**A gravity analysis of the Alpine Fault and the DFDP-2
drill site, Whataroa valley, South Westland, South
Island, New Zealand**

Steve Jenkins

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Abstract

The second phase of drilling into the Alpine Fault (DFDP-2), was completed in the Whataroa River valley, a former glacial valley located in central Westland, South Island, New Zealand. The site is located next to a steep hillside on the hanging-wall, ~1 km southeast of the mapped surface trace of the Alpine Fault. Projection of the hillside suggests a sediment thickness of 100 ± 40 m at the drill site; however, the sediment thickness was approximately double pre-drill estimates. Additionally, the surface expression and shallow geometry of the Alpine Fault in the Whataroa River valley, is not well-defined due to post-glacial burial of the fault zone. This thesis describes a gravity study designed to better constrain sub-surface structure beneath the DFDP-2 drill site and across the Alpine Fault.

During this study, 466 new high-precision gravity observations were collected (standard error = 0.015 mGal) and amalgamated with 134 existing gravity stations, yielding comprehensive coverage of gravity data across the study area. A high density of observations was achieved within pre-determined zones, in addition to regional measurements so that residual gravity anomaly maps could be produced. The maps reveal: a negative residual gravity anomaly interpreted as a dextrally-offset glacial channel at least 350-450 m deep; steep localised gravity gradients near the Alpine Fault and DFDP-2 drill site that are interpreted as faulted and/or eroded boundaries; and a negative gravity anomaly adjacent to the DFDP-2 drill site that is interpreted as the deepest point of an over-deepened glacial lake.

Gravity models were used to estimate the bedrock-sediment interface geometry near the DFDP-2 drill site and Alpine Fault. Structural inversion of the density boundary next to the drill site suggests either a moderately-dipping reverse fault or sub-vertical erosional wall exists beneath the hillside. Additional constraints on physical properties from direct density measurements or seismic velocity determinations and direct constraints on sediment thickness and layer geometry from seismic surveys will in future allow this new high-precision gravity dataset to be modelled more effectively.

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“We find no vestige of a beginning, - no prospect of an end”

James Hutton, 1788

Table of Contents

Abstract.....	iii
Acknowledgments.....	v
Table of Contents.....	vii
List of Figures	xi
List of Tables	xv
Chapter 1 Introduction	1
1.1 Project motivation and objectives	1
1.1.1 Project motivation	1
1.1.2 Project objectives.....	6
1.2 Study area	7
1.2.1 Whataroa River valley	7
1.2.2 Tectonic setting of the South Island	9
1.2.3 Geological setting	15
1.2.4 South Island glacial history and geomorphology	23
1.3 Previous geophysical studies.....	29
1.3.1 South Island Geophysical Transect	29
1.3.2 Seismicity	31
1.3.3 Gravity	33
1.3.4 Geodesy	36
1.4 Gravity model constraints	37
1.4.1 Borehole data	37
1.4.2 Active-source seismic data	40
1.4.3 Gravity data	42
1.4.4 Rock density	42
1.5 Thesis structure.....	46

Chapter 2	Gravity and methodology	48
2.1	Gravity theory.....	48
2.2	Earth's gravity	49
2.2.1	Relative and absolute gravity measurement	50
2.2.2	Temporal variation of measured gravity	51
2.2.3	Variation of gravity with latitude	55
2.2.4	Variation of gravity with elevation.....	57
2.2.5	Variation of gravity with topography	59
2.2.6	The Bouguer gravity anomaly	63
2.3	Data acquisition and reduction	64
2.3.1	Data acquisition	64
2.3.2	Data reduction.....	66
2.3.3	Uncertainty in the Bouguer gravity anomaly	67
2.4	Regional-residual separation	73
2.4.1	Mathematical methods.....	73
2.5	Gravity modelling.....	76
2.5.1	Two-Dimensional modelling.....	76
Chapter 3	Results.....	79
3.1	Introduction	79
3.2	Gsolve gravity reduction results.....	79
3.2.1	Gsolve gravity reduction methods.....	79
3.2.2	Survey residual analysis	83
3.2.3	Tidal and drift analysis	83
3.3	Existing gravity data.....	85
3.3.1	Whataroa gravity data.....	86
3.4	New gravity data	87
3.4.1	New gravity station locations	87
3.5	Gravity maps	87
3.5.1	Amalgamation of gravity data	88
3.5.2	Bouguer gravity anomaly map	90
3.5.3	Residual anomaly map	92
Chapter 4	Gravity models.....	100

4.1	Introduction	100
4.2	Gravity modelling.....	100
4.3	Forward gravity models.....	100
4.3.1	DFDP-2 drill site	101
4.3.2	Alpine Fault	104
4.4	Whataroa gravity models.....	105
4.4.1	DFDP-2 gravity models.....	106
4.4.2	Alpine Fault gravity models	110
4.5	Gravity structural inversion and uncertainty	115
Chapter 5	Discussion and conclusions.....	120
5.1	Discussion	120
5.1.1	Gravity maps	120
5.1.2	Sub-surface geometry	123
5.2	Future work	126
5.3	Recommendations	126
5.4	Conclusions	127
Appendix A	Gravity Charts.....	128
Appendix B	Detailed Gravity Meter Technique.....	132
Appendix C	Gravity Data	134
Appendix D	Position survey data.....	157
Appendix E	Gsolve Data	169
Bibliography		204

List of Figures

Figure 1.1: Map of the plate tectonic setting of New Zealand.....	2
Figure 1.2: Diagram of the orographic climate regime over the western slopes of the central South Island.....	3
Figure 1.3: Simplified geological map of central Westland in the South Island.	5
Figure 1.4: Topographic map of the study area and the Whataroa floodplain.	8
Figure 1.5: Cross-section showing crustal structure beneath central South Island.....	10
Figure 1.6: Estimates of Late Quaternary strike-slip rates along the Alpine Fault.....	12
Figure 1.7: Topographic map showing the surface expression of the Alpine Fault at three different scales.	14
Figure 1.8: Cross-section of shallow Alpine Fault showing fault wedge structure.	15
Figure 1.9: Basement geology of New Zealand.....	16
Figure 1.10: Surface geology map of the Whataroa study area.	22
Figure 1.11: Ice extent of the Late Otiran glaciation in Central Westland.	23
Figure 1.12: The NZ-INTIMATE climate event stratigraphy.	25
Figure 1.13: SIGHT transects 1 and 2 extending across the central South Island.....	30
Figure 1.14: 2-D gravity model across the Whataroa floodplain.....	34
Figure 1.15: Gravity maps of the Whataroa floodplain.	35
Figure 1.16: Cross-section through DFDP-1 boreholes.....	38
Figure 1.17: Geological log of Quaternary sediments sampled in DFDP-2A.	39
Figure 1.18: Seismic refraction model along SIGHT transect 1 across the Whataroa floodplain and Alpine Fault.	41
Figure 1.19: Gravity model of a portion of SIGHT transect 1 across the Whataroa floodplain and Alpine Fault.	43
Figure 2.1: Earth-tide variations, Whataroa study area, May 2015.	52
Figure 2.2: A gravity meter drift curve.	54
Figure 2.3: Earth's topographic, ellipsoid and geoid surfaces.....	56

Figure 2.4: The free-air correction for an observation at a height h above the vertical datum.....	58
Figure 2.5: The Bouguer correction.....	59
Figure 2.6: The gravitational effect of topography.....	60
Figure 2.7: The Hammer (1939) graticule used for the calculation of terrain corrections.	61
Figure 2.8: Key examples of LiDAR inner terrain correction.	70
Figure 2.9: Empirical CDF plot of the difference between GPS heights and LiDAR DEM heights.	71
Figure 2.10: Modelling of a linear and quadratic polynomial surface fitted in x-y-g space to regional Bouguer anomaly points.	74
Figure 2.11: Schematic of a two-dimensional model and relative coordinate system.	77
Figure 3.1: Regional topographic map of the central West Coast.	81
Figure 3.2: CDF plot of the residuals from Gsolve's normal least squares solution (Method 1)	82
Figure 3.3: CDF plot of the residuals from Gsolve's decoupled least squares solution (Method 2).	84
Figure 3.4: CDF plot of the calculated tidal effects for repeat gravity readings.	84
Figure 3.5: Scatter plot of the calculated tidal effects and residuals for repeat gravity readings.	85
Figure 3.6: Existing gravity stations over the Whataroa floodplain and Whataroa River valley.....	86
Figure 3.7: New gravity stations over the study area in the Whataroa River valley. ..	88
Figure 3.8: Absolute gravity difference and separation distance between existing and new gravity stations	89
Figure 3.9: Bouguer gravity anomaly map of the Whataroa floodplain.	91
Figure 3.10: Bouguer gravity anomaly map of the study area in the Whataroa River valley.....	93
Figure 3.11: Regional-residual separation of the Whataroa River valley.....	94
Figure 3.12: Residual anomaly map of the DFDP-2 drill site in the Whataroa River valley.....	97
Figure 3.13: Residual anomaly map of the Alpine Fault at the entrance of the Whataroa River valley.....	98

Figure 4.1: Aerial photograph of the DFDP-2 drill site.....	102
Figure 4.2: Forward gravity models.....	103
Figure 4.3: Aerial photograph of the study area.	106
Figure 4.4: Residual gravity map of the DFDP-2 drill site showing Profile 1.	107
Figure 4.5: Gravity Model 1A for Profile 1 at the DFDP-2 drill site.	108
Figure 4.6: Gravity Model 1B for Profile 1 at the DFDP-2 drill site.....	109
Figure 4.7: Residual gravity map showing all five gravity profiles.	110
Figure 4.8: Gravity Model 2 for Profile 2 across the Alpine Fault.....	111
Figure 4.9: Gravity Model 3 for Profile 3 across the Alpine Fault.....	112
Figure 4.10: Gravity Model 4 for Profile 4 across the Alpine Fault.....	113
Figure 4.11: Gravity Model 5 for Profile 5 across the Alpine Fault.....	114
Figure 4.12: Inferred location of the Alpine Fault surface trace across the Whataroa River valley.....	115
Figure 4.13: Model 1A structural inversion and uncertainty.....	117
Figure 4.14: Model 1B structural inversion and uncertainty.	118
Figure 5.1: Calculated mean density of lake silts sampled in DFDP-2.	124
 Figure E.1: Drift curves for all 34 survey loops produced using Gsolve.	 203

List of Tables

Table 1.1: Mean P-wave velocities and bulk densities of rock types known in the study area.	45
Table 1.2: Mean wet densities from the PETLAB rock catalogue.	45
Table 3.1: Absolute gravity difference between observed and recorded values at 9 reference stations from the New Zealand gravity network.	82
Table A.1: Hammer terrain correction chart.	130
Table A.2: Calibration table for a Lacoste & Romberg model G-519 gravity meter.	131
Table C.1: Gravity data collected during this study.	155
Table E.1: Survey measurements processed using Gsolve for 10 absolute gravity reference stations of the New Zealand gravity network.	170
Table E.2: Survey measurements processed using Gsolve for the entire gravity survey.	194

Chapter 1 Introduction

1.1 Project motivation and objectives

1.1.1 Project motivation

The New Zealand continent straddles the highly-active and complex Australian/Pacific Plate boundary. The Pacific Plate migrates westward and subducts beneath the Australian Plate along the Hikurangi Trench in the northeast, while the Australian Plate migrates eastward and subducts beneath the Pacific Plate along the Puysegur Trench in the southwest of New Zealand (Litchfield et al., 2014; Okaya et al., 2007; Sutherland et al., 2000; Wallace et al., 2007). The Alpine Fault connects the Hikurangi and Puysegur subduction zones, forming a continental-convergence boundary extending ~740 km through the central South Island of New Zealand (Figure 1.1) (Litchfield et al., 2014; Okaya et al., 2007; Sutherland et al., 2000; Walcott, 1978).

