PROTECTION OF AUTHOR’S COPYRIGHT

This copy has been supplied by the Library of the University of Otago on the understanding that the following conditions will be observed:

1. To comply with s56 of the Copyright Act 1994 [NZ], this thesis copy must only be used for the purposes of research or private study.

2. The author's permission must be obtained before any material in the thesis is reproduced, unless such reproduction falls within the fair dealing guidelines of the Copyright Act 1994. Due acknowledgement must be made to the author in any citation.

3. No further copies may be made without the permission of the Librarian of the University of Otago.
Geophysical survey of the Paringa River valley, South Westland

Jeremy William Kilner
2005

Supervised by Prof. Richard Norris and Dr. Andrew Gorman
Abstract

The Paringa River valley runs perpendicular to the Alpine Fault, the dominant structural feature of the South Island, New Zealand. Previous geological mapping has contributed much to the understanding of South Westland geology, but a number of questions about the geology, structure and evolution of Paringa River region have been left unanswered. In this study a review of this region’s geology was undertaken, together with new gravity and magnetic surveys of the Paringa River valley. Work included modelling the basement profile beneath the river flats, identifying origins and evolution of specific valleys, completing the geological map of the region and analysing Western Province intrusives in the Paringa River valley.

Mapping of Blackwater Creek showed amphibolite facies, quartzofeldspathic protomylonites with a prominent S-C fabric exposed in Blackwater Creek grading eastwards into schist at the eastern margin of exposure. Pseudotachylytes discovered within the protomylonites indicated minor, high stress seismic ruptures at depth within the Alpine Fault zone.

The geochemical analyses of Paringa Western Province intrusives indicated the South Westland region may have paired Paleozoic I- and S-type granitoids which parallel the well-recognised Cretaceous paired plutonic belts. Intruded lamprophyre dykes are thought to be associated with the same subduction episode as the granitoid plutons.

The magnetic survey unfortunately did not contribute to increased understanding of the region. The gravity survey provided valuable data, although the normal uncertainties in interpretation of gravity data were compounded by the two-dimension modelling in an area of rapidly changing basement topography.

Gravity modelling of the Paringa River valley and the NE trending valley indicated significantly deep (400-600 m) U-shaped, glacially excavated valleys. The Alpine Fault was imaged in the gravity profiles beneath the valley fill, concurring with Simpson's (1992) mapping of the Alpine Fault trace.

The Paringa River is postulated to have drained through the NE trending valley northwards before switching to its present southwards course in response to progressive strike-slip offset.
along the Alpine Fault. This proposal forms the basis of a theory of sequential reoccupation of drainage west of the Alpine Fault.
Acknowledgments

The highlight of my year was the time spent at Paringa, Westland, doing the field work for this project. I wish to thank my supervisors Professor Richard Norris and Dr Andrew Gorman of the Geology Department, University of Otago, for giving me the chance to work in an area that has always had special links for me. My special thanks go to Tony and Glynis Condon of Paringa who welcomed me into their home, looked after me, gave me the run of their place and their internet, and fed me so wonderfully.

I am very grateful for the support and guidance I received from the staff and students of the University of Otago Geology Department. My special thanks go to thank Professor Richard Norris and Dr Andrew Gorman for their advice and critical comments, and especially their willingness to respond when comments on the drafts were wanted back immediately. I also wish to thank: Professor Alan Cooper whose help was vital to the completion of the geochemical component of this project; Steve Read for his assistance on computer graphic problems; Matt Hill for leading me through the construction of the Terrane Correction, being there to bounce ideas off and provide alternative ideas on modeling; Damien Walls who would always be there to help out with computer problems; Virginia Toy for her suggestions regarding pseudotacylytes and proofreading; Lorraine Patterson who helped me through the XRF preparation process; Brent Pooley who made the thin-sections; James Scott for his petrology advice and other helpful comments; and Dushan Jugum for his time spent on the final proofreading.

Thanks Bridget, Emilie, Hanne, Kelly, Leigh, Lisa, Lyndon and Manja (from the fourth year room) for making this year a great experience. Last, but not least, my thanks go to my family for their support and encouragement throughout the year, and, as the project came to an end, for advice and proofreading.
# Contents

Abstract ........................................................................................................... i  
Acknowledgments ............................................................................................ iii  
Contents page ................................................................................................... iv  

1: Introduction ................................................................................................ 1  
1.1 Background .............................................................................................. 1  
1.2 Fieldwork ............................................................................................... 2  
1.3 Previous work .......................................................................................... 3  
1.3.1 Geology ............................................................................................... 3  
1.3.2 Geophysics .......................................................................................... 5  
1.4 Regional geology .................................................................................... 6  
1.5 Geophysical Methods ............................................................................. 7  
1.6 Aim and objectives ................................................................................ 9  
1.7 Layout ..................................................................................................... 11  

2. Geology ....................................................................................................... 12  
2.1 Introduction: Geology of the field area ................................................... 12  
2.1.1 Description of basic geology ............................................................... 12  
2.1.2 Aims for geological section ............................................................... 13  
2.2 Structure ............................................................................................... 13  
2.2.1 The Alpine Fault ............................................................................... 13  
2.3 Basement rocks ..................................................................................... 16  
2.3.1 Western Province rocks .................................................................... 16  
2.3.2 Paringa Granitoids .......................................................................... 18  
2.3.3 Lamprophyre .................................................................................... 26  
2.3.4 Geochemistry conclusions ................................................................ 30  
2.3.5 Haast Schist ..................................................................................... 31  
2.3.6 Pseudotachylyte .......................................................................... 38  
2.3.7 Blackwater Creek conclusions ........................................................... 41  
2.4 Quaternary Deposits ............................................................................ 42  
2.4.1 Fluvio-glacial deposits ................................................................... 42  
2.4.2 Paringa Formation .......................................................................... 43  
2.4.3 Recent/fan deposits ......................................................................... 45  

3. Geophysics .................................................................................................. 46  
3.1 Introduction ............................................................................................ 46  
3.2 Instrumentation ...................................................................................... 46  
3.3 Gravity survey ........................................................................................ 47  
3.4 Data reduction ....................................................................................... 51  
3.4.1 Introduction to gravity data reduction ............................................... 51  
3.4.2 Latitude correction ........................................................................ 51  
3.4.3 Topography corrections ................................................................... 53  
3.4.4 The combined Bouguer anomaly: the residual anomaly ................. 55  
3.5 Data uncertainties and errors ................................................................. 56
1: Introduction

1.1 Background

This report details the findings of a geological and geophysical based survey undertaken in the Paringa River valley, South Westland (Fig. 1-1). Paringa is situated ~60 km northeast of the township of Haast by way of State Highway 6 (SH6). A significant feature of South Westland is the high rainfall, 4-6 m per year (NIWA), caused by the dominant westerly weather system and the orographic effect of the Southern Alps. There are two key consequences of this high rainfall: high rates of erosion and extremely thick vegetation. The high rates of erosion ensure that the landscape is dynamically changing with landslides creating new exposures and depositing sediment. The vegetation is generally impenetrable, which restricts field mapping mainly to creek beds.

The Paringa River, which runs perpendicular to the dominant feature of the South Island, the Alpine Fault, is a moderate sized river system that carries water from the Southern Alps to the Tasman Sea. It meanders across a wide sediment-filled valley and is constrained by the basement valley walls and various human created stop banks. Moderately high mountains ring the Paringa River, with Mt. Argentum (1236 m) to the east and Mt Kinnaid (1227 m) to the south. Lower elevation 500-700 m hills surround the Paringa River valley to the north and down stream to the west. These surrounding mountain peaks are deeply incised by short gullies that flatten dramatically in profile once the fluvioglacial gravels of the main valley floor are encountered. Consequently, in their lower reaches, these creeks meander in much the same way as the main Paringa River.
The purpose of this project was to use and evaluate two geophysical methods, namely gravity and magnetic techniques, to investigate geological features in the South Westland region, that mapping is unable to resolve. The Paringa River valley was chosen because previous geological mapping had raised questions about the geology, structure and evolution of the region. Geophysical methods allow the interpretation of the Paringa valley basement profile including delineation of structural features. Poor field exposure in the Paringa River valley, because of the extensive cover sediments, has contributed to the scarcity of geological data. Therefore, through the use of geophysical methods it may be possible to add information to the overall geology and help define the Paringa River region's Quaternary evolution.

Previous work was undertaken in the region by G.D.H Simpson for his Geology (Hons) project in the early 1990s. The geological map Simpson (1992) constructed from this fieldwork was used as the basis for this current project. Additional mapping by C. Higham (1996) in the Mahitahi River valley to the northeast, along with mapping undertaken as part of this project, is collated in the Geological Map of the Paringa region (Map 1).

1.2 Fieldwork

The fieldwork research for this project was undertaken over approximately 20 days. Most of the time spent acquiring geophysical data (17 days), and the remaining three days spent mapping and collecting samples. Time was also spent with Professor R.J. Norris accompanied by Professor A.F. Cooper and Ph.D. candidate V. Toy, and later with geophysics supervisor Dr. A. R. Gorman. The geophysics component of fieldwork was split between 14 days collecting gravity data, two days collecting magnetic data and one day collecting barometric altimeter data. The majority of the geophysical data was collected from the Paringa River valley, proximal to the SH6 Paringa River bridge, with the rest being gravity data gathered from Doughboy Creek (DB), 6 km NE of the Paringa River valley.
1.3 Previous work

1.3.1 Geology

Geological work undertaken in South Westland is detailed in chronological order in the following paragraphs. The basis for this project was the information provided by Simpson (1992) and Simpson et al. (1994), however.

In 1879 Haast created a geological map of Westland, which mapped the extent of the glacial and recent sediments. Other workers included C.E Douglas in the early 1900s, who compiled both topographic and geological maps that formed the basis for subsequent work in the region (Simpson, 1992). The Alpine Fault was first recognised as a major fault by Wellman and Willets in 1942 and the determination of total strike-slip displacement of around 480 km was reported by Wellman in 1949 (Wellman, 1955).

Wellman in his 1955 report described many of the lithological and structural features of South Westland including Quaternary deposits such as the Paringa Formation. Interestingly, Wellman in 1935 made a magnetometer survey of West Coast beaches with the aim of identifying sub-surface gold-bearing black-sands. It is unclear from Wellman's report of 1955, but the outlet of the Paringa River may have been one of those visited. Wellman (1955) also described the NE trending valley that connects the Paringa and Mahitahi valleys, a glacially modified tectonic depression, floored by recent gravels.

Suggate (1968) inspected the Paringa Formation in relation to the ice retreat following the last glacial maximum and the subsequent sediment infilling of the valley. He explored the inferred uplift on the eastern side of the Alpine Fault that had raised the sediments above the present river gravels. Calculations of the uplift rate were made from the marine sediments at the base of the Paringa Formation. Taking into account the paleo-sea level, the depth of deposition, and the isostatic rebound, an uplift rate of 10.7 mm/yr was calculated. The Paringa Formation appeared to record the retreat of the glacier up the Paringa valley and followed by marine invasion and the subsequent infilling (Suggate, 1968).

The work reported in Simpson (1992) and Simpson et al. (1994) provides the majority of the information on which this current work was based. His research addressed some of the lack of...
detailed geological mapping in the Paringa region up until this point. One aspect covered by Simpson's work was the schist-mylonite transition on the eastern side of the Alpine Fault. He mapped the trace of the Alpine Fault up Filleul Creek and discovered a 'tectonic window' where the underlying western province rocks are surrounded by overthrust Haast Schist, indicating an abandoned section of the Alpine Fault, and the formation of a thrust nappe in the Ward Hill region. This work changed the understanding of the evolution of the Alpine Fault through the Paringa region.

Within the Paringa River valley itself, Simpson (1992) mapped the anticlinal structure of Little Paringa Hill and described the arrangement of protomylonites, Paringa Formation and fan-deposits. In particular the Paringa Formation was subdivided into four major facies: (1) laminated marine silts, (2) shallow marine sands, (3) fluvial gravels and (4) highly carbonaceous cyclic sediments containing forest horizons, lake sediments and fluvial deposits (Simpson et al, 1994). Simpson investigated these sediments with reference to the inferred uplift rate of the Alpine Fault and the effects of the last glacial maximum.

Approximately 9 km NE of the Paringa River valley lies the Mahitahi River, where Higham (1996) mapped the mineralogy and structure of the Alpine Fault zone and examined late-Quaternary sediments. These late-Quaternary sediments were called the Mahitahi Formation by Higham and resemble those of the Paringa Formation to some degree, with a similar age. The Mahitahi Formation differs in the more simplistic stratigraphy, with +30 m of laminated silt grading into quartz sands before a transition into laminated muds. The deposition history has presumably been simpler than that of the Paringa Formation and may reflect the greater structural complexity of the Paringa River valley.

The Nuvel 1 A model (DeMets et al, 1994) indicates that total relative displacement across the Australian and Pacific plate boundary is $35.5 \pm 1.5$ mm/yr parallel and $10.1 \pm 1.5$ mm/yr perpendicular to the Alpine Fault, thus illustrating the transpressional nature of the plate boundary. However, the net slip-vector of the Alpine Fault is only $\sim 75\%$ of this total displacement, with the rest partitioned onto structures mainly to the east of the Alpine Fault. Displacement on the Alpine Fault itself is often partitioned onto more northerly striking thrust segments and more easterly striking strike-slip segments. The Paringa River region is one of these structurally complex sections. This partitioning of total fault displacement onto discrete
segments is attributed to interplay between plate kinematics and erosion (Norris & Cooper, 2001).

1.3.2 Geophysics

Very little geophysical work has been undertaken in the Paringa River area. The establishment of the New Zealand Primary Gravity network as detailed by Robertson & Reilly (1960), included the placement of an absolute gravity station in the Paringa River valley. This Primary Gravity station has since been destroyed with the construction of the new road bridge in the late 1970s to early 1980s.

Other notable work in the Paringa region was the development of surveying marks across the Alpine Fault. These were constructed in the early 1970s to measure relative movement across the fault. This survey network was set up across many of New Zealand's major faults. The intention was to revisit these sites every five years to resurvey and determine the accumulated strain across the fault (Blick, 1973). This programme appeared to be abandoned after only five years, the reasons being unclear to this author. The local landowner suggested, however, that the new road bridge obscures many of the survey lines, which may have contributed to the abandoning of this project in the Paringa River valley at least. In subsequent years, the advent of GPS facilitated the continuation of geodetic strain measurements across the Alpine Fault zone in the Paringa Region (Beavan et al, 1999).

From the 1950s through to the mid-1980s, and especially concentrated in the late 1970s and early 1980s, there was a considerable amount of regional geophysical research undertaken in New Zealand. The geophysical division of the New Zealand Department of Scientific and Industrial Research (DSIR), forerunner to the modern Geological and Nuclear Sciences (GNS) published numerous reports during the late 1970s to the mid-1980s. From these records it is clear that geophysical work was not attempted in the South Westland region. However, it is still beneficial to study examples of similar work from other areas, in order to form a basis for comparison.

The Moutere depression in the Nelson region features a sediment filled basin bound by basement rocks. While considerably larger at 23 km wide than the 1-3 km of the Paringa River valley, the comparison is useful. Anderson (1980) detailed the gravity survey used to
determine the basement topography and sediment thickness. The geophysical data allowed the identification of a linear positive anomaly that was attributed to a basement ridge and sediment thickness maxima were identified in selected locations across the basin. The data have, in places, been supplemented by seismic lines and rare drill cores and these have provided constraints on geophysical models, thus providing insight into the usefulness of such models.

Anderson (1987) also examined another sediment-filled basin: the Hamner depression. This basin, situated in North Canterbury, is thought to have formed as a pull-apart basin along the Hope Fault, resulting in a sediment-filled basin bounded by basement rock. The geophysical investigation undertaken there involved a gravity survey and resulted in the development of models describing basement topography and maximum sediment thickness.

The southern Manuherikia Valley in Central Otago is another location where geophysical techniques have been used to determine basement topography and sediment thickness. The report by Hatherton (1986) showed that the basement rock in the Manuherikia valley is similar to the Schist found at Paringa. In this report two seismic refraction lines had previously been acquired across this valley, but had proven inconclusive. Gravity data were subsequently obtained and allowed modelling of this sediment filled valley and models describing the basement topography were developed as a result.

More recently, Kleffmann (1999, and Kleffmann & Stern, in revision) used gravity methods to interpret basement profile and overlying sediments sequence in the MacKenzie Basin, Central Canterbury. Used in conjunction with seismic reflection techniques, gravity modelling was beneficial in interpreting basement profiles, faults and sedimentary layers.

1.4 Regional geology

The Paringa River region is dominated by two basement rocks types separated by the Alpine Fault, which runs diagonally across the field area from SW to NE (Map 1). To the west of the fault are the Paleozoic greywackes and argillites of the Greenland Group suite of rocks (Simpson et al, 1994). Distributed throughout the Greenland Group basement are intruded granitoids, basalts and lamprophyres. To the east of the Alpine Fault lie the Haast schists (Simpson et al. 1994). Eastern basement rock consists of the Haast schist, a metamorphic
overprint of pumpellyite-actinolite to amphibolite facies over the Caples and other terrains (Mortimer, 2004). Uplift over the last 5 million years has exhumed mylonites that formed at depths of ~5 km. The result is a 1 km wide zone of mylonitised Haast Schist adjacent to the Alpine Fault trace (Norris & Cooper, 2003).

Within the Paringa River valley itself are the marine and lacustrine sediments of the Paringa Formation, exposed because of uplift associated with Alpine Fault activity. Overlying the Paringa Formation and the basement rocks are Pleistocene fluvioglacial sediments along with Quaternary to recent fan and fluvial deposits. The boundary between the fan deposits and the recent fluvial deposits is difficult to determine because the origins of the clasts are from the same source; the Haast Schist. In addition, the fan deposits will have been reworked into recent river deposits given the activity of the various watercourses.

For the purposes of the gravity and magnetic survey, other rock properties are important, namely the densities of the different rock types for the gravity survey and the magnetic susceptibility for the magnetic survey. The Greenland Group rocks, and the Haast Schists and mylonites are of very similar density at around 2.67 Mg/m³. The density of the Paringa Formation and the cover sediments is more difficult to determine but is expected to be controlled by the porosity of the sediments, which should lie within a defined range.

