

4.3 Provenance

The highly volcanoclastic nature of sediments within the Otago / Southland section of the Murihiku Supergroup suggests deposition was adjacent to and relatively proximal to a volcanic arc. Throughout all sections, samples are moderately to poorly sorted, with grain sizes ranging from silt sized (below .06 mm) to very coarse (up to 2 mm). Grains tend to be sub-angular to sub-rounded, with quartz and feldspar grains tending to be more angular than the ductile rock fragments.

The dominance of plagioclase feldspar in all analysed samples and the lesser proportion of quartz grains suggests this source area was of intermediate volcanic composition. Furthermore, the poor sorting and angularity of grains suggests rapid deposition with little reworking or long-distance transport from source to depositional area.

Geochemical analysis by Black et al. (1993); Roser et al. (2002); Briggs et al. (2004) show that there is a clear change in source over time (Figure 1-3). Briggs et al. (2004) postulate that sediment source was likely to be calc-alkaline in character, hypothesising that most of the volcanic rocks in the source catchment of the North Island Murihiku were probably

Figure 4-10 Normalised QFL plot for Southland Syncline Murihiku samples. Divisions are taken from Dickinson et al. (1983).

Table 4-1 Averaged modal data from Southland Syncline Murihiku samples.

Age (NZ stages)	Br-Bo	Hu	Kt (L)	Kt (U)	Pluto-1 Kt (L)
n	2	1	4	14	16
Q	1.3	2.6	0.1	13.9	0.7
F	53.4	84.3	22.8	48.9	12.6
L	45.3	13.1	77.0	37.2	86.8

Q-Quartz; F-total feldspar; L-total lithic fragments. Ages relate to New Zealand chronological stages, L – Lower U - Upper. Note and Pluto-1 data from well drilling sidewall cores (Shell Todd Oil Services Ltd, 1991).

comprised of both andesite, with medium potassium richness, and dacite with medium to high potassium content.

This differs from the South Island succession in that the Murihiku rocks of the Catlins area displays very low potassium feldspar occurrences. This difference is likely due to the changes in arc evolution over time, with more felsic input from Late Jurassic times onwards.

Modal analysis of quartz, feldspar and lithic composition from all field locations reflect the volcanic provenance of the Murihiku rocks in the Southland Syncline (Figure 4-10). Furthermore, the angularity of grains and the high ductile grain content, as well as the presence of less stable accessory minerals, clinopyroxene and micas, indicate that these are first cycle sediments.

Modal framework grains from all locations have been averaged by age of deposition (Table 4-1) and shows an overall increase in quartz content with time. This trend is in line with previous work by MacKinnon (1980) who also identified a similar trend in the outcropping Murihiku in the Catlins district, whilst also recognising a slight increase in the ratio of K-spar

Table 4-2 averaged modal data for Murihiku sandstone samples from the Southland Syncline.

(After MacKinnon, 1980). As cited in Roser et al. (2002).

Age n	Early Triassic 3	Mid- and Late Triassic 9	Jurassic 8
Q	2	8	12
F	24	39	43
L	74	53	45
P/F	0.98	0.9	0.88
Lv/L	0.99	0.97	0.91
Lm	0.6	1.2	2.1
Detrital mica	0.2	0.9	1.7

Q – Quartz; F – total feldspar; L – total lithic fragments; P/F – plagioclase/total feldspar; Lv/L – lithic volcanic/total lithic clasts; Lm – metamorphic lithics.

to total feldspar from .98 in the Early Triassic to .88 in the Jurassic (Table 4-2). Furthermore, when compared to Pluto-1 well data (Table 4-1), the composition of North Island Murihiku rocks is in line with similar aged rocks from the Catlins region and supports the hypothesis that more siliceous input didn't increase until after the Middle Jurassic. Interestingly Briggs et al. (2004) records a decrease in modal quartz during this time, with highest percentages (18 %) in Late Triassic samples and lowest (7%) in samples of Late Jurassic age, i.e. a reverse of what is observed in the southern portion of the supergroup.

These temporal and spatial variations of modal grains between the two discreet sections of Murihiku are consistent with sediment derived from an evolving arc source.

The data presented here, when combined with geomorphological identification from outcrop mapping, reflects the compositional changes over time and are consistent with provenance from an evolving volcanic arc i.e. Roser et al. (2002). Sediment input from an uplifted / incised basement block may also have provided a secondary source to the Murihiku depositional basin (Figure 4-10 & Figure 6-2) and would account for felsic conglomeratic clasts in outcrop. The almost complete lack of felsic material in the observed thin section (and reported as being insignificant in the wider Murihiku rocks of the Catlins district (Speden, 1971)) is likely due to albitization of feldspars.

Spatial and temporal changes along the length of the Murihiku sedimentary basin (Figure 1-3) further support the hypothesis that source material was derived from multiple source areas and again reflects the evolving tectonic and volcanic arc provenance of the Murihiku rocks.

Cook et al. (1999b) identifies that within the offshore geology of the Great South Basin, the Murihiku Terrane extends as far south as Stewart Island and that the most likely source material for initial deposition of the terrane is the Median Batholith (Figure 6-2). Noda et al. (2004) also supports this hypothesis, further suggesting that the Brook Street Terrane may also have provided late stage clastic input into the Murihiku basin.

4.4 Diagenesis

Diagenesis across all samples reflects the highly volcanoclastic provenance of the Murihiku rocks and the high percentage of ductile grains present within. Low grade zeolite metamorphism affects the Murihiku Supergroup throughout all regions of New Zealand (Coombs, 1954; Black et al., 1993). This is evident as laumontite and to a lesser extent, heulandite cementation of matrix and associated albitization of framework grains.

Within the sampled sections for this work, the most common diagenetic mineral is chlorite. This is observed infilling pore space and replacing pyroxenes in volcanic rock fragments. It is also often seen replacing the matrix to form intergranular cement (Figure 4-4, Figure 4-2 & Figure 4-8).

Calcite also predominates as a cement in several samples (e.g. Figure 4-7). Calcite is likely to have originated from the clay rich matrix in conjunction with the albitization of feldspathic detrital framework grains or from the dissolution of bioclastic material (macrofossils) within the sediment.

Figure 4-11 Montage of petrographic data, DMJ-04 – Dummy's Beach, Southland.

Images on top row left-right show: field sample and drilled core plugs, SEM images 500 x and 100x magnification respectively. Both SEM images taken using back scatter imaging at 15kv setting. Bottom row left to right: thin sections at 10 x plane polarisation, 10 x cross polarisation, 40 x cross polarisation. All thin sections impregnated with blue dye for porosity determination.

Studies of zeolite facies metamorphism within the Murihiku have identify that there is a close relationship between albitization and zeolitization, with the albitization of plagioclase directly correlated to grain size (Boles, 1974; Boles & Coombs, 1977; Boles, 1991; Black et al., 1993). Samples studied in this thesis show that sandstones with a high degree of calcite cementation tend to show lower albitization. Calcite formation during early diagenesis may therefore act to limit zeolitization.

Fracturing of brittle framework grains and conglomerate clasts is not common, although does occur in some samples (Figure 4-4). Given the significant depth of burial and later exhumation (Noda et al., 2004), this lack of grain crushing is likely due to the early formation of pore filling calcite cement. Deformation of ductile grains is however significant, with grains often almost completely disaggregated (Figure 4-1). Compaction of these grains creates sutured or arcuate grain contacts, choking pore throats and drastically reducing permeability and intergranular porosity. Dissolution of framework grains has also occurred and is a likely source of the abundant clay cementation present.

The ratio between lithic and feldspar grains is directly proportional to variations in grain size. Across all samples, any significant decrease in grain size will result in a reduction of ductile lithic content and an increase in feldspar content. This relationship reflects transportation distance from source and related winnowing that detrital grains undertake during this process.

Table 4-3 Tabulated porosity / permeability data from Southland Syncline Murihiku Supergroup.

Location	Facies	n	Avg Porosity %	Avg Permeability mD	Age (NZ stages)
Dummy's Beach False Islet Shades Beach Waikawa Harbour Curio Bay	Fluvial	35	9.4	0.2	Kt (U)
Cathedral Caves					Kt (L)
Owaka Heads	Paralic	3	7.6	0.0	Kt (U)
Cannibal Bay	Shelf	4	6.8	0.0	Kt (U)
Warnock Rd					Kt (L)
Roaring Bay	Upper Slope	4	5.1	0.0	Br
Sandy bay	Base of Slope	2	4.5	0.0	Hu

Note general decrease in porosity with depositional environment and correlating age / depth of burial. n=45. NZ stages refer to New Zealand geological units Ururoan (Hu) to Upper Temaikan Kt (U) (see Figure 2-2).

The most significant diagenetic process that affects porosity / permeability of sandstones within the Murihiku rocks, is the reduction of these physical properties by zeolitization and cementation. Chlorite extensively replaces volcanic lithics and feldspars, and presents as a dual phase diagenetic process with initial fibrous lining of pores and a secondary infilling of remaining porosity by euhedral crystals (Figure 4-9).

The general lack of brittle framework crushing suggests that the dual stage chloritization occurred early in the diagenetic process. This cementation effectively eliminated all macro porosity leaving only micro porosity from dissolution of framework grains and from fracture porosity (Figure 4-11).

Any pore space not filled by chlorite was then potentially occupied by calcite and later zeolite. As aforementioned, these two diagenetic minerals were emplaced while the rocks still contained considerable intergranular macro porosity (Figure 4-7). Minor authigenic, cubic pyrite nodules are present in occasional samples (FMJ-05), with XRD analysis of selected samples also identifying this small inclusion (2% of sample).

Occasional secondary porosity is visible as isolated pores resulting from dissolution of a specific grain, however these pores are rare and have no impact on reservoir quality.

4.5 Porosity and permeability

Porosity values were determined from point count data as visual porosity (300 counts) following the Gazzi- Dickinson point-counting method (Ingersoll et al., 1984), and from core plug analysis (Appendix 2). Porosities across all samples are low with minimum porosities recorded of 2.3% in sample ShMJ-02, Shades Beach (Upper Temaikan). The maximum recorded porosity (14.3 %) was measured from sample DMJ-04, Dummy's Beach (Upper Temaikan) (Figure 4-11).

Visual porosities (both in hand specimen and in thin section) are low in all samples, reflecting the highly indurated nature of the Murihiku rocks in the study area.

Across all samples, permeability was also low, with the majority of samples recording a null value. A maximum permeability value of 2.03 mD was recorded in sample DMJ-04 (Figure

Figure 4-12 Porosity / permeability plot for Murihiku samples by facies.