The current and 3-Myr-average estimates of relative Australian/Pacific plate velocities near the Alpine Fault are each 36 mm/yr, with a 6-9 mm/yr shortening component perpendicular to the fault (Beavan et al., 2002; DeMets et al., 2010). Plate motion during the past 45 Myr has resulted in ~850 km of dextral offset, of which 440-470 km has been accommodated along the Alpine Fault (Sutherland, 1999b; Wellman and Willett, 1942). Uplift southeast of the fault adds a significant high-angle reverse oblique component to its displacement, responsible for ~20 km of tectonic uplift and formation of the Southern Alps since 6-7 Ma (Cox and Sutherland, 2007; Norris and Cooper, 2007; Sutherland et al., 2000; Van Avendonk et al., 2004; Walcott, 1998).

The Southern Alps lie in the path of a westerly atmospheric circulation pattern, resulting in a dramatic orographic climate regime over the western slopes (Koons, 1990; Shulmeister et al., 2004). Heavy rainfall (> 10 m/yr) occurs west of the Main Divide, while precipitation rates are significantly lower to the east (≤ 1 m/yr), creating a rain shadow (Henderson and Thompson, 1999). Due to the mid-latitude setting and high

Figure 1.1: Map of the plate tectonic setting of New Zealand.

The Pacific plate migrates west and subducts beneath the Australian plate along the Hikurangi Trench in the northeast, while the Australian plate migrates east and subducts beneath the Pacific plate along the Puysegur Trench to the southwest of New Zealand. Both subduction zones are connected by the Alpine Fault through the central South Island. Figure from Kleffmann (1999).

elevations associated with the Southern Alps (≤ 3.8 km), much of the precipitation falls as snow and widespread glaciation occurs periodically within glacial cycles (Petit et al., 1999; Suggate, 1990; Suggate and Almond, 2005). Erosion correlates strongly with precipitation, where more extensive erosion (~ 10 mm/yr) occurs on the western slopes creating an orographic asymmetry (Figure 1.2) (Adams, 1980a, b; Cox and Sutherland, 2007; Fitzsimons and Veit, 2001; Hicks et al., 1996).

The rate of erosion correlates with the rate of uplift in the western and central Southern Alps keeping them in a dynamic equilibrium, while also restricting the width of transpressional deformation to a zone 90-100 km wide (Koons, 1990; Norris and Cooper, 2003; Tippet and Kamp, 1995; Walcott, 1998). Uplift rates and regional

Figure 1.2: Diagram of the orographic climate regime over the western slopes of the central South Island.

Geology and the effects of Australian-Pacific plate transpression are also shown in block diagram. High rates of erosion on the western slopes (~ 10 mm/yr) have developed an orographic asymmetry. Figure from Cox and Sutherland (2007).

elevation diminish both in the northern and southern sections of the fault, restricting the area of maximum deformation to the central South Island (Kamp and Tippett, 1993; Little et al., 2005; Norris and Cooper, 2003; Walcott, 1998), making it a particularly useful area for investigating transpressional tectonics, faulting and mountain formation (Okaya et al., 2007).

The Alpine Fault is thought to accommodate ~ 60 – 80 % of the plate motion which has been estimated using Quaternary slip-rates (Norris and Cooper, 2001; 2007; Sutherland et al., 2000; Sutherland and Norris, 1995; Walcott, 1978). However, well-constrained estimates of Alpine Fault Quaternary slip-rates are restricted to the northern and southern sections of the fault where offset surface markers are widely available (Barth et al., 2013; Norris and Cooper, 2001, 2007; Sutherland et al., 2006). High rates of erosion on the western slopes of the central Southern Alps have erased offset surface

markers along the central Alpine Fault, making it a difficult area to quantify and constrain fault kinematics (Norris and Cooper, 2007). Gravity surveying can be used to model offset sub-surface features, providing an alternative option to quantify fault kinematics in areas that lack traditional offset surface markers, such as the central Alpine Fault. However, uncertainties associated with the offset and slip-rates estimated with this technique can be significant (Davy, 2012; 2013).

The surface expression and sub-surface structure of the central Alpine Fault has been refined using recent light detection and ranging data (LiDAR) (Barth et al., 2012; Langridge et al., 2014), and a synthesis of surface mapping data (Norris et al., 2012), confirming the non-linear form of the fault trace and serial partitioning of the fault zone that was originally recognised by Norris and Cooper (1995) and Norris and Cooper (1997). However, the surface expression and shallow geometry of the Alpine Fault at the mouth of the Whataroa River valley, near the site of a large-scale Alpine Fault drilling project (Townend, 2009), is not well-defined due to post-glacial burial of the fault zone. Reliable sub-surface data is required to further constrain the location of the fault trace and shallow fault structure.

The Alpine Fault represents the largest seismic hazard in the South Island, and a detailed earthquake record has been constructed. Over the last 7900 years, there have been 24 large-scale earthquakes (M_w 7.6-8.2) occurring along the fault approximately every 330 years (Berryman et al., 1992, 2012; Hull and Berryman, 1986; Sutherland and Norris, 1995). The most recent was in 1717 C.E. (Sutherland et al., 2007; Wells et al., 1999), resulting in a 27 % model-dependent probability of a large-scale earthquake occurring on the Alpine Fault in the next 50 years (Biasi et al., 2015). The Alpine Fault is, therefore, late in its earthquake cycle, and provides an opportunity to survey and understand the characteristics of a fault before the occurrence of a large-scale earthquake.

The Deep Fault Drilling Project (DFDP) is an international science project involving researchers from more than a dozen countries (Townend et al., 2009). The project involves drilling through the sub-surface plane of the Alpine Fault to investigate the tectonic signal associated with exposed surface rocks, seismogenesis, and mineralization (Sutherland et al., 2012; Townend et al., 2013; Toy et al., 2015). The first phase of drilling (DFDP-1) was completed in 2011 at Gaunt Creek, where two boreholes were successfully drilled through the principal slip zone (PSZ) at depths of

91 m and 128 m (Sutherland et al., 2012). The second phase of drilling (DFDP-2) was completed early in 2015 in the Whataroa River valley, ~7 km northeast of Gaunt Creek (Figure 1.3). DFDP-2 aimed to target the fault plane at 1 km depth, and drill to a total depth of 1.3 km. However, technical difficulties resulted in a total drilled depth of 893 m, ~200 m short of the PSZ (Sutherland et al., 2015).

Figure 1.3: Simplified geological map of central Westland in the South Island. DFDP-1 was completed at Gaunt Creek ~7 km southwest of the Whataroa township. DFDP-2 was completed early in 2015 in the Whataroa River valley. Also shown are the Southern Alps, and the surface trace of the Alpine Fault (red line). Figure modified from Townend et al. (2013).

Pre-drill estimates of sediment thickness at DFDP-2 were 100 ± 40 m; however, the observed sediment thickness in the DFDP-2B borehole was 240 m (Sutherland et al., 2015). Additional analysis of geophysical constraints is needed to fully understand the sub-surface geometry surrounding the DFDP-2 drill site. This was a key motivation for this project.

1.1.2 Project objectives

The aim of this project is to acquire new gravity data and construct a gravity map of the Whataroa River valley, particularly near the DFDP-2 drill site and the Alpine Fault. By making measurements of the Earth's gravity field at appropriately spaced intervals, and analysing the data to extract the gravity signal associated with near-surface rock units, it is possible to model the bedrock-sediment interface geometry near the DFDP-2 borehole, and define the shallow structure of the nearby Alpine Fault. Existing gravity data will be amalgamated with new gravity measurements to maximise the coverage of the dataset. This project is a necessary contribution to the ongoing multi-disciplinary research of an active continental plate boundary, and is important in understanding the broader structure surrounding the DFDP-2 borehole, as well as the complex interplay between tectonics, glacial processes, and sedimentation.

The primary objectives of this project are prioritised as follows:

1. Acquire new gravity data and integrate with existing gravity measurements to produce a comprehensive gravity map of the Whataroa River valley near the Alpine Fault and DFDP-2 drill site.
2. Extract a regional gravity field of the Whataroa River valley so that gravity anomalies associated with short-wavelength shallow (<500 m) density anomalies can be isolated i.e. effects of long-wavelength surface topography and crustal root removed.
3. Produce preliminary gravity models of: the bedrock-sediment interface near the DFDP-2 drill site and across the Alpine Fault. Further modelling will require integration with other geophysical data, such as seismic-reflection data. These data are not yet published and hence more sophisticated modelling is outside the scope of this thesis.

1.2 Study area

1.2.1 Whataroa River valley

This study encompasses an approximate 5 x 5 km geographic area located at the entrance of the Whataroa River valley in central Westland, ~30 km north of Franz Josef and ~70 km south of Hokitika. The Alpine Fault strikes northeast (~055°) through the centre of the study area and dips to the southeast at an angle of ~30-60° (Barth et al., 2012; Davey et al., 1995; Davey, 2010; Kleffmann, 1999; Norris et al., 2012; Sutherland et al., 2015). DFDP-2 is located on the hanging-wall ~1 km southeast of the mapped fault trace. The study area is bound to the west by the Price Range and to the east by Adams Range, where elevations exceed 1000 m a.s.l. (Figure 1.4).

A glacio-fluvial outwash plain with low topographic relief and well-defined lateral and terminal moraines extends north-north-east and west of the study area as far as the western coastline. The Whataroa floodplain contains two lakes of glacial origin that define western and eastern termini of the last glacial maximum (LGM) (Almond et al., 2001). During the LGM, the Whataroa glacier occupied a deep trough and extended from the Whataroa valley onto the coastal plain (Almond et al., 2007; Suggate, 1990; Suggate and Almond, 2005). The trough was later filled by late-glacial and post-glacial alluvium following the retreat of the Whataroa glacier (Cox and Barrell, 2007). Ongoing dextral-reverse movement along the Alpine Fault has displaced the sub-parallel Whataroa River that flows through the study area and across the fault, creating a distinct bend in its trajectory, a common pattern observed along the entire length of the fault. Uplift associated with the reverse component of fault slip has created raised fluvial terraces upstream of the fault.

Figure 1.4: Topographic map of the study area and the Whataroa floodplain. Other points of interest are the Whataroa township, Price Range, Adams Range, the DFDP-2 drill site (yellow dot), and the two glacial lakes (Wahapo & Rotokino). The Alpine Fault (red line) strikes NE through the ~5x5 km study area (dashed box), where ongoing dextral offset has displaced the Whataroa River. Inset map shows the position of the study area with respect to the central South Island. Fault data obtained from the New Zealand Active Faults Database (NZAFD).

1.2.2 Tectonic setting of the South Island

The Alpine Fault is characterised by dextral (horizontal) slip, with a component of vertical displacement to the southeast of the fault trace. It is continuous at the surface for ~740 km, extending from offshore near Fiordland to the northern South Island, forming an oblique continental-convergence zone between the Australian and Pacific plates (Okaya et al., 2007; Sutherland et al., 2000). In the upper South Island, the northern section of the Alpine Fault is linked to the Hikurangi subduction zone via a series of predominantly continental strike-slip fault zones, known as the Marlborough Fault System (Walcott, 1978), while the southern section of the Alpine Fault links directly to the Puysegur subduction zone near the Fiordland region (Barnes et al., 2001; Okaya et al., 2007; Sutherland et al., 2000).