Magnetic susceptibility is a measure of the degree that a rock can be magnetised and is a dimensionless unit. The susceptibility is mainly derived from the type and concentration of more susceptible minerals in the rock. The magnetic susceptibility of the basement rocks has been shown to be very similar, with values of around $10^{-4}$ (Whiteford & Lumb, 1975), while the magnetic susceptibilities of the cover sediment is thought to be slightly less because of the higher porosity. The presence of water trapped in high porosity zones such as a fault plane may also be utilised in a magnetic survey.

1.5 Geophysical Methods

Geophysical techniques are commonly used to define structural and lithological features that are buried under sediments. Structural features such as folds and faults, lithological features such as crustal rock distributions, and archaeological features such as buried structures, are all
common geophysical targets. Many techniques have been devised to acquire geophysical information as quickly and efficiently as possible. Examples of geophysical techniques include, seismic, gravity, magnetic and electrical surveys.

Ideally, surface geophysical surveys will cover the entire extent of the presumed target. However, in this case the Paringa River crossed the field area and hence the geometry of the field area was a factor of which the geophysical methods used had to be capable of dealing with.

Shallow seismic

Of the various geophysical techniques, seismic surveys often provide the best resolution when imaging sub-surface structures. However, seismic surveys are labour intensive and are subject to complex data analysis issues. They also rely on assumed seismic velocity properties of the rock units. Therefore seismic solutions, like all geophysical techniques, are non-unique and often rely on parallel geophysical and geological methods to provide constraints that allow more defined solutions.

One concern when designing a seismic survey is the avoidance or reduction of noise. Noise can be defined as the deflection of a seismic trace by anything other than energy reflected once from an interface (Little, 1999). Noise can result from many different sources; natural, cultural or from the seismic methods themselves. Natural sources of noise include animals moving, the wind and flowing water. Other sources of noise can be anthropogenic in origin, such as moving vehicles (Little, 1999). Noise can be very detrimental to the quality of seismic data obtained. The major source of noise in the Paringa valley was from the Paringa River that ran directly through the field area. As a result, shallow seismic work was not considered for this project. The technical obstacles to overcoming the noise problem would have been insurmountable.

Gravity survey

Gravity surveys show anomalies in the gravitational field of a region and from these, density boundaries can be interpreted. From the boundaries, interpretations can be made concerning the shape and distribution of basement topography. Regional characteristics of sedimentary basins are commonly investigated using gravity techniques. Complexity is introduced by
reductions that need to be made to the data to account for features that affect the gravitational field but are not of specific interest to the survey. The variations in the regional field can often be greater than field variations caused by the targeted feature, and therefore data corrections need to be very carefully calculated. A gravity survey was the main geophysical method used in this project.

*Magnetic survey*

Magnetic surveys show anomalies in the magnetic field of a region. Similar to the gravity survey, corrections are needed to remove regional magnetic effects before local anomalies can be identified. However, there are fewer corrections to be made to magnetic surveys than to gravity surveys. The main use of magnetic surveys is the identification of ore bodies which characteristically have different magnetic properties to country rock. Other uses have been found however, that take advantage of the polarity of ground water. These result in an electric current and hence a magnetic field, for example, ground water trapped in a porous fault plane. A magnetic survey of the Paringa River valley was undertaken as part of this project. The data gained however was unhelpful for the aims of this project.

*Other methods*

Many other geophysical methods have been developed to investigate the sub-surface. However, as many are specific in their application and targets and hence are not as versatile as gravity and magnetic methods. This survey was restricted to gravity and magnetic techniques.

1.6 *Aim and objectives*

The aim of this project was to use geophysical techniques to investigate some of the questions raised by Simpson's work in the Paringa River valley region in 1992. The objectives of this study are listed below, each with questions or subsections that were considered and intended to elucidate the main aim. These are to:

1. Model the basement topography beneath the Paringa Valley
   - Has it got a deep base similar to the Fiordland style fiords?
   - Is it shallow based, with just a thin veneer of Paringa Formation marine/lacustrine sediments overlain by minimal river gravels?
Chapter 1: Introduction

(2) Identify the Alpine Fault beneath the gravel infill

Use gravity and magnetic methods to visualise the Alpine Fault

- Is the basement displaced beneath the gravels on the line of Simpson's (1992) proposed fault, as would be expected from this model?
- Has a fault block been preserved beneath the cover sediments?
- Can the position of the Alpine Fault across the Paringa River valley be constrained?
- Can the position of the abandoned section of Alpine Fault be constrained?

(3) Compare Alpine Fault uplift rates

Correlate Simpson's (1992) uplift rates to the vertical component of the offset implied by the depth of the valley floor, assuming this offset began following the ice retreat from the valley.

(4) Identify the origin of the NE trending valley connecting the Paringa Valley with that of the Doughboy Creek and Maihitahi River (from now on referred to as the NE trending valley).

- What is the basement topography?
- How deep is the basement?
- Can the alpine fault be constrained?
- What is the vertical component of the offset on the Alpine Fault?
- What is the origin of the NE trending valley?

(5) Investigate the Paringa River evolution

- How has the offset along the Alpine Fault affected the development of the Paringa geomorphology?

(6) Complete the geological map of the region by mapping the NE trending valley

(7) Analyse the western province intrusive rocks of the Paringa River valley region

- How do these intrusive rocks relate to similar rocks in the greater Western Province region?
- What is their origin?
Chapter 1: Introduction

1.7 Layout

Chapter 2 reviews the Paringa region's geology, including work undertaken as part of this project: mapping of Blackwater Creek, and geochemical analysis of the Paringa granites and lamprophyre dykes. Chapter 3 contains the methods and results of the geophysical survey. The final chapter, chapter 4, interprets the results of the preceding sections and presents the conclusions based on the work contained in this report.
2. Geology

2.1 Introduction: Geology of the field area

The focus of this project was to use geophysical methods to explore aspects of Paringa's geology not able to be identified using geological mapping. However, a summary of the geology of the Paringa region is presented in the section below however. Geological mapping was also undertaken in the NE trending valley to connect earlier work in the region by Simpson (1992) and Higham (1996). There are four aspects of the geology section; (1) the geology of the Paringa region; (2) Blackwater Creek geology; (3) geophysical implications of the geology; and (4) geochemistry of the Paringa granites and lamprophyre dyke.

2.1.1 Description of basic geology

The geological map of Paringa (Map 1) displays the major features of the region. The trace of the Alpine Fault traverses the region from the NE down towards the SW margin of the map. The Alpine Fault forms the major discontinuity along the Australian and Pacific plate boundary, and accounts for a large proportion of interplate slip, \( \approx 25 \text{ mm/yr} \) (Norris & Cooper, 2001) of the total 37 mm/yr based on NUVEL 1A (DeMets et al, 1994). Oblique convergence has resulted in the uplift of the Southern Alps and the associated exhumation of deep crustal rocks to the east of the fault over the last few million years (Norris & Cooper, 2001). The Alpine Fault divides the Western Province rocks from the Eastern Province rocks with the Greenland Group metasediments, granites and volcanic rocks to the west and the Haast Schists to the east. The Alpine Fault structure is not as simple as it first appears, because segments have developed that partition the transpressional strain onto thrust structures linked by more easterly trending strike-slip segments (Norris & Cooper, 1995, Simpson et al, 1994). The result is a complex system of faults across the Paringa River valley and up Filleul Creek (Simpson et al, 1994). Associated with the processes that have caused the segmentation of the Alpine Fault has been the formation and abandonment of a thrust nappe, which forms Ward Hill in the SW corner of the field area. Quaternary sediment derived, from high erosion rates in the surrounding mountains, infill all the low lying valley regions.
2.1.2 Aims for geological section

There were two main aims of this section of the project: (1) to complete the geological map of the wider Paringa region by mapping the NE trending valley, thereby linking two previous mapping projects (Simpson, 1992, and Higham, 1996); and to (2) determine the geochemistry of the Paringa granites and lamprophyre dykes. An additional aim was added with the recognition of pseudotachylyte during mapping of the fault zone. This initiated more detailed work as neither Higham nor Simpson recorded any of these.

2.2 Structure

2.2.1 The Alpine Fault

The dominant structural feature of South Westland is the Alpine Fault which strikes approximately 055°. The fault marks out the western boundary of the Southern Alps, before trailing offshore in northern Fiordland.

Relative plate tectonics-plate boundary dynamics

The Nuvel 1A model (DeMets et al, 1990, 1994) indicates that total relative displacement across the Australian and Pacific plate boundary is 35.5 ± 1.5 mm/yr parallel and 10.1 ± 1.5 mm/yr perpendicular to the Alpine Fault. However, field mapping indicates that strike-slip rates along the length of the Alpine Fault consistently equate to \( \dot{\gamma} \approx 27 \pm 9 \) mm/yr (Norris & Cooper, 2001). Thus, not all transform displacement is accommodated on the Alpine Fault, with ~25% thought to be partitioned onto parallel structures mainly to the east (Norris & Cooper, 2001). This distribution of strain across the broader South Island is supported by the geodetic work detailed in Beavan et al. (1999). GPS positioning of survey marks in the central South Island has shown significant strain distributed within 20 km of the Alpine Fault, with additional strain recorded over at least another 60 km to the eastern margin of the Southern Alps.

Partitioning of fault-normal displacement

Field mapping throughout South Westland indicates that displacement on the Alpine Fault is often partitioned onto linked sections of the fault that accommodate either transform or compressional motion. An example of this is the Waikukupa thrust to the North of Paringa,
which shows evidence of slip partitioning (Norris & Cooper, 1997). While the Alpine Fault appears linear on large-scale maps or on satellite pictures, at a smaller-scale the fault is observed to partition into sections with slightly different orientations. This characteristically occurs where the fault intersects a major fluvial valley. These partitioned faults have different orientations depending on their dominant motion, with transform sections oriented with a more easterly strike and a steeper dip (50-70°) and thrust sections striking more northerly with shallow dips of around 25-40° (Cooper & Norris, 1997).

Norris & Cooper (1995) describe the systematic partitioning of the Alpine Fault characterised by oblique thrusts linked to dominantly strike-slip segments, which is apparent on a scale of 1-5 km. Figure 2-1 displays a stylised representation of the Alpine Fault partitioning where thrust segments are linked by more easterly strike-slip segments. This style of slip partitioning of a major transpressional fault does not appear to be a common feature of transpressional continental plate boundaries. For example, the San Andreas fault system partitions transform and compression displacement onto distinct parallel structures, in contrast to the Alpine Fault where partitioning occurs on differently oriented segments on the same structure. These authors attribute the Alpine Fault style partitioning to the nature of the oblique ductile fault zone at depth, and the brittle zone with a surface cut by steep topography. These surface corrugations control the strength distribution in the near-surface crust, therefore allowing thrust and strike-slip segments to develop. The concentration of displacement on the Alpine Fault itself, rather than the San Andreas style parallel partitioning, is thought to be caused by the large amount of erosion across the plate boundary which causes high exhumation rates, hence bringing hotter, weaker rock to the surface along the east-side of the Alpine Fault, resulting in the localising of failure along the fault (Koons et al, 2003).

**Little Paringa Hill**

The Little Paringa Hill is an anticlinal structure adjacent to the current Alpine Fault trace (Fig. 2-3). The formation of this structure is attributed to local stress perturbations caused by the
partitioning of Alpine Fault displacement onto thrust and strike-slip segments. This has caused a restraining bend or antidilational jog (Norris & Cooper, 1995) in the Paringa valley, resulting in anomalously high uplift and the creation of the Little Paringa Hill anticline (Simpson et al, 1994).

Figure 2-2: Cross-section down the centre of the Paringa River valley (as interpreted by Simpson, 1992). This cross-section lies approximately parallel to the SE end of the P-DS survey line of this project. The x and y axis have the same scale. From NW to SE the cross-section illustrates a fault block preserved beneath the cover sediments. To the SE structural complexity associated with the development of a restraining bend in the Alpine Fault caused localised stress and induced high uplift rates. The result is exposure of basement rocks and the Paringa Formation at Little Paringa Hill.
2.3 Basement rocks

2.3.1 Western Province rocks

2.3.1.1 Greenland Group

Occurrence

Greenland Group rocks are found on the western side of the Alpine Fault. Exposure in the field area is minimal and is generally restricted to creek beds, for example near the old Paringa Bridge northern abutment (GR 277161). Intruded into the Greenland Group are granites and lamprophyre dykes. The Greenland Group rocks form the footwall side of the Alpine Fault and are found in conjunction with both the fault and mylonites of the Haast Schists up the relatively inaccessible Filleul Creek valley (Simpson, 1992).

Age

The Greenland Group is thought to be Ordovician in age based on fossiliferous evidence (Cooper, 1989).

Description

The following is a description of the Greenland Group rocks from work by Simpson (1992). Typically the Greenland Group rocks are fine grained, well-sorted, well-lithified, micaceous meta-sediments. Initial outcrop appearance is massive; however, on closer inspection subtle variations in grain size are apparent and represent original bedding. A weak foliation is commonly observed, though strike and dips are highly variable, suggesting the sequence is complexly deformed. Thin (1-2 cm), variably orientated quartz veins crosscut the sandstone in places. These quartz veins increase in abundance near intruded quartz pegmatite, and are orientated sub-parallel to the contact Simpson (1992).

Petrography

The meta-sandstones of the Greenland Groups are dominated by quartz (35%), and contain biotite (30%), plagioclase (up to 15%), and minor muscovite (<5%) and apatite (Simpson, 1992). A more detailed description can be found in Simpson (1992).
Chapter 2: Geology

Geochemistry

Simpson (1992) describes the whole rock analysis of the Greenland Group sandstones based on published work by Mason (1961) and Nathan (1976). These analyses variously describe the Greenland Group rock as quartzose and generally poor in feldspar and lithic fragments.

Geophysical implications

The density of the Greenland group meta-sediments have rarely been studied in the Paringa Region. Whiteford and Lumb (1975) list only 7 samples from the Paringa map sheet (S77), and of these only one is identified as sandstone. Minimal data have been obtained regarding geophysical properties. Appraisal of this catalogue indicates a remarkable heterogeneity in density for the basement forming rocks (including the granitoid), with a range of 2.6-2.8 Mg/m³. The magnetic susceptibility of the Greenland group rocks is around 10⁻³ (Whiteford and Lumb, 1975) which is comparable to other basement rocks in the region.

Discussion

The Greenland Group rocks were not mapped as part of this project although they were observed in the field, for example, at the old bridge abutment (GR 277161, as described earlier). Their distribution and geophysical properties are important aspects for the gravity survey component of this project however. For example, on the transects across the 'lower' Paringa valley (P-TM and P-TU) as well as the transect across the NE trending valley (DB survey line), the Greenland Group rocks form one side of the basement being surveyed. Depending on the relative density of the Greenland Group rock with respect to the Haast Schist basement rock, corrections would have to be made for this density contrast. However, this does not appear to be a problem as the density of these two basement rocks is virtually indistinguishable (based on Whiteford & Lumb, 1975).
2.3.2 Paringa Granitoids

Only limited work has been done on the Paringa Granites. The published information is mainly restricted to Tulloch & Challis (2000). These authors do not assign the Paringa granite to any of the New Zealand suites of plutons, but describe them as miscellaneous. Two samples are known to have been collected by Tulloch as their record is in Petlab (GNS database). The lack of interpretation surrounding these two samples may result from the nature of these samples, as they were not collected in situ. More recently work by Tulloch (pers. comm. 2005) has provided additional analyses. This project seeks to contribute to the limited existing data on the Paringa granitoids through geochemical analyses. This should enable a comparison to other granites found nearby, such as the Haast granites (Randall, 2004), while also relating them to major plutonic suites recognised from the Western Province of New Zealand (Tulloch, 1983). The end result will determine the magmatic origin of these granites and therefore relate them to the tectonic setting at the time of emplacement.

Occurrence

The granitoids are found to the west of the Alpine Fault. However, because of the dense vegetation, the extent of the granitoids is difficult to determine and only three small exposures were found. Samples were collected from these three locations:

1. Abandoned quarry (GR 292171) on the west flank of an unnamed hill, from now on referred to as Hill 150 (OU76009).
2. Active quarry (GR 252157) on the north flank of Ward Hill, sample OU76007.
3. From an exposure on the bank of Dicks Creek (GR 248155), sample OU76008.

The granitoids are thought to intrude the Greenland Group sandstones, although the contact was not observed.

Age

Various ages have been determined for the Paringa granitoids. The earliest work used K-Ar analysis of biotite and indicated an age of 286 ± 12 Ma (Late Carboniferous; Hurley et al. 1962, in Simpson, 1992). Aronson (1965) used Rb-Sr dating of biotite, muscovite and whole rock samples of schist from Moeraki Bluff (~10 km south of Paringa). The c. 330-360 Ma
dates produced by this method are thought to represent the age of contact metamorphism caused by granitoid intrusion. More recent U-Pb dating indicates a c. 360 Ma for the Paringa granitoids, which correlates with the Aronson data (Tulloch & Kimbrough, unpublished data; reported in Tulloch & Challis, 2000). More recent U-Pb dates have given an age of 367 ± 2 Ma (pers. comm. Tulloch, 2005).

**Description**

In outcrop the Paringa granitoids are medium grained, mesocratic, holocrystalline and equigranular.

**Petrography**

Samples collected for geochemical analysis and those from fieldwork of Simpson (1992) contain a very similar lithology when viewed in thin-section. The granitoid is a medium-grained, hypidiomorphic granular granite. The samples collected for geochemical analysis are described below. The percentage compositions were estimated visually.

Feldspars (65%) dominated sample OU76009 (H150G), with plagioclase dominant over orthoclase. Quartz (25%) and biotite (5%), with alteration to chlorite, were common. Other constituents included minor hornblende, epidote, titanite and trace apatite and magnetite.

Sample OU76007 (Q1) contained feldspars (60%) with plagioclase dominant over orthoclase, with quartz (20%), biotite (10%), and hornblende (5%). Minor constituents were epidote, titanite, apatite and magnetite.