Due to the null permeability values for most samples, these were assigned a nominal .001 mD to enable them to plot on the graph.

Table 4-4 Murihiku Supergroup porosity / permeability, Pukearuhe-1.

Pukearuhe-1				
Sample		Depth (m)	Porosity (%)	Permeability (mD)
Zone 4	8	1917	17	0.65
	9	1924	15	0.75
	10	1932	4	1.33
	11	1952	12	0.49
	12	1958	4	1.15
Zone 5	13	2244	26	0.75
	14	2249	18	1.06
	15	2258	24	0.78
	16	2300	10	0.001
	17	2335	24	1.01
	18	2347	28	0.83

4-11). It is important to note that this sample had slight fracture porosity / permeability and therefore may give unrepresentatively high values.

When plotted by facies, the porosity / permeability data (Figure 4-12) shows a distinct increase in porosity from deep water to terrestrial. This correlation is also reflected in the age of these samples, with the older samples tending to display lower porosity values (Table 4-3). This correlation is reflective of the diagenetic effects these rocks have been exposed too.

Where available, the inclusion of porosity / permeability data for Murihiku samples in petroleum industry well data, shows there is a close correlation between measured samples analysed from the Southland Syncline region and from those of the North Island samples (Figure 4-13).

Whilst a number of petroleum wells have intersected the Murihiku Supergroup strata in the North Island, Pluto-1 is the only well to present core measured, porosity and permeability data (Figure 4-13). Both Pukearuhe-1 and Waka Nui-1 intersected the Murihiku, however only log derived porosity / permeability values are given for Pukearuhe-1 (Table 4-4), with qualitative porosity values given for Waka Nui-1, stating only very minor porosity was observed (Cook, 1999). The log derived values from Pukearuhe-1 likely over

Figure 4-13 Porosity / permeability plot per sample location in the Southland Syncline.

Measured permeability's with null values were assigned a nominal .001 mD value to allow plotting. Note Pluto-1 well data is also included.

represent the physical properties of the rock, as they likely represent fracture porosity / permeability rather than primary reservoir potential.

A number of previous studies have presented porosity values for the Murihiku rocks within the Southland Syncline. Cook et al. (1999a) noted that porosity measurements from a number of sandstones along the Catlins coast range from 4 to 16% with an average of 10%. The maximum and mean porosity from that study are similar to those from this current study (average 8.5%). Boles (1974) records between 1.8% and 7.2% porosity (average 4.6%) in Triassic Murihiku rocks at Hokonui Hills, but further details on the type or size of pores (e.g., macro vs. micro) is not provided and no permeability measurements are given.

4.6 X-ray Diffraction (XRD)

A small selection of nine samples were selected for quantitative X-ray Diffraction (XRD) analysis (Appendix 1). All sample preparation and interpretive work was undertaken by the GNS Science Geothermal Analytical Laboratory, Wairakei.

The purpose of this analysis was to allow identification of clay mineralogy to be determined, thus helping to determine the diagenetic minerals that have precipitated within the Murihiku rocks of the Catlins district.

XRD analysis has confirmed thin section work that feldspars are the dominant mineral present. Interestingly, the older samples (CcEJ-02 – Kt(L), BMJ-02 – Kt(L), SEJ-09 – Hu and RLT-06 – Br-Bo) all contained a higher percentage of quartz than was observed in thin section (Table 4-5) (see Figure 2-2 for age definitions). This high percentage of XRD identified quartz is attributed to lithics with a quartz content (e.g., andesitic rock fragments) and to authigenic clay mineralisation.

Zeolite mineral type was identified by XRD analysis as laumontite, the dominant zeolite species present, comprising up to 11 percent total rock. Also present in small quantities is stilbite, and whilst not identified in XRD samples, heulandite is identified in the youngest rocks of the Southland Syncline (Middle Jurassic) by Speden (1971).

Albitization of feldspar grains is also common with most samples displaying this transition. No potassium feldspar was identified in the samples analysed for XRD and this is consistent with thin section microscopy work which also failed to identify any framework grains of this composition.

Clay mineral identification confirmed an abundance of chlorite as the dominate clay mineral present in these samples. Smectite clays also present which comprises up to 21 percent total rock in sample SEJ-09 from Sandy Bay.

A number of heavier iron rich minerals were also identified such as pyrite, sericite and Fe-Ti oxides (Table 4-5).

Table 4-5 XRD mineral percentages for Murihiku Supergroup Sandstone samples.

	Abundance %								
	CcEJ-02	SEJ-09	RLT-06	BMJ-02	CMJ-10	DMJ-04	FMJ-05	ShMJ-03	WMJ-07
	2016001478	2016001479	2016001480	2016001481	2016001482	2016001483	2016001484	2016001485	2016001486
Quartz	18	27	50	30	3	4	16	16	13
Plagioclase	55	52	39	55	88	85	75	74	65
Montmorillonite					2	8			
Chlorite	8			9			5	5	5
Clinopyroxene	15				2		2	5	
Stilbite	4				5				
Calcite		21							
Laumontite			11	6					5
Magnetite						3			
Pyrite							2		
Titanite									12

Field sample numbers are given for identification i.e. SEJ-09. A reference table is listed in Appendix 1. 10 digit numbers are assigned by GNS as internal identification.

Margin of Error: Abundance estimates are determined through successive refinement of cell parameters; the position, width and orientation of each mineral. Values are given to the nearest whole number. The margin of error for phase concentrations is proposed as follows: 0-10 %±10%; 10-50%±5%; 50-100%±2%.

4.7 Scanning Electron Microscope (SEM)

SEM imagery was undertaken to better understand the relationship between framework grains, pore space and any clays present. Twenty representative samples from all 11 outcrop locations were imaged at GNS Science, using a JOEL NeoScope bench top SEM JCM-6000 at 15 kv setting with both back scatter and secondary images taken at 50x, 100x, and 500x zoom levels (six images per sample).

Figure 4-14 SEM micrograph of Shades Beach, Middle Jurassic.

Sample ShMJ-03, image settings at 15kv at 500x magnification. Red arrow indicates Chlorite platelets. Yellow arrow indicates blocky calcite.

Due to the highly cemented nature of all samples and the very low porosity, imaging of any pores was problematic.

Figure 4-14 shows a micrograph for Shades Beach, Southland. The SEM image shows minor macro porosity with pore lining chlorite platelets stacked face to face (right of image). Blocky calcite additionally fills pore space between detrital framework grains.

Figure 4-15 SEM micrograph of Owaka Heads, Middle Jurassic.

Sample OMJ-01, image settings at 15kv at 500x magnification. Yellow arrow indicates partially dissolved feldspar grain.

Detrital feldspar grains are often resorbed, appearing fluted under the SEM (Figure 4-15). Although no XRD analysis was undertaken on this sample it is likely that this framework grain is albite. Dissolution of such framework grains has created secondary microporosity. Average porosity for this sample was 7.6% with nil permeability recorded (Figure 4-13).

Figure 4-16 shows a micrograph from Roaring Bay, Otago. This Late Triassic sample has undergone significant compaction and cementation from both silicate and carbonate cementation as well as zeolitization (with laumontite making up 11 percent total rock, Table 4-5).

Zeolites are often difficult to differentiate from other cements without undertaking quantitative energy dispersive X-ray analysis. This interpretive work was not undertaken during the course of this thesis, as the purpose of SEM work was to inform and illustrate grain texture. As such, all identification of cements is made through reference material e.g. Welton (1984).

Figure 4-16 SEM micrograph of Roaring Bay, Late Triassic.

Sample RLT-06a, image settings at 15kv at 500x magnification. Yellow arrows indicate blocky, pore filling laumontite. This is confirmed from XRD analysis (Table 4-5). Red arrow highlights significant pore filling cement against a framework grain.

4.8 Reservoir quality

Within the Late Triassic to Middle Jurassic samples of the Murihiku Supergroup of the Southland Syncline, all sample are of poor reservoir quality. They display low porosities and negligible permeability and have been significantly affected by diagenesis. Across all depositional facies and age ranges, intergranular porosity has been filled by authigenic chlorite and calcite, and additionally been altered by zeolitization. Any macro porosity remaining after this early stage diagenesis, was likely destroyed through compaction of ductile grains which would also have choked the pore throats, further reducing permeability.

The majority of remaining measured porosity analysed during this thesis work are therefore attributed to microporosity. This has likely occurred due to partial dissolution of framework grains or retained within the intergranular clays.

Occasional isolated macro porosity is present, however this does not contribute to the rocks reservoir potential as the pores are totally isolated.

Across all 11 outcrop locations investigated within this thesis, only one sample displayed any sort of reservoir potential. The outcrop at Dummy's Beach (Figure 2-1 & Figure 4-11) displayed porosity of 14% and 2 mD at 5 Mpa confining pressures. The sample of Upper Temaikan age, is a medium to coarse sandstone, with a high lithic content. A potential cause for these physical properties is the fractured nature of the samples analysed, leading to an anomalous reading. It does however provide an interesting potential target for future research. The fractured nature of the sample is consistent with well data from both Pluto-1 and Pukearuhe-1, where any reservoir potential in Murihiku rocks from those wells was recognised to have been from fractured successions (Forder & Bennett, 1988; Shell Todd Oil Services Ltd, 1991).

Table 4-3 highlights that the younger rocks of the Murihiku Supergroup may exhibit better potential reservoir quality. As aforementioned, the offshore successions of younger Murihiku Supergroup could contain up to another 6 km of sediment, deposited from Middle Jurassic to Late Cretaceous time, or about 85 ± 10 Ma (Kamp & Liddell, 2000).

By Early Cretaceous time, sedimentation was originating from an evolved volcanic arc that at that time had a much higher siliceous component i.e. Roser et al. (2002) (Figure 1-3). It

can therefore be hypothesised that the younger portions of the Murihiku preserved in the offshore Great South Basin would contain more quartz framework grains with these sediments potentially less deeply buried and therefore less altered by low-grade burial metamorphism. Offshore, where it is hypothesised that these younger Murihiku successions will occur, there is potential that the rocks retain more of their original porosity / permeability due to this lower level of metamorphism.

It is therefore recommended that any future petroleum exploration of the Murihiku focus on these younger sediments. Further research into their depositional facies will also be required to align them to the depositional facies identified through this research, as containing reservoir potential.