The Alpine Fault was inherited from an Eocene rift and passive margin that formed at ~45 Ma during the initiation of the Cenozoic plate boundary through New Zealand (Cox and Sutherland, 2007; Sutherland, 1995, 1999b; Sutherland et al., 2000). Horizontal displacement along the Alpine Fault initiated during the late Oligocene and early Miocene as oceanic crust of the Australian plate was subducted below the Fiordland region at the Puysegur trench, while rigid continental crust of the Australian plate (northwestern South Island, North Island and Challenger Plateau) acted as an indenter into weaker continental crust of the Pacific plate (eastern South Island, Chatham Rise and Campbell Plateau) (Cox and Sutherland, 2007; Sutherland et al., 2000; 2009). The long term result of horizontal and vertical displacement is ~440-470 km dextral offset of bedrock terranes (Berryman et al., 1992; Sutherland, 1999b; Wellman, 1955), and uplift of the Southern Alps (Adams, 1979; Wellman, 1953, 1979).

Crustal shortening and thickening due to convergence

There has been ~90-100 km of crustal shortening in the South Island since 6-7 Ma (Walcott, 1998), of which 60-80% has been accommodated on the southeast-dipping Alpine Fault, resulting in ~20 km of tectonic uplift (Beaumont et al., 1996; Beavan et al., 1999; Koons, 1990; Norris and Cooper, 2001; Sutherland et al., 2000; Sutherland and Norris, 1995; Tippet and Kamp, 1993; Walcott, 1978). The remaining 20-40% of plate-perpendicular motion is accommodated on reverse faulting both east and west of the Alpine Fault within the ~90 km deformation zone (Beavan et al., 1999; Sutherland

et al., 2006), as well as a component of shallow shortening through folding within the fault wedge of the central Alpine Fault (Barth et al., 2012).

During plate convergence along the Alpine Fault, ~17 km of crustal thickening has occurred ~20 km east of the Main Divide of the Southern Alps (Scherwath et al., 2003). Crustal thickness increases from 20-30 km east and west of the South Island to 37-48 km beneath the region of crustal shortening (Figure 1.5) (Bourguignon et al., 2007b; Davey et al., 2007; Davey et al., 1998; Kleffmann et al., 1998; Scherwath et al., 2003; Smith et al., 1995; Stern and McBride, 1998; Stern et al., 2000; Stern, 1995; Van Avendonk et al., 2004; Wellman, 1979).

Figure 1.5: Cross-section showing crustal structure beneath central South Island.

Plate convergence causes crustal thickening beneath the Main Divide of the Southern Alps forming a 37-48 km thick crustal root. Colour scale and contour values represent seismic velocity. Figure from Stern et al. (2007).

South Island crustal thickening may be the result of a decollement located at the base of the Pacific crust (Koons, 1987), which is weaker and less resistant than the Australian crust (Beaumont et al., 1996; Sutherland et al., 2000; 2009; Van Avendonk et al., 2004). Convergence causes detachment of the over-riding metamorphosed sedimentary rocks from underlying oceanic lithosphere along the decollement (Beaumont et al., 1996; Stern et al., 2007; Stern, 1995). After detachment, the old oceanic lithosphere thickens with the mantle lithosphere (Stern, 1995; Walcott, 1998), while the detached schists and greywackes are obducted along the Alpine Fault, forming the Southern Alps (Davey et al., 1998; Smith et al., 1995; Sutherland, 1995; Walcott, 1998). Consequently, the brittle-ductile transition shallows from ~15 km to

~5-8 km beneath the region of crustal shortening (Koons, 1987; Norris and Cooper, 1995; Walcott, 1998).

Simple models of continental-convergence in the underlying mantle lithosphere show thickening is driven by intracontinental subduction, in which crust and mantle lithosphere are delaminated and one slab of mantle lithosphere underthrusts the other (Mattaer, 1986; Matte et al., 1996; Meyer et al., 1998), which has been suggested as the driving mechanism of mantle lithosphere thickening below the Southern Alps (Beaumont et al., 1996; Wellman, 1979). However, teleseismic P-wave delay data suggests a more uniform thickening of mantle lithosphere below the Southern Alps, as if mantle lithosphere beneath continental crust behaves as a continuum (Stern et al., 2000). Additionally, the thick crustal root is at least twice as thick as expected for Airy isostatic compensation of the Southern Alps topographic load, which is thought to be due to a colder and, hence, denser mantle lithosphere acting as an effective load at the base of the crust (Bourguignon et al., 2007a).

Relative Australian/Pacific plate motion and surface displacement rate

The current and 3-Myr-average estimates of relative Australian/Pacific plate velocities near the Alpine Fault are each 36 mm/yr, with a 6-9 mm/yr shortening component perpendicular to the fault (Beavan et al., 2002; DeMets et al., 2010). The rate of plate-parallel-motion for the past 24 Myr has resulted in ~850 km of dextral offset, of which ~440-470 km has been accommodated along the Alpine Fault (Sutherland, 1999b; Wellman and Willett, 1942). This amount of accommodation is evident from estimates of Quaternary strike-slip rates, indicating that as much as 50-80% of plate-parallel motion is accommodated along the Alpine Fault (Barth et al., 2013; Cox and Sutherland, 2007; Sutherland et al., 2006).

Figure 1.6 shows estimates of Quaternary strike-slip rates on the Alpine Fault. The most southern sections of the Alpine Fault are almost pure dextral strike-slip (Barnes et al., 2001; 2005; Cooper and Norris, 1995; Norris and Cooper, 2001), which have the highest net dextral-slip rate along the fault (31 ± 3 mm/yr) (Barnes, 2009), while the rate decreases northwards to between 23–29 mm/yr in South Westland (Barth et al., 2013; Sutherland et al., 2006; Sutherland and Norris, 1995). Central sections of the fault, located between Haast River and Taramakau River, have estimates of dextral

Figure 1.6: Estimates of Late Quaternary strike-slip rates along the Alpine Fault.

Alpine Fault strike-slip rates are highest in the southwest where they steadily diminish northeast through the central fault sections toward the Hope Fault. Figure from Barth et al. (2013).

strike-slip rates of 28 ± 4 mm/yr (Norris and Cooper, 2001), 27 ± 5 mm/yr (Norris and Cooper, 1997), > 22 mm/yr at Gaunt Creek (Cooper and Norris, 1994), 29 ± 6 mm/yr (Wright, 1998), and 13.6 ± 1.8 mm/yr at Inchbonnie (Langridge et al., 2010).

High rates of erosion on the western slopes of the Southern Alps have erased offset surface markers along the central Alpine Fault (Henderson and Thompson, 1999; Koons, 1989), making it a difficult area to quantify and constrain fault kinematics. Better data are still required from the central Alpine Fault to demonstrate a variable strike-slip rate (Norris and Cooper, 2007). Horizontal motion diminishes northwards (Norris and Cooper, 2001), where the remaining 20-50% of parallel-plate motion is partitioned onto the Marlborough Fault System, particularly the Hope Fault (Langridge et al., 2010), as well as a component of horizontal motion by clockwise block rotations and oblique-dextral reverse faulting up to 80 km southeast of the Alpine Fault (Sutherland et al., 2006; Wallace et al., 2007).

Uplift rates and elevation diminish both in the northern and southern sections of the fault, restricting the area of maximum deformation to the central South Island, where the dip-slip rate on the Alpine Fault near Aoraki/Mt Cook is locally up to 10 mm/yr (Norris and Cooper, 2001), and uplift rates to the east of the fault are > 8 mm/yr (Batt, 2001; Little et al., 2005; Simpson et al., 1994).

Alpine Fault surface expression and shallow geometry

The Alpine Fault can be divided into three geographic segments based on fault geometry, named here as the southern sections, central sections and northern sections.

South of Haast River, the southern sections of the Alpine Fault consist of linear en-echelon traces, striking 050-055°, which are sub-vertical to steeply southeast-dipping (Barnes et al., 2001; 2005; Norris and Cooper, 2007). Between Haast River and Taramakau River, the central sections of the Alpine Fault are best described at three different scales (Figure 1.7) (Barth et al., 2012). At the first order ($< 10^6$ - 10^4 m), the central Alpine Fault is remarkably straight with a continuous surface expression and no step-overs >1 km (Sutherland et al., 2007). At the second order (10^4 - 10^3 m), the central sections of the fault are serially partitioned, consisting of non-linear, $\sim 055^\circ$ -striking, shallow-dipping (30° - 40°), oblique-slip thrust faults (Norris et al., 1990), connected by ENE-WSW- to ESE-WNW-striking, strike-slip transfer faults (Cooper and Norris, 1995). At the third order (10^3 - 10^0 m), the fault is parallel-partitioned into asymmetric positive (reverse) flower structures, or fault wedges, in the hanging-wall. The fault wedges are ~ 300 m wide and are bounded by dextral-normal and dextral thrust faults rooted at shallow depths (< 600 m) on a planar, moderately southeast dipping, dextral-reverse fault plane (Figure 1.8) (Barth et al., 2012). South of Taramakau River, the northern sections of the Alpine Fault consist of linear traces that are consistent with oblique-slip faulting on a steeply-dipping fault that merges into the Marlborough Fault System near Inchbonnie in the central South Island (Langridge et al., 2010).

Surface geological data (Sibson et al., 1979) indicate the central Alpine Fault zone dip at depth is $\sim 45^\circ$ towards the southeast, which is consistent with more recent models based on magnetotelluric, seismic and GPS data (Beavan et al., 1999; Davey et al., 1998; Eberhart-Phillips, 1995; Leitner et al., 2001; Stern et al., 2007). Analysis of fractures and foliation planes identified in basement rock from borehole data in the Whataroa valley (DFDP-2) reveal a fabric dip of 45 - 55° towards the southeast (145°) (Sutherland et al., 2015), consistent with regional fracture patterns and basement rock foliations east of the fault trace (Hanson et al., 1990; Little et al., 2002; Norris et al., 2012). Seismic imaging of the shallow Alpine Fault structure in the centre of the Whataroa valley, ~ 2 km below the DFDP-2 borehole, reveals a sharp and pronounced reflector dipping to the southeast at $\sim 40^\circ$, interpreted as the main fault plane of the Alpine Fault (Kovacs et al., 2013; Lay et al., 2015).

West of the Whataroa River, near Arthur Creek, a steep fault zone strikes ESE (075°) and contains at least two prominent lineaments dominated by dextral strike-slip.

Figure 1.7: Topographic map showing the surface expression of the Alpine Fault at three different scales.

(A) Large-scale ($<10^6$ - 10^4 m) extent of the central Alpine Fault between Haast River and Taramakau River. Notice the remarkably straight surface trace. (B) Serially partitioned segments of oblique-slip thrust faults connected by strike-slip transfer faults of the order of 10^4 - 10^3 m in length. (C) Small-scale (10^3 - 10^0 m) extent of the central Alpine Fault showing parallel partitioned asymmetric faulting. The Whataroa River valley is shown on the far right of the image. Figure from Barth et al. (2012).

Conversely, to the north of Whataroa River, the Alpine Fault strikes 055° as an oblique thrust zone (Barth et al., 2012; Norris et al., 2012), highlighting the complexity of the fault zone across the Whataroa valley, because it is near a junction between a strike-slip and oblique thrust segment (Barth et al., 2012; Norris et al., 2012). In the immediate sub-surface, the dip of the fault plane shallows to sub-horizontal at the base of the thrust sheet due to gravitational collapse of the range front (Cooper and Norris, 1994; Norris and Cooper, 1995).

Figure 1.8: Cross-section of shallow Alpine Fault showing fault wedge structure.