Sample OU76008 (DC01) contained feldspars (60%) with plagioclase dominant over orthoclase, with quartz (30%), and biotite (5%). Minor constituents were epidote, allanite, titanite, apatite and magnetite.

**Geochemistry**

**Sample collection**

The Hill 150 sample (OU76009) was found at the surface of the quarry face and judging by the angular faces and size, it is reasonable to assume that the sample came form the immediate
area. The sample from the active quarry (OU76007) was collected in situ. The Dicks Creek sample (OU76008) was removed from a highly weathered rock face: the face orientated with a fracture surface parallel to the creek's eroded bank. The sample was extremely difficult to collect and had a weathered rind. Attempts were made to ensure minimal rind was introduced into the analysed sample (see below).

_Crushing_

A sledge hammer and a rock hammer were used to crush the bulk rock samples followed by further crushing using a pneumatic crusher. Obvious weathered chips, especially from the DC01 sample, were removed throughout the crushing process. The chips were then reduced to powder in a tungsten carbide Tema® mill.

_XRF preparation_

Glass disks for major element analysis were made from 0.64 g of powdered sample using an Automated Fusion Technology Ltd. Phoenix 4000® casting machine. Pressed powder disks for trace analysis were produced from 5 g of the powdered sample. The volatile content was determined by the loss on ignition (LOI) method. 2.0 g of crushed sample was placed in a McGregor® furnace at 1150° C for one hour, with the weight loss resulting from loss of H₂O, CO₂, Cl, F and oxidation of Fe²⁺.

X-ray fluorescence (XRF) major and trace element analysis was undertaken on the granitoid samples. The method of sample collection and preparation is detailed below. Major element concentrations (expressed as weight % oxides), and trace element concentrations (expressed as parts per million) were determined at the University of Otago, Geology Department's Phillips® PW2400 sequential x-ray fluorescence spectrometer (XRF), following the general procedure outlined by Norrish and Chappell (1977). The major and trace element data is displayed in appendix A.

_Geochemical Classification_

Many classification schemes for granitoid rocks have been developed based on whole rock geochemistry (e.g. Frost et al. 2001). Other schemes have concentrated on the source rock
type, for example the S and I type classification of Chappell & White (2001). Between them, magmatic origins and related tectonic settings can be determined.

One well recognised classification is the total alkalis vs. silica (TAS) diagram (after Cox et al. 1979), which is used to give a preliminary classification of plutonic rocks. The TAS diagram classifies the Paringa granitoids as granodiorite, which concurs with analysis by Tulloch & Challis (2000).

Volcanic rocks have classically been subdivided into two major magma series: alkaline and subalkaline. TAS diagrams can be used to show this subdivision; the granodiorite field and hence the Paringa granitoids are classed as subalkaline. Additionally, the subalkaline field is usually further subdivided. This subdivision is often on the basis of K$_2$O vs. SiO$_2$ (after Le Maitre et al., 1989). Using this method, the Paringa granitoids plot within the calc-alkaline field. This division is confirmed by the modified alkali-lime index (MALI) of Frost et al. (2001) which clearly shows the Paringa granitoids plotting in the calc-alkaline field (Fig. 2-3). Therefore the Paringa granitoids are classified as calc-alkaline granodiorite.

Comparison with Western Province granitoids

The Western Province basement metasediments are intruded by numerous granitoid plutons. Considerable work has been undertaken to group these granitoids according to geochemical characteristics. The following paragraphs detail the process undertaken to determine how the Paringa granodiorite relates geochemically to other granitoids from the Western Province.
The Paringa samples collected as part of this field work were compared to two previously collected samples from the Paringa region (Tulloch, unpublished data, Petlab) these samples are described as creek float and as such are not as reliably constrained as the samples collected as part of this project. In addition, granite samples from the Haast region (Randall, 2004) and median composition samples from the major granitic suites in the Westland region were included for comparison (Tulloch & Kimbrough, 2003).

![Figure 2-4. K2O-Na2O-CaO-tetrahy plot comparing the Paringa granodiorite to major Western Province plutons (as used by Tulloch, 1983). The Haast granitoids (Randall, 2004) are plotted, clearly showing composition differences to the Paringa granitoid.](image)

The Paringa granitoids are plotted on a K2O-Na2O-CaO-tetrahy plot (Fig. 2-4), which Tulloch (1983) used to compare composition differences between the Western Province granitoid suites. The Paringa granitoids plot within the characteristic composition of the Separation Point Suite. Furthermore, the Paringa granites are significantly different to the Haast granitoids, suggesting significant differences in tectonic setting.

Further investigation of the difference between the Haast and Paringa granitoids was undertaken. The I- and S type classification is commonly used to differentiate between granitoids. This classification uses a range of distinctive geochemical relationships to ultimately differentiate between granitoids derived by the melting of metasediments (S) or an
igneous source (I). The K$_2$O vs. Na$_2$O plot of Chappell & White (2001) clearly shows the Paringa granitoids plotting in the I-type zone and the Haast granitoids plotting in the S-type zone (Fig. 2-5). The presence of hornblende in the Paringa granitoid thin-section supports this assertion, as this is characteristic of I-type granitoids (Chappell & White, 2001).

Previously it was observed that Paringa granodiorite plotted in the Separation Point Suite zone of the K$_2$O-Na$_2$O-CaO-tenary plot (Fig. 2-4). An additional plot was created to test the apparent similarity. Tulloch & Kimbrough (2003) used the ratio of Sr/Y-Y to identify granites of the Western Province of New Zealand. This ratio can be used to differentiate between the three main suites of granitic rock. A high ratio of Sr/Y-Y (HiSY) is indicative of the Separation Point granites, whereas a low ratio of Sr/Y-Y (LoSY) indicates Median Suite granites; a slightly elevated Sr/Y-Y ratio indicates the Rahu Suite. As figure 2-6 shows, the Paringa granites plot on the lower end of the HiSY zone which is defined as Sr/Y >40 (Tulloch & Kimbrough, 2003). This fits with the previous evidence that implies the Paringa granites are equivalents of the Separation Point Suite.

However, the 126-105 Ma (Cretaceous) age of the Separation Point Suite contrasts with the age of the much older Paringa granodiorite (c. 360 Ma: Tulloch & Kimbrough, unpublished data; reported in Tulloch & Challis, 2000). Care needs to be taken therefore, when using geochemical properties, such as S- and I-type characteristics for determining how a particular pluton fits into the Western Province granitoid scheme. There are at least two I-type
granitoids, the Paringa granitoid and the Separation Point Suite, intruded into the Western Province that are geochemically similar. In summary:

(1) Paringa granodiorite has a similar composition to the Separation Point Suite, based on the K2O-Na2O-CaO ternary plot (Fig. 2-5), the I-type granitic composition (Fig. 2-6) and the Sr/Y-Y ratio (Fig. 2-7). However, the Paringa granodiorites are considerably older than this suite.

(2) The Paringa granodiorites have a similar age to the Haast granitoids (Palaeozoic; Randall, 2004), but, the Paringa granodiorites (I-type) are of significantly different composition to the Haast granitoids (S-type) and are inferred to have a different source rock (igneous or metasediment respectively).

(3) Chronological evidence suggests that the Paringa granodiorite and the Haast granitoid were emplaced as the result of the same Palaeozoic tectonic activity. Tectonic and magmatic events in Palaeozoic New Zealand have previously been grouped into a number of loosely related events termed the Tuhuan orogeny. (Cooper, 1989).

More recently, Tulloch et al. (pers. comm. 2005) have proposed that the Paringa granodiorites are part of a wider suite of granitoids, linked by age and I-type geochemistry, called the Paringa Suite. The constituent granitoid are spatially widespread from Fiordland to Nelson and constitute the Hauroko, Dolphin, Milford, Pembroke and Riwaka granitoids along with the Paringa granodiorite. The inference is made that because they are related geochemically and chronologically they are potentially of the same tectonic origin.

Tulloch et al. (pers. comm. 2005) extends this theory to include all of the various Palaeozoic plutons in the Western Province. The result is two sets of I-type granitoids and two sets of S-type granitoids from the Palaeozoic. The Karamea Suite is the S-type Suite relatively closely related to the Paringa Suite in time. Tulloch (pers. comm. 2005) tentatively links these two suites because of relatively similar ages. He has some doubts, however, surrounding the timing of the tectonic event that may have formed these two chemically different suites.
However, the characteristic sequence of S-type granitoids preceding I-type granitoids, as described by Chappell & White (2001), is observable with these two suites.

In conclusion, care needs to be taken when ascribing a granitoid to a Western Province Suite, as there appear to be at least two granitoid suites, spread in time across the Palaeozoic to the Cretaceous, that have broadly similar I-type granitoid properties. A parallel series of S-type granitoids are apparent in the Western Province over time. Potentially the I- and S-type granitoids of the Palaeozoic have a similar common tectonic origin to the one that created the Cretaceous paired suites granitoids (Tulloch & Kimbrough, 2003). Consequently, the Paringa granitoids (I-type) and the Haast granitoids (as part of the S-type Karamea Suite, Randall, 2004), may have been emplaced as a result of a common tectonic origin.
2.3.3 Lamprophyre

Occurrence

Only one example of this type of mafic intrusive material was found in the Paringa region, at Hill 150 (GR292171). This sample was not found in situ but in the clearing of shattered rock and overgrown scrub of the abandoned quarry. The shattered rock consisted of granite and lamprophyre. The author is confident that the sample is from the immediate area because the considerable size, weight, non-worn faces and position at a topographic high indicate that the rock had not been transported, either by human activities, or by natural processes.

The lamprophyre dykes described by Simpson (1992) in the quarry at GR252157 were not observed during the current fieldwork. Extensive quarrying will have dramatically changed the profile of this site, possibly removing the lamprophyre dykes. However, the extremely unstable eastern end of the quarry was not closely inspected.

Age

There are no known ages for the Paringa lamprophyre dykes. Lamprophyre dykes from Northern Westland are thought to be 78-84 Ma in age based on K-Ar dates (Adams & Nathan, 1978). However, these are distant from the Paringa region and uncertainty surrounds the connection between the Northern Westland lamprophyres and the Paringa lamprophyres.

Description

The lamprophyre sample collected from GR292171 is fine grained and grey to green in colour. The contact with the granitoid is planar with a sharp boundary. The description by Simpson (1992) of the lamprophyre dykes at the active quarry is perhaps useful, as the description of the rock sample itself is similar to the sample taken from Hill 150. It must be noted that the following description was made for a dyke swarm at a different location to that of the OU76010 sample. The dykes described by Simpson were up to 1 m thick, planar and laterally continuous, with a strike of between 050° and 070° and a moderately steep dip to the SE. The contact between the dyke and the surrounding rock was sharply defined (Simpson 1992).
Chapter 2: Geology

Petrology

Sample OU76010 contained brown 'basaltic' hornblende (25-30%), possibly kaersutite. Plagioclase (60%) was restricted to the groundmass, with minor quartz (5%) clinopyroxene, magnetite and titanite. The sample displays equigranular to panidiomorphic textures as described by Rock (1991).

Geochemistry

Method

The methods used to prepare the lamprophyre sample for XRF analysis are given in section 2.3.2 (granitoid geochemistry). Note that additional bulk rock reduction methods were used. In addition to the manual crushing using sledge and rock hammers, the OU76010 sample was reduced in size using a diamond bit saw and abrading the saw-cut faces.

Classification

Based on the total alkalis vs. silica (TAS) diagram of Le Maitre et al. (1989) The OU76010 sample was classified as a basaltic andesite. However, alteration of the mafic component and the panidiomorphic texture indicate the sample was a lamprophyre.

The OU76010 sample was compared to average whole rock compositions of the five major lamprophyre groups taken from Rock (1991). Figure 2-8 displays OU76010 normalised to the average calc-alkaline lamprophyre major element composition of Rock (1991). Three other lamprophyre samples were included in the analysis to provide a comparison: Sample 75 was from nearby Haast (Randall, 2004), sample AFCCT21B from the vicinity of the Haast-Paringa Cattle Track, north of Haast River and HRS15 a representative sample from the Hohonu Dyke swarm in Northern Westland (Waigt et al., 1995).
et al, 1995). Figure 2-9 normalises the samples against an alkaline lamprophyre average composition. The Haast sample (Randall, 2004) and the Paringa sample were very similar in composition and it was apparent that the calc-alkaline average was a good fit for both these samples. This analysis contradicts that of Randall (2004) who classified sample 75 (Haast) as an alkalic-camptonite based on CIPW normative calculations based on Plagioclase > Orthoclase (after Le Maitre, 1989). This analyses indicates both OU76010 (Paringa) and sample 75 are calc-alkaline spessartites based on the same Plagioclase > Orthoclase normative values. In addition, AFCCT21B (Haast-Paringa Cattle Track) and HRS15 (North Westland) are clearly closely allied to the alkaline group of compositions. Graphical presentation of the other three lamprophyre average compositions was deemed unnecessary because of the widely different major element weight compositions these groups represent. The Paringa and the Haast lamprophyre samples have very similar compositions and it is reasonable to consider that they were intruded as part of the same magmatic system.

Rock (1991) suggested that calc-alkaline lamprophyre dykes are often associated with calc-alkaline granitoid plutons, especially of I-type granites. This association is reflected in the Paringa region with the geochemical classification of the Paringa granites as I-type, calc-alkaline, granodiorites. This association is difficult to test, however, without the age of the lamprophyre dykes known. The only ages are from dykes in Northern Westland and figures 2-8 and 2-9 shows these to have different geochemical signatures.

The missing piece of information is the age of these South Westland calc-alkaline lamprophyre dykes. The North Westland lamprophyres and the Paringa and Haast lamprophyres have no geochemical connection. Based on this evidence, the assumption that the Paringa and Haast lamprophyres are of a similar Cretaceous age as the Hohonu lamprophyres is not supported (field association indicates the Hohonu lamprophyres are late-
Cretaceous or younger in age, Waight et al, 1998). Thus a tenuous coeval relationship between calc-alkaline I-type granitoids and calc-alkaline lamprophyres is suggested. If this relationship is correct the Lamprophyres are Palaeozoic in age. They were intruded following the emplacement of the I-type Paringa granitoid in a subduction zone setting. S-type granitoids, such as the Haast granitoids, intruded before the I-type granitoids and therefore were already crystallised by the time the calc-alkaline lamprophyres intruded. However, dating of the Paringa lamprophyre dykes is needed to determine how close this relationship is.
2.3.4 Geochemistry conclusions

Granitoids

- Paringa granitoid is classified as an I-type calc-alkaline granodiorite.
- Despite the geochemical signature the Paringa granitoid is not part of the Separation Point Suite, which raises the problem of using geochemical similarities on their own to align granitoids to the Western Province suites.
- The Palaeozoic age of the Paringa granitoid indicates a coeval relationship with the Haast S-type granitoids. It is possible a subduction zone setting in the Palaeozoic gave rise to paired I- and S-type granitoids, similar to the Cretaceous paired I- and S-type granitoids described by Tulloch and Kimbrough (2003).

Lamprophyre

- The Paringa lamprophyre dyke is classified as a calc-alkaline spessartite.
- It has a similar geochemical signature to the Haast lamprophyre (sample 75), but different to the Haast-Paringa Cattle Track (AFCCT21B) and North Westland (HRS15) lamprophyre dykes.
- The Cretaceous age of the North Westland lamprophyre may not be a good estimate for the Paringa lamprophyre.
- Rock's (1992) relationship of calc-alkaline lamprophyres intruding I-type calc-alkaline granitoids soon after emplacement may be the pattern observed at Paringa.
- The calc-alkaline lamprophyre followed the I-type granitoids at Paringa and intruded the S-type plutons at Haast.
2.3.4 Haast Schist

Occurrence

The basement rock on the eastern side of the Alpine Fault is the Haast schist. Thick vegetation restricts exposure to creek beds in the most part, despite the wide expanse of the Haast Schist.

Age

The Haast Schist is a metamorphic overprint of pumpellyite-actinolite to amphibolite facies over the Caples and other terrains (Mortimer, 2004). The Haast Schist becomes progressively more mylonitised westward toward the Alpine Fault trace, from schist to the east, to protomylonite, mylonite and ultramylonite adjacent to the fault trace (Norris & Cooper, 2003). The mylonitic rocks were formed at amphibolite facies conditions at depths of 20-30 km. Uplift over the last 5 million years has exhumed mylonites that formed at depths of up to 25 km. The result is a generally up to 1 km wide zone of mylonitised Haast Schist adjacent to the Alpine Fault trace (Norris & Cooper, 2003). The Alpine Fault is rare in this aspect as it has the deep seated mylonite zone exhumed along the active surface trace (Norris & Cooper, 2003).

Description

Four branches of Blackwater Creek on the eastern side of SH6 in the NE trending valley was mapped as part of this project (Map 1). This work was undertaken to join the mapping undertaken by Simpson (1992) in the Paringa region and Higham (1996) at the Mahitahi River.

The next section is a description of the Haast Schist found in the Paringa region based on the work of Simpson (1992). This is followed by a description of the features found in Blackwater Creek, which was mapped as part of this project.

Quartzofeldspathic Schist

Quartzofeldspathic schist is the most dominant lithology of the Haast Schist in the Paringa valley and features coarse segregation banding of quartz-feldspar inter-layered with mica.
Chapter 2: Geology

Garnet-free psammites dominate over garnet-pelite varieties. Quartz veins are common and difficult to distinguish from quartz segregations, apart from obvious cross-cutting relationships (Simpson, 1992).

The following is the mineral assemblage described by Simpson (1992) for the Paringa region: quartz, plagioclase, muscovite, biotite, with varying amounts of garnet, opaque, epidote, allanite, and apatite. Simpson (1992) described the plagioclase as ranging from An$_{20}$ to An$_{40}$, which means that the quartzofeldspathic schist is part of the amphibolite facies as defined by Mortimer (2000).