Chapter 5

5.1 Seismic analysis of the Great South Basin

5.1.1 Introduction

The offshore Great South Basin (GSB) is located to the southeast of New Zealand, and is approximately 100,000 km² in size (Figure 6-3). The GSB is situated east and south of southern New Zealand, extending in an easterly direction toward the submarine Campbell Plateau (Lipski, 2004). The basin extends to 50°S with water depths ranging from shallow coastal waters near the South Island and Stewart Island, to base of slope depths greater than 1,500 m. Contiguous with its northern boundary is the Canterbury sedimentary basin.

For the purpose of this thesis, a high level assessment of the geological formation and petroleum exploration history of the GSB is made. Additionally, identification of Murihiku Supergroup structures within the basin are made in a number of seismic reflection lines, highlighting possible areas for future oil and gas exploration.

5.1.2 Basin formation

The GSB and adjoining Canterbury Basin were formed during a period of late Mesozoic extension at the eastern margin of Gondwana during breakup of the super continent, broadly coinciding with the late phases of the Rangitata Orogeny (Suggate et al., 1978). A subsequent period of mid-Cretaceous rifting further created accommodation space allowing >10 km of sediment accumulation of Late Cretaceous-Neogene age rocks to be deposited (Cook et al., 1999b).

Throughout the long-lived Permian-mid-Cretaceous subduction on the eastern margin of the Gondwana supercontinent, a number of tectonostratigraphic terranes accreted to the Gondwana margin to form the present day basement underlying the GSB. The basement terranes of New Zealand (or Zealandia) that underlie the GSB comprise the Western Province rocks of the Buller and Takaka terranes and Eastern Province rocks (Landis & Coombs, 1967; Mortimer et al., 2014). These two provinces are separated from each other by the Median Batholith (Figure 1-1 & Figure 5-2).

Figure 5-1 Stratigraphy of the Great South Basin, displaying formations penetrated by all wells. Sequence stratigraphy divisions after OMV New Zealand 2010, modified from Schjølter et al. (2010).

The Eastern province rocks include the Brook Street, Murihiku, Dun Mountain / Matai and Caples and Torlesse terranes (Coombs et al., 1976; Bishop et al., 1985; Cook et al., 1999b) (Figure 5-2). Beneath the GSB these terranes strike NW-SE and are separated from each other by large scale faults or melange belts that reflect the varied extensional, transform and compressional history of the basin's evolution (Constable & Crookbain, 2011).

Deformation within the GSB is largely confined to the Cretaceous, with Gondwana-rift related extensional faulting forming horst and graben structures that dominate the basement architecture and allow the GSB to be divided into a number of sub-basins (Figure 5-2) (Beggs, 1993). Structural fabric within the basin generally runs sub-parallel to accretionary strike orientation (i.e., NW-SE), although late Cenozoic compressional faulting along the north western margin of the basin has reactivated Mesozoic structures which generally have a distinct SW-NE orientation (Cook et al., 1999b).

This Mesozoic structural orientation reflects initial basin formation during the rifting phase from ~105 Ma. One of these structures is the ENE-WSW striking Sisters Shear Zone, which had offset of ~4 km (Kula et al., 2009; Ghisetti, 2010). Initiating in the Late Cretaceous (~89 Ma), this offshore extensional detachment fault system projects along the northwest boundary of the GSB (Kula et al., 2009) (Figure 5-2). This structural trend is reflected by onshore, north-east trending faults in the region, such as the Pullers, Mill Creek and Settlement Faults (Turnbull & Allibone, 2003). This period of basin rifting was completed by 82 Ma (Ghisetti, 2010).

Post-rift from 82 to 19 Ma was a relatively quiescent, tectonically passive phase, with only minor pulses in deformation occurring during this time (Ghisetti, 2010). These pulses in deformation are hypothesised to relate to local subsidence occurring during compaction of water rich sediments undergoing rapid burial or from far field stress generated in adjacent regions (Ghisetti, 2010).

During the period of mid Cretaceous rifting, clastic deposition within the basin were sourced from Western and Eastern Province rocks and the Median Batholith, including the volcanoclastic sediments of the Murihiku Supergroup. These sediments were deposited into the large, complex half-graben system created by the expanding rift (Cook et al., 1998). Representative facies within the Murihiku Supergroup included terrestrial, fluvial deltaic to marine, base of slope, fan and turbidite sequences (see Chapter 3).

Cook et al. (1999b) postulates that field information from near Stewart Island shows Murihiku sediments present at that location, and if this is correct, then the Supergroup strata would appear to extend over both the Brook Street Terrane and the Median Batholith in places.

This hypothesis is supported by Ghisetti (2010) who also identifies that the Brook Street Terrane is overthrust by the Murihiku Terrane along the Letham Thrust Fault. Furthermore, lithological data collected from basement cuttings in Tara-1 are postulated by Cook et al. (1999b) to represent Jurassic Murihiku Terrane strata. Onshore-offshore continuation of the Murihiku Terrane can be clearly mapped on seismic data (Figure 5-2, Figure 5-4 & Figure 5-6). Within the nearshore portion of the GSB, seismic data shows compressional features that are structurally contiguous with the onshore from this region, indicating that these features are unequivocally part of the Murihiku Supergroup (Ghisetti, 2010; Brady, 2011). In the deeper parts of the basin, mapping of these structures is made difficult due to resolution of seismic data at depth.

Figure 5-2 clearly shows a series of fault bounded, NW-SE trending depocentres that are aligned with the structural trend of the underlying basement terranes. Seismic interpretation undertaken by OMV New Zealand (Constable & Crookbain, 2011), concludes that the northern depocentre contains excellent half graben architecture (Figure 5-3) that has resulted from late Mesozoic extension and is likely underlain by Matai Terrane basement rocks, whilst in the Central Sub-basin depocentre, deeper parts of the succession likely contain Murihiku Supergroup rocks (Cook et al., 1999a; Cook et al., 1999b; Brady, 2011; Constable & Crookbain, 2011).

5.1.3 Petroleum activity in the GSB

Petroleum exploration within the basin began in the 1970's, and to date, over 50,000 line kilometres of 2D and three modern 3D seismic reflection surveys have been acquired. Despite this data coverage the basin however remains lightly explored with just eight wells drilled. Kawau-1A, drilled in 1979 by Hunt International Petroleum Co Ltd was a sub-commercial gas/condensate discovery with recoverable reserves of 461bcf, proving the basin has a working petroleum system. Two other wells within the basin, also drilled by Hunt International; Tara-1 and Toroa-1 had strong shows, although neither well was tested.

Figure 5-2 Inferred position of offshore basement terranes within the GSB (top). Bottom image is a 3D view of top basement (mid Cretaceous). Central sub-basin and more northerly depocentres are clearly defined through structural controls exerted by terranes. Note the on / offshore extension of NW-SE Hillfort Fault (red arrow) marking the northern boundary of the Murihiku Supergroup. The SW-NE trending trace of Sister Shear Zone is highlighted with yellow arrow. (After Constable & Crookbain, 2011).

Figure 5-3 DUN06-07 seismic line showing half graben architecture in the northern sub-basin. The seismic line is orientated NW-SE. Chronostratigraphic Intervals correlate to ages of OMV New Zealand (see Figure 5-1). Horizontal scale is ~50 km, vertical scale is 3-6 seconds TWT. (After Constable & Crookbain, 2011).

Whilst interest within the basin has remained constant since offshore exploration began, it has failed to see the required investment to properly de-risk this frontier basin. Prospectivity remains high however, with a proven petroleum system driving exploration.

To date all wells have drilled the Cretaceous – Cenozoic sedimentary succession, targeting basement highs (with the exception of Toroa-1 and Rakiura-1, as these wells failed to reach basement) (Figure 5-1) (Cook et al., 1999b). The emerging Jurassic Murihiku play is opening up new opportunities for exploration companies looking for stacked pay intervals in the basin.

Figure 5-4 DUN06-19 seismic line delineating the Southland Syncline. The folded sedimentary strata of the Southland Syncline forming the large central block. The structure forms a large four-way dip closure at the Kawau Sandstone level (top Hoiho Group, see Figure 5-1) and amplitude anomalies are indicated. The probable flat-spot at the crest of the structure suggests reservoir bearing intervals. Line interpreted by GNS Science. (After Uruski & Ilg, 2006).

5.1.4 Murihiku seismic character

Deposition of the long lived Murihiku Supergroup rocks, resulted in accumulation of thick sedimentary successions within the offshore. Lithologies are represented by coals, sandstones, carbonaceous mudstones, siltstones and conglomerates (see Chapter 3). These lithologies were deposited in fluvial, paralic, shelf and slope settings during transgressive and regressive phases of deposition. As shown in this study, the Late Triassic to Middle Jurassic reflects an overall regression. Within the North Island occurrences of the Supergroup, Late Jurassic rocks transgress to become fully marine during that time (i.e., a transgression after the Middle Jurassic). A regressive phase is then noted from latest Jurassic & earliest Cretaceous becoming non-marine again (G Browne, pers. comm.

Figure 5-5 OMV08-121 seismic line showing fluvial and deltaic package, Early Cretaceous.

Top box shows uninterpreted section, bottom shows interpreted succession in a half graben. (After Constable & Crookbain, 2011).

Figure 5-6 GP10-306BP1003 seismic line showing faulting and deformation of the Murihiku. Vertical scale is 1.9 sec TWT, horizontal scale is ~22 km. (After Brady, 2011).

February 2017). It can therefore be hypothesised that this trend would also occur in the GSB at that time.

As shown in this study, the most prospective reservoir rocks within the Murihiku Supergroup are Middle Jurassic and younger fluvial sandstones. To date no petroleum wells have intersected the Murihiku at depth within the GSB, so it is difficult to attribute seismic velocities to this sedimentary package. Seismic facies interpretation must therefore be employed to identify any potential features within this sedimentary package.

Facies mapping is defined by Sangree and Widmier (1977) as the identification of a three dimensional seismic reflection package containing specific characteristics which differentiate it from surrounding patterns. These characteristics are identified through the internal and external geometry of the feature in combination with its unique seismic velocity. Fluvial seismic facies tend to have variable amplitude velocities with discontinuous reflectors displaying parallel to convergent nature (Cook et al., 1999b).

Potential fluvial reservoir intervals are evident as illustrated in Figure 5-4 & Figure 5-5. Figure 5-4 shows parallel, high amplitude reflectors at the apex of the Southland Syncline and are suggested to be a reservoir bearing intervals within this pre-rift section by Constable and Crookbain (2011).

Figure 5-7 DUN06-09 seismic line showing Late Jurassic Murihiku Supergroup.