The southeastern half of the fault wedge is bounded by dextral-normal faults and the northwestern half comprise dextral thrust faults, forming an anticlinal ridge. This complex array of faults are inferred to be rooted at shallow depths (<600 m) on a planar, moderately southeast dipping, dextral-reverse fault plane (Barth et al., 2012).

1.2.3 Geological setting

South Island basement terranes

The basement geology of South Island is separated into two continental fragments with different histories, the Western Province and Eastern Province (Mortimer, 2004). Figure 1.9 shows the distribution of basement rock in New Zealand.

Basement rocks of the Western province are a fragment of Gondwana continental crust (Cooper, 1989; Münker and Cooper, 1999), which extend from northwest Nelson to Fiordland along the west coast of the South Island and occur on Stewart Island (Cooper and Tulloch, 1992; Turnbull et al., 2010; Turnbull and Allibone, 2003). Similar rocks occur on the offshore Campbell and Challenger plateaus (Beggs et al., 1990, Wood, 1991, Wodzicki, 1974). Two dominant basement units of the Western province are the Takaka and Buller terranes (Cooper, 1989; Mortimer, 2004; Münker and Cooper, 1999).

Figure 1.9: Basement geology of New Zealand.

The map shows the main terranes once accreted to the Gondwana margin. These have since been intruded by batholiths, overprinted by metamorphism and deformation, then twisted and offset during the formation of the Australian/Pacific plate boundary. Figure from Cox and Sutherland (2007).

The Takaka terrane consists of siliciclastic, carbonate and volcanic rocks of Cambrian to Early Devonian age (Cooper, 1989; Cooper and Tulloch, 1992), which record a history of terrane accretion onto the Gondwana margin (Münker and Crawford, 2000).

The Buller terrane is the westernmost terrane in New Zealand and forms the basement rock of the West Coast of the South Island (Cooper and Tulloch, 1992), consisting of metamorphosed Ordovician quartz-rich clastics, siltstone and black shale (Cooper, 1989). Both terranes were intruded by granites in two main episodes, once during the Karamea Suite intrusive event in the Late Devonian (Muir et al., 1998; Tulloch, 1988), and again during the formation of the Paparoa and Hohonu batholiths, which were emplaced in the Cretaceous (Tulloch and Kimbrough, 1989; Waight et al., 1997). Along the West Coast of the South Island, the Buller terrane is overlain by 2000-4000 m of Cenozoic sediments (Cox and Barrell, 2007; Davey, 2010; Davy et al., 2013; Nathan et al., 1986).

Basement rocks of the Eastern Province extend throughout the southern, central and northern South Island, comprising of five basement terranes accreted onto the Western Province crust of Gondwana (Mortimer, 2004). In the north and central South Island, the Rakaia subterrane of the Torlesse terrane is dominated (>95 %) by a turbiditic submarine Permian to Late Triassic quartzofeldspathic sandstone-mudstone (argillite) that was deposited as an accretionary wedge complex, derived from a relatively unweathered source averaging near granodiorite composition, likely from an active continental volcanoplutonic arc (Mortimer, 2004; Roser and Korsch, 1999; Wandres et al., 2004). In the south, the Caples terrane is a tectonically imbricated, weakly metamorphosed sequence of poorly fossiliferous marine volcanoclastic Permian-Triassic greywacke and argillite that was deposited as submarine fan deposits in lower trench-slope basins and on a trench floor adjacent to an island arc, before juxtaposition with the Rakaia terrane (Roser et al., 1993). The Rakaia/Caples terrane contact has been overprinted by Haast schists, a metamorphic belt that has been buried to a maximum of 30-35 km (Grapes and Watanabe, 1992; 1994; Holm et al., 1989), where most prograde mineral growth took part in the Middle Jurassic to Early Cretaceous (Mortimer, 2000, 2004). South of the Caples terrane is the Dun Mountain-Maitai, Murihiku and Brook Street terrane metasediments that show cooling age patterns that indicate low-grade metamorphism in earliest Permian to latest Jurassic times (Adams et al., 2002).

Exhumation of the Haast schist belt was episodic, with most of the low-grade (greenschist and lower) section being at the surface by 110 Ma, during ridge subduction at the Gondwana margin in the mid-Cretaceous (Bradshaw, 1989; Mortimer, 2004).

Following ridge subduction at the Gondwana margin, the New Zealand region underwent northeast directed extension (Bradshaw, 1989; Laird and Bradshaw, 2004), resulting in continental breakup ~83 Ma between New Zealand, Australia and Antarctica, and the development of the Tasman Sea and Southwest Pacific Ocean (Gaina et al., 1998; Sutherland, 1995, 1999a; Weissel et al., 1977). Further extension and post-rift thermal subsidence between 80-60 Ma occurred over the New Zealand region (Laird and Bradshaw, 2004), followed by the cessation of Tasman Sea spreading at ~52 Ma (Gaina et al., 1998), and the formation of the Australian/Pacific plate boundary since ~45 Ma, transforming an initial Eocene passive margin into the present day Alpine Fault (Kamp, 1986; Sutherland, 1999b; Sutherland et al., 2000). Deeper (~25 km) amphibolite facies Haast schists, as well as Torlesse greywackes, were exhumed along the Alpine Fault from ~20 Ma to the present day due to Australia/Pacific plate convergence (Adams, 1981; Cooper, 1980; Davey et al., 1998; Holm et al., 1989; Smith et al., 1995; Sutherland, 1995; Walcott, 1998). Additionally, the Alpine Fault offsets basement terranes horizontally by 440-470 km in South Island, consistent with dextral strike-slip motion (Berryman et al., 1992; Sutherland, 1999b; Wellman, 1955), and has juxtaposed the Eastern and Western provinces (Figure 1.9).

Fault rocks

Exhumation of amphibolite facies Haast schists during the past 5 Myr (Adams, 1981; Cooper, 1980; Holm et al., 1989) has also resulted in exposure of mylonite and protomylonite up to 1 km wide adjacent to the Alpine Fault east of the surface trace (Reed, 1964; Sibson et al., 1979, 1981). The degree of mylonitisation decreases heterogeneously eastwards across the fault zone from gouge and cataclasite in contact with Late Quaternary sediments or Western Province bedrock, through ultramylonite, mylonite and protomylonite over a distance of ~1 km, before transitioning into the amphibolite facies schist protolith (Cox and Barrell, 2007; Norris and Cooper, 2003; 2007; Sibson et al., 1979). This transition was observed in the Whataroa valley when drilling into basement from ~1 km southeast of the Alpine Fault (DFDP-2), where a moderately-dipping strongly-foliated sequence transitioned from schist to protomylonite to mylonite downhole to a depth of 893 m (Sutherland et al., 2015). The fault zone of the Alpine Fault has been observed in detail at Gaunt Creek, ~7 km southwest of the Whataroa valley, where field studies and drilling (DFDP-1) define

four main types of fault rock (Cooper and Norris, 1994; Norris and Cooper, 2007; Schleicher et al., 2015; Sibson, 1977; Sibson et al., 1981; Sutherland et al., 2012; Toy et al., 2015; Toy et al., 2008):

- **Hanging-wall ultramylonite:** The hanging-wall of the Alpine Fault within ~100 m of the principal slip zone (PSZ) is composed of ultramylonitic fault rocks exhibiting a planar foliation formed during ductile shearing at temperatures exceeding that of the brittle-creep transition at ~300°C.
- **Hanging-wall cataclasite:** Within ~20 m of the PSZ, there is a progressive downward transition from ultramylonite to paler green cataclasite. These cataclasites are typically faulted and exhibit random-fabric structure, resulting from brittle deformation at depths of ~4-8 km.
- **Fault gouge and ultracataclasite:** The central part of the fault zone consists of ultracataclasite and fault gouge, which forms in a narrow, discrete, ultrafine-grained, brownish-grey interval with very high smectite clay concentration at shallow depths.
- **Footwall cataclasite:** The footwall section of the fault zone consists of a grey-white structureless quartz- and feldspar-rich cataclasite beneath the PSZ, distinct from hanging-wall cataclasite. Over the next ~15 m, this material is interlayered on a sub-meter scale with foliated and unfoliated cataclasites.

Quaternary sedimentary rocks

Glaciers covered the Whataroa floodplain extending from the Whataroa River valley out toward the current coastline during the New Zealand Last Glacial Maximum (LGM), between ~26-17 ka (Alloway et al., 2007; Barrell et al., 2013; Barrell, 2011; Barrows et al., 2013; Golledge et al., 2012; Herman and Braun, 2008). During multiple glacial cycles, of progressively lesser extent, ice abutted and modified hills of older Quaternary glacial tills, producing moraines of Otiran (LGM) and pre-Otiran age, and associated aggradational outwash plains (Cox and Barrell, 2007; Cox et al., 2013; Evans et al., 2010; Suggate, 1990; Suggate and Almond, 2005). West Coast glacial tills are generally grey in colour and consist of bouldery gravels, sands, silt and clay; and glacial outwash is a poorly sorted silty gravel (Cox and Barrell, 2007).

During glacial retreat, beginning at the end of the LGM (~18 ka) (Barrows et al., 2013; Suggate, 1990; Vandergoes et al., 2005), the deep trough once occupied by the Whataroa glacier was infilled with late-glacial alluvium (Cox and Barrell, 2007; Cox et al., 2013). Coseismic uplift on the hanging-wall of the Alpine Fault, followed by subsequent down-cutting by Whataroa River, led to raised terraces southeast of the fault and development of aggradational fans at the margins of the coastal plain (Cox and Barrell, 2007; Cox et al., 2013; Sutherland, 1996). An offset late-glacial aggradational terrace on the hanging-wall of the Alpine Fault in the Whataroa Valley provides a record of vertical displacement on the fault (Adams, 1979; 1980a, b; De Pascale and Davies, 2014; De Pascale, 2014; Wellman, 1953).

Sedimentation is highly episodic, involving infrequent pulses of aggradation following major earthquakes (Almond et al., 2000; Howarth et al., 2012; McSaveney, 2002), high-intensity rainstorms (Henderson and Thompson, 1999), large landslides (Korup et al., 2004), and historic migration of river channels (Griffiths and McSaveney, 1986). Alluvial sediments exposed by the Whataroa River are typically coarse-to-fine grained angular schist gravels, separated by young soil horizons containing rooted tree stumps, evidence of infrequent pulses of river aggradation, with intervening periods of relative stability and river down-cutting (Almond et al., 2000; McSaveney, 2002).

West of the Alpine Fault, beneath Quaternary sediments, Ordovician Greenland Group quartz-rich metasediments of the Buller Terrane and gneissic intrusions of Late Devonian and Cretaceous granitoids are overlain by a sequence of Paleogene to Neogene sedimentary rocks ~2000-3000 m thick (Nathan et al., 1986), although some granitic intrusions are exposed near the range front (Cox and Barrell, 2007; Cox et al., 2013). Where the Whataroa River valley crosses the Alpine Fault, a paleo-glacial channel is now filled with ~200-350 m of post-glacial alluvium, highlighting the dramatic decrease in sediment thickness toward the range front (Davey, 2010; Davy et al., 2013; Kovacs et al., 2013; Lay et al., 2015). The old glacial channel is thought to represent an ice-erosion surface dating from ~17-18 ka, when the retreat of LGM ice began (Barrows et al., 2013; Cox and Barrell, 2007; Vandergoes et al., 2005). Immediately southeast of the Alpine Fault, a thicker-than-predicted layer of Quaternary sediment was encountered during drilling (DFDP-2), which sampled a rapidly deposited glaciolacustrine sequence, overlain by deltaic sands and post-glacial

alluvium, indicating the presence of a large pro-glacial lake (Cox et al., 2015; Sutherland et al., 2015).