Amphibolites

Amphibolites make up a minor part of the Haast Schist assemblage. They occur as horizons interlayered within quartzofeldspathic schist. There were two main types of amphibolites: coarse grained (>2 mm) and fine grained (<2 mm). The coarse grained amphibolites were mainly composed of hornblende, feldspars and variably sized garnet porphyroblasts. Fine grained amphibolite consists of hornblende, epidote and minor feldspars. The amphibolites were characteristically layered due to varying amounts of garnet and hornblende, and because of grain size. The bands of layering were generally continuous across the width of most exposures, although the internal structure of these bands was often highly deformed, with isoclinal folds and boudinage structures (Simpson, 1992).

The mineral assemblage of the amphibolites is different for the coarse and fine grained types. The coarse grained amphibolites featured, hornblende, garnet, epidote, plagioclase, quartz, titanite, an opaque, and minor apatite, chlorite and rutile. The fine grained amphibolite comprised hornblende and epidote, with minor quartz, titanite and plagioclase. The fine grained had an equigranular appearance with most minerals 0.2-2 mm in size, with quartz and plagioclase forming the groundmass around the more regular shaped hornblende and epidote (Simpson, 1992).

Pegmatites

Pegmatites are common in the Paringa region (Simpson, 1992), composed of quartz, feldspar, mica and less commonly garnet. Pegmatites form layers parallel to the foliation, although they
can be weakly discordant to the foliation. They have sharp contacts and are often found with thinner pegmatites in close proximity. The regional extent of the pegmatites is wide, with Norris and Cooper (1997) mapping them from Paringa to Franz Josef, ~100 km to the NE. Pegmatite mineralogy consists of quartz, plagioclase, K-feldspar, muscovite, biotite and garnet (Norris & Cooper, 2003). Wallace (1974) suggested that the pegmatites formed as wet partial melts under metamorphic conditions similar to that of the amphibolite facies schist. The pegmatites have been deformed by strain associated with the mylonitisation of the Haast Schists. (Norris & Cooper, 2003).

Metacherts

Metacherts are uncommon in the Paringa region, however Simpson (1992) discovered examples in the headwaters of Waituna Creek which is the next drainage system to the south of Blackwater Creek in the NE trending valley. He described them as generally thin (<50 cm) horizons that are laterally continuous. These metacherts were internally banded with layers varying from 2 mm to 10 cm and comprised of quartz, garnet or a combination of the two. These internal layers are often deformed into isoclinal folds. In this study clasts of metachert were not identified in the exposures found up Blackwater Creek. A metachert boulder was identified in the creek float and it is presumed that samples in situ might be discovered if mapping was taken further towards the headwaters.

Blackwater Creek

The rock exposure in these creeks was found to be characteristically poor with large accumulations of boulders and gravel covering most in situ rock. While some basement rock found at the valley margins was not covered by vegetation, it was characteristically highly altered, with blocks breaking away in the hand. Furthermore, the narrow confines of the gorge walls, boulder accumulations and water volume, made access difficult. The north branch was the most accessible and contains the best rock exposures. The branch immediately to the south is less accessible but an equivalent distance was accessed.

Topography indicates there are four gorges stretching down from the Douglas Range supplying the lower Blackwater Creek with water and sediment. Map 1 shows the layout of the creeks, and provides the names that I have applied for ease of reference in this study.
Chapter 2: Geology

Blackwater Creeks were numbered from the NE end towards the SW. Hence the creek furthest to the NE is designated branch 1, with branch numbers increasing to the SW.

Branch 1

Branch 1 was the most geologically informative site with good rock exposures between 240 m and 280 m; this section of the creek is shown in figure 2-9.

![Sketch map of Blackwater Creek (branch 1)](image)

Figure 2-9: Sketch map of Blackwater Creek (branch 1), detailing the locations of exposed basement and the lithology at these locations. The S-C fabric is observed in the first section of exposed basement but not further to the east. This is interpreted as the eastern margin of the protomylonite zone.

(a) Quartzofeldspathic schist is the dominant lithology exposed in Blackwater Creek. S-C fabrics characteristic of the protomylonitic grade of textural overprint were found (Fig. 2-10). Pseudotachylytes were found sup-parallel to the mylonitic foliation with small (<1 cm), generally high angle, veins protruding into the surrounding rock. A thin (1 cm) pegmatite was observed.
Chapter 2: Geology

Figure 2-10: Quartzofeldspathic schist protomylonite. Pods with preserved Alpine schist fold structures (e.g. F) occur between regions of mylonitic foliation (Sm). A pegmatite vein (P) has been boudinaged during mylonitic deformation, indicating it is older than the Alpine fault deformation. Knife 4 cm (photo V. Toy, 2005).

(b) Pseudotachylite was exposed by fluvial erosion of the basement creek bank. The pseudotachylite was sub-parallel to the protomylonitic foliation. Pseudotachylites were not described by Simpson (1992) in the course of mapping the Paringa region, nor by Higham (1996) in her mapping of the Mahitahi region. A slab of protomylonite containing the pseudotachylite was removed and further measurements were taken in the laboratory. Description and interpretation of the pseudotachylite is made in Chapter 2.3.

(c) A narrow (>10 cm) layer of garnet amphibolite was identified within quartzofeldspathic schist that displayed mylonitic shears (Fig. 2-11).

(d) A lack of S-C fabric was observed in quartzofeldspathic schist, indicating the edge of the proto-mylonite zone.

(e) Quartz veins (<5 cm) with isoclinal folds was observed within the quartzofeldspathic schist.
Figure 2-11: Garnet amphibolite layer in quartzofeldspathic schist. This foliation is displaced by a prominent mylonitic shear zone (labelled C). (Photo V. Toy, 2005).

(f) Coarse-grained garnet amphibolite with a weak wavy foliation, coarser-grained horizons with 3-10 mm crystals were associated with concentrations of garnet.

(g) Numerous pegmatites parallel to foliation were present, with the thickest being <10 cm, and were laterally continuous for the width of the exposure (>3 m). The pegmatites contain micas that were partially aligned with foliation. Garnet crystals were prominent. The quartzofeldspathic schist surrounding the pegmatites had a laterally continuous foliation with no evidence of mylonitic shears, supporting the observation from (d) that the Blackwater Creek section marks the eastern extent of the protomylonite zone.

Branch 2

Branch 2 was considerably larger than 3 and a considerable volume of water passes down the creek. Considerable quantities of rock debris appear to fill the gorge, perhaps caused by slope failure upstream supplying the creek with rock material. This made access up the narrow gorge extremely difficult. The elevation attained up this branch was ~290 m, which is comparable to the elevation that was attained up branch 1; however, there were only poor, highly weathered rock exposures.
Chapter 2: Geology

Branch 3

Branch three was considerably narrower than either 1 or 2, and contained poorly exposed basement rock covered in extensive algae growth, preventing close inspection.

Branch 4

Branch 4 was not visited as the dry drainage path was only discovered at the end of the final day of fieldwork. Based on the width of the drainage path, which was comparable to branch 3, only a small volume of water passes down branch 4 perhaps indicating a similar size of creek up towards the basement rocks, which in branch 3 is extremely narrow with poor rock exposure. Although, aerial photos indicate the gorge of branch 4 is larger than that of 2 and 3, suggesting it may be larger and perhaps contain rock exposures comparable to branch 1.

Geophysical consequences of the Haast Schist

The geophysical properties of the Haast Schist are not thought to vary significantly depending on the specific lithology listed above. Small density variations may arise from fracturing of the schist and were described by Udy (1987) as crush zones. Filling of the fractures with water is the probable cause of the low density.
2.3.3 Pseudotachylyte

Introduction

Pseudotachylyte is an example of a fault rock, formed during the process of seismic rupture along a fault plane. Extreme stress in this shear zone will often produce a rock composed of a matrix of microscopic grains called cataclasites (Sibson, 1975). If frictional heating caused by this rapid displacement is significant, then this fine material may be melted to form a glassy rock called pseudotachylyte. It is thought that pseudotachylytes form near the base of the seismogenic zone (<10 km in the Alpine Fault zone), in conjunction with high normal stress and a rapid deformation rate (Sibson, 1975). Uplift of the originally ductile mylonites results in a drop in pressure and temperature to levels where the seismic slip along a discrete planar fracture becomes the dominant failure process (Sibson et al, 1979). Pseudotachylyte is the friction melt developed along this planar fracture zone. At shallower depths the confining pressure is lower and fault gouge is produced instead (Park, 1997). However, the strain

Figure 2-12. Protomylonitised quartzofeldspathic schist with presumed pseudotachylyte generation surface (arrowed) sub-parallel to the mylonitic foliation. Veins splay out from the generation surface at a high angle into the surrounding rock. The lengths of these veins are ~1 cm. The generation surface varies in thickness up to 1mm.
Chapter 2: Geology

conditions that produce pseudotachylytes are not well understood and this will be discussed in more detail later.

Description

Within the protomylonites of the north branch of Blackwater Creek a dense, black, aphanitic material is present. It features a characteristic fault and injection vein relationship indicative of pseudotachylyte, as defined by Sibson (1975). The orientation of the inferred generation surface is indistinguishable from that of the protomylonite foliation of 075°/58° S (Fig. 2-14). Because of slight variations in the mylonitic S-C fabric however; the pseudotachylyte crosscuts the foliation in some places. The thickness in the main generation surface varies from significantly less than 1 mm up to 1 mm. Veins offshoot from the main body into both the upper and lower surrounding protomylonite, some at a high angle and others at lower angles (Fig. 2-14). These veins are generally thicker than the main body and do not appear to travel more than ~1 cm from the inferred generation surface. The ductile lineation on the mylonite foliation trends 03°/073°, which contrasts with the average of 105° published by Koons et al. (2003). The amount of slip on the generation plane was not able to be determined.

Interpretation

Without scanning electron microscope analysis of the presumed pseudotachylyte we cannot be absolutely certain that the sample obtained is, in fact, a pseudotachylyte and not an ultracataclasite. However, the assumption is made based on the widespread occurrence of pseudotachylyte throughout the Alpine Fault zone (Sibson et al., 1979). The high angle veins are most probably extension fractures formed in the dilatational zone created at the propagation point of the rupture, as observed by Di Toro et al. (2005). The lower angle veins, judging by their thick irregular shape, are probably from the exploitation of weakness within the surrounding rock during rupture. The penetration distance of the veins is most likely limited by the rate of dissipation of the frictional heat and the minimal linking of weak zones within an amphibolite-facies mylonitised metamorphic rock.

The presence of pseudotachylyte in mylonites at more than 100 m from the Alpine Fault trace indicates that not all seismic strain is being released on the Alpine Fault plane. However, it is
not clear how much offset is associated with pseudotachylyte generation events (Sibson et al., 1979). Evidence from offset terraces indicate that only ~70% of total plate relative motion is taken up on the Alpine Fault itself, with the rest partitioned onto parallel structures to the east (Norris & Cooper, 2000). The presence of pseudotachylyte in the mylonitised zone of the Haast Schist indicates that some of the remaining partitioned strain is being released within the first few hundred metres of the rock east of the Alpine Fault. Other lines of evidence that support partitioning onto eastern structures such as GPS (Beavan et al, 1999) do not have the resolution to distinguish strain distribution in such a narrow zone. As such, this distributed strain would be indistinguishable from strain on the Alpine Fault plane itself.

Kanamori & Heaton (2000) suggest that for a 1 mm thick zone of frictional melt, a Mw >3 seismic event is required. The lack of significant seismic events of this magnitude in the seismically subdued zone of the central Alpine Fault zone, between major rupture events (Beavan et al, 1999), indicate that pseudotachylytes were probably formed during major Alpine Fault seismic events and associated aftershocks. However, Leitner et al. (2001) have since indicated that there have been small seismic events in the vicinity of the Alpine Fault zone, perhaps indicating that pseudotachylyte may form, distributed more evenly though time, rather than being dependent on major ruptures.

A more important point is that, in general, pseudotachylytes are not found very close to the fault trace, but occur in the Alpine Fault zone mylonites and protomylonites away from the fault trace (Sibson et al, 1979). This may be because either: (1) any formed close to the fault are destroyed by subsequent deformation and gouge formation, whereas those formed at a greater distance are preserved; and/or (2) pseudotachylytes form during minor, high stress faulting in the wall rocks rather than major faulting along the main fault. They may form before the major displacement, due to stress build up, during the dynamic rupture of the main fault due to dynamic loading of the wall rocks, or as aftershocks following major rupture (Sibson, 1975). However, determining the mode of formation is difficult as the seismic events that formed the pseudotachylyte occurred well before the pseudotachylyte was exposed at the surface.
2.3.4 Blackwater Creek conclusions

- Mapping of Blackwater Creek found that the northern branch contained the best exposures of basement rock. Blackwater Creek branches to the south had very much poorer exposures because of considerable quantities of rock debris or vegetation cover.

- Amphibolite facies, quartzofeldspathic protomylonites with a prominent S-C fabric were exposed at the western end of the Blackwater Creek section. S-C fabrics could not be identified in quartzofeldspathic schist at the eastern end of the accessible basement exposure.

- Another indicator of the reduction of mylonitisation along the exposed basement was from the thickness difference of pegmatites. A thin (1 cm) pegmatite was identified at the western end of the creek section, whereas at the eastern end, numerous pegmatites were identified with thicknesses up to 10 cm, indicating the pegmatites to the east had undergone less deformation than the western example. The interpretation made from this observation is limited however, by the small sample size (n=1) from the eastern end of the creek section. Nonetheless, as the eastern distribution of S-C fabrics indicate there was differential deformation across the length of the section mapped.

- Based on estimates by Norris & Cooper (2003), the distance of the eastern margin of protomylonites from the trace of the Alpine Fault is 300-1000 m. Unfortunately, this width varies with location along strike of the Alpine Fault. At the Blackwater Creek section, the distance from the eastern margin of the protomylonites to the Alpine Fault trace is at least 500 m. The Alpine Fault is not exposed at this location so its location is estimated based on regional mapping and topography.

- Mapping in the Paringa region had not previously identified pseudotachylyte, but its presence is to be expected, as pseudotachylyte distribution through the protomylonite zone is well documented (Sibson et al, 1979).

- Pseudotachylytes within the protomylonite zone indicate small, high shear stress, seismic slip at depth distributed throughout the Alpine Fault zone.
2.4 Quaternary Deposits

2.4.1 Fluvio-glacial deposits

The oldest Quaternary deposits mapped by Simpson (1992) and Mortimer et al. (1984) are very poorly sorted matrix-supported tills and moderately sorted outwash deposits. Clasts range in size from 4 m boulders to silt-sized particles. Exposures are poorly stratified apart from silt horizons that are commonly laminated, and are generally well consolidated.

Three distinct glacial deposit surfaces were recognised by Mortimer et al. (1984) using aerial photos, and were attributed to three separate ice advances. However, poor exposure and vegetation cover impeded the identification of these surfaces in the field. Simpson (1992) thought it impractical to attempt to distinguish between these surfaces and treated the glacial deposits as a single unit. This is reflected in map 1, where the fluvioglacial deposits are mapped as one unit.

Geophysical importance

The fluvioglacial deposits are not a major factor of the geophysical mapping as they are restricted to the SW side of the field area, forming part of Ward Hill. The location of Greenland Group rock on the

Figure 3-15: Stratigraphic column of the Paringa Formation. Facies A, at the base would have formed in a fiord-style setting towards the end of the last glacial period. The predominance of medium to coarse gravels of the Paringa Formation, suggests a level of homogeneity in the density of the Paringa River valley cover sediments, thus allowing a simple, single density contrast to be used to model the Paringa River valley.
lower portion of Ward Hill indicates there is still a considerable component of basement rock at the margins of the Paringa valley. The gravity survey will, at the most therefore, only be minimally affected in the Ward Hill region by the lower density that is assumed for the fluvio-glacial deposits.

2.4.2 Paringa Formation

Occurrence

The presence of fluvial sands, marine silts and lacustrine deposits was noted in the Paringa Valley by Wellman, who first described them in 1951 with a later revision in 1955 (as detailed in Wellman, 1955). Later, Suggate (1968) excluded the fluvio-glacial deposits from the Paringa Formation. In 1992 Simpson undertook detailed analysis of the Paringa Formation. It is the work by Simpson that is reviewed in this section.

The Paringa Formation is a thick sequence of sediments that is exposed to the east of the Alpine Fault in the Paringa valley. Exposures are found in the raised anticline, which Simpson referred to as 'Little Paringa Hill', a name that will be continued to be used here.

Age

The Paringa Formation marks the cessation of the last glacial maximum in the Paringa region. Radiocarbon dates of marine shells in the marine silts of facies A (see below) indicate an age of 15,700 ± 700 years B.P. for the base of the Paringa Formation (Simpson et al, 1994), while radiocarbon dating of wood nearer the top indicates an age of 3,570 ± 40 years B.P. (Simpson et al. 1994).

Description

Simpson et al (1994) subdivided the Paringa Formation into four major facies: (1) laminated marine silts; (2) shallow marine sands; (3) fluvial gravels; and (4) highly carbonaceous cyclic sediments containing forest horizons, lake sediments and fluvial deposits. The stratigraphic column (Fig. 2-15) shows the sequence of sediments that form the Paringa Formation.
Chapter 2: Geology

Discussion

What should be noticed are the different depositional settings that these sediments formed in. Facies A indicates a marine setting with the presence of marine fossils and laminated silts. The presence of angular schist embedded in the silt suggests the presence of floating ice. Microfossil evidence suggests a depth of deposition of at least 40 m below sea level (Simpson, 1992). The increased grain size, cross-bedding and erosion surfaces suggest facies B is a shallowing of the marine depositional system. Above the sands is a 40-50 m thick layer of massive, moderately sorted gravels, with silt lenses and occasional, poorly sorted boulder conglomerates with eroded bases. This facies indicates a fluvial system. The topmost facies D, contains repeated highly-carbonaceous layers separated by laminated silts and gravels. The carbonaceous layers feature logs, branches and root systems of various sizes. Facies D is thought to represent a period of cyclic lake formation and destruction caused by periodic damming of the Paringa River.

Facies A through C appear to record the southeastern retreat of ice from the last glacial maximum. Facies D indicates a mixed fluvial/lacustrine regime associated with disturbance in the Paringa valley, presumed to be associated with uplift on the Alpine Fault (Simpson, 1992).