Top two boxes show uninterpreted section and the bottom box shows interpreted nested channels with high amplitude channel sands and apparent gullwing architecture. Vertical scale is in seconds, TWT. Colour bar on right shows amplitudes.

Other work undertaken by explorers in the basin have identified fluvial facies within the Early Cretaceous, 'basement' to K20 section (see Figure 5-1) (Figure 5-5). In this interpretation by Constable and Crookbain (2011), these fluvial successions tend to have a somewhat chaotic, lower amplitude character than the laterally continuous higher amplitude deltaic facies. These could reflect high energy deposition (such as at False Islet or Waikawa Harbour) or a potential coaly facies, perhaps deposited through overbank processes.

Within the underlying Murihiku succession, these types of deposits are also present. Figure 5-7 shows characteristic "gullwing" channel and levee structures in the upper Jurassic section, with high amplitude parallel reflectors interpreted by this author to be sands. The adjacent nested channels display a more chaotic character with onlap of these channels onto the existing channel margins and are interpreted to reflect periods of rapid deposition. Such channels would likely include sands as part of their sediment fill.

As mentioned above, the continuous onshore-offshore nature of the Murihiku Terrane has enabled several trapping styles to be identified within this package. In the nearshore portion of the basin, fault bounded structural closure is common against NW-SE trending ridges and are interpreted to reflect the major antiform and synforms mapped within the onshore Catlins region (Figure 5-6) (Brady, 2011). Further basinward into the Central Sub-Basin, the Murihiku thrusts upwards into the overlying sediments (Figure 5-4). Trapping at this level will occur as both structural and stratigraphic plays. These may occur either as structural drapes over basement highs (Figure 5-4), or as deepest sediment fill in onlapping onto the margins of half and full graben structures. Stratigraphic pinch-out on channel margins is also likely, as channel avulsion occurs (Figure 5-7). Throughout the basin these variations in play type, creates significant variability, and provides an abundance of exploration targets for industry.

Going forward, the pre-rift / earliest syn-rift Murihiku Supergroup in the GSB will require significant further scientific evaluation in order to further de-risk this emerging play.

Chapter 6

6.1 Discussion

6.1.1 Scope of thesis

In this chapter the key findings from chapters 3 to 5 will be addressed and discussed. The thesis has attempted to undertake:

- Detailed lithological, sedimentological and facies observations and interpretations, from outcropping Late Triassic to Middle Jurassic Murihiku rocks of the Southland Syncline.
- A description of the mineralogy of these rocks to determine provenance, diagenetic history and reservoir quality (including porosity and permeability measurements linked to the petrography).
- Review of GSB Murihiku prospectivity.

Much of this work has not been undertaken by previous workers. In particular, the addition of facies interpretations for Murihiku outcrops included here have not previously been undertaken. Secondly, the depositional trends between the Late Triassic and Middle Jurassic has not previously been described. Thirdly, no previous work has undertaken to measure porosity and permeability in the Murihiku outcrop rocks (as opposed to petrographic porosity determinations).

Chapter 3 deals with the primary aim of this study which was to undertake mapping of selected Murihiku Supergroup outcrop locations of Triassic and Jurassic age within the Southland Syncline. Lithological and sedimentological aspects of these outcrops are interpreted and depositional facies assigned to each location.

Chapter 4 investigates the secondary main aim of this study and assesses the petrographic properties of selected samples acquired during outcrop mapping. This chapter also deals with the provenance and diagenetic history of samples, utilising X-Ray diffraction and scanning electron microscopy imaging to support this aspect of the study.

The third main focus of this study, and also covered in this chapter, evaluates what, if any, reservoir potential the Murihiku Supergroup may have. Porosity and permeability testing

was undertaken in conjunction with the aforementioned techniques on selected samples, in order to assess these properties.

Chapter 5 gives a brief overview of the geological evolution of the Great South Basin and looks at Murihiku occurrences within the offshore basin. Reservoir facies identification is suggested as are trapping and play types.

6.1.2 Facies interpretation

On the northern limb of the Southland Syncline, between deposition of rocks at Roaring Bay (Oretian, Late Triassic) and those Sandy Bay (Ururoan, Early Jurassic), a marine transgression occurred (Figure 6-1). This is evident in outcrop between the two locations by a deepening in the interpreted depositional environment. At Roaring Bay (to the north of Sandy Bay) the interpretation presented here is of an outer shelf to slope, channel facies. As sedimentation continued into the Early Jurassic, Sandy Bay outcrops are interpreted to be deep water, base of slope, overbank turbidite facies.

As deposition continued into the Middle Jurassic, the youngest outcropping rocks in the Southland Syncline (False Islet Formation, Middle Jurassic, Upper Temaikan) reflect a regional regression during that time. From Sandy Bay, Early Jurassic (Ururoan) to Cannibal Bay, Middle Jurassic (Lower Temaikan) deposition shifts from base of slope, to a shallow water / shelfal and finally to a fully terrestrial facies at False Islet. Immediately to the south of the Southland Syncline axis at False Islet, the outcrop at Owaka Heads (Upper Temaikan) transitions back to a shallow water / paralic facies. Inland at Warnock Road quarry outcrop, Middle Jurassic (Lower Temaikan), the depositional environment reflects a shallow water / shore face facies (Figure 6-1).

South of Warnock Road quarry, all other outcrops studied are interpreted to be terrestrial facies with both braided river and meandering fluvial depositional elements recognised. This transition thus represents a significant regressive phase during deposition at that time. It is important to note that not all outcropping Murihiku rocks on the southern limb of the Southland Syncline were deposited in a terrestrial environment, with older, marine facies exposed in crests of local anticlines (Speden, 1971).

The observed terrestrial environments reflect a range of fluvial environments, from broad high energy floodplain or braided river system, such as those outcropping at Waikawa

Figure 6-1 Murihiku Supergroup, Southland Syncline by age, facies, location, group, formation and lithology. Central panel displays transgressive / regressive sequence. Green and yellow triangles represent regional fining stages refer to New Zealand geological time units (see Figure 2-2). Note, blank sections indicate lack of sufficient

Harbour (Upper Temaikan), to a meandering river facies with overbank architecture at Curio Bay (Upper Temaikan).

6.1.3 Petrography

The samples selected for petrographic analysis comprise very fine to coarse grained, feldspathic and lithic arenites and feldspathic and lithic wackes, as classified by Williams et al. (1982). The age range for samples is Late Triassic (Oretian) to Middle Jurassic (Upper Temaikan) and they are predominantly characterised by poor sorting, sub-angular to sub-rounded grain texture, and high lithic content. Depositional environments range from deep marine, base of slope, fan turbidites to fluvial terrestrial facies (see Chapter 3 for detail).

The four petrographic features that characterise the volcanoclastic sandstones sampled are: 1) their generally low quartz content, 2) a high percentage of volcanic rock fragments, 3) an abundance of plagioclase feldspar and 4) a high clay content. These attributes reflect the highly volcanogenic nature of samples collected.

Quartz is subordinate to other framework grains in almost all samples, averaging 10 modal percent and dominated by monocrystalline grains. Modal petrographic analysis identified that quartz percentages, whilst always small, did increase slightly from Late Triassic to Middle Jurassic samples (Chapter 3). This increase is consistent with previous studies that also noted this trend (Coombs, 1954; Speden, 1971; MacKinnon, 1980). Interestingly whilst petrographic work undertaken by Shell Todd Oil Services Ltd (1991) for Pluto-1 in the North Island showed a similar quartz percentage in Lower Temaikan samples (Figure 1-3 & Table 4-1), Briggs et al. (2004) identified a reverse trend for modal quartz percentages within the North Island Murihiku samples, showing in that study that modal quartz percentages decreased from Early Jurassic to Middle Jurassic (Briggs et al., 2004). These spatial and temporal changes along the length of the Murihiku Terrane reflect the derivation from an evolving arc source and localised plutonic basement input due to uplift in the hinterland, weathering and erosion.

In all analysed samples plagioclase feldspar was the only feldspar observed, averaging 51 modal percent across all samples, the highest mineral component identified. The lack of potassium feldspar is consistent with previous workers in the region who identified that orthoclase is a very minor constituent of most rocks in the Southland Syncline (Speden,

1971). The low amounts of acidic volcanic content in samples points to a source that was dominated by intermediate composition. The increase in modal quartz percentage through time indicates that as the arc evolved, more siliceous material was provided to the depocentre (Figure 1-3).

Through XRD analysis of samples, albitization of feldspar was identified. This replacement process can help explain the lack of alkali feldspar in samples.

Volcanic lithic grains dominate, with subordinate sedimentary and rare metamorphic lithic grains also present. The high percentage of these ductile grains accounted for 39 modal percent of analysed samples. The grains themselves tend to be sub-angular to sub-rounded suggesting that transport distance from source was relatively short. However, the depocentre must have been a sufficient distance from direct volcanic input, as any lava flows or pyroclastic material are not observed within the Murihiku Supergroup, (Coombs, 1954; Speden, 1971; Carter, 1979; Pole, 2001). Furthermore, the high percentage of these grains remaining in samples points to these rocks being first order sedimentary cycle.

The high cementation of Murihiku rocks is a significant factor in determining any reservoir potential. All analysed samples have undergone low-grade zeolite metamorphism with laumontite, stilbite and to a lesser extent heulandite (as identified by XRD analysis). Cementation in all samples is high (up to 76 % of total rock), with both quartz and carbonate cementation common.

The most common cementing mineral is chlorite that presents with an amygdaloidal texture. Chlorite cementation can occur as a dual phase process, firstly occurring as a fibrous cement that partially or totally fills primary porosity. Where the pore space is not entirely filled, a secondary euhedral chlorite crystal infills any remaining porosity. Alternatively, primary fibrous chlorite may also be filled by calcite or secondary zeolitization (Figure 4-9).

Calcite cementation is also very common and can account for up to 21 percent of total rock and tends to occur in finer grained rocks. Calcite is likely to have originated from the clay rich matrix in conjunction with the albitization of feldspathic detrital framework grains, or from the dissolution of bioclastic material (macrofossils) within the sediment.

Samples studied in this thesis show that sandstones with a high degree of calcite cementation tend to show lower albitization. Furthermore, studies of zeolite facies metamorphism within the Murihiku have identified that there is a close relationship between albitization and zeolitization, with the albitization of plagioclase directly correlated to grain size (Boles, 1974; Boles & Coombs, 1977; Boles, 1991; Black et al., 1993; Noda et al., 2004). Calcite formation during early diagenesis may therefore act to limit zeolitization.