Geological map

The surface geology of the study area and Whataroa floodplain are shown in Figure 1.10. East of the Alpine Fault is an approximate 1 km wide mylonitic and curly schist zone adjoining the amphibolite facies schist protolith. The metamorphic grade decreases steadily eastwards, with pumpellyite-actinolite Permian to Late Triassic quartzofeldspathic sandstone-mudstone of the Rakaia subterrane within 15 km of the fault trace (not shown). West of the Alpine Fault, quartz-rich Paleozoic sediments and granites of the Australian plate are buried below moraines of Otiran (LGM) and pre-Otiran age, limiting basement outcrop to isolated hills and the cores of some hill ranges. Late-glacial and post-glacial alluvium occupies the Whataroa glacifluvial outwash plain between moraine covered hill ranges (Cox and Barrell, 2007; Cox et al., 2013).

South Westland Fault

The South Westland Fault (SWF) is a thrust fault system on the central West Coast striking subparallel to and lying ~5 km west of the Alpine Fault near Whataroa (Figure 1.10), according to a joint interpretation between seismic and gravity data (Davey, 2010; Davy et al., 2013). The SWF marks the northwest limit of plate boundary deformation (Kamp et al., 1992; Sircombe and Kamp, 1998; Walcott, 1998), and bounds the southeast limit of the South Westland Basin, a predominantly offshore sedimentary basin which partially overlaps the coastal plain west of the Alpine Fault (Davy et al., 2013; Nathan et al., 1986; Sircombe and Kamp, 1998). During the Mid-Miocene, the SWF developed as a series of southeast-dipping thrust faults, where dip-slip displacement of ~3500 m resulted in the formation of a crustal monocline structure (Cotton, 1956).

Figure 1.10: Surface geology map of the Whataroa study area.

Blue contours represent groundwater elevation above sea level in shallow alluvium. Various wells and boreholes are also shown. Note the location of the South Westland Fault relative to the Alpine Fault. Figure from (Cox et al., 2013).

1.2.4 South Island glacial history and geomorphology

Glacial history

The Southern Alps have experienced cyclic glaciations that were initiated in the Pliocene $\sim 2.5 \pm 0.1$ Ma (Suggate, 1990). The most recent cold period, known as the Otiran glaciation, from ~ 75 -18 ka (Nelson et al., 1993; Suggate, 1990; Suggate and Almond, 2005), culminated in a glacial maximum on the West Coast of the South Island between 26-17 ka (Barrows et al., 2013). During this period, ice coalesced in front of the main mountain valleys to form piedmont lobes extending as far as the western coastline (Figure 1.11) (Golledge et al., 2012; Herman and Braun, 2008; Suggate and Almond, 2005).

Figure 1.11: Ice extent of the Late Otiran glaciation in Central Westland.

Modelled ice extent shaded by thickness and contoured by surface elevation. Geomorphological data is shown overlying modelled ice extent, with modelled glacier outlines over geomorphology. Brown areas represent LGM moraines, and green areas are pre-LGM moraines. Figure from Golledge et al. (2012).

Three major glacial advances, of progressively lesser extent, have been well-constrained on the West Coast within the last glacial cycle based on the tephrochronology, mapping and exposure dating of glacial deposits (Barrows et al., 2013; Suggate, 1990; Suggate and Almond, 2005). These distinct glacial advances are

represented by the Loopline, Larrikins, and Moana Formations, separated by brief interstadials (Barrows et al., 2013). Refer to Figure 1.10 for the glacial geomorphology near the study area with formations labelled. The Loopline Formation advance culminated at 24.9 ± 0.8 ka, and stratigraphically lies immediately below the widespread Kawakawa/Oruanui tephra deposited 25.4 ± 0.08 ka (Barrows et al., 2013; Vandergoes et al., 2013a; Wilson, 2001). The Larrikins Formation was deposited during a single glacial advance lasting ~1000 years between 20.8 ± 0.5 to 20.0 ± 0.5 ka (Barrows et al., 2013). The Moana Formation represents the deposits of the last major ice advance on the West Coast culminating at 17.3 ± 0.5 ka (Barrows et al., 2013). These observations can be correlated with cooling of the adjacent oceans (Barrows and Juggins, 2005; Barrows et al., 2007), lowering of the treeline on the West Coast and throughout New Zealand (Heusser and Van de Geer, 1994; Vandergoes et al., 2013b), and the extent of glaciers on other land masses within the Southern Hemisphere (Barrows et al., 2011; Douglass et al., 2006; McCulloch et al., 2005). Moreover, the timing of glacial advances on the West Coast determined by Barrows et al. (2013) fits within the NZ-INTIMATE climate event stratigraphy, which defines three cold events in the period from 30 ka to Termination 1 at ~18 ka (Figure 1.12) (Barrell et al., 2013). The Loopline Formation advance occurred at the end of NZce-10, the Larrikins Formation advance occurred midway through NZce-6, and the Moana Formation advance occurred immediately following Termination 1 in early NZce-5.

The emergence from glacial conditions following the termination of the LGM in New Zealand (post-Termination amelioration; NZce-5) spans a period from ~18 ka to 15.64 ± 0.41 k.y. (Barrell et al., 2013), with evidence of an initial and rapid retreat of ice from LGM positions ~18 ka occurring on both sides of the Southern Alps and in the North Island (Almond et al., 2001; Newnham et al., 2003; Putnam et al., 2013; Shulmeister et al., 2005; Vandergoes and Fitzsimons, 2003; Williams, 1996). Evidence from south Westland (Sutherland and Norris, 1995), and more recently from Whataroa (Cox et al., 2015) suggests that following retreat from LGM limits, West Coast glaciers had receded over the Alpine Fault by ~16.3-14.8 ka, which is the onset of the Late-glacial mild episode (NZce-4) (Barrell et al., 2013). Mild late-glacial conditions were succeeded at 13.74 ± 0.13 ka by a cooler climate (Late-glacial cool episode; NZce-3), which after 12.55 ± 0.14 ka gave way to a progressive ascent to full interglacial

Figure 1.12: The NZ-INTIMATE climate event stratigraphy.

Colours represent characteristic atmospheric temperatures (orange = warm, blue = cold). Chronostratigraphic divisions are (1) major climate phases in New Zealand; (2) New Zealand climate-based time-stratigraphic stages; and (3) global marine-oxygen isotope scale (MIS) stages (Barrell et al., 2013).

conditions that were achieved by 11.88 ± 0.18 ka and continue to the present day (Holocene Interglacial; NZce-1) (Barrell et al., 2013; Vandergoes et al., 2005).

During the Late-glacial cool episode (NZce-3), it is suggested that widespread glacier resurgence in the Southern Alps culminated ~13 ka, at the peak of the Antarctic Cold Reversal (ACR), which is a well-constrained period of reverse cooling in Antarctica from ~14.54 to 12.76 ka (Anderson and Mackintosh, 2006; Lemieux-Dudon et al., 2010; Putnam et al., 2010; Turney et al., 2007).

West Coast glaciers, such as Fox and Franz Josef, are characterised by some of the highest mass turnover rates on Earth, with annual precipitation of up to ~14 m (Henderson and Thompson, 1999), ice velocities of ~1 m/day (Purdie et al., 2008), and response times of 7-20 years (Anderson et al., 2008; Fitzharris et al., 1992; Purdie et al., 2008). These glaciological characteristics combine with high sediment yield in a tectonically active mountain terrain to create active subglacial and proglacial river and outwash fan systems (Davies and Smart, 2007; Davies et al., 2003). These large depositional centres are reworked by glacier snouts to construct latero-frontal moraine loops during periods of ice advance (Tovar et al., 2008). Glacial advance and retreat, and therefore the subsequent formation of moraines and pro-glacial lakes, is not necessarily climatic in origin. Debris from large rock avalanches deposited on ablation zones can affect glacier mass balance significantly, with corresponding implications for glacier behaviour and moraine emplacement (Shulmeister et al., 2009; Tovar et al., 2008).

Denudation and uplift

The crest of the Southern Alps lies 15-30 km southeast of the Alpine Fault, and corresponds to the Main Divide (drainage divide). Elevation increases toward the central South Island where the highest peak, Aoraki/Mount Cook, reaches 3754 m a.s.l. The Southern Alps orogen is asymmetric, changing eastward across the mountain range from steep and intensely dissected western slopes, to strongly glaciated mountains along the Main Divide, to more subdued eastern landscapes characterised by intermontane basins and broad alluvial plains (Cox and Sutherland, 2007; Tippet and Kamp, 1995).

The Southern Alps form a barrier to dominant westerly atmospheric circulation, intercepting air masses of both temperate and sub-tropical origin (Koons, 1990; Shulmeister et al., 2004). Under prevailing westerly flow, moisture evaporated from the Tasman Sea is forced to rise up and over the Southern Alps, resulting in significant precipitation, especially on the western slopes (Henderson and Thompson, 1999).

Erosion correlates strongly with precipitation, where more extensive erosion (~10 mm/yr) occurs on the western slopes (Adams, 1980a, b; Cox and Sutherland, 2007; Fitzsimons and Veit, 2001; Hicks et al., 1996). Erosion rates produce an expected geomorphic pattern consistent with the observed orogenic asymmetric geomorphology across the Southern Alps (Whitehouse, 1986).

The primary mode of erosion within the South Island is gravitational mass wasting produced by debris flows, landslides and rock avalanches which are more common in areas of fault-zone weakened bedrock, such as the highly-active central Southern Alps (Hovius et al., 1997; Korup et al., 2004; McSaveney, 2002). Present sediment yields from glaciated and deglaciated basins in the South Island are similar (Griffiths, 1979; Griffiths, 1981), leading to the hypothesis that erosion rates are equal during glacial and interglacial periods (Whitehouse, 1986). In regions of rapid tectonic uplift, such as the central Southern Alps, the rate of fluvial and glacial erosion, and therefore relief amplitude is controlled by the rate of uplift, irrespective of climate (Herman et al., 2007; 2010). A coupled system is proposed whereby the removal of Pacific plate material by erosion enhances uplift, and uplift of rocks into the westerly circulation pattern concentrates erosion, forming a dynamic equilibrium between uplift and erosion (Koons, 1990; Norris and Cooper, 2003; Walcott, 1998). Consequently, the Southern Alps have been maintained in a near steady-state elevation for the past million years, with a steady rate of uplift and erosion during both glacial and interglacial cycles (Herman et al., 2010; Koons, 1989, 1995). However, the geomorphology of valleys and ridges are unlikely to reach steady-state, due to the differing characteristics in geomorphic expressions of fluvial and glacial erosion (Herman and Braun, 2006).

Glacial erosion widens and deepens valleys while removing little material from the valley walls, forming U-shaped valleys (Adams, 1980a; Herman et al., 2007). Fluvial erosion involves downcutting and removing material from the valley walls, forming V-shaped valleys, enhanced by coseismic slip on the Alpine Fault and uplift of the hanging-wall (Adams, 1980a; Sutherland, 1996). After total glacial retreat on the West Coast at the onset of the Holocene Interglacial $\sim 11.88 \pm 0.18$ ka (Barrell et al., 2013), the dominant mode of erosion has been fluvial. Since then, most valleys have changed from U- to V-shaped and have been incised by rivers and dissected by debris flows, landslides and rock avalanches (Herman and Braun, 2006; Hovius et al., 1997; Korup et al., 2004). The Whataroa valley has experienced substantial denudation, where

estimates of the total present-day erosion rate and sediment discharge rate in the Whataroa valley is 11.4 mm/yr and 1.1×10^6 m³/yr respectively (Korup et al., 2005). In Whataroa valley, denudation is concentrated ~10 km upstream from the Alpine Fault (Nibourel et al., 2015), where rates of erosion are broadly equivalent to Alpine Fault dip-slip rates and rock uplift rates east of the fault trace (Adams, 1980a; Batt, 2001; Cox and Sutherland, 2007; Little et al., 2005; Norris and Cooper, 2001).