Geophysical importance

The implications of the Paringa Formation for this project are as follows;

1. The presence of ~65 m of sediments on the up-thrown side of the Alpine Fault indicates there is most likely a great thickness of sediment on the down-thrown side of the fault;

2. Drop stones in the basal marine silts suggest the Paringa valley contained a glacier during the last glacial maximum, which suggests the Paringa valley owes its current geomorphology to glacial erosion processes; and

3. The sequence of sediments indicates there is a history of sedimentation leading to infilling of the Paringa River valley. Marine silts are overlain by shallow marine sands, which in turn are overlain by gravels, followed by fluvial/lacustrine deposits and the rest of the valley infill is topped off by recent river gravels. The implication is that the majority of the sediments, by volume, are unconsolidated medium to coarse gravels and a single porosity can
safely be assumed. This simplifies the process of determining the density of the Paringa valley cover sediments, which is an important parameter for the gravity survey of the Paringa valley.

2.4.3 Recent/fan deposits

The majority of the low lying, flat ground in the Paringa region is composed of recent gravels derived from erosion of the surrounding mountains. On the lower slopes of the surrounding mountains, extensive fans of gravel extend out from the deep gorges cut in the basement rock. These fans have linked up into extensive, relatively shallow-sloping, basal flanks of the mountains especially down the NE trending valley. Here the fan deposits are covered by ~1 m of dirt and plant matter. Most of the fan deposits have been extensively grown over by thick vegetation, and therefore access is mainly limited to creek beds.

The fan deposits are composed of clasts of basement rock from nearby creeks. Flat ground in the Paringa and the NE trending valley is composed of recent gravels and alluvium. The gravels are made up of a variety of lithologies, derived from erosion of the surrounding mountains. The dominant clast types are quartzofeldspathic schist and greywacke, presumably from higher up the Paringa catchment. Reworking of fan deposits and older deposits is common, with fan deposits in the lower slopes of Blackwater Creek being eroded and transported down to the flatter base of the NE trending valley.

*Implications for geophysics*

The key concern of the gravity survey is the determination of relative density between the basement rocks of the Paringa region and the cover sediment that in-fills the Paringa and NE trending valleys. One of the main components of gravity modeling is the determination of the density of the infilling sediment. This undertaking was made considerably because the recent gravels that make up the majority of the cover sediment are derived from the same source as the basement. This component of the geophysical methods will be described later in Chapter 3.7.2: the determination of density.
3: Geophysics

3.1 Introduction

Gravity meter readings can be reduced to measures of actual acceleration of gravity, or, relative gravity differences in gravitational acceleration between two points. An absolute gravity survey is more informative than a relative gravity survey as it is possible to link the data collected to earlier work while still enabling the determination of differences between locations. This raises the question of why relative gravity surveys are used if absolute surveys can determine all necessary information. The amount of time needed to obtain reliable absolute gravity measurements is time prohibitively however, so predominantly relative gravity surveys are used. Furthermore, a relative survey can be used to replicate an absolute gravity survey if it is tied to a location of known absolute gravity.

3.2 Instrumentation

Absolute gravity instrumentation

Absolute gravity measurements can be taken using two methods; the weight drop and the pendulum. The weight drop measures the change in velocity over a known distance for a free falling mass and from this, acceleration caused by gravity can be calculated. The period of swing on a pendulum can be used to determine gravitational acceleration if the length of the pendulum is known. Obtaining reliable absolute gravity measurements is very time consuming and therefore relative measurements of gravity are more commonplace (Kearey et al, 2002).

Relative gravity instrumentation

Relative gravity is measured using a portable instrument called a gravimeter. In the simplest sense, the gravimeter measures the length of a spring attached to a mass to work out the gravitational acceleration acting on the mass. The mass of the object attached to the spring stays constant whatever the location of the gravimeter, although the force acting on the mass changes according to variations in local gravitational acceleration. The mass will weigh more or less depending of the gravitational acceleration, and the spring will stretch or contract in response to the force exerted by the mass. The reading from the gravimeter is based on this change in spring length.
Chapter 3: Geophysics

The Worden Gravimeter

The instrument used in this survey was a Worden Gravimeter. This uses a system of springs and levers to maximise sensitivity to gravitational acceleration while retaining a level of practicality. The Worden Gravimeter is very sensitive and a precision of 0.01 mGals or around $10^{-8}$ of the Earth's gravitational field can be obtained. Unfortunately this sensitivity also leads to effects not associated with the gravitational field, such as temperature or vibrations, being observed. Quartz is utilised in the construction of the springs and levers, minimising the effects of temperature, while a vacuum flask surrounds the delicate internal workings for further protection.

3.3 Gravity survey

There is a network of known absolute gravity sites spread across New Zealand called the New Zealand Primary Gravity Network (Robertson & Reilly, 1960). Relative gravity surveys in New Zealand can be tied to this network, and a survey showing absolute gravity values can be calculated. Unfortunately, over the years since the construction of the Primary Network, the networks integrity has been steadily eroded because of the impact of road realignments and other constructions. These have changed the physical nature of the network base stations or have removed landmarks. The Paringa Primary Gravity Network station has been such affected, as the construction of a new road bridge has removed the Primary Network station. While the location is known from coordinates, the road elevation has been raised and has destroyed the ability to make an accurate measurement at the station. Therefore this study is a relative gravity survey and is not linked to the Primary Gravity Network. As such, the results cannot be referenced to other projects. However because the aims of this project were related to determining local structural features, it was not dependent on knowledge of absolute gravity.

Survey design

The gravity survey was designed to maximise the range of information gathered while also taking into account the restricted time available for field data collection. Creating a grid of survey lines across the Paringa River valley was rejected as an option very early in the design process, because of the vast amount of time this would require. The chosen layout was a
series of distinct lines designed to cover the range of features suspected to be buried beneath the surface gravels of the Paringa River valley. The result was six gravity survey lines in the Paringa River valley and one line in the valley that trends to the NE along the Alpine Fault. Of the Paringa River survey lines, three ran longitudinally down the valley and were called P-DS, P-DL and P-DF. The P denotes that the line is within the Paringa River valley, while the D indicates the "down valley" direction of the survey line. The third letters (S, L and F) are arbitrary designations.

The other three lines traversed the valley, hence the P-T designation, P-TM, P-TE and P-TU. The final letter is indicative of the lines lateral position in the valley; U-for upper valley, E for east, M for middle. There were plans for a western line, but it was not possible to complete because of access and logistical reasons. The survey line in the NE trending valley was termed the DB survey line in reference to Doughboy Creek within which the gravity survey was made (Fig. 3-1).

Method of looping

The Worden Gravimeter is sensitive to very minute changes in the gravity field. The causes of these perturbations in the gravity field may mask the signal from desired features such as subsurface rocks in the vicinity. Therefore the removal of these undesired effects is vital to the success of the gravity survey in the study. In this study many of these effects were removed in the data reduction phase, as described in Chapter 3.4, while others were removed
while undertaking the gravity survey by keeping track of temporal changes in the gravity field at the base station. Unwanted gravity effects that were accounted for in this way included tides, instrument drift and temperature fluctuations.

Tides cause the mass of the earth to be redistributed on a timescale equivalent to the tides themselves. For a gravity survey close to a tidal region, such as the Paringa River valley, correcting for tidal effects is important. The Earth’s tides effect the gravity field by changing the distributing of mass on a ~12 hour time scale. The design of the Worden gravimeter means it requires constant correction, because a spring under constant tension is used to support the mass used to measure the gravity field. This spring will continue to lengthen throughout its life, so a drift correction made regularly throughout the gravity survey will counter this effect.

The most efficient way to remove these effects is through the design of the gravity survey. An integral part of a relative gravity survey is the reference of all gravity observations to a common point. This point is termed the gravity base station and all gravity observations are thereby constrained in time by regular base station observations. In this study these base station observations were plotted and a linear relationship between two points in time was constructed. The intervening gravity observations were modified by an amount that was consistent with this linear relationship. This was done by making the assumption that the gravity field could be approximated by a linear relationship over a short time span. Using this method allows the correction of all the previously mentioned sources of instrument drift.

A negative aspect of looping is the time required to repeatedly reoccupy the base station. A shorter reoccupation time ensures a more accurate relationship between the confining observations, but this needs to be balanced against the reduced number of field observations that can be made during this shortened period of time. Reoccupation was undertaken every 60 minutes, although for some distant loops this extended to 90 minutes.

**Base station placement**

The base station allows comparisons to be made between all gravity observations made in the entire field area. The positioning of this base station must be such that it is easily accessible to the entire field area so that it can be reoccupied many times throughout the course of the
Chapter 3: Geophysics

gravity survey, as detailed in chapter 3.4 on drift correction. Gravity station P-TE05 was chosen as the base station for this survey because it was conveniently located by SH6.

The base station (P-TE05) was relatively close to an absolute gravity base station created as part of the Primary Gravity Network (Robertson & Reilly, 1960). This Primary Gravity station could not be used in this gravity survey because road construction associated with the current Paringa River bridge had removed most indicators of its location, although its position was located using a digitised map from the original Robertson and Reilly report (1960) (Appendix 2). The current elevation of the original Primary Network Station was a problem as the existing bridge embankment was ~1 m above the former embankment. This elevation difference was estimated from the remains of the former bridge buttress still visible. This elevation difference, the close and dangerous proximity of the busy SH6 and the vibrations generated by passing vehicles, resulted in the Primary Gravity Network base station being rejected as the base station used for this project.

To enable this project to be related to the absolute gravity network, the correlation between the primary network station and this project's base station was observed. However because of the uncertainties involved in determining the exact location of the Primary Gravity Network base station, and this project's emphasis on local structures particular to this valley, this correlation was not deemed critical to the success of the project.

Elevation determination

Constraining the elevation of the gravity survey stations is a vital aspect of reducing the gravity anomaly (see Chapter 3.4) and was therefore given important consideration when undertaking the gravity survey.

The Garmin-12 GPS unit was not able to reliably indicate elevation data with the accuracy needed for this survey. The elevation output was highly inaccurate at times, with discrete locations varying up to ±20 m, presumably in response to limited, high-angle, satellite distribution. A preferred method would have been to use a differential GPS system, which would have given elevations accurate to a few centimetres. However, the University of Otago Geology department GPS system was unavailable during the time period available for this fieldwork. The elevations of the gravity stations were undertaken therefore using a Barigo
Chapter 3: Geophysics

barometric altimeter, an instrument that uses the atmospheric pressure gradient to create an elevation reading accurate to 1 m. A barometric altimeter is very sensitive to atmospheric pressure changes and on some occasions was observed to deviate many tens of metres in the course of an hour, usually in conjunction with easily observable changing weather conditions. Consequently the instrument needed to be regularly calibrated at locations of known elevation. This calibration was accomplished by a looping field method similar to the method used for the gravity readings. This allowed the barometric altimeter to be set at a known elevation, following which the gravity survey stations were visited, and reoccupation of the original location completed the loop.

3.4 Data reduction

3.4.1 Introduction to gravity data reduction

Before the data from the gravity survey can be interpreted, corrections must be made to account for variations in the Earth's gravitational field that are not caused by density differences in the underlying rock. These corrections are known collectively as gravity reduction (Kearey et al, 2002). Essentially the desire is for the theoretical gravitational acceleration to be determined for an exact field location and then a comparison can be made to the actual reading. The difference between the two is called an anomaly. This anomaly results from variations in the gravity field caused by subsurface geology and associated densities. There are two main contributors to the data reduction process: firstly, a correction for the latitude of the survey, and secondly, a correction for topography in the field area. This correction is broken down into three equations. All these corrections are detailed in the following paragraphs. The final step inputs these corrections into the Bouguer anomaly, also known as the residual anomaly, which displays the difference between the theoretical reading for that location and that from the field survey. Giving the gravity field anomaly caused by subsurface geology.

3.4.2 Latitude correction $6g_L$

Gravity varies with latitude because of the non-sphericity and rotation of the Earth. Three points are important in relation to the global gravity field:
(1) The centrifugal acceleration resulting from the rotation of the Earth has a negative effect on the gravity field. An important aspect of this rotation is that the tangential velocity is greatest at the equator. Its effect on the gravity field is minimised towards the equator, therefore reducing the strength of the gravity field (Kearey et al, 2002).

(2) The best approximation of the Earth is a polar flattened ellipsoid, with a difference between the equatorial and polar radii of approximately 21 km. This means a point at the equator is more distant from the centre of mass of the Earth than a point in a polar region. This greater distance from the Earth's centre of gravity results in a decrease in the gravity field at equatorial locations. The effect on the gravitational field is greater than that of the centrifugal acceleration; however, their effect is in the same direction; reducing the strength of the gravity field at the equator.

(3) These two effects are partially offset by the mass distribution of the Earth concentrated around the equatorial bulge that increases the gravity field strength (Kearey et al, 2002). The net result is that the gravity field varies according to latitude, with an increase in the gravity field towards the poles.

The following equation allows the quick computation of the effect of latitude on the observed gravity readings (from Kearey et al, 2002):

\[
6g_L = 0.00081 \sin^2 \theta \text{mGal/m N-S}
\]

Where:

- \(6g_L\) = the latitude correction
- N-S = north or south relative to the base station
3.4.3 Topography corrections

Latitude correction is based on the assumption of a simple ellipsoid shape but this is not a realistic representation of the Earth. The Earth has topographic features that not only increase the radius of the Earth at that location but also add mass from the body of rock Fig. 3-2. For the theoretical gravity field to be known, the effect of topography needs to be calculated. This is done in three parts; the Free Air Correction (FAC), the Bouguer Correction (BC) and the Terrain Correction (TC). These corrections are detailed below and are displayed in figure 3-3. Note that the Bouguer Correction should not be confused with the Bouguer Anomaly.

Figure 3-2: The effect of topography on the calculation of theoretical gravity. A greater distance from the centre of the Earth usually results in a lower gravitational acceleration (Lillie, 1999).

Figure 3-3: (a) the free-air correction for an observation at a height above datum. (b) the Bouguer correction. The shaded section corresponds to a slab of rock of h thickness extending to infinity in the horizontal frame of reference. (c) The terrain correction, which accounts for over corrections made by the Bouguer anomaly (Kearey et al. 2002).
Free Air Correction (FAC)

The free-air correction (FAC) corrects for the reduction in gravity with increased elevation, equivalent to an increase in the distance from the centre of mass of the Earth (Kearey et al, 2002). The residual anomaly calculation is as follows (from Kearey et al, 2002):

\[ \text{FAC} = (0.3086 \text{ mGal/m}) \times h \]

Where:
\( h \) = elevation in metres above a common point, usually sea level or as in this project the gravity base-station.

Bouguer Correction (BC)

The gravitational effect of the additional mass underlying elevated regions is addressed by the Bouguer correction. The Bouguer correction approximates an infinite slab of rock with a thickness of equal to the elevation above the datum.

The Bouguer Correction calculation is as follows (from Little, 1999):

\[ \text{BC} = (0.112 \text{ mGal/m}) \times h \]

Where:
\( h \) = elevation in metres above a common point, either sea level or as in this project the gravity base-station.

Terrain Correction (TC)

The infinite slab assumed by the BC may oversimplify the topography to an extent where the topography is not accurately represented and thus the theoretical gravity field is poorly constrained. This is especially apparent in regions with significant topographic relief. The Terrain Correction (TC) is always added to the combined BC and FAC correction because any negative topography surrounding a gravity station will be over corrected by the BC, while any rock mass above the station will not have been accounted for. The mass from above the station will exert an upward attraction therefore reducing gravity. Adding the TC addresses this problem. The TC is more complex to calculate than the FAC or BC.
The TC in this study was determined using the method described by Woodward & Ferry (1973). A computer process was used to speed up the calculations. There were five steps; (1) a digital terrain model was constructed for the Paringa region, which extended out to 22 km as recommended; (2) a graticule was constructed to represent the Hammer zones; (3) a zonal mean function in ArcInfo® calculated the mean elevation of each Hammer zone; (4) using the formula from Woodward & Ferry (1973), the gravitational effect of each Hammer zone was calculated; (5) all Hammer zones were summed resulting in a TC for each gravity observation.

The Woodward & Ferry (1973) calculation for each zone:

\[ g = \left( \frac{2 \pi G \sigma}{N} \right) \times \left[ R_1 - R_2 + \sqrt{(R_1^2 + h^2)} - \sqrt{(R_2^2 + h^2)} \right] \]

Where:
- \( G \) = Universal Gravitational Constant
- \( \sigma \) = density of the terrain (= 2.67 Mg/m\(^3\))
- \( N \) = number of compartments in the zone
- \( R_1 \) = inner radii of the zone
- \( R_2 \) = outer radii of the zone
- \( h \) = estimated mean height difference

3.4.4 The combined Bouguer anomaly: the residual anomaly

The Bouguer anomaly or residual anomaly is a calculation of all the corrections made as part of the data reduction process. It forms the basis for the interpretations of the gravity survey.

The residual anomaly calculation is as follows (from Kearey et al, 2002):

\[ \Delta g_B = g_{\text{obs}} - \Delta g_L + \text{FAC} - \text{BC} + \text{TC} \]

Where:
- \( \Delta g_B \) = Combined Bouguer anomaly or residual anomaly
- \( g_{\text{obs}} \) = Observed gravity reading
- \( \Delta g_L \) = Latitude Correction
The gravity data is displayed in appendices 3.

### 3.5 Data uncertainties and errors

Uncertainty can be introduced by the three stages of data acquisition and analysis; field methods, data reduction and modelling. Table 3-1 lists the potential sources of error relevant to this study from field methods and data reduction, with an estimation of size. The errors associated with the modelling assumptions will be discussed later (Chapter 4). The relative size of these uncertainties compared to the residual anomaly is the problem for gravity surveys. If this difference is small it may become difficult to determine if features of the residual anomaly in fact result from uncertainty. Further discussion on the influence of uncertainty is presented later, including errors specific to assumptions surrounding the use of two-dimensional modelling.