6.1.4 Provenance

Across all outcrops, Murihiku sediments reflect a strongly volcanoclastic provenance. It is hypothesised here and in agreement with previous workers (Speden, 1971; Carter, 1979; Noda et al., 2002) that the source was an evolving andesitic volcanic arc. This proximity could have provided significant amounts of detrital material in the form of air fall deposits and lava flows. Whilst there is no direct evidence in the study area of either the latter or of any pyroclastic material, a significant proportion of conglomerate clasts and individual detrital grains are comprised of this intermediate – felsic igneous source material (Mackie, 1935; Speden, 1971; Roser et al., 2002). The lack of lava flows therefore suggests that sediment deposition was some distance from source. This is further supported by the roundness of individual clasts, which are generally sub-angular to sub-rounded. Additionally, the moderate amount of felsic igneous clasts observed in conglomerates suggests that granitic basement rock must have been exposed in the broader catchment area allowing such granitoid rocks to feed into the Murihiku depocentre (Mackie, 1935; Speden, 1971) (Figure 6-2). The implication of this is that if there was a volcanic arc (i.e. intermediate andesitic) adjacent to the Murihiku depocentre, there must have been saddles or paleovalleys across the arc, whereby rivers were able to bring granitic clasts from the Median Batholith or further afield, and deposit them along with the arc volcanoclastic sediments (Figure 6-2). This palaeographic interpretation is supported by Speden (1971) who also made similar observations during his mapping of the Papatowai Subdivision. Paleocurrent measurements taken from fossilised logs, basal sole marks, flutes and cross bedding, both from this author and previous workers (Speden, 1971; Carter, 1979; Pole, 2001; Noda et al., 2002), indicate a general paleo-flow direction from south west to north east. This detritus was transported through a series of meandering rivers systems where

significant rainfall events and moderate gradients enabled entrainment of large boulders (up to 3 m diameter at Waikawa Harbour, although Speden (1971) records a 15 m diameter boulder in the McPhee Cove Conglomerate).

These flood events also likely overtopped the channel levees, flooding the surrounding landscape and felling the local forests, such as at Curio Bay, Shade Beach, Dummy's Beach and Cathedral Caves. Evidence of this is widespread throughout the southern mapped sections, and is well documented by previous authors (Speden, 1971; Pole, 2001).

As sediment transport progressed towards the north east, the geomorphology appears to become dominated more by lowlands topography, allowing the rivers to slow and also transition into a poorly constrained fluvial environment, thus enabling finer sediment to be deposited. During this phase of transport, coals were also deposited, likely in abandonment channels and overbank areas (Figure 6-2).

From Lower Temaikan time and older, no terrestrial facies occur within the study area. As mentioned previously, a transition to paralic and deeper water depositional environments were observed in outcrop for these older sediments. As age increases, the depositional environment deepens, with sediment transported across the slope (most likely via submarine channel feeder systems). Interestingly, terrestrially derived material was also

Figure 6-2 Late Triassic to Middle Jurassic depositional model for the Murihiku Supergroup. Sediment source from the Median Batholith, across the contemporaneous volcanic arc, into the Murihiku basin. Note incision into possible uplifted plutonic basement rocks. Red lines indicate depositional environment for mapped outcrops. Note the overbank architecture. Assumed paleoflow direction towards the northeast. No scale is assumed.

deposited in these deep water sediments i.e. leaf fossils at Roaring Bay, supporting the work of (Shepard & Dill, 1966). The deepest facies observed in the study area is described at Sandy Bay, where deposition occurred in a base of slope, fan system with turbidite deposits.

6.1.5 Paleolatitude and paleoclimate

During the Triassic-Jurassic, deposition along the Gondwana margin occurred at high paleo latitudes (Mortimer, 2004). Reconstructions of climatic conditions during this time by Elliot and Hammer (1996), suggest a latitude of about 60° S. Evidence from the Transantarctic Mountains, which were paleo-located with the Zealandia, points to a temperate climate with weather profiles suggesting a strongly seasonal climate (Elliot & Hammer, 1996). Pole (2001), also hypothesises that climatic conditions during the Jurassic were likely to be highly seasonal, suggesting that the paleoclimate was prone to periods of high rainfall. Evidence of this is observed in the presence of large boulders within the field area, suggesting an environment capable of entraining this coarse-grained material during flood events.

The general lack of coal seams, other than thin, laterally discontinuous units, further indicates that climatic conditions during deposition of the Murihiku Terrane were variable.

6.1.6 Longevity of the Murihiku system

This thesis demonstrates the large differences that occur stratigraphically and geographically through the region. This reflects the long lived, roughly 140 My (possibly up to ~180 My) deposition along the Gondwana margin of the Murihiku Supergroup, which resulted in at least 10 km of sediment fill. Kamp and Liddell (2000) further suggest that the degree of induration and apatite fission track data shown by the Murihiku rocks of the north Waikato region in the North Island, indicate that a further 3-6 km of Early Cretaceous sediment may have been deposited above the latest Jurassic units exposed onshore near Port Waikato, and subsequently then removed by erosion. Those authors state that the accumulation of the Murihiku Supergroup may have maintained its volcanoclastic character until c. 100 Ma, when active volcanism apparently ceased (Coombs et al 1992), with a younger section (100-85 Ma) possibly occurring as intra-terrane reworking of sediments (Kamp & Liddell, 2000).

Outcrop thickness determinations, plus the potential of additional Cretaceous strata (Kamp & Liddell, 2000), suggests that as much as 16 km of Murihiku sedimentary package may still exist in the offshore. In addition, Coombs et al. (1996) hypothesise that very few unconformities are present. If this thicker sedimentary package remains, it presents an exciting new petroleum system prospect.

The overall regressive trend seen throughout the Early to Middle Jurassic in the Southland Syncline Murihiku Supergroup rocks may be replicated in the latest Jurassic, earliest Cretaceous. Evidence of this is noted by Briggs et al. (2004) who identifies that Murihiku Supergroup rocks outcropping at Kawhia Harbour in the North Island, reflect two main regressive phases resulting in non-marine deposition. They identify the first as occurring in the Early–Middle Jurassic and coinciding with the regressive phase observed in the Southland Syncline portion of the Murihiku Terrane. The second observed regressive phase observed in the North Island is noted by Briggs et al. (2004) as occurring in the latest Jurassic Huriwai Group at Port Waikato (Figure 2-3). These two regressive phases represent the outbuilding of a large delta plain over shelf and slope sequences (Ballance, 1988). Murihiku Supergroup lacustrine rocks of Earliest Cretaceous have also been observed in the south Auckland area (G Browne, pers. comm. 2016).

The continued deposition of terrestrial Murihiku Supergroup rocks into the Cretaceous holds the potential that these rocks that have not undergone the same degree of burial, and hence be less diagenetically altered and of lower metamorphic grade. The source rock potential of these deposits both from coals and lacustrine deposits also holds exciting potential for the youngest rocks of the Murihiku Supergroup.

Further investigations should focus on de-risking the reservoir potential of Murihiku rocks and expanding the knowledge of the other petroleum system elements such as sealing capacity and source potential of Murihiku coals and lacustrine rocks, both of these being topics beyond the scope of this thesis.

6.1.7 Reservoir potential

The intermediate arc provenance of the Murihiku, influenced porosity and permeability and resulted in a high degree of primary porosity loss through cementation and ductile grain smearing. The effect was a virtually complete loss of reservoir potential noted within

the samples analysed, with almost all samples displaying negligible macro-porosity. It is likely that prior to burial diagenesis, Murihiku rocks would have contained considerable intergranular macro-porosity and permeability. The general lack of brittle framework grain crushing reflects the significant cementation by chlorite and calcite. Early diagenetic precipitation of these minerals would have virtually eliminated all macro-porosity and may have originated from meteoric fluid flow during burial.

Any porosity values recorded in samples were likely due to micro porosity, originating from dissolution of framework grains or from fracture porosity, such as at Dummy's Beach. At this location, porosity and permeability values of 14.3% and 2 mD were recorded (Figure 4-11).

When plotted by facies, porosity / permeability data show a distinct increase in porosity from older to younger rocks (i.e. deep water to terrestrial facies) (Figure 4-12 & Table 4-3). This correlation likely reflects increasing diagenesis and metamorphism in the older, more deeply buried rocks.

The overall reservoir potential of the analysed Murihiku samples in the Southland Syncline is low, with all rocks displaying zeolitization and extensive loss of porosity and permeability due to cementation and ductile grain deformation. These diagenetic effects have virtually eliminated all macro porosity and choked pore throats, isolating any micro-porosity generated through dissolution of framework grains or matrix.

The Late Jurassic terrestrial sediments (and indeed possible younger rocks not observed in outcrop) may hold some reservoir potential. Drilling results from petroleum exploration wells that have intersected Murihiku rocks in the North Island suggest as much (Forder & Bennett, 1988; Shell Todd Oil Services Ltd, 1991; Milne & Quick, 1999), but no such wells have been drilled in the offshore Great South Basin adjacent to the outcrop area examined here (see discussion below).

Future work on the sedimentological petrography of the Murihiku should focus on characterisation of reservoir facies. It is suggested that this work focus on the youngest terrestrial occurrences of Murihiku rocks. Additional porosity / permeability investigations should be undertaken along sample sets from the Nelson and North Island outcrops of the

terrane and should again focus on the younger successions, as based on this study, these show the greatest reservoir potential.

6.1.8 Implications for Great South Basin exploration

The Great South Basin is situated west of the submarine Campbell Plateau (Lipski, 2004) to the southeast of the New Zealand landmass (Figure 6-3). The basement terranes of Western Province rocks of the Buller Terrane and Eastern Province rocks of the Brook Street, Murihiku, Dun Mountain / Matai and Caples Terranes (Coombs et al., 1976; Bishop et al., 1985; Cook et al., 1999b) comprise traditional acoustic basement in the Great South Basin. The western and eastern provinces are separated from each other by the Median Batholith (Figure 1-1). Accretionary terranes of the Eastern Province extend to the southeast of New Zealand's South Island and reflect both crystalline and metasedimentary basin fill.

Deformation within the GSB is generally low with structural fabric dictated by the Mesozoic accretionary strike orientation (NW-SE). Late Cenozoic compression in the north of the basin show Mesozoic structures which have a distinct SW-NE orientation (Cook et al., 1999b).