Pro-glacial lakes

The large Whataroa outwash plain contains two moraine-dammed lakes (Lake Wahapo and Lake Rotokino) that mark ice termini of the last glacial maximum (Almond et al., 2001). Recent drilling (DFDP-2) has revealed the presence of previously unknown and older pro-glacial lake sediments, which may even be contiguous with the oldest sediments in Lakes Wahapo and Rotokino. These DFDP-2B lake sediments have since been buried beneath post-glacial alluvium (Cox et al., 2015; Sutherland et al., 2015).

Pro-glacial lakes can be impounded by ice, moraine, landslide debris or bedrock (Carrivick and Tweed, 2013). Depending on the local topography and hydraulic pressure gradients, ice-dammed lakes can form supraglacially, subglacially, or ice-marginally, and are usually associated with ice margin advance or thickening, which results in the impounding of water (Carrivick and Tweed, 2013; Tweed, 2011). Ice-dammed lake formation is a gradual process usually linked to glacier mass balance and ultimately, climatic forcing. However, sudden glacial advance during surging can block drainage channels and form ice-dammed lakes independently of climate (Carrivick and Tweed, 2013; Tweed, 2011).

The formation of moraine-dammed lakes is quasi-periodic and usually associated with periods of glacier retreat or down-wasting following previous ice advance (Carrivick and Tweed, 2013; Korup and Tweed, 2007). However, it has been suggested that the development of large terminal moraines result from non-climatic processes, such as large landslides (e.g. the Waiho Loop moraine) (Shulmeister et al., 2009; Tovar et al., 2008). Moraine-dammed lakes expand rapidly into topographic lows formerly occupied by ice or major meltwater channels, fed by precipitation and glacial meltwater during glacial retreat (Carrivick and Tweed, 2013). Moraine-dammed lakes often develop on debris-covered glaciers as debris-charged glacial snouts become separated from more rapidly ablating ice up-glacier and eventually stagnate. The resulting ice-

cored moraine serves an effective dam to meltwater runoff leading to pro-glacial lake development (Carrivick and Tweed, 2013; Lukas, 2011). Moraine-dammed lakes also develop in depressions formed by large masses of buried ice (Carrivick and Tweed, 2013; Kääb and Haeberli, 2001).

Formation of landslide-dammed lakes in glacial environments is stochastic and usually associated with slope de-buttressing on glacier retreat (Carrivick and Tweed, 2013; Korup, 2002; Korup and Tweed, 2007). Steep U-shaped glacial valleys once occupied by ice are particularly prone to slope failure (Korup et al., 2004). River-damming landslides are triggered by heavy rainfall and snowmelt, seismicity or by undercutting (Korup, 2002). Landslide-dammed lakes are often ephemeral since the dam is typically made from unconsolidated material that is prone to failure. Moreover, landslide-dammed lakes generally form in steep mountain terrain where denudation rates are high, consequently decreasing their size due to rapid infill of sediment (Hicks et al., 1990; Korup et al., 2006).

Bedrock-dammed lakes are common in mountainous terrain where glacial erosion of sub-glacial bedrock and/or sediment develops a glacial over-deepening, resulting in reigels (bedrock ridge) which form effective dams (Cook and Swift, 2012). Depending on its location, the evolution of a pro-glacial lake may involve a combination of dam types, or evolve through a sequence of different lake/dam configurations (Carrivick and Tweed, 2013).

1.3 Previous geophysical studies

1.3.1 South Island Geophysical Transect

The South Island Geophysical Transect (SIGHT), was a New Zealand-USA collaborative project in the early 1990's that aimed to understand the deformation of lithosphere at a continent-continent collisional plate boundary (Davey et al., 1998). The SIGHT project involved a comprehensive range of geophysical measurements to derive 3-D structural models of the South Island orogen. These measurements include active-source and passive (earthquake) seismology, magnetotelluric and electrical studies, petrophysics and gravity measurements (Davey et al., 1998; Eberhart-Phillips et al., 2010; Eberhart-Phillips and Bannister, 2002; Okaya et al., 2007; Scherwath et al., 2006; Scherwath et al., 2003; Stern et al., 2000; 2007; Van Avendonk et al., 2004). The data

were acquired along two main onshore/offshore transects across the central South Island, perpendicular to the Australian/Pacific plate boundary (Figure 1.13).

Figure 1.13: SIGHT transects 1 and 2 extending across the central South Island.

The black box indicates where SIGHT transect 1 passes through the study area near Whataroa. Figure from Davey (2010).

The onshore section of SIGHT transect 1 extends southeastward from the West Coast near the mouth of the Whataroa River, across the Alpine Fault and over the Main Divide to the east coast along the Rangitata River (Van Avendonk et al., 2004). SIGHT

transect 2 runs parallel to transect 1, extending southeastwards from the Karangarua River in south Westland, across the Alpine Fault and over the Main Divide before passing through Tekapo and the Cannington Basin to the east coast, south of Timaru (Scherwath et al., 2003).

Seismic velocity models derived from refracted and reflected arrivals along transect 1 (Van Avendonk et al., 2004) and transect 2 (Scherwath et al., 2003), as well as first arrival travel-time tomography of passive seismic data (Eberhart-Phillips and Bannister, 2002) provide an image of a crustal root ~100 km wide, which reaches a maximum depth of ~45 km directly below a regional (-80 mGal) Bouguer gravity low (Henrys et al., 2004). In order to satisfy the regional gravity low, a high-density mantle body is inferred to be lying ~100-200 km beneath the crustal root, as indicated by teleseismic P-wave delays (Scherwath et al., 2006; Stern et al., 2000).

1.3.2 Seismicity

The distribution of seismicity in New Zealand provides information on Alpine Fault processes and deformation distribution along the Australian/Pacific plate boundary. The pattern of seismicity in New Zealand has been recorded since the mid 1880's, but was first analysed between 1956-75 (Hatherton, 1980), and later between 1964-87 (Reyners, 1989), before an upgrade to the New Zealand National Seismograph Network (NZNSN) between 1986-2001 allowed more comprehensive analysis (Anderson and Webb, 1994; Petersen et al., 2011).

The Australian/Pacific plate boundary can be separated into three zones based on the distribution of seismicity. Deep seismicity identifies subducting Pacific lithosphere to depths of ~200 km southwards along the eastern margin of the North Island to the northern South Island where it abruptly terminates at the junction between the Marlborough Fault System and the Alpine Fault (Davey et al., 2007). The central Alpine Fault is characterised by low rates of shallow seismicity (Leitner et al., 2001) that vary systematically with distance from the fault (Bourguignon et al., 2015). In the southern South Island, deep seismicity identifies subducting Australian lithosphere at depths of ~140 km beneath the Fiordland region (Davey et al., 2007).

Between 1995-96, the South Island Passive Seismic Experiment (SAPSE) accurately improved the knowledge of seismicity in the South Island, particularly under the Southern Alps (Anderson et al., 1997). The SAPSE experiment included an array

of 26 broadband and 14 short-period recording seismographs deployed over the South Island, concentrated over the central Southern Alps for up to 12 months. A total of 5491 earthquakes were recorded, as well as the majority of the shots of the active source seismic shooting of SIGHT (Davey et al., 1998). Leitner et al. (2001) investigated the long-term regional seismicity of the Southern Alps using data from the SAPSE experiment, the NZNSN, and from a local network at Lake Pukaki in the central Southern Alps (Reyners, 1988). A uniform seismogenic depth of 12 ± 2 km for the central South Island was observed, except for a shallower depth of 8-9 km beneath the highest topography of the Alps. Additionally, a low seismogenic rate for the central Alpine Fault suggests elastic strain is being stored, indicating the potential for large-scale earthquakes (Leitner et al., 2001).

Between 2006-07 O’Keefe (2008) investigated microseismicity along the central Alpine Fault using data from a temporary seismic network installed between Harihari and Fox Glacier. A maximum seismogenic depth of 15 km for the region was observed, reducing to 10 km below regions with the highest orogenic uplift rates. The seismicity takes on a “horseshoe” pattern for earthquakes above a magnitude of Mw 1.6, where a low seismicity zone is apparent in the central survey region, noted previously (Eberhart-Phillips, 1995; Leitner et al., 2001) as a 20-30 km wide low-seismicity triangle between Harihari and Franz Josef.

The Southern Alps Microearthquake Borehole Array (SAMBA) of ten short-period seismometers was established between 2008-09 (Boese et al., 2012), offering a dense station spacing (~8 km) near the central Alpine Fault. To date, SAMBA has been recording continuously and was temporarily supplemented in 2010 by the DFDP10 network as part of the Deep Fault Drilling Project (Sutherland et al., 2012; Townend et al., 2009; 2013). In early 2012, the 20-station WIZARD network commenced operation, replacing and expanding the DFDP10 network (Boese et al., 2012; Thurber et al., 2015). The central area of the SAMBA network near Franz Josef exhibits the highest seismicity rate in the region, while the central Alpine Fault is a region of anomalously low background microseismicity (Boese et al., 2012; Bourguignon et al., 2015). The spatial variations in current seismicity observed in the central Southern Alps, as well as localised seismic tremor and low-frequency earthquakes are indicative of variable fluid and stress conditions near the Alpine Fault (Boese et al., 2014; Boese et al., 2012; Chamberlain et al., 2014; Wech et al., 2012).

1.3.3 Gravity

Prior to a gravimetric and active-source seismic study across the Whataroa Floodplain (Brikke, 2007), the shallow structure of the Alpine Fault had received relatively minor geophysical attention. With a focus on the basement geometry and upper-crustal velocity structure of the Alpine Fault, Brikke (2007) used seismic data of the SIGHT transect 1 (Davey et al., 1998), gravity data from GNS Science, and new gravity observations to construct a seismic and gravity model of the Whataroa floodplain. Figure 1.14 shows Brikke's 2-D gravity model oriented parallel to the Alpine Fault intersecting the Whataroa River. The key results of this study are:

- Deep U-shaped glacial channels buried beneath the floodplain to a maximum depth of 550 m below the Whataroa River;
- The presence of an elongated southeast-northwest oriented negative residual gravity anomaly, dextrally offset by 3-4 km northeast from the entrance to the Whataroa River valley. Assuming the gravity anomaly represents a glacial erosion surface carved during the Waimea glaciation (~140 ka), a mean strike-slip rate of 25 mm/yr is inferred on the Alpine Fault at Whataroa;
- Two kettle holes below the Whataroa Floodplain, inferred to have been carved by the Waimea and subsequent Otira glaciations;
- The horizons of Quaternary and Tertiary sediments, as well as the basement rock of the Australian plate appear to be unperturbed by the plate boundary.

In 2012, a gravimetric study of the central West Coast (Davy, 2012; Davy et al., 2013) combined existing and new gravity observations to expand the gravity coverage of the Wanganui, Whataroa, and Fox River floodplains. The aim of the study was to model glaciotectionic structures in the footwall of the central Alpine Fault and explain the processes responsible for their formation. The gravity data were used to produce gravity maps (Figure 1.15) and 2-3/4D gravity models of the sub-surface structure beneath the floodplains. Gravity models revealed possible dextral offsets of buried geomorphology by the Alpine Fault since the LGM. The key findings of the study are:

Figure 1.14: 2-D gravity model across the Whataroa floodplain.