<table>
<thead>
<tr>
<th>measurement</th>
<th>uncertainty</th>
<th>uncertainty in mGal</th>
</tr>
</thead>
<tbody>
<tr>
<td>repeatability</td>
<td>0.02 dial units</td>
<td>0.02 mGal</td>
</tr>
<tr>
<td>elevation</td>
<td>± 1 m</td>
<td>0.42</td>
</tr>
<tr>
<td>latitude</td>
<td>± 5 m</td>
<td>negligible</td>
</tr>
<tr>
<td>terrain correction</td>
<td>25% of 5.2 mGal</td>
<td>1.3 mGal</td>
</tr>
<tr>
<td><strong>Total uncertainty</strong></td>
<td><strong>25% of 5.2 mGal</strong></td>
<td><strong>1.74 mGal</strong></td>
</tr>
</tbody>
</table>

Table 3-1: Estimated uncertainties

The maximum error from the terrain correction is thought to be 25% (Woodward and Ferry, 1973). The terrain correction uncertainty was calculated from the Hammer zones B through G as it was thought the uncertainty contributed by the zones outside this is negligible based on the large distance from the gravity station. The maximum total uncertainty of a residual gravity value is obtained by summing the individual uncertainties. The independent nature of the uncertainties is thought to ensure that few if any of the readings will be affected by the maximum anomaly. Nonetheless, it is noted the uncertainty calculated here is of considerable size compared to the residual anomaly, raising concerns about the ability of the gravity survey to provide adequate data for short-wave gravity features in the survey.
3.6 Regional Anomaly

The regional anomaly is very important when trying to model and interpret the residual anomaly; therefore some correction must be made to ensure the residual anomaly is only influenced by the target feature, in this case, the sediment filled Paringa valley (subsequently called the target). Despite the corrections made to the observed data during the calculation of the residual anomaly, there are still gravity features that are not caused by the target. These result from regional perturbations to the gravity field. The source of these perturbations is varied. Of importance to the Paringa region is the Southern Alps, with both the extreme topography and the less dense crustal root underlying the mountain range influencing the gravity field. The regional gravity field caused by the Southern Alps is not of particular interest, as it is variations in the gravity field caused by local subsurface density contrasts that is the target. Therefore the regional anomaly is removed from the residual anomaly. This is commonly done by two steps: using published Bouguer anomaly maps which allow the regional anomaly gradient to be determined, and making gravity measurements at either end of the survey area (distal so as to be unaffected by the target anomaly) and fitting these to a linear trend. Commonly these two methods are undertaken in conjunction, with the published Bouguer anomaly map indicating the general orientation of the regional trend, and the measurements fully constraining the regional trend.
Figure 3-4: Bouguer anomaly map of the Paringa region (Blick, 1979). The Paringa River valley is identified by the red arrow. The red dashes indicate the locations of gravity readings close by the Paringa River valley, which were used to construct the Bouguer anomaly. The regional anomaly trend decreases towards the SE. The small number of data points is a result of the low resolution of this Bouguer anomaly map. The scale bar denotes 10 km, while the black arrow indicates north.

Both of these steps have limitations for this study. The published Bouguer anomaly map for the Paringa region (Fig. 3-4; Blick, 1979) is not very informative. Few gravity stations contribute to the regional anomaly and within the Paringa River valley itself, the anomaly isogrids form a ring around the Primary Network gravity station indicating a region with a minimal regional gradient. This isograd pattern is not very likely considering the NE trending of the gravity low centred on the Southern Alps, and is possibly a result of fewer gravity readings in the region than Blick (1979) would have desired. The large distance between stations is in contrast to the distances involved in this project, causing the resolution of the published Bouguer anomaly to be much coarser than for this project. Care had to be taken in using this published map, as short wavelength perturbations would not be represented in the published Bouguer anomaly. What is apparent is that the regional anomaly is probably oriented towards the east or SE, judging by the broad anomaly pattern.

The second step of making gravity measurements at either end, to determine the regional anomaly in the Paringa region, was flawed as well. The lack of locations where observations
spanning the entire field area could be made, with minimal influence from the target feature, ensured that a regional trend could not be calculated using the standard method described above. The method devised to estimate the regional anomaly is detailed below.

**Method of regional anomaly calculation in the Paringa River valley**

An alternative method was developed for this gravity survey. Based on the previously described regional anomaly calculation, it involved extrapolating beyond the survey region to estimate readings unaffected by the target anomaly. However, as the observations were being made within the Paringa valley, they will have been influenced by the target feature, thus introducing additional uncertainty. Furthermore, the assumption that the calculated trend line represents a planer regional trend also introduced uncertainty.

To minimise error introduced by this method, the two gravity observation stations used to extrapolate the regional trend were chosen according to strict criteria. The requirements were that they should:

1. Span the entire field area.
2. The trend line created between them should lie sub-parallel to the estimated regional trend.
3. The position relative to the target feature should be equivalent, for example at the basement/cover sediment transition.

The transect survey lines P-TM and P-TU were chosen, as they spanned the entire length of the field area in the orientation of the regional anomaly as roughly estimated from the published Bouguer anomaly map (Blick, 1979). The two readings from the SW ends of these two lines (P-TM13 and P-TU09 respectively) were chosen as they were at margins of the valley and were at the basement/cover sediment transition. At these two points the profile of the basement would be minimal and the observed reading should reflect this, allowing a comparison between two points with the least effect from the target. These two lines were modelled using GravCad and a bulk shift was applied that allowed the best fit to the residual anomaly (discussed further in 3.7.3). The difference between the two bulk shifts gave an estimation of the regional anomaly trend. Using the distance between the two points, a linear trend was calculated and applied to the entire field area, with the assumption that this linear trend represented a planer trend.
There are a number of problems associated with this method. Firstly, it was not known how equivalent the two points chosen were relative to the basement/cover sediment transition. This along with the basement profile and depth will have an effect on the calculated trend. Thus the calculated regional anomaly will have an unknown component related to the P-TM and P-TU lines themselves. Secondly, the orientation of the regional field may be different to the calculated one and if there is a difference, it will not be known.

The calculated regional anomaly was the best estimate of the regional gravity field for the Paringa valley. The calculation used was because of the scarcity of information contained in the published regional anomaly map. Additionally, the geology, topography and vegetation of the Paringa area prevented more normal methods of regional anomaly calculation. The errors associated with this method are likely to be greater than those of a more standard method; however, it was difficult to specify the size of these errors.

3.7 Modelling

3.7.1 Introduction

Interpretations of gravity anomaly data are non-unique therefore modelling programs are used routinely to help compare different solutions for residual gravity anomalies effectively. Modelling programs allow the efficient comparison of a range of density contrast profiles that can be interpreted for geological properties such as the basement/cover sediment contact sought in this project. As with any modelling routine, there are numerous assumptions made that have a significant effect on the output. For this reason constraints imposed by parallel methods, such as seismic reflection surveys, drill cores or geologic data, are always sought to constrain the overall interpretation.

3.7.2 Density determination

For gravity modelling the most critical modelling parameter is the density contrast between the cover sediments and the underlying basement rock. Due to the absence of core sampling in the Paringa region, rock density data has been inferred from basement rocks throughout the greater South Westland region (Whiteford & Lumb, 1975). Unfortunately, there are virtually no data on the density of cover sediments in Whiteford & Lumb's publication, and as other
gravity studies in New Zealand have shown, the density of cover sediments is more variable than for basement rocks generally found in the South Island (e.g. Anderson, 1987; Anderson, 1980; and Hatherton, 1986).

Other gravity surveys throughout New Zealand (e.g. Kleffmann, 1999) have attempted Nettleton’s method (detailed in Burger, 1992) where readings are made across a topographic feature allowing the calculation of a basement density value and accurately modelling the known topographic feature. There are, however, problems with this method as it can remove the anomalies sought in the survey. The requirements for a simple geometry topographic feature to enact this technique were not meet in the Paringa field area, so this method of density determination was not attempted.

Nonetheless, the composition of the Paringa River valley cover sediments allowed a simple calculation to be made to determine the density contrast between the two rock types. The overlying sediments are essentially derived from the basement rock. As a result, the main constraint on the density contrast between the basement and the cover sediment is the porosity of the cover sediment. The young age of the cover sediments (> 15,000 yrs, Simpson et al. 1994) indicates that consolidation of these predominantly gravel-sized sediments will be minimal; therefore the porosity is likely to be high, probably somewhere between 24-36% (Domenico & Schwartz, 1998). Thus the density contrast can be expressed as:

\[
\Delta \text{contrast} = (\Delta_{\text{basement}} - \Delta_{\text{water}}) \times N
\]

Where; \( \Delta_{\text{basement}} \) is commonly estimated to be 2.67 Mg/m\(^3\) from many different gravity surveys throughout New Zealand, especially in studies where the density is not known (Hatherton, 1986) and \( \Delta_{\text{water}} \) equals 1.00 Mg/m\(^3\).

Using these porosity and density parameters, a sensible range of density contrasts can be obtained, as follows;

- Minimum density contrast \( (N = 24\%) = -0.4 \text{ Mg/m}^3 \)
- Median density contrast \( (N = 30\%) = -0.5 \text{ Mg/m}^3 \)
- Maximum density contrast \( (N = 36\%) = -0.6 \text{ Mg/m}^3 \)
3.7.3 Numerical Modelling

Two-Dimensional modelling

Two-dimensional modelling is used to reduce complexity when modelling three-dimensional geologic bodies, such as down the length of a valley. It assumes that no variation occurs in the third dimension. In reality it is difficult, perhaps impossible, to find anything that continues infinitely on the Earth. Therefore limits have been applied to define the level of variation possible in the third-dimension before the model is considered adversely influenced by such variation. For the purposes of gravity surveys it is considered that if the body extends out two to three times the depth of the body then two-dimensional modelling can be used (Nettleton, 1976). Therefore it is assumed that if the body perpendicular to the line of profile extends out with little variation for two or three times the depth of the section, then the effects of the lack of infinite properties can ignored.

GravCad W program

The GravCad modelling program calculates the effects of two-dimensional polygons of varying size, shape, and density contrast that represent potential geological bodies and then compares the effect on a calculated anomaly. A nonlinear (Marquardt-Levenberg) inversion is used to calculate the gravitational affect of all polygons entered in the model, thus a best-fit calculated anomaly is produced for the entered data. The user then changes the polygon to make the theoretical anomaly fit as closely as possible to the measured residual anomaly. Assumptions are made to allow the use the GravCad program: namely that (1) polygons have infinite strike length, i.e. in the third non-modelled dimension; and (2) each polygon is of a constant assumed density, for example, any compaction of sediment with depth is ignored.

The GravCad Bulk Shift

The GravCad model requires that the residual anomaly is less than zero, for a negative density contrast, such as cover sediment filled basement valley, to be modelled. Since this project is only concerned with relative gravity values, the residual anomaly was calculated in reference to the base station without reference to absolute gravity values. Therefore the survey is a
purely relative gravity survey and the relative difference between the observed readings is the
only aspect of the residual anomaly of importance. Thus the addition of a bulk shift is easily
applied to the residual anomaly and is in many ways equivalent to shifting the data to a
regional trend. The disadvantage of using a bulk shift in place of tying the residual anomaly to
an absolute network is that the bulk shift is applied using interpretation and is therefore
subject to interpretation error. However, as described earlier, tying this survey to the New
Zealand absolute gravity network proved to be difficult and may have contained significant
but difficult to quantify, errors. It would also require an estimation of the regional anomaly.

*Interpreting gravity residual anomalies*

The types of anomalies that may be present in the data can be used to assist in the
interpretation of residual anomalies. The following is a summary of gravity anomalies in
Anderson (1980).

(1) Short-wave length, low amplitude anomalies can often be attributed to inaccuracies, such
as elevation uncertainty or gravimeter error. It is commonly impossible to determine the
cause of these low amplitude fluctuations, therefore, they cannot be just removed as they
may reflect basement features.

(2) Short-wave length, low amplitude anomalies may occur because of subtle density
changes, perhaps because of crush zones in basement rock (Udy, 1987), intrusive plutons
or from porosity variations.

(3) Elongate, large amplitude anomalies can usually be attributed to structural complexity,
such as basement shallowing and/or faults.

### 3.8 Gravity model descriptions

The position of the survey lines is shown on figure 3-1. In the Paringa River valley, two lines
(P-TM and P-TE) transect the valley to the west of the Alpine Fault, while one line (P-TU)
transsects the valley to the east of the Alpine Fault. Three other survey lines run longitudinally
down the Paringa valley, P-DS down the middle of the valley, while P-DL and P-DF are
closer to the margins of the valley parallel to P-DS.
3.8.1 P-TM line

P-TM transects the 'lower' Paringa River valley (to the west of the Alpine Fault) at the NW extent of the field area. The Paringa River truncates the NE end of the line.

*Residual anomaly description*

Gravity anomaly features (Fig. 3-5):

1. Anomaly minimum (<-4.5 mGal) at both ends of the survey line with the SW end corresponding to the margin of the valley (-1.1 mGal);
2. Anomaly maximum (-6.8 mGals) corresponding to the middle of the valley;
3. Truncation of the NE end of the line matching the position of Paringa River; and
4. The range of the residual anomaly is 5.7 mGal.

The observed anomaly profile is smooth and simple, containing no perturbations at any of the observation stations. As a result, the basement topography is also estimated to be simple, with a lack of basement highs and lows on a scale large enough to be resolved in this model.

*The Model*

The P-TM model (Fig. 3-5) indicates that the basement follows a roughly U-shaped profile across the valley. If an arbitrary density difference of -0.5 Mg/m³ is adopted for the valley fill, then the basement depth for this model is 580 m. The SE end of the line is best fit where the cover sediment thins out into a wedge at the margin of the valley. It is unclear from the modelling if this feature results from an edge affect or is a feature of the basement profile. Possibly post-glacial fluvial erosion has formed a more moderate basement gradient towards the valley margins. Another explanation is maybe the thin wedge reflects the gradual thinning out of sediments along the topographic profile of the valley wall and because the surface topography has been removed the wedge appears to extend horizontally out to a considerable distance.
Constraining the density of the valley fill

The basement depth value quoted above is only relevant for this particular model and its density contrast. The following explores the implications of density contrasts in gravity modelling.

The apparent simplicity of this model lends itself to the exploration of the range of basement depths that could realistically be applied to this model. The density contrast between the basement and cover sediments has a direct influence on the basement depth produced by the model. The density contrast, as explained earlier, is controlled by the likely porosity of the cover sediment.

Figure 3-5: The P-TM survey line model, at the NW edge of the field area. The model shows a simple U-shaped profile.
Chapter 3: Geophysics

If probable porosity values are ignored for the time being and a range of density contrasts are entered into the model, it becomes apparent that a very wide range of basement depths can be modelled. A very small density contrast (-0.19 Mg/m³) produces a very deep basement profile at 7550 m. In comparison a very large density contrast (-0.960 Mg/m³) produces a shallow valley of 275 m. The small density contrast produces a basement profile of >7 km, which is unreasonable considering the depth of the oceanic sea floor is generally not as deep as this. Additionally, the small component of uplift on the Western Province will act to reduce basement depth over time thus causing the current basement depth to be shallower than during the last glacial maximum. The shallower basement depth of 275 m is not unreasonable in itself; however, the porosity required for this large density contrast is calculated to be 57%, unreasonable for all but the finest sediments (Domenico & Schwartz, 1998). This is unlikely given that the Paringa Formation, the oldest and the least porous cover sediments in the Paringa valley, is mainly composed of gravel-size clasts, while coarse gravels dominate the current fluvial system that provides the rest of the sediment cover. Therefore a cover sediment thickness of 275 m is also unreasonable.

With reasonable density contrast values of between -0.4 and -0.6 Mg/m³, as described in 3.7.1, the range of minimum basement depths can be modelled. The resulting range of basement depths fall between 900 and 420 m. The models that follow show a median density contrast of -0.5 Mg/m³. This corresponds to a median porosity of 30%. However, the range of basement depths corresponding to -0.4 Mg/m³ (24% porosity) and -0.6 Mg/m³ (36% porosity) will also be stated.
3.8.2 P-TE line

The P-TE survey line runs sub-parallel to P-TM on the east, although it is still to the west of the Alpine Fault. The Paringa River truncates the NE end of the line.

Residual anomaly description

Gravity anomaly features (Fig. 3-6):

1. Anomaly minimum (<-4.5 mGal) at both ends of the survey line;
2. Anomaly maximum (-8.1 mGal) corresponding to the middle of the valley;
3. An abrupt change in gradient ($\Delta$ 1 mGal over ~100 m) 380-480 m (corresponding to the middle of the valley);
4. Truncation of the NE end of the line matching the position of Paringa River; and
5. The range of the residual anomaly is 4.9 mGal.

Model

The P-TE model has similarities to the P-TM model in that it is roughly U-shaped and features a narrow wedge at the SE margin. This similarity is to be expected because of their close proximity and similar orientation. There was difficulty in modelling the offset between the fourth and fifth station readings (380 m and 480 m respectively). Models that attempt to replicate the residual curve by increasing the basement depth and by narrowing the profile result in a narrow V-like geologically implausible valley profile. Additional models that introduced angled structures to replicate faults, failed to provide appropriate calculated anomalies.

There are two potential causes for this modelling difficulty. First, the observed data points may be in error; either the original field measurements could be in error, from perhaps an unnoticed shock transmitted to the instrument. Second, three-dimensional features in the basement profile, such as localised basement highs that influence the gravity field but are not traversed by the survey lines may contribute to the residual curve (these will be discussed later in Chapter 4). Hence, the proposition is that perturbations in the residual curve result from a non-modelled third-dimensional feature of the basement or from a field issue such as a shock to the gravimeter.
Chapter 3: Geophysics

The basement depth is calculated to be 620 m, with a range of 1050 m to 530 m. However, it should be noted that the calculated anomaly does not closely fit the residual curve in the centre of the line (corresponding to the centre of the valley). Additionally, the central section of the line will have the greatest influence on the basement depth being the location of the anomaly maximum (-8.1 mGal). In conclusion, the modelled basement depth is thought to be less certain than for the P-TM line.

Figure 3-6: The P-TE survey line is far more difficult to model than the P-TM line because of the >1 mGal contrast between gravity stations at 400 and 500 m.
3.8.3 P-TU line

P-TU transects the 'upper' Paringa valley to the east of the Alpine Fault. Fan deposits truncate the NE end of the line.