The various terranes that underlie the basin strike NW-SE and are separated from each other by large scale faults or melange that reflect the different extensional, transform and compressional history of the Basin's evolution (Constable & Crookbain, 2011). The Murihiku Terrane underlies the Central Sub-basin and comprises earliest basin fill occurring as both pre-rift and earliest syn-rift sedimentation (Figure 5-2).

The extent of the Murihiku Terrane is bounded along its northern extent by the Hillfoot Fault and is hypothesised to extend to near Stewart Island (Cook et al., 1999b), thrusting over the Brook Street Terrane along the Letham Thrust Fault (Ghisetti, 2010). The field data from near Stewart Island indicates that the Murihiku Terrane may unconformably lie over the Brook Street Terrane and the Median Batholith in places and potentially sole the base of Tara-1 (Cook et al., 1999b).

Within the onshore Catlins district of the South Island, antiform and synform features of the Murihiku Terrane can be clearly seen in seismic reflection data in the offshore (Figure 5-4). Outcrop mapping and petrographic analysis has identified fluvial facies of Middle

Jurassic and it is speculated here, that reservoir potential may also exist in younger equivalents. Work by OMV New Zealand Ltd (Constable & Crookbain, 2011) and Greymouth Petroleum (Brady, 2011) have identified fluvial reservoir facies in offshore Late Jurassic / Early Cretaceous rocks (Figure 5-4 & Figure 5-6). Seismic character of these fluvial facies tend to have variable amplitude velocities with discontinuous reflectors displaying a parallel to convergent nature (Cook et al., 1999b).

Future work on the Murihiku play analysis in the GSB should therefore focus on seismic facies mapping in the deeper parts of the basin or in thrust sections. Velocity models for Murihiku sediments and correlating with known Murihiku occurrences in the North Island will also help to unlock the potential of this petroleum system.

Figure 6-3 Great South Basin.
Graduated colours show sediment depth. (After NZP&M, 2014).

Chapter 7

7.1 Conclusions

Whilst a significant amount of work has been done on the biostratigraphy and organic geochemistry of the Murihiku Supergroup in the Southland Syncline, far less work has been undertaken on the sedimentological and petrographic aspects of this long lived Permian to middle Cretaceous Supergroup.

- For the first time a continuous sedimentological description of the Late Triassic to Middle Jurassic succession outcropping in the Southland Syncline is made here. By assessing the region as a whole, it is presented here and for the first time that a marine transgression occurred from Late Triassic (Oretian) (as seen at Roaring Bay, slope, channel facies) to Early Jurassic (Ururoan) (as seen at Sandy Bay, Base of slope overbank facies). This maximum marine transgression observed at Sandy Bay is subsequently followed by an overall regional regression. This is reflected in outcrop moving south along the coast from that location, with the outcrops also younging in that direction. This regression is represented by a shallowing of depositional environment from Sandy Bay through paralic deposition in Middle Jurassic (Lower Temaikan) to fluvial facies outcrop exposed at multiple locations along the southern limb of the regional syncline. These fluvial facies represent the youngest rocks exposed within the syncline and are of Middle Jurassic age (Upper Temaikan).
- Through Paleocurrent measurements and provenance analysis undertaken during petrographic review, an evolving, intermediate arc derived sediment source has been identified, with transportation from the southwest to the northeast.
- Petrographic review of outcrop samples confirms the volcanoclastic nature of the sandstones of the Murihiku Supergroup in the Southland Syncline and can be typed as feldspathic and lithic arenites and feldspathic and lithic wackes. These sediments have undergone zeolite facies metamorphism with laumontite, stilbite and to a lesser extent heulandite cementation occurring. Chlorite is the predominant cementing mineral occurring as a dual phase process. Initial chloritization will

almost completely fill primary pore space. Where primary porosity remains, it is infilled with either calcite or zeolite cement, further eliminating primary porosity.

- The high degree of cementation (up to 76 percent of total rock) occurs as both siliceous and carbonate cement. It is shown in this study that this cementation will act two fold. Firstly to resist mechanical compaction of brittle framework grains and secondly, in those samples with high calcite precipitation formed during early diagenesis, these samples will display lower zeolitization. The high degree of ductile lithic grains (up to 39 modal percent), which are often smeared between brittle grains, effectively chokes pore throats and virtually eliminates all permeability.
- Another first for this study is porosity and permeability analysis of Murihiku Supergroup rocks within the Southland Syncline. Samples were acquired during field work from a representative selection of Late Triassic to Middle Jurassic sandstones allowing inferences about reservoir quality to be made. The majority of samples collected show poor reservoir potential. However, Middle Jurassic, fluvial facies rocks hold some potential, with porosities up to 14.3% and permeability's up to 2 mD. This generally poor reservoir potential is reflective of the volcanoclastic provenance and high degree of diagenesis of Murihiku rocks that have effectively eliminated any reservoir potential. It is hypothesised that younger Murihiku rocks of Middle Jurassic and younger may still be present in the offshore successions and may therefore hold better reservoir potential due to their lesser degree of zeolitization and other diagenetic effects.
- Seismic facies mapping of Murihiku rocks in the Great South Basin shows these somewhat prospective fluvial facies are present in the deeper parts of the basin.
- Future work on the sedimentological petrography of the Murihiku Supergroup should focus on further characterisation of reservoir facies. It is suggested that this work focus on the youngest terrestrial occurrences of Murihiku rocks. Additional porosity / permeability investigations should be undertaken along the Nelson and North Island sections of the terrane and should again focus on the younger successions, as these showed promise in this study and also in exploratory drilling in the North Island.

Chapter 8

8.1 References

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Chapter 9

9.1 Appendices

Appendix 1 Field register

The following tables contain a register of field samples and their associated locations. GPS coordinates are given in WGS84. Analytical techniques used during this project are assigned to the respective sample and designated by a “Y” in each row if that analysis was used on that sample.

Date	Location	Lithology	Formation	Sample #	Age	Thin section	Poro/perm	XRD	SEM	Southing	Easting	Datum
5/12/2014	Blackhead Quarry	fine sst	Purakauiti Fm	BMJ-01	Middle Jurassic	Y				-46.5071	169.5792	WGS84
15/03/2015	Blackhead Quarry	fine sst	Purakauiti Fm	BMJ-02	Middle Jurassic	Y	Y	Y	Y	-46.5070	169.5788	WGS84
12/03/2015	Cannibal Bay	VF sst	Purakauiti Fm	CaMJ-01	Middle Jurassic	Y	Y		Y	-46.4676	169.7601	WGS84
12/03/2015	Cannibal Bay	F sst	Purakauiti Fm	CaMJ-02	Middle Jurassic					-46.4676	169.7598	WGS84
25/03/2015	Cathedral Caves	F-M sst	Purakauiti Fm	CcEJ-01	Early Jurassic	Y	Y		Y	-46.6082	169.3803	WGS84
25/03/2015	Cathedral Caves	M sst	Purakauiti Fm	CcEJ-02	Early Jurassic	Y	Y	Y	Y	-46.6078	169.3801	WGS84
8/12/2014	Curio Bay	F-M sst	False Islet Fm?	CMJ-01	Middle Jurassic	Y				-46.6615	169.1082	WGS84
8/12/2014	Curio Bay	M-VC sst	False Islet Fm?	CMJ-02	Middle Jurassic	Y				-46.6615	169.1082	WGS84
8/12/2014	Curio Bay	VC sst	False Islet Fm?	CMJ-03	Middle Jurassic	Y				-46.6617	169.1080	WGS84
2/03/2015	Curio Bay	VF-V sst	False Islet Fm?	CMJ-04	Middle Jurassic					-46.6626	169.1045	WGS84
2/03/2015	Curio Bay	F-M sst	False Islet Fm?	CMJ-05	Middle Jurassic	Y	Y		Y	-46.6624	169.1046	WGS84
2/03/2015	Curio Bay	sst	False Islet Fm?	CMJ-06	Middle Jurassic					-46.6628	169.1050	WGS84
3/03/2015	Curio Bay	M sst	False Islet Fm?	CMJ-07	Middle Jurassic	Y	Y		Y	-46.6618	169.0977	WGS84
3/03/2015	Curio Bay	M-Co sst	False Islet Fm?	CMJ-08	Middle Jurassic					-46.6622	169.1019	WGS84
3/03/2015	Curio Bay	F-M sst	False Islet Fm?	CMJ-09	Middle Jurassic					-46.6622	169.1019	WGS84
3/03/2015	Curio Bay	Co-Pb sst	False Islet Fm?	CMJ-10	Middle Jurassic	Y	Y	Y	Y	-46.6622	169.1020	WGS84
6/03/2015	Dummy's Beach	F sst	False Islet Fm?	DMJ-01	Middle Jurassic					-46.6325	169.2567	WGS84
6/03/2015	Dummy's Beach	F sst	False Islet Fm?	DMJ-02	Middle Jurassic					-46.6324	169.2569	WGS84
6/03/2015	Dummy's Beach	Co-Vco sst	False Islet Fm?	DMJ-03	Middle Jurassic	Y	Y		Y	-46.6324	169.2573	WGS84
24/03/2015	Dummy's Beach	M-sst	False Islet Fm?	DMJ-04	Middle Jurassic	Y	Y	Y	Y	-46.6328	169.2561	WGS84
7/12/2014	False Islet	M sst	False Islet Fm	FMJ-01	Middle Jurassic	Y				-46.4796	169.7501	WGS84
7/12/2014	False Islet	F-M sst	False Islet Fm	FMJ-02	Middle Jurassic	Y				-46.4795	169.7501	WGS84
7/12/2014	False Islet	F-M sst	False Islet Fm	FMJ-03	Middle Jurassic	Y				-46.4795	169.7501	WGS84
7/12/2014	False Islet	C-P sst	False Islet Fm	FMJ-04	Middle Jurassic					-46.4795	169.7502	WGS84
12/03/2015	False Islet	M sst	False Islet Fm	FMJ-05	Middle Jurassic	Y	Y	Y	Y	-46.4796	169.7500	WGS84
12/03/2015	False Islet	M-Co sst	False Islet Fm	FMJ-06	Middle Jurassic	Y	Y		Y	-46.4795	169.7501	WGS84
12/03/2015	False Islet	Cgl matrix?	False Islet Fm	FMJ-07	Middle Jurassic					-46.4795	169.7500	WGS84
25/03/2015	False Islet	M sst	False Islet Fm	FMJ-08	Middle Jurassic	Y	Y		Y	-46.4786	169.7499	WGS84