Above: map showing the location of the gravity profile. Below: 2-D gravity model. (a) shows the observed and modelled gravity anomaly, and (b) shows the modelled gravity signature (Brikke, 2007).

- Three buried glacial channels in the Whataroa floodplain that are dextrally offset from the originating Whataroa valley. The deepest channel has a maximum depth of ~800 m beneath the Whataroa River, consistent with a large negative gravity anomaly northwest of the Alpine Fault that was originally recognised by Brikke (2007);

Figure 1.15: Gravity maps of the Whataroa floodplain.

Above: Bouguer gravity anomaly map showing a large (-35 mGal) anomaly (1) extending northeast towards Lake Rotokino (2), northwest towards the western coastline (3), and south towards the Whataroa River valley (4). A strong trend in the Bouguer gravity field appears perpendicular to the Alpine Fault (5). Below: residual gravity map showing a large negative gravity anomaly (-8 to -9 mGal) extending northeast towards Lake Rotokino (1), northwest into the northwestern splay of the floodplain (2), and south towards the Whataroa River valley (3), where the anomaly is thought to be dextrally offset by ~2 km. Black dots represent gravity stations. Gravity data has been extrapolated. Maps from Davy (2012).

- Dextral offset of an ice-erosion channel along the Alpine Fault since the LGM is estimated to be 370 ± 160 m in the Whataroa floodplain;
- Assuming a channel formation age of 19 ± 1 k.y., an approximate 370 m offset corresponds to a dextral strike-slip rate of 19 ± 9 mm/yr for the Whataroa floodplain;
- A gravity profile along SIGHT transect 1 with a focus on the footwall of the Alpine Fault, allows for a joint interpretation of gravity and seismic data. The gravity model defines the South Westland Basin and delineates the location of the South Westland Fault, which is 2-3 km closer to the Alpine Fault than previously thought.

1.3.4 Geodesy

GPS-derived site velocities within the Australian/Pacific plate boundary zone through New Zealand help to quantify where strain is accumulating and how slip is partitioned, allowing for quantification of the total ‘plate motion budget’ (Wallace et al., 2007). Consistency between datasets spanning millions of years (paleomagnetic and structural geology), thousands of years (active fault data), and decades (GPS), suggests that short-term datasets such as GPS are highly relevant to understanding longer-term plate boundary zone deformation (Wallace et al., 2012). GPS studies of vertical and horizontal velocities of the bounding Australian/Pacific plates in the South Island provide the following interpretations of plate boundary zone deformation (Beavan et al., 2010; Beavan et al., 2007; Beavan et al., 1999; Wallace et al., 2007):

- 50-70% of the Australian/Pacific plate motion is occurring as steady slip or shear on a down-dip extension of the Alpine Fault below a locking depth of 5-8 km;
- Vertical velocity rates of ~ 5 mm/yr occur either side of the crest of the Southern Alps and ~ 20 -30 km southeast of the Alpine Fault;
- The observed vertical velocity distribution over the Southern Alps suggests that interseismic coupling on the Alpine Fault falls to zero by 13-18 km depth;

- Up to 5 mm/yr of inter-plate movement is accommodated on fault zones within the Southern Alps up to ~100 km east of the Alpine Fault.

1.4 Gravity model constraints

1.4.1 Borehole data

Borehole data provide valuable information on the lithology and stratigraphy of the Whataroa valley and nearby Alpine Fault, providing a useful geological constraint on gravity data. In 2011, Deep Fault Drilling Project (DFDP) boreholes DFDP-1A and DFDP-1B were drilled at Gaunt Creek, ~7 km southwest of the Whataroa River valley during the first phase of DFDP (Sutherland et al., 2012; Townend et al., 2009). As previously discussed in section 1.2.3, four main fault-rock units with different thicknesses were identified in DFDP-1 boreholes (Sutherland et al., 2012; Toy et al., 2015). Figure 1.16 shows a cross-section through the fault zone at Gaunt Creek.

For this study, we assume a correlation between the shallow fault zone stratigraphy sampled at Gaunt Creek and the shallow fault zone stratigraphy expected in the Whataroa River valley. The shallow fault zone stratigraphy provided by Sutherland et al. (2012), coupled with an interpretation of shallow fault zone structure adjacent to the Whataroa River (Barth et al., 2012; Norris et al., 2012), is an important consideration when attempting to model the shallow Alpine Fault structure in Whataroa valley using gravity data.

Late in 2014, the second phase of drilling in the Whataroa River valley (DFDP-2) produced two boreholes (DFDP-2A & DFDP-2B) ~1 km southeast of the mapped surface trace of the Alpine Fault, revealing a thicker than predicted Quaternary sediment overlying a basement sequence that transitioned from schist to protomylonite to mylonite downhole to a depth of 893 m (Sutherland et al., 2015). Figure 1.17 shows the Quaternary sediments sampled in DFDP-2A.

Figure 1.16: Cross-section through DFDP-1 boreholes.

(A): Fault zone structure consisting of four main fault-rock units with different thicknesses sampled in DFDP-1A & 1B. Outcrop geology shown in (B) on the Alpine Fault at Gaunt Creek in the central South Island (C). Bold line is the principal slip zone (PSZ). Figure from Sutherland et al. (2012).

The DFDP-2A Quaternary sequence is interpreted to comprise (Cox et al., 2015; Sutherland et al., 2015): fluvial-glacial gravels (0-58 m); grading downward into sandy lake delta sediments (59-77 m); overlying a monotonous sequence of lake mud and silts, with rare pebble-cobble diamictite (77-206 m); with a basal unit (206-240 m) containing coarse cobbles and boulders that may represent a distinct till/diamictite. The contact between Quaternary sediments and schist bedrock was sampled at 240 m depth in DFDP-2B. Radiocarbon dating of plant fragments indicate 70 m of upper lacustrine and deltaic sediments (129-59 m) were deposited rapidly between 16.35-15.8 ka. Overlying alluvial gravels are much younger (<1 ka), with evidence of pulses of rapid aggradation (Cox et al., 2015).

Figure 1.17: Geological log of Quaternary sediments sampled in DFD-2A.
Figure from Sutherland et al. (2015).

1.4.2 Active-source seismic data

Crustal seismic reflection data acquired from SIGHT transect 1 (Davey et al., 1998) were used by Davey (2010) to construct a seismic refraction model striking perpendicular to the Alpine Fault in the Whataroa valley. Figure 1.18 shows SIGHT transect 1 and the seismic model of Davey (2010). Within the bounds of the study area, the model defines the geometry of two main sedimentary layers with P-wave velocities of 2.0-2.7 km/s and 3.5 km/s, overlying a basement rock with a P-wave velocity of 4.7-5.6 km/s. The thicknesses of the sedimentary layers near the Alpine Fault range from 150-400 m for the upper layer and 100-300 m for the lower layer. These layers correlate to onshore drill holes Harihari-1 and Waiho-1 (Smart, 1971, 1972), as well as offshore seismic data in the region (Nathan et al., 1986; Sircombe and Kamp, 1998), and are inferred to be Quaternary glacial sediments overlying Mid-Late Miocene sediments (Davey, 2010).

The WhataDUSIE controlled-source seismic project, led by researchers from the University of Otago (New Zealand), TU Bergakademie Freiberg (Germany), and the University of Alberta (Canada), provided high-resolution coverage (4-8 m geophone spacing, 25-100 m shot spacing) along a 5 km profile across the Alpine Fault in the Whataroa valley (Glomb et al., 2013; Kovacs et al., 2013; Lay et al., 2015). The profile extends upstream from the Whataroa bridge along the SIGHT transect 1 (Davey et al., 1998), with a focus on the shallow (upper 1 km) hanging-wall of the Alpine Fault, and is supplemented by focused hammer-source seismic data (Kovacs, 2011). Preliminary P-wave velocity models of the upper 5 km reveal a 200-350 m thick sedimentary layer with velocities of ~2.3 km/s above a schist basement with velocities of 4.5-5.5 km/s. A pronounced low-velocity layer with velocities of approximately 3.5 km/s can be observed within the basement at 0.8-2 km depth. Small-scale low-velocity anomalies appear at the top of the basement and can be correlated to the Alpine Fault zone (Lay et al., 2015).

Figure 1.18: Seismic refraction model along SIGHT transect 1 across the Whataroa floodplain and Alpine Fault.

Above: simplified topography of the Whataroa region showing the SIGHT receiver transect. Inset map shows the study area for this project. Below: refraction model of Davey (2010) showing dimensions and velocities for each layer. Red arrows indicate approximate bounds of the study area for this project. Figures from Davey (2010).

1.4.3 Gravity data

With a focus on the Whataroa floodplain, Davy et al. (2013) provides a gravity model along a 20 km section of the SIGHT transect 1 (Davey et al., 1998), allowing for a joint interpretation with the seismic model of Davey (2010). The gravity model of Davy et al. (2013) is shown in Figure 1.19. Between the South Westland Fault (SWF) and the Alpine Fault, the model defines the geometry of two main sedimentary layers inferred to be Quaternary glacial sediments overlying Mid-Late Miocene sediments. East of the Alpine Fault, the model defines the geometry of a single sedimentary unit, inferred to be Quaternary glacial sediments overlying basement rock. There are slight differences between the seismic model of Davey (2010) and the gravity model of Davy et al. (2013), the most significant being a difference in basin depth directly east of the SWF with the gravity model ~500 m shallower. However, the two models are broadly consistent, providing a comprehensive joint interpretation along the footwall portion of SIGHT transect-1 on the Whataroa floodplain.

1.4.4 Rock density

Gravity anomalies result from a density contrast between a rock body and its surroundings. The density among rock types is therefore the most critical and least variable gravimetric parameter, where the most common rock types have densities in the range between 1.60 g/cc and 3.20 g/cc (Kearey et al., 2013).

The bulk densities of rock types within the study area can be estimated using the Nafe-Drake velocity-density relationship following Ludwig et al. (1970), and Gardner's rule (Gardner et al., 1974), derived for sedimentary rocks. Both methods are discussed below.

Figure 1.19: Gravity model of a portion of SIGHT transect 1 across the Whataroa floodplain and Alpine Fault.

Model dimensions and bulk densities are based on the seismic modelling of Davey (2010) and rock catalogues of Whiteford and Lumb (1975). Rock units are based on onshore boreholes Harihari-1 and Waiho-1 (Smart, 1971, 1972). Gravity model from Davy et al. (2013).

Seismic velocity relations

Variation in porosity is the main cause of density variation in sedimentary rocks. Thus, in sedimentary rock sequences, density increases with depth, due to compaction, and with age, due to progressive cementation (Kearey et al., 2013). As cementation and rock density increases with depth, so does compressional seismic velocity allowing for density determination from seismic velocity relations (Gardner et al., 1974; Ludwig et al., 1970; Nafe and Drake, 1963). Ludwig et al. (1970) present this relation graphically, known as the Nafe-Drake curve, which is expressed numerically in equation 1.1 (Brocher, 2005):

$$\rho(g/cm^3) = 1.6612(V_p) - 0.4721(V_p)^2 + 0.0671(V_p)^3 - 0.0043(V_p)^4 + 0.000106(V_p)^5 \quad (1.1)$$

Equation 1.1 is valid for V_p between 1.5 and 8.5 km/s.