Residual anomaly description

Gravity anomaly features (Fig. 3-7):

1. Anomaly minimum (-0.4 mGal) at the SW end of the survey line corresponding to the valley maximum (-2.8 mGal) towards the NW end of the line, with a slight anomaly reduction (∼0.2 mGal) from the observation at 300 m to the most NE observation at 200 m.

2. Truncation of the NE end of the line matching the position of Paringa Formation and fan deposits in this SE section of the field area; and

3. The range of the residual anomaly is 2.4 mGal.

Model

The P-TU model (Fig. 3-7) is shallow and wide when compared to the P-TM and P-TE lines. The U-shape of the survey lines to the west of the Alpine Fault has been much reduced and a more gradual descent to the deepest point of the model is observed. The basement depth is modelled to be 180 m with a maximum and minimum of 230 m and 150 m respectively. The truncation of the NE end of the line due to its inaccessibility is unfortunate as only the SW side of the basement profile could be modelled with constraints imposed by the residual anomaly.

The continuation of the basement topography beyond the extent of the surveyed line is reasonable and fits with Simpson's (1992) mapping of the NE side of the Paringa River with fan deposits forming a broad terrace in that region of the valley. The raised topography of the terrace may be indicative of the thickness of the sediment in this location rather than a raised basement covered by a thin veneer of sediment. The residual anomaly would be expected to show an anomaly reduction to the NE if the basement was close to the surface. This interpretation is limited by the truncation of the NE end of the line due to inaccessibility.
Figure 3-7: The P-TU survey line, to the east of the Alpine Fault. This model produces a much shallower basement profile than P-TM or P-TE survey lines.
3.8.4 DS line

The P-DS survey line is the longest line in the survey and runs down the centre of the Paringa River valley from the most NW end of the field area to the inaccessible fan-deposit/Paringa Formation bank at the SE end.

Residual anomaly description

Gravity anomaly features (Fig. 3-8):

1. Anomaly generally at a maximum (-6.5 to -5.8 mGal) from the NW end of the line towards the SE. A dramatically reduction occurs around 1850 m where the anomaly deduces to a minimum (-1.9 mGal);
2. Truncation of the SE end of the line matching the Paringa Formation/fan deposit river terrace;
3. A small gap in the data corresponded to where the Paringa River crosses the survey line; and
4. The range of the residual anomaly is 4.7 mGal.

Model

Simpson (1992) traces the Alpine Fault across the Paringa Valley using geological knowledge. The placement of this trace is roughly where the model predicts the Alpine Fault trace should be (Map 1).

The P-DS model shows a basement depth of ~400 m at the NW end which fluctuates towards the SE end. The maximum and minimum depths calculated were 490 m and 350 m respectively. The varying basement depth forms in response to short-wave fluctuations in the residual anomaly, potentially indicating localised highs and lows in the basement profile. These, however, are within the limits of uncertainty and may be artefacts from the data reduction process in the residual anomaly. The abrupt gradient steepening at ~1750 m indicates a dramatic reduction in the basement depth. The following two models show different basement profiles that form a calculated anomaly similar to the residual anomaly. Model A (Fig. 3-8) features a NW dipping basement offset at around 1850 m. Model B (Fig. 3-9) uses a SE angled fault, designed to represent the presumed Alpine Fault orientation.
Both models provide a reasonable fit for the residual curve. The short-wavelength fluctuations between 1000 and 1750 m are difficult to model using realistic basement profiles. However, the basement profile features (i.e. basement highs and lows) that may have caused these residual anomaly fluctuations, are at too greater a depth for small variations in the geologic model to be reflected in the calculated anomaly.

Figure 3-8: The P-DS survey line, this model displays the non-unique properties of gravity modelling. If the following figure (3-10) is compared to this one it is found that the calculated anomaly is virtually the same, however; the basement profile is very different with contrasting dip directions for the proposed fault.
Figure 3-9: The P-DS model with a SE dipping fault, which is consistent with geological mapping of the Alpine Fault structure. This model indicates that the surface trace of the Alpine Fault is located around the position where the survey line crosses the Paringa River.
3.8.4 P-DL line

The P-DL line is located SW and runs sub-parallel to the P-DS line. The line was positioned to intersect the Alpine Fault across the Paringa River valley without a data gap caused by the Paringa River.

Residual anomaly description

Gravity anomaly features (Fig. 3-10):

1. Anomaly reduces from a maximum (-3.2 mGal) at the NW end to a minimum (-4.7 mGal) at the SE end of the survey line;
2. Small (Δ0.3 mGal) fluctuations in the anomaly especially at the NW end; and
3. The range of the residual anomaly is 1.5 mGal.

Model

Model A (Fig. 3-10) indicates the basement depth is relatively constant from the NW end towards the SE. The basement reduces in depth at ~600 m from the NW end of the model. The depth of the basement is modelled as 340 m, with a maximum of 380 m and a minimum of 220 m. As with previous models, short-wavelength perturbations of the residual curve are difficult to model. The basement profile shows a general shallowing towards the SE. Model B (Fig. 3-11) shows an alternative model of the basement profile. The basement profile features a SE dipping plane developed to represent the Alpine Fault. However, due to the narrow range of the residual anomaly (Δ 1.5 mGal) the fault plane can be transposed along the survey line with little effect on the calculated anomaly.
Chapter 3: Geophysics

Figure 3-10: P-DL survey line, model A, showing the simplest basement profile shape that can model the residual anomaly.
Figure 3-11: The P-DL model B, uses a SE dipping offset to model the Alpine Fault transecting the line, however, the gravity data for this survey line is ambiguous and interpreting structural features from a residual anomaly with a such a small variation is difficult.
3.8.5 P-DF line

The P-DF line is positioned NE of the P-DS line and is positioned to intersect the presumed position of the Alpine Fault. The NW end is truncated by the Paringa River and the SE end is truncated by the base of Little Paringa Hill.

Residual anomaly description

Gravity anomaly features (Fig. 3-12,13):

1. Anomaly minimum (-3.7 mGal) at the SE end of the survey line;
2. Truncation of the NW end of the line matching the position of Paringa River;
3. Truncation of the SE end of the line matching the position of Little Paringa Hill;
4. The range of the residual anomaly is 1.6 mGal.

Model

The P-DF model indicates a basement depth that is fairly constant, with a small deepening towards the middle of the line and an abrupt shallowing at the SE end. The depth of the basement at the deepest part is 300 m, with a maximum of 450 m and a minimum of 270 m. Model A (Fig. 3-12) presents one basement model to explain the anomaly curve. Here, using a simple NW dipping face, the resulting calculated anomaly had a good fit to the residual anomaly. Model B (Fig. 3-13) features a SE dipping plane to represent a reverse dipping fault. Here too, the calculated anomaly closely matches the residual curve. It is difficult therefore to
differentiate between these two models using the gravity data and the interpretation of the basement profile is dependent on a geological interpretation of likely Alpine Fault structure.

The inherent assumptions made as part of the regional anomaly estimation have a strong affect on the basement depth estimate. Similar to the P-DL and P-DS lines, the P-DF survey line is difficult to constrain as the line is 'floating' away from known basement margins. Using GravCad to estimate the block shift was unreliable, and therefore, the model was unable to provide additional information surrounding the depth of basement. A considerable level of uncertainty surrounded the depth estimate with the basement depth estimate reliant on the regional anomaly being representative of the real regional anomaly.

Figure 3-13: The P-DF (B) model uses a SE dipping plane to model the Alpine Fault.
3.8.6 DB line

The DB line transects the NE trending valley from roughly east to west. On the eastern side of SH6 the gravity observations were made up the southern bank of Doughboy Creek. To the west of SH6 observations were made on the hunting track, the flood plains and banks of the lower DB creek. An effort was made to keep the survey line as straight as possible while traversing the NE trending valley.

Residual anomaly description

Gravity anomaly features (Fig. 3-14):

1. Anomaly minimum (<-3.2 mGal) at both ends of the survey line;
2. Anomaly maximum (-8.6 mGal) corresponding to the middle of the valley;
3. An abrupt change in gradient (Δ1.2 mGal over ~100 m) corresponding to the middle of the valley; and
4. The range of the residual anomaly is 5.9 mGal.

The DB residual anomaly features a high at both ends of the line with a reduction towards the middle of the line, reminiscent of the P-TM and P-TE residual anomalies. The regional trend from the Paringa River valley was applied, along with an additional bulk shift of -28 mGals, to satisfy the requirements of the GravCad model. This bulk shift was applied arbitrarily and is therefore subject to added uncertainty. This may increase the uncertainty surrounding the modelling of some parameters such as the basement depth. The basement profile should only be minimally affected.

Model

The DB model indicates that the basement profile roughly follows a U-shape profile. The depth of the basement, at 600 m (with a maximum of 900 m and minimum of 520 m), is considerable and certainly comparable to transects across the Paringa River valley. The eastern side of the model is more difficult to model because of the apparent offset in the residual anomaly. This offset is comparable to the one found in the P-TE line. It is within the level of uncertainty and could potentially be ignored. However, when the entire residual anomaly is observed it appears there is a pattern in the gradient that results in this offset,
Chapter 3: Geophysics

perhaps indicating an interesting feature in the basement profile. Model A (Fig. 3-14) uses a simple basement profile to model an anomaly offset similar to the residual offset. This model has limited success, with the difficulty of making fine adjustments to the calculated anomaly when the depths of the basement profile are at such great depth. Model B (Fig. 3-15) models the basement profile using a reverse-fault style structure. Similar to model A, difficulties were encountered when trying to match the calculated anomaly to the residual anomaly, with the offset on a scale too small to model using basement profile changes at such great depth. The range of the residual anomaly and the DB model indicate the depth of the NE trending valley is comparable to the Paringa River valley.

Figure 3-15: Model A
Figure 3-15: Model B
3.9 Magnetic Survey

The magnetic survey was undertaken to provide an additional source of information to back up the gravity data, which was the major aspect of the geophysical aspect of this project. Potentially the magnetic data would be used to delineate the Alpine Fault, either by locating basement proximity from the strength of the magnetic or from the magnetic field surrounding water trapped in the fault plane. Unfortunately the magnetic data do not appear to be as informative as had been hoped. The background information on the magnetic survey is described below, along with a description of the field method. The following section contains a description of what could have been expected from a survey of this type in this location, followed by a description of what was actually found in the magnetic survey.

3.9.1 Magnetic surveys

The Earth generates a magnetic field (the geomagnetic field), that can be observed at any point in the vicinity of the Earth, for example, at the Earth's surface. This field can be perturbed by magnetically susceptible rocks at or near the surface of the Earth. Magnetically susceptible rocks cause localised effects on the geomagnetic field resulting in magnetic anomalies. In turn the magnetic anomalies can be used to interpret the rocks which have caused the anomalies. Magnetic surveys are used in many situations because of the versatility of the technique. They can be land, sea or air based (Kearey et al, 2002). For this project the emphasis was on a surface based magnetic survey aiming to use differential magnetic susceptibility of the basement rocks and the overlying sediments to delineate the potential Alpine Fault up-thrown block. The magnetic susceptibility of water may also cause anomalous magnetic readings and had the potential to therefore provide additional information on structures in the Paringa River valley.

3.9.2 The field survey

The magnetic field strength was measured using a Geometrics G-856AX portable proton precession magnetometer.
Diurnal variation correction

Reduction of magnetic data is necessary to remove from the observations any causes of magnetic variation other than those arising from the magnetic effects of the subsurface. This is a much simpler task than for the gravity survey, as the magnetometer does not drift through the day. However, temporal variations in the magnetic must be removed, this was done by using a looping field method.

Field procedure

The magnetic survey followed the same survey lines as the gravity survey with two exceptions, firstly an extra line was made roughly parallel to the P-DF survey line, called P-DG, and secondly no magnetic survey was taken along the Doughboy Creek gravity survey line. The reasons for these exceptions arose from P-DG being the test run of the equipment along an easily accessible farm track, while no magnetic data was collected along the DB survey line because of surface water in close proximity.

Similarly to the process for undertaking the gravity survey, a base station was regularly reoccupied to allow the removal of the diurnal variation component of the magnetic data. This involved a method identical to the gravity drift correction where a series of field observations were bracketed either side of base station observations. A linear relationship was determined between these two base station observations and intervening readings were then corrected to this linear relationship. As with the gravity survey it was assumed that the magnetic field could be approximated by a linear relationship between the two base station readings.

3.9.3 What could have been expected from a magnetic survey of this type?

There were two sources of magnetic anomaly that potentially could have been observed in the Paringa River valley. Firstly if the magnetic susceptibility of the basement rocks was substantially different to that of the overlying valley fill, then any differences in the proximity of the basement to the surface might have resulted in a magnetic anomaly. Such a contrast in basement proximity might be the result of a fault block in the valley. Secondly, a magnetic anomaly could have been caused by concentrations of water along a structure such as a fault. This water may develop a perturbation in the geomagnetic field, which may be observable at the surface.
3.9.4 What was observed in the magnetic survey of Paringa River valley

Unfortunately once the magnetic anomalies were plotted, there did not appear to be any relationship between them and any features noted in the gravity anomalies. In addition the magnetic anomalies appeared to reflect regions of swampy ground and correlate with electric fences and power lines. For example survey line P-TM (Fig. 3-16) featured a negative association with surface water at the SW end of the line. The magnetic data can be found in appendices 4.

Figure 3-16: The magnetic data plotted against the distance form the NE end of the P-TM survey line. The gravity residual anomaly is shown to help indicate where in the valley the negative anomalies were situated. The SW end of the line corresponds to farm land with considerable surface water. The two gaps in the magnetic anomaly, at around 250 and 550 m, correspond to electric fences and overhead power lines. Other survey lines showed the same pattern of significant negative anomalies associated with surface water. The positive part of this magnetic anomaly correlates to the deepest part of the basement (based on the gravity survey), however; none of the other survey lines support this relationship.
4. Geophysics interpretation

This chapter contains the interpretations based on this survey of the Paringa River valley. All interpretations are based on the gravity survey with constraints imposed by geological knowledge of the region. The magnetic data were not used in the interpretation of the Paringa River region because the target did not appear to affect the magnetic field in a consistent manner. Major anomalies were associated with surface water and it is thought this was the cause of the signal observed in the magnetic data. The numbering system corresponds to the main objectives listed in the introduction (see Chapter 1.6).

4.1 Basement topography of the Paringa valley

The use of gravity surveys to model basement profiles has been in use for many years (see references in 1.3.2). The same technique has been applied for this survey, with the transect profiles (P-TM, P-TE and P-TU) showing the interpreted cross-sectional profile of the Paringa valley. These transect lines show U-shaped profiles that closely resemble classic glacially eroded valleys (Benn & Evans, 1998). However, small-scale or short-wavelength fluctuations in the residual anomaly can complicate the models generated using the Gravcad modelling program. There are three reasons why it is difficult to model the small-scale fluctuations in the residual curve:

(1) The model presumes that a two-dimensional body causes the residual anomaly, and any features of the anomaly caused by features in the third-dimension are not modelled. The result is geologically unrealistic models when trying to develop a geologic model to match the residual anomaly.

(2) The short-wavelength fluctuations in the residual anomaly are too small for the modelling to account for. At the depths to basement predicted by the model, the distance to any actual basement features will be too close to other basement features and therefore will be swallowed up in the anomaly. For example, if the size of the causative body is significantly smaller than the depth, modelling will have difficulty predicting the shape of the body.

(3) The assumption of only two densities may be too simplistic. For example, cover sediment grainsize inhomogeneity and compaction may result in layers of variable density.
Chapter 4: Interpretation

This has not been accounted for during the modelling of the Paringa region. Drill cores within the cover sediment would be required to determine density and the likely extent of density variations within the sediment.

**Depth-subject to large uncertainties**

The depth of the basement profiles is subject to considerable uncertainty. There are two causes of this: (1) the non-unique properties of gravity modelling where density contrast has a direct effect on modelled basement depth; and (2) the assumption that the geometry of the field area could be adequately modelled using a two-dimensional model.

**Non-uniqueness of ϕ/ρ versus depth**

There are two parameters that control the calculated anomaly when modelling a residual anomaly: these are the position of the density contrast (which can be manipulated by the user in real time) and the density contrast between the polygons (representing the geologic units as described earlier).

Thus we have two parameters that can be adjusted over a wide range of values and are still able to match the calculated anomaly to the residual anomaly. Usual practice is to add constants to the model that limit either the range of the polygons or the density contrast. These include parallel geophysical methods, such as seismic reflection profiles, or come from drilling, which may determine basement depth and/or density contrasts. With additional information of this type the level of uncertainty can be decreased. Unfortunately none of this parallel data was available for the Paringa region. Therefore, the only constraints on the model are the creation of geologically reasonable polygons based on existing geological knowledge and calculations of probable density contrasts.

Fortunately the cover sediment in the Paringa River valley is derived from the same rock type as the surrounding basement, so that the density contrast between cover and basement results from the void space in the sedimentary cover, which is characteristically high in sedimentary rocks. The level of porosity will result in differences in density as these pore spaces will predominantly be filled by less dense water. The density contrast can therefore be better
determined by looking at the level of porosity, as has been explained earlier (see section 3.7.2).

When it came to modelling the residual anomaly it became apparent that using a smaller density contrast resulted in the modelling of a greater depth, and conversely, using a greater density contrast resulted in a shallow basement profile. The problem is that with no constraints other than the level of porosity in the cover sediments, a range of basement profiles can be modelled all of which are plausible. The lack of any constraining data in this survey beyond that offered by geological knowledge, resulted in a wide range of basement depths for the Paringa and the NE trending valley. This has been shown by the range of plausible basement depths described earlier during interpretation of each model (see section 3.8).

During the process of modelling it became apparent that it was easier to fit the calculated anomaly to the residual anomaly when the density contrast was high. Furthermore, the low-density contrast (-0.4 Mg/m³) sometimes produced geologically unreasonable models. It is suspected therefore, that the density contrast between the basement and the cover sediment is highly probable to lie between the high-density contrast (-0.6 Mg/m³) and the middle density contrast (-0.5 Mg/m³). Thus the range of the basement depths fall between 400 m and 600 m. The basement depths (>600 m) modelled using the low-density contrast (-0.4 Mg/m³) were thought less plausible.