Date	Location	Lithology	Formation	Sample #	Age	Thin section	Porosity/perm	XRD	SEM	Southing	Easting	Datum
14/03/2015	Owaka Heads	M sst	Tuhawaiki Fm	OMJ-01	Middle Jurassic	Y	Y		Y	-46.4833	169.7117	WGS84
14/03/2015	Owaka Heads	F sst	Tuhawaiki Fm	OMJ-02	Middle Jurassic					-46.4847	169.7128	WGS84
5/12/2014	Roaring Bay	Conglomerate	Maitai Fm?	RLT-01	Late Triassic					-46.4462	169.8003	WGS84
5/12/2014	Roaring Bay	Conglomerate	Maitai Fm?	RLT-02	Late Triassic					-46.4462	169.8003	WGS84
5/12/2014	Roaring Bay	fine sst	Maitai Fm?	RLT-03	Late Triassic	Y				-46.4462	169.8004	WGS84
20/03/2015	Roaring Bay	M sst	Maitai Fm?	RLT-04	Late Triassic					-46.4464	169.7995	WGS84
20/03/2015	Roaring Bay	Co sst	Maitai Fm?	RLT-05	Late Triassic	Y	Y		Y	-46.4464	169.8000	WGS84
20/03/2015	Roaring Bay	M sst	Maitai Fm?	RLT-06	Late Triassic	Y	Y	Y	Y	-46.4464	169.7997	WGS84
6/12/2014	Sandy bay	V Fine Sst	Otekura Fm	SEJ-01	Early Jurassic					-46.4535	169.7822	WGS84
6/12/2014	Sandy bay	V Fine sst-zst	Otekura Fm	SEJ-02	Early Jurassic					-46.4549	169.7801	WGS84
6/12/2014	Sandy bay	ssst	Otekura Fm	SEJ-03	Early Jurassic					-46.4549	169.7799	WGS84
6/12/2014	Sandy bay	tuff?/sst	Otekura Fm	SEJ-04	Early Jurassic					-46.4549	169.7798	WGS84
6/12/2014	Sandy bay	ssst	Otekura Fm	SEJ-05	Early Jurassic					-46.4550	169.7797	WGS84
6/12/2014	Sandy bay	ssst	Otekura Fm	SEJ-06	Early Jurassic	Y				-46.4550	169.7795	WGS84
6/12/2014	Sandy bay	ssst	Otekura Fm	SEJ-07	Early Jurassic					-46.4549	169.7793	WGS84
23/03/2015	Sandy bay	F-M sst	Otekura Fm	SEJ-09	Early Jurassic	Y	Y	Y	Y	-46.4551	169.7797	WGS84
6/03/2015	Shades Beach	M sst	False Islet Fm?	ShMJ-01	Middle Jurassic	Y	Y		Y	-46.6402	169.2356	WGS84
24/03/2015	Shades Beach	M-Co sst	False Islet Fm?	ShMJ-02	Middle Jurassic	Y	Y			-46.6421	169.2361	WGS84
24/03/2015	Shades Beach	M-Co sst	False Islet Fm?	ShMJ-03	Middle Jurassic	Y	Y	Y	Y	-46.6421	169.2362	WGS84
8/12/2014	Waikawa Harbour	F sst	False Islet Fm?	WMJ-01	Middle Jurassic	Y				-46.6461	169.1430	WGS84
8/12/2014	Waikawa Harbour	C sst	False Islet Fm?	WMJ-02	Middle Jurassic					-46.6461	169.1430	WGS84
8/12/2014	Waikawa Harbour	Cgl matrix	False Islet Fm?	WMJ-03	Middle Jurassic	Y				-46.6462	169.1433	WGS84
4/03/2015	Waikawa Harbour	M sst	False Islet Fm?	WMJ-04	Middle Jurassic					-46.6324	169.1526	WGS84
5/03/2015	Waikawa Harbour	M-Co sst	False Islet Fm?	WMJ-05	Middle Jurassic	Y	Y			-46.6461	169.1473	WGS84
5/03/2015	Waikawa Harbour	Cgl matrix	False Islet Fm?	WMJ-06	Middle Jurassic	Y	Y		Y	-46.6462	169.1437	WGS84
7/03/2015	Waikawa Harbour	M-Co sst	False Islet Fm?	WMJ-07	Middle Jurassic	Y	Y	Y	Y	-46.6316	169.1532	WGS84

Appendix 2 Porosity & permeability

Field samples were prepared for porosity and permeability analysis at GNS Science, Lower Hutt, by drilling 21.5 mm diameter x 45 mm long core plugs from large field samples. Plugs were sampled perpendicular to depositional bedding. Each drilled sample was measured and weighed before and after drying in a rock lab oven at 120 °C for 12 hours, to identifying the pore volume and bulk volume of the sample, thus allowing porosities to be calculated.

Permeability of the samples were measured using compressed air injection whilst contained within a Hoek triaxial cell. Increasing confining pressures of 5, 10, 15 and 20 MPa were utilised to simulate pressure at various depths.

Sample number refers to field numbers, i.e. DMJ-03. Where a number has an 'a' or 'b' next to it, this indicates that more than one core plugs was drilled the one field sample. If this letter is subsequently followed by 'i' or 'ii', this indicates that the plug was long enough to be cut in half, thus creating two separate plugs.

Water content is calculated from the variance between 'wet' and 'dry' weights.

Dry densities are determined through the calculation of 'dry mass' / bulk volume.

Sample Number	Water Content	Dry Density	Voids Ratio (e)	Porosity (n)	Confining Pressure	Air Permeability	
	%	t/m ³		%	MPa	millidarcy	m/sec (x10 ⁻⁹)
BMJ-02a	1.4	2.51	0.07	6.9	5	0	0
BMJ-02ai	1.4	2.52	0.07	6.8	5	0	0
BMJ-02b	1.4	2.51	0.08	7.1	5	0	0
CaMJ-01	1.2	2.52	0.07	6.5	5	0	0
CcEJ-01a	2.2	2.49	0.08	7.8	5	0	0
CcEJ-01b	2.3	2.50	0.08	7.6	5	0	0
CcEJ-02a	3.0	2.43	0.11	9.9	5	0	0
CcEJ-02ai	3.1	2.44	0.11	9.6	5	0	0
CcEJ-02b	3.0	2.42	0.12	10.5	5	0.20	1.98
CMJ-05a	4.3	2.37	0.14	12.1	5	0	0
CMJ-05b	4.4	2.39	0.13	11.6	5	0	0
CMJ-07a	3.7	2.44	0.11	9.6	5	0	0
CMJ-07b	3.8	2.44	0.11	9.8	5	0	0
CMJ-10a	5.0	2.34	0.16	13.5	5	0	0
CMJ-10b	5.2	2.33	0.16	13.8	5	0	0
CMJ-10bi	4.9	2.32	0.16	14.0	5	0	0
DMJ-03a	4.4	2.39	0.13	11.6	5	1.99	19.30
DMJ-03b	4.1	2.41	0.12	10.8	5	0.54	5.19
DMJ-03c	3.9	2.42	0.12	10.4	5	0.15	1.45
DMJ-04a	6.8	2.34	0.15	13.4	5	0.50	4.83
DMJ-04b	7.0	2.29	0.18	15.2	5	2.03	19.60
FMJ-05a	1.9	2.51	0.08	7.2	5	0	0
FMJ-05b	1.8	2.54	0.06	6.0	5	0	0
FMJ-06a	1.4	2.54	0.06	6.0	5	0	0
FMJ-06b	1.4	2.55	0.06	5.6	5	0	0
FMJ-08a	2.0	2.57	0.05	4.7	5	0	0
FMJ-08b	2.1	2.58	0.05	4.6	5	0	0
OMJ-01a	2.1	2.47	0.09	8.4	5	0	0
OMJ-01b	2.7	2.38	0.13	11.9	5	0	0
OMJ-01c	2.2	2.64	0.02	2.4	5	0	0
RLT-05a	0.4	2.62	0.03	3.1	5	0	0
RLT-05ai	0.5	2.60	0.04	3.7	5	0	0
RLT-05aii	0.5	2.61	0.03	3.3	5	0	0
RLT-06c	2.9	2.42	0.12	10.3	5	0	0
SEJ-01a	1.8	2.57	0.05	4.7	5	0	0
SEJ-01b	1.4	2.58	0.04	4.3	5	0	0
ShMJ-01a	2.3	2.44	0.11	9.6	5	0	0
ShMJ-01b	2.5	2.48	0.09	8.3	5	0	0
ShMJ-02a	1.0	2.64	0.02	2.3	5	0	0
ShMJ-02b	1.3	2.62	0.03	3.0	5	0	0
ShMJ-03a	3.4	2.44	0.11	9.7	5	0	0
ShMJ-03ai	3.4	2.41	0.12	10.7	5	0	0
WMJ-05a	3.5	2.44	0.11	9.7	5	0	0
WMJ-05b	3.5	2.44	0.11	9.8	5	0	0
WMJ-06b	4.4	2.42	0.12	10.6	5	0.21	2.03
WMJ-06c	4.5	2.43	0.11	10.0	5	0	0
WMJ-07a	2.8	2.43	0.11	10	5	0.15	1.49
WMJ-07b	2.8	2.44	0.11	9.8	5	0.22	2.08

Appendix 3 Petrography

Thin sections were prepared at Victoria University of Wellington, following the method of Dickinson (1985) with additional blue dye staining to assist in the visual identification of porosity. Slides were also dipped in hydrofluoric acid to enable differentiation of feldspars and easier identification carbonates, this was done following the method of Houghton (1980).

Grain identification and percentages were undertaken following the Gazzi-Dickinson point-counting method (Ingersoll et al., 1984). 300 counts were made per slide and plotted on ternary diagrams to display their normalised quartz, feldspar and lithic content, enabling provenance to also be determined (Chapter 3).

Use of the Gazzi-Dickinson method minimizes variation of composition with grain size, thus allowing the assignment of sand sized crystals and grains within larger fragments to the category of the crystal or grain, rather than to the category of the larger fragment (Ingersoll et al., 1984).

Figure 9-1 Photomicrograph of sandstone sample ShMJ-03, Shades Beach (Middle Jurassic). Image shows framework grains surrounded by minor carbonate cementation (Cb), Clay 1 (C1) and Clay 2 (C2). Zoom 10x under cross polarisation.

Eleven constituent parts were identified within each thin section and are displayed in Table 9-1. Due to the subordinate nature of sedimentary and metamorphic rock fragments (the latter being identified in only one sample) to igneous rock fragments, these grains are combined here under igneous rock fragments (IRF). Due to the absence of potassium feldspar in all samples, this is not included in the table below. Two main clay minerals were identified in thin section (Figure 9-1). Clay 1 is subordinate to Clay 2 in all samples and is represented by a red stained equant balls ~1 μm surrounding grain edges and is most likely hematite. Clay 2 presents as a needle-like, tabular clay and is a golden yellow colour under cross polarisation. The clay is confirmed by XRD analysis as comprising of chlorite. Table 9-2 displays point count data from Petroleum well Pluto-1.

Table 9-1 Thin section point count data for Murihiku Supergroup rocks of the Southland Syncline.

Field															
Sample	Spacing	Mag	COUNT	Plag	Feld	Mica	Qtz (P)	Qtz (M)	Matrix	IRF	Pore	Cement	Clay 1	Clay 2	UNK
BMJ-02	4	40x	300	23		0	33	72	33	13	0	0	35	89	2
CaMJ-01	4	40x	300	69		1	0	0	0	43	0	0	31	155	1
CcEJ-01	4	40x	300	143		10	10	0	0	40	3	0	25	66	3
CcEJ-02	4	40x	300	82		6	1	0	0	55	4	0	20	132	0
CMJ-07	4	40x	300	95		0	0	0	114	41	0	0	38	12	0
CMJ-10	4	40x	300	73		0	1	0	90	68	2	0	14	52	0
DMJ-03	8	10x	300	67		0	8	0	0	123	8	0	1	92	1
DMJ-04	8	10x	300	9		0	0	0	0	173	30	0	4	79	5
FMJ-05	4	40x	300	61		1	0	0	0	162	0	0	18	57	0
FMJ-06a	4	40x	300	73		0	0	0	0	149	0	0	20	58	0
FMJ-06b	4	40x	300	117		0	1	0	0	112	0	0	18	52	0
FMJ-08	4	40x	300	68		0	0	0	0	153	0	0	17	61	1
OMJ-01	4	40x	300	86		1	3	0	0	68	0	0	1	139	2
OMJ-05	4	40x	300	79		0	1	0	0	72	0	0	52	96	0
RLT-05	8	10x	300	193		0	6	0	11	30	1	0	24	34	1
RLT-06	4	40x	300	45		0	4	0	33	1	0	1	95	120	1
SEJ-09	4	40x	300	86		3	37	0	24	22	0	82	16	30	0
ShMJ-01	4	40x	300	118		3	13	57	40	2	2	1	14	48	2
ShMJ-02	4	40x	300	84		15	5	26	10	10	0	130	13	4	3
ShMJ-03	4	40x	300	116		12	14	40	39	10	3	4	10	48	4
WMJ-05	4	40x	300	46		9	3	0	0	150	0	0	24	68	0
WMJ-06	4	40x	300	76		0	6	0	0	93	1	0	20	103	1
WMJ-07	4	40x	300	131		5	11	0	0	51	3	0	10	84	5

Qtz (P)=Polycrystalline quartz Qtz (M)=Monocrystalline quartz, Plag Feld=plagioclase lrf=igneous rock fragments,
 Carb=carbonate, Pore=visible porosity, Clay 1=Haematite, Clay 2=Chlorite, UNK=unknown minerals.

Table 9-2 Pluto-1 point count data, collated from well completion report PR1766.

Pluto-1 point count data from sidewall cores																
Sample	Depth (m)	Qtz	Cht	Kfe	Pla	Irf	Mic	H-M	opq	Ana	Carb	Mat	Clay	V-P	AvGS	Rock
SWC64	1824	1			22	49	0		1		1		26		0	Reworked Murihiku
SWC58	1847				5	64	0						11	0	2	Murihiku
SWC57	1851				2	83							15	1	1	Murihiku
Core	1866	1	0		5	72			0				21	1	1	Tuff
PL10	1867				3	83							14		1	Murihiku
PL16	1871	1			7	75							17		1	Murihiku
PL22	1874	1			13	60					1		26		0	Murihiku
Core	1877	0			9	79							11	0	1	Tuff
SWC56	1885	2	0		16	43			0		15		24		0	Murihiku
SWC37	2161	1			7	75			1	3	2		12	0	0	Murihiku
SWC28	2375	0			0	4	78		0		6		11		1	Murihiku
SWC25	2417	1			6	74					0		20		1	Murihiku
SWC22	2488	0			11	12			0		1		75		0	Tuff
SWC16	2612	1	0	0	7	62	0	1	0	0	7		23	0	1	Murihiku

Qtz=quartz Chl=chert Kfe=potash feldspar Pla=plagioclase Irf=igneous rock fragments

Mrf=metamorphic rock fragments Srf=sedimentary rock fragments Hic=mica

H-H=heavy minerals Opq=opaques Ana=analcite Carb=carbonate

V-P=visible porosity AvGS=average grain size (mm).

Appendix 4 X-Ray Diffraction (XRD)

The following histograms are outputs from the X-ray Diffraction analysis that was undertaken on selected samples (Appendix 1).

Report Number: 2016030402
Report Date: 16/03/2016

To: Greg Browne
GNS Science
1 Fairway Drive
Avalon
Lower Hutt

Quantitative XRD Analysis

Dear Greg

RE: Client Reference: Murihiku Terrane Sandstones & Mudstones; Purchase Order: 510PBR32-00
New Zealand Geothermal Analytical Laboratory reference numbers: 2016001475 - 2016001486

This report presents interpretive quantitative XRD results conducted on 12 samples received from Greg Browne on 4 March 2016.

The samples were initially prepared by chipping and crushing. They were then spiked with 10% zinc oxide (internal reference). X-ray diffraction data of the samples was collected using a Philips X'Pert Pro instrument utilising CoK α radiation and the following operating conditions:

Start Position [$^{\circ}$ 2Th.]	2.000
End Position [$^{\circ}$ 2Th.]	80.000
Step Size [$^{\circ}$ 2Th.]	0.050
Scan Step Time [s]	1.00
Generator Settings	40 kV, 35 mA

The mineralogy of the samples was determined using PANalytical interpretive software *X'Pert High Score* and data plotted and labelled as shown in Figures 1 - 12.

Quantitative mineral percentages were determined using *Sietronics Pty. Ltd.* quantitative software *Siroquant* (see Table 1).

If you have any queries please do not hesitate to email or phone.

Yours sincerely

Debra Chappell, PhD
XRD Analyst

Bruce Mountain, PhD
Senior Geochemist

New Zealand Geothermal Analytical Laboratory
GNS Science
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Quantitative XRD Analysis

Sample Identification: CcEJ-02 Laboratory Reference No: 2016001478

Figure 4. XRD scan showing the mineralogy of sample CcEJ-02 as indicated by the labelled scan peaks

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Report Number: 2016030402
Report Date: 16/03/2016

Quantitative XRD Analysis

Sample Identification: SEJ-09 Laboratory Reference No: 2016001479

Figure 5. XRD scan showing the mineralogy of sample SEJ-09 as indicated by the labelled scan peaks

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Quantitative XRD Analysis

Sample Identification: CMJ-10
Laboratory Reference No: 2016001482

Figure 8. XRD scan showing the mineralogy of sample CMJ-10 as indicated by the labelled scan peaks

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Report Number: 2016030402
Report Date: 16/03/2016

Quantitative XRD Analysis

Sample Identification: WMJ-07 Laboratory Reference No: 2016001486

Figure 12. XRD scan showing the mineralogy of sample WMJ-07 as indicated by the labelled scan peaks

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Appendix 5 Sandy Bay stratigraphic columns

The below stratigraphic columns include additional lithological features identified during field work.

Appendix 6 Analysis image montages

The following set of montaged images graphically present all analytical investigations undertaken during this field work.

For all panels, images on top row left-right show: field sample and drilled core plugs, SEM images 500 x and 100x magnification respectively, at 15kv setting. Bottom row left to right: thin sections at 10 x plane polarisation, 10 x cross polarisation, 40 x cross polarisation. All thin sections impregnated with blue dye for porosity and dipped in hydrofluoric acid to enable differentiation of feldspars and easier identification carbonates

Sample: SEJ-09

Age: Early Jurassic
 Location: Sandy Bay
 Avg Porosity: 4.5%
 Avg Permeability: Nil

XRD Mineralogy:
 Qtz: 27%
 Plagioclase: 52%
 Clays: 11% (Laumontite)

Sandy Bay, Early Jurassic 09 BS

Sandy Bay, Early Jurassic 09 BS

Sample: FMJ-05

Age: Middle Jurassic
 Location: False Islet
 Avg Porosity: 6.6%
 Avg Permeability: Nil

XRD Mineralogy:
 Qtz: 16%
 Plagioclase: 75%
 Clays: 09% (Chlorite, CPX, Pyrite)

False Islet, Middle Jurassic 05

False Islet, Middle Jurassic 05

Sample: BMJ-02

Age: Early Jurassic
Location: Warnock Rd Quarry
Avg Porosity: 7%
Avg Perm: Nil

XRD Mineralogy
Qtz: 30%
Plagioclase: 55%
Clays: 15% (Chlorite, Laumontite)

Sample: CcEJ-02

Age: Early Jurassic
Location: Cathedral Caves
Avg Porosity: 10%
Avg Permeability: .2mD (5MPa)

XRD Mineralogy:
Qtz: 18%
Plagioclase: 55%
Clays: 37% (Chlorite, CPX, Stilbite)

Sample: DMJ-04

Age: Middle Jurassic
 Location: Dummy's Beach
 Avg Porosity: 14.3%
 Avg Permeability: 2mD (5MPa)

XRD Mineralogy:
 Qtz: 04%
 Plagioclase: 85%
 Clays: 12% (Pyrite, Montmorillonite)

Sample: ShMJ-03

Age: Middle Jurassic
 Location: Shades Beach
 Avg Porosity: 10.2%
 Avg Permeability: Nil

XRD Mineralogy:
 Qtz: 16%
 Plagioclase: 74%
 Clays: 10% (Chlorite, CPX)

Sample: WMJ-07

Age: Middle Jurassic
Location: Waikawa Harbour
Avg Porosity: 9.9%
Avg Permeability: .22mD (5MPa)

XRD Mineralogy:
Qtz: 13%
Plagioclase: 65%
Clays: 22% (Chlorite, Laumontite, Titanite)

Sample: CMJ-10

Age: Middle Jurassic
Location: Curio Bay
Avg Porosity: 13.8%
Avg Permeability: Nil

XRD Mineralogy:
Qtz: 03%
Plagioclase: 88%
Clays: 09% (CPX, Stilbite, Montmorillonite)