Assumption of two-dimensionality

Another source of uncertainty was the assumption that a two-dimensional geological model could adequately represent the Paringa region. The rule that the geological feature needs to continue indefinitely along strike (or more practically for 2-3 times the depth of the model) has not been followed. This will certainly have an affect on the models developed with GravCad. More specifically, the geometry of the Paringa River valley means that for the 'down valley' survey lines (P-DS, P-DL and P-DF) the two-dimensional assumption used to justify the use of the modelling program is poorly upheld.

The model does not attempt to account for the mass in the third dimension. The result is that the density contrast (basement) is calculated in closer proximity than in reality. Hence the
'down valley' survey lines indicate a shallower basement depth than transect survey lines (P-TM, P-TE and P-TU), because the model has not calculated the additional gravitational acceleration caused by the basement walls. The orthogonal orientation of the transect lines (P-TM, P-TE and P-TU) to the valley margins ensures that in the third-dimension the geology does continue 'indefinitely' along strike, resulting in the model adequately modelling the residual anomaly. Thus, transect survey lines (P-TM, P-T and P-TU) are better indicators of the basement depth of the Paringa river valley.

It needs to be mentioned that using a three-dimensional model would also have be problematic. To enable a three-dimensional geological model to be created a comprehensive set of data is needed, more so than for a two-dimensional model. Furthermore, the problem remains of a lack of constraining data in the Paringa region to be able to reduce uncertainty. Using a three-dimensional model may reduce the uncertainty surrounding the 'down valley' survey lines. However, this is less of a concern than the $\phi/\rho$ vs. depth problem, because transect lines model basement profiles were unaffected by the three-dimensional problem.

However, despite these uncertainties the basement profiles clearly show a significantly deep (400-600 m) U-shape that is characteristic of glacially eroded valleys (Benn & Evans, 1998). The following section examines studies on glacially eroded valleys in Fiordland, New Zealand, and elsewhere in the world to find information that support the basement depths estimations made by this model.

**Comparison to other fiord profiles**

Modeled basement depths can be compared to other regions to assess whether the values are reasonable. The most obvious place to look is the dramatic landscape of Fiordland, just 300 km SE along the West Coast. Here it is known that glaciers of the last glacial maximum formed the steep valleys that are seen today and which are now invaded by the sea. Bathymetry of the fiords indicates that the bases of these fiords are up to 400 m below sea level (Garlick et al, 2001). This of course is only part of the picture, with many other factors needing to be accounted for. These include that; (1) the depth of sediment overlying the basement rock of the fiord is not taken into account by the bathymetric data; (2) tectonic uplift through the South Westland and Fiordland region of the South Island is complex, with differential uplift across the region; and (3) the rate of erosion is rapid because of the high
rainfall which means that it is difficult to use the distance between the top of the mountain range down to the base of the fiord as a measurement of relative fiord depth.

There is little seismic data available for the Fiordland region so the thickness of sediment presumed to infill basement depressions is unconstrained by seismic observations. However, seismic data do exist from fiord environments in other parts of the world. One example is from Muir Inlet, Glacier Bay, Alaska, where a seismic reflection survey has been run down the centre of the fiord (Knoppes & Hallet, 2002). Figure 4-1 shows the results of this seismic profile. What is immediately obvious is the prevalence of basement highs and lows, both small and large scale, that indicate that glacial erosion does not leave a smooth surface. Also obvious is that, sediments in this fiord characteristically build up to 100 m thick, ignoring the basement highs. In addition, the distance from the top of the sediments to the sea level is comparable to the Fiordland observations. Obviously this does not necessarily mean that the fiords of New Zealand are the same as the Alaska example. However, it does indicate the potential for considerable thicknesses of sediment to overlie basement rock, for fiords to have considerable basement depth below sea level and for them to have variable scale basement highs and lows. Therefore the modelled basement depths of ~600 m within the Paringa River valley are not unreasonably deep.

Figure 4-1: Seismic reflection profile down the centre of Muir Inlet, Glacier Bay, Alaska. Of interest is the ~100 m of sediment overlying the basement, and the small and large scale irregularities in the basement topography, even when the vertical exaggeration is taken into account (from Knoppes & Hallet, 2002).
4.2 Alpine Fault identification

The large positive anomaly at the SE end of the P-DS survey line appeared to be the best location to observe the presence of the Alpine Fault in these data. The increased gravity reading indicated an increase in the gravitational acceleration implying that the denser basement was closer to the surface here than in the NW. There were three simple ways of modelling this residual anomaly. These were by: (1) inserting a vertical transition from a deeper basement surface to a shallow surface, (2) using a NW dipping face, and (3) inserting a SE dipping face. All three could be made to fit the residual anomaly, once again showing the non-unique solutions that characterise gravity modelling. Additional knowledge was required to allow the interpretation of the basement profile. The Alpine Fault is partitioned onto fault sections with different orientations, dip angles and slip vectors (see section 2.2), thus the dip of the fault cross-cutting the P-DS may vary. Additionally, if the fault does not intersect the survey line at a right angle, simple geometry dictates that the apparent dip will be less than the actual fault angle. However, a likely dip angle is somewhere between 50° and 70° SE, so the model featuring a SE dipping transition between the lower basement and the upper was more likely to represent the Alpine Fault as it traversed the Paringa River valley.

There were two variables when constraining the Alpine Fault: the position and the dip angle. If one of these is known the other can be calculated. The problem for this survey was that both variables were unknown therefore neither could be solved with any precision. Only best approximates for both variables could be used. With this uncertainty in mind, the gravity models indicate the location of the Alpine Fault is comparable to Simpson’s (1992) estimation.

4.3 Alpine Fault uplift rates

Using the geophysical data to interpret uplift rates on the Paringa section of the Alpine Fault was not feasible mainly because of uncertainties in determining basement depth. Additionally, uncertainties arose from how constant the uplift rate, as determined by Kostro (2003), is for the entire South Westland Province. The Alpine Fault offset across the Paringa valley may be influenced by the local uplift concentrated at Little Paringa Hill (13.7 mm/yr) or may only reflect regional uplift (8.0 mm/yr) (both uplift rates from Simpson et al, 1994).
Meanwhile, three-dimensional effects caused by the geometry of the Paringa valley and the Alpine Fault also cause uncertainty.

The inverse, where uplift rates from Simpson et al. (1994) could be used to constrain the geophysical data, is potentially helpful. However, there are problems. The relative vertical offset on the Alpine Fault calculated from the uplift on the eastern side of the Alpine Fault and from the western side. Simpson et al. (1994) provided two uplift rates: 8.0 mm/yr for regional uplift and 13.7 mm/yr for local uplift concentrated on Little Paringa Hill. It was not known however, if the Alpine Fault in the centre of the Paringa River valley, where survey line P-DS was positioned, was influenced by an localised uplift or not. Additionally, the partitioning of Alpine Fault displacement onto discrete segments (as described in 2.2) may result in low vertical offset if the segment crossing the Paringa valley was predominantly transformed.

Uplift rates on of the Western Province basement have only recently been well constrained in the Knight's Point region ~20 km SW of Paringa. Based on uplifted marine terraces at Knight's Point, an uplift rate of 0.9 mm/yr was calculated by Kostros (2003). When compared to an average regional uplift rate of 8.0 mm/yr at Paringa (Simpson et al, 1994), vertical offset over 15,000 years would equate to ~100 m. This offset is considerably less than the fault offset produced by the modelling (Fig. 3-9). If the higher local uplift rate of 13.7 mm/yr calculated by Simpson et al. (1994) is used, the offset becomes ~200 m. This however, is still at the lower end of the vertical offset predicted by the gravity models. The apparent difference between the calculated vertical offset and the gravity model offset may be caused by the three-dimensional nature of the Paringa River valley. The 'down valley' survey lines did not meet the requirements of using two-dimensional modelling. The current offset difference indicated that the complexity of the Paringa River valley may be more problematic than previously thought. Uplift of the eastern side of the fault will have narrowed the basement profile, causing the basement walls to be even closer to the survey stations than on the down thrown side, thus causing even greater gravitational acceleration on the residual anomaly that was not accounted for in the modelling. Furthermore, strike-slip displacement will have displaced the eastern basement laterally to the SW, thus narrowing the basement even further and generating further three-dimensional problems for the survey line. It was considered that
the use of a two-dimensional model in an area of complex geometry was the main problem when constraining the gravity models using Alpine Fault vertical offset.

4.4 The NE trending valley

*Basement profile*

The basement topography of the DB survey line was similar to transects across the Paringa valley to the west of the Alpine Fault (P-TM and P-TE). It had a deep U-shaped profile and narrow wedges extending out at the margins, that may either be artefacts of the modelling process or else represent the thinning out of cover sediment. The residual anomaly showed a small anomaly fluctuation ($\Delta1.2$ mGal) at $\sim900$ m that may indicate an anomalous structural feature, such as the Alpine Fault, which geological mapping indicated should intersect the survey line (Map 1). This residual anomaly offset was small and was within the limits of error. This entire structural interpretation therefore was based on one observation reading. The creation of a model to fit this offset was difficult, as figure 3-15 attests. The input of an east dipping fault plane fitted the residual anomaly, although other models without this east dipping-structure (Fig. 3-14) fitted the residual anomaly just as well. Essentially the gravity data were not able to image the Alpine Fault to an extent that was helpful in advancing the understanding of Alpine Fault structure in the NE trending valley.

*Basement depth*

The depth of the basement was difficult to determine, as the regional trend developed in the Paringa River valley may not represent the gravity field in the NE trending valley. In addition, bulk shift was hard to apply as it was difficult to determine the transition between cover sediments and basement which was used in the Paringa valley to help constrain the regional effect. However, it was apparent that the depth to the basement of the NE trending valley was considerable and was comparable to that of the Paringa River valley. Thus with the U-shaped profile and considerable depth, the NE valley was considered to be a glacially eroded valley as Wellman predicted in 1955.
4.5 The Paringa River's evolution and geomorphology

Glacial origins

The significant depth and U-shaped basement profile of the Paringa River valley to the west of the Alpine Fault indicated that glacial erosion was responsible for the formation of the current basement profile. The Paringa valley to the east of the Alpine Fault (as indicated by the P-TU survey line) did not show this deep U-shaped profile, although, this was to be expected as uplift on this side of the fault would raise the basement in this region. The NE trending valley showed a similar basement profile to the Paringa profile as well as a comparable depth. This evidence, coupled to the dextral strike-slip motion recognised for the plate boundary, made it highly plausible that the upper Paringa River (east of the Alpine Fault) once fed into the NE trending valley which linked to the Ohinemaka River flat and out to the sea. During glacial periods, of which there have been many during the late-Quaternary period (Nelson et al, 1985), the drainage channels would have been intensely eroded leading to the U-shaped basement profiles seen in the gravity survey models. The offset along the Alpine Fault would have made the NE trending valley longer with less direct access to the sea, presumably making the topographic gradient less steep and making it more difficult for the glacier to flow. At this point, the glacier (or river) took a shortcut from the NE trending valley and followed a more direct route to the sea. It is quite probable that an existing drainage system was utilised and once entrained in this system further erosion widened the valley to the present Paringa River valley basement profile. Based on 27 mm/yr transform displacement on the Alpine Fault (Norris & Cooper, 2001) at the end of the last glacial maximum the (~15 ka) the offset would have been ~380 m: not enough to have blocked off the western Paringa River valley. This observation supported the gravity models that showed the lower Paringa River valley as being formed by glacial erosion. The glacial erosion thought to have eroded the current basement profile of the NE trending valley was presumably formed from previous glacial maxima.

Sequential reoccupation of western province valleys

It could be concluded from the NE trending valley basement profile that the valley profile was most likely to have been part of the Paringa drainage system, and was potentially part of an even older drainage system, for example the Moeraki River system 15 km to the SW. The potential for a sequential reoccupation of drainage courses on the west-side of the Alpine
Fault is suggested. The uplift rate on the western side of the fault is significantly less than for the eastern-side of the Alpine Fault (Kostro, 2003), therefore western-side drainage courses will not have been uplifted and destroyed by erosion over the last half million years, allowing the preservation of these drainage courses for reoccupation by the following eastern-catchment. In this scenario, eastern-side drainage systems would occupy a series of existing western drainage systems over time, as detailed below.

The Ohinemaka River flat at the north end of the NE trending valley provides further evidence of sequential reoccupation of western drainage courses. This 3-6 km wide river flat must have been formed by a substantial drainage system because a large volume of basement rock has presumed to have been removed to form this expansive river flat. However there is no significant drainage system on the east side of the Alpine Fault at this location that could have provided the enormous volume of water and ice required for this level of erosion. The minor creeks directly opposite the Ohinemaka River flat, such as Doughboy Creek, are simply not big enough to be considered as a source for these large water volumes. Therefore the interpretation from Ohinemaka River flat is that strike-slip motion on the Alpine Fault has offset the eastern side drainage system that supplied the Ohinemaka River flat drainage system. The prime candidate is the Paringa River valley, as this is the first major eastern side drainage system that lines up with the Ohinemaka River, flat if strike-slip offset along the Alpine Fault is progressively removed.
Further supporting observations from the South Westland region support this theory of sequential reoccupation. For the Paringa River capture hypothesis to work, the other major eastern drainage system in the immediate region, the Moeraki River, should follow a similar sequence of reoccupation. From observations of the South Westland region, from Moeraki River to Mahitahi River (Fig. 4-2), it is apparent there is a sequence of eroded valleys to the west of the Alpine Fault: Moeraki River to the SW, Paringa River, and finally Ohinemaka River flat to the NE. If Lake Paringa is included as geomorphology suggests it should be, there is a sequence of western drainage systems separated by ~5 km along the strike of the Alpine Fault. If offset on the Alpine Fault is progressively removed, the Moeraki catchment is

![Fig. 4-2: Topographic map of the wider Paringa region. The two major river catchments the Moeraki and Paringa Rivers lie on the east side of the Alpine Fault. The proposed sequence of western-side drainage courses lie to the west side of the Alpine Fault. Right lateral strike-slip displacement on the Alpine Fault shifts the western drainage courses to the north east compared to the western catchments. 5 km of displacement roughly equates to 200 ka. The eastern catchments took advantage of existing western drainage courses on their path to the sea. Note the northerly trending kinks in the Moeraraki and Paringa valleys where the Alpine Fault crosses. This is estimated to be continuation or the start of eroding north-east trending valleys as the Alpine Fault progressively offsets the east and west sides of the rivers. (1:50,000 NZ TopoMap)
proposed to have drained down the Ohinemaka River to the sea, then occupied the Paringa River, then Lake Moeraki, and finally shifted to its current position opposite the lower Moeraki River. The valley containing The Windbag Creek is proposed as a southern equivalent of the NE trending valley, and was the course of the Moeraki drainage system when the eastern Moeraki River and western drainage systems were not directly aligned. The Paringa River has only occupied the Ohinemaka River followed by the current west Paringa River as progressive transform offset transposes the Paringa catchment further to the south. It is estimated in the future that the Moeraki catchment will eventually drain out onto the expansive coastal plains of the Haast region. The Paringa catchment will eventually abandon the current western Paringa River and occupy Lake Paringa, followed by the lower Moeraki River, before it too will drain onto the Haast coastal plains.

Fig. 4-2: Topographic map of the wider Paringa region. The two major river catchments the Moeraki and Paringa Rivers lie on the east side of the Alpine Fault. The proposed sequence of western-side drainage courses lie on the west side of the Alpine Fault.

The ~5 km interval between the western drainage systems roughly equates to 200 ka years of transform offset along the Alpine Fault (based on ~24 mm/yr, as a median rate of transform offset from Sutherland et al. 2005; and Sutherland & Norris, 1995). Interestingly, the period ~200 ka years ago coincides with the previous glacial maximum (Chappell & Schakleton, 1986). Although as noted earlier, the profile of the NE trending valley was formed by glacial erosion, and it is not necessary for glaciation and the direct lining up of eastern and western drainage systems to coincide. The expanse of coastal plains to the north and south of the Moeraki to Ohinemaka section of South Westland means that the theory of sequential reoccupation of Western Province valleys cannot be tested further. The coastal plains found to the north and south offer little hindrance to glaciers or rivers, therefore these drainage systems will not be progressively 'dragged' north with strike-slip displacement along the Alpine Fault.
5. Conclusion

Conclusions drawn from this study are summarised below:

- Amphibolite facies, quartzofeldspathic protomylonites with a prominent S-C fabric exposed in Blackwater Creek grade eastwards into schist lacking and S-C fabric at the eastern margin of exposure.

- Pseudotachylytes within the protomylonites indicate minor, high stress seismic ruptures at depth within the Alpine Fault zone.

- The Paringa granitoids are I-type in composition similar to those of the Mesozoic Separation Point Suite. Their Paleozoic age however precludes their being part of the Separation Point Suite. This highlights the danger of using I and S-type characteristics to affiliate granitoids to Western Province Suites.

- The Paringa calc-alkaline lamprophyres do not closely match the geochemical signature of lamprophyre dykes from the late Cretaceous Hohonu Dike Swarm. The inference is made that the lamprophyre dyke is Paleozoic, based on published global patterns of calc-alkaline lamprophyres intruded into closely preceding I-type granitoids, such as that of the Paringa granitoids.

- Gravity modelling of the Paringa River valley indicates a significantly deep (~550 m) U-shaped, glacially excavated valley or fiord.

- The Alpine Fault is imaged in the gravity profiles beneath the valley fill and is in agreement with Simpson's (1992) mapping of the Alpine Fault trace. Numerous problems were encountered surrounding the use of two-dimensional modelling in regions of complex geometry, which resulted in considerable uncertainty.

- Gravity modelling indicates that the NE trending valley is U-shaped and of significant depth, suggesting a glacial origin. The Paringa River is postulated to have drained through this valley northward before switching to its present course.
Chapter 5: Conclusion

- A theory of sequential reoccupation of western drainage systems is suggested. Based on the sequence of drainage systems to the west of the Alpine Fault, the presence of the glacially eroded NE trending valley, and continuing transform displacement along the Alpine Fault.
References


Petlab Unpublished data, GNS.