Gardner's rule (Gardner et al., 1974), derived for sedimentary rocks, is valid for V_p between 1.5 and 6.1 km/s, expressed in equation 1.2 (Brocher, 2005):

$$\rho(g/cm^3) = 1.74(V_p)^{0.25} \quad (1.2)$$

Table 1.1 shows the range of calculated bulk densities for the geological units in the study area using the P-wave velocities of Christensen and Okaya (2007), Davey (2010), and Lay et al. (2015) in equations 1.1 and 1.2.

Rock catalogues

Presently, no direct measurement of rock density from DFDP-2 is available. However, a catalogue of rock samples from throughout the South Island can be used to infer appropriate bulk densities to be analysed during gravity modelling.

PETLAB is the rock catalogue and geo-analytical database of New Zealand (Mortimer, 2005). The database contains locations, descriptions and analyses of rock samples collected throughout New Zealand. Wet density measurements compiled from many sources (e.g., Hatherton and Leopard, 1964; Whiteford and Lumb, 1973) cover 89 rock types collected at 9256 locations in New Zealand. Table 1.2 gives the mean wet density for rock types known in the study area. Note that this does not include any fracture porosity, which is likely in damaged rocks within ~1 km of the Alpine Fault.

Table 1.1: Mean P-wave velocities and bulk densities of rock types known in the study area.

Mean P-wave velocities calculated from laboratory measurements (Christensen and Okaya, 2007), and from the seismic models of Davey (2010) and Lay et al. (2015). Bulk densities of geological units calculated using Nafe-Drake and Gardner empirical relations (Brocher, 2005).

Rock type	Mean V_p (km/s)	STD (km/s)	Max (km/s)	Min (km/s)	(N)	ρ (g/cm ³)	
						Nafe-Drake	Gardner
Quaternary gravel	2.3	0.3	2.7	2.0	4	2.03	2.14
Miocene sediments	3.5	-	-	-	1	2.32	2.38
Schist (Alpine Schist)	5.6	0.5	6.7	4.9	12	2.64	2.68
Alpine Fault mylonite	5.8	0.2	6.0	5.6	3	2.68	2.70
Phyllite (Buller Terrane)	5.6	0.7	6.5	3.9	12	2.64	2.68
Granite (Tuhua)	5.9	0.1	6.0	5.7	6	2.70	2.71

Table 1.2: Mean wet densities from the PETLAB rock catalogue.

Rock type	Mean (g/cm ³)	STD (g/cm ³)	Max (g/cm ³)	Min (g/cm ³)	Samples
Quaternary gravel	2.31	0.27	2.58	1.87	9
Miocene sediments	2.38	0.90	2.60	2.24	12
Schist (Alpine Schist)	2.73	0.12	3.10	2.12	419
Alpine Fault mylonite	2.76	0.09	2.93	2.62	11
Phyllite (Buller Terrane)	2.66	0.04	2.71	2.64	4
Granite (Tuhua)	2.64	0.08	2.94	2.33	288

1.5 Thesis structure

The thesis is structured as follows:

- **Chapter 1:** An introduction to the study area and its geological history, providing the motivation and objectives of the project and discusses previous work completed by others.
- **Chapter 2:** Provides the theory of gravity and its use as a geophysical tool for exploring the sub-surface, and covers field measurement and data reduction methods used for this gravimetric survey.
- **Chapter 3:** Presents results of the new gravity survey. Key outputs are new Bouguer and regionally-corrected residual gravity anomaly maps of the Whataroa study area.
- **Chapter 4:** Presents two-dimensional forward gravity models, which were initially used during gravity survey design, and then developed and improved on the basis of new data. Targeted features include the Alpine Fault and the area surrounding the DFDP-2 drill hole in the Whataroa River valley.
- **Chapter 5:** Discusses the results found in Chapters 3, and 4, and their implications for understanding the broader structure surrounding the DFDP-2 borehole, as well as the complex interplay between tectonics, glacial processes, and sedimentation.

Chapter 2 Gravity and methodology

This chapter summarises the theory of gravity and the methods used to acquire and reduce gravity data.

2.1 Gravity theory

Newton's universal law of gravitation states that any two objects exert a gravitational force (F) of attraction on one another. The magnitude of the force is proportional to the product of the gravitational mass of each object (m_1 and m_2), and inversely proportional to the square of the distance between them (r^2), as expressed by equation 2.1 (Burger et al., 2006; Gerkens, 1989):

$$F = G \frac{m_1 m_2}{r^2} \quad (2.1)$$

where G is Newton's universal gravitational constant (Mohr et al., 2012):

$$G = 6.673 \pm 0.001 \times 10^{-11} \text{ m}^3/\text{kg}/\text{s}^2 \quad (2.2)$$

If we assume the Earth is a uniform sphere with a radius (R_e) and a mass (M_e), the force (F) acting on a mass (m) on Earth's surface is given by equation 2.3:

$$F = G \frac{m M_e}{R_e^2} \quad (2.3)$$

Newton's second law of motion states that the acceleration (a) of an object produced by a net force (F) is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass (m) of the object, summarised in equation 2.4 (Burger et al., 2006; Gerkens, 1989):

$$F = ma \quad (2.4)$$

Equating Newton's first law of universal gravitation (equation 2.3), and Newton's second law of motion (equation 2.4) we are left with acceleration due to gravity (g):

$$F = ma = mg = G \frac{mM_e}{R_e^2} \quad (2.5)$$

$$g = \frac{GM_e}{R_e^2} \quad (2.6)$$

Hence, gravitational acceleration (g) depends on the distribution of nearby mass, and can be used as a constraint on geological models of the sub-surface (Kearey et al., 2013). The SI units of acceleration (a) are m/s^2 . The Gal, after Galileo, is a CGS unit of acceleration used extensively in gravimetry and is defined as 1 cm/s^2 (Kearey et al., 2013).

2.2 Earth's gravity

Earth is not a perfect sphere with a uniform mass distribution (Telford et al., 1990). The magnitude of gravity on Earth's surface is affected by five primary factors: latitude, elevation, Earth's tidal fluctuations, nearby terrain (topography), and sub-surface density variations (Telford et al., 1990). There is a wide range in density among rock types, and therefore inferences can be made on the distribution of strata and sub-surface structure.

The gravity surveying method involves use of a highly-sensitive gravity meter to measure the gravitational attraction exerted by the Earth at a measurement station located on Earth's surface (Milsom, 2003). Lateral variations in gravity due to lateral changes in rock density result in gravitational anomalies in the vicinity of the observation point (Burger et al., 2006). The goal of processing gravity data is to identify and remove any measurement signals that are not related to geologic features. Such signals include: instrumental drift, time variability caused by Earth's tides, and the predictable gravitational effects of latitude, elevation, and topography.

2.2.1 Relative and absolute gravity measurement

Absolute gravity is defined as the long-term average value of gravity at a point in space (Burger et al., 2006). Absolute gravity measurements can be directly compared with other older data (Schubert, 2015). In this study, surveying was conducted by obtaining relative gravity measurements from a grid of survey points using a relative gravity meter, which were later reduced to absolute gravity values through repeat measurements at absolute gravity reference sites.

To determine an accurate value for absolute gravity, corrections must be made for instrumental drift and tares between calibrations (McCubbine et al., 2016; Schubert, 2015; Telford et al., 1990). To correct for drift and obtain absolute gravity at each observation point it is essential to occupy at least one site of established absolute gravity before and after the course of surveying. An absolute gravity reference station, or tie site, serves as a control point for relating gravity observed at reference stations with gravity determined at survey sites.

The absolute gravity (g_{abs}) of each survey site is thus calculated using equation 2.7 (Burger et al., 2006; Telford et al., 1990):

$$g_{abs} = g_{relative} - g_{ref} + g_{abs ref} \quad (2.7)$$

where $g_{relative}$ is the relative meter reading at a survey site, g_{ref} is the relative meter reading at the absolute reference station, and $g_{abs ref}$ is the absolute gravity value recorded at the reference station.

The New Zealand gravity network

GNS Science maintains a database of terrestrial gravity observations made across New Zealand since the 1940's (Stagpoole, 2013). The gravity network consists of ~40,000 gravity observations made by different institutions primarily using Lacoste and Romberg D and G relative gravity meters. All observations in the database are tied to the New Zealand Primary Gravity Network (Robertson and Reilly, 1960) by a method of least squares (McCubbine et al., 2016; Woodward and Carman, 1984).

The New Zealand Primary Gravity Network was established in the 1960's as a series of absolute gravity control points for relative gravity observations (Robertson, 1960; Robertson and Reilly, 1960). The Primary Gravity Network stations were reoccupied during the 1980's and additional observations were made on survey

benchmarks around New Zealand (Stagpoole, 2013). Today, many of the Primary Gravity Network stations that were located on railway station platforms or roads that have been demolished or realigned are no longer locatable. Consequently, absolute gravity reference stations established on permanent benchmarks maintained by Land Information New Zealand (LINZ) are now the recommended reference sites for gravity surveys using relative gravity meters, and reference value precision is typically <0.01 mGal, i.e. better than the precision of most relative gravity meters (Stagpoole, 2013).

The New Zealand gravity network has been published in maps of Bouguer, free-air, and isostatic anomalies at scales of 1:250,000 and 1:1,000,000 (Reilly, 1972). In the central South Island, station density varies from 3-5 per km² to 1 per 10 km² (Reilly and Whiteford, 1979; Reilly, 1972).

Whataroa study area reference stations

Within the study area, two absolute gravity reference stations of the New Zealand gravity network were routinely occupied during surveying: SA80 and SA86. The reference stations are recorded in the GNS gravity database, which includes absolute gravity values listed in International Gravity Standardisation Net 1971 (IGSN71), coordinates relative to the New Zealand Geographic Datum 2000 (NZGD2000), and orthometric heights relative to the Lyttelton Vertical Datum 1937 (LYTTHT1937).

2.2.2 Temporal variation of measured gravity

Tidal variation

The gravity meter is able to detect changes in gravity caused by Earth's tides (Burger et al., 2006; Telford et al., 1990). The range of gravity variation due to the Earth's tides can be significant, ~ 0.3 mGal, changing at a rate of ~ 0.05 mGal/hr (Burger et al., 2006; Telford et al., 1990). Figure 2.1 shows interpolated and measured tidal variations for a gravity meter located in the Whataroa study area during surveying in May 2015. As seen in Figure 2.1, the gravity variation is smooth and relatively slow, and is therefore included in the instrumental drift correction (Telford et al., 1990).

Figure 2.1: Earth-tide variations, Whataroa study area, May 2015.
Gravity readings have been corrected for instrumental drift.

Meter drift correction

Instrumental drift is a phenomenon related to instrumental instabilities that cause the dial reading of the gravity meter to gradually drift with time even when gravitational acceleration remains constant (Burger et al., 2006; Telford et al., 1990). These instabilities are caused by several factors, including temperature changes and elastic creep in the meter's highly sensitive springs (Milsom, 2003). Additionally, drift may be caused by mechanical stresses and strains in the meter's mechanism as it is transported, subjected to vibrations, left unclamped, or subjected to heat stresses (Milsom, 2003). Older meters, such as the Lacoste-Romberg G-model meter used in this study, are highly susceptible to drift, which must be measured and eliminated from relative gravity measurements (Burger et al., 2006; Milsom, 2003).

Measurement strategy

The net result of instrumental drift and Earth's tidal effects is that repeated measurements at a single gravity station will change with time. To correct for drift, a looping procedure is adopted, whereby designated gravity reference stations are reoccupied every 3-4 hours (Telford et al., 1990). It is unnecessary and inefficient to use the same reference station for repeat measurements because any intermediate station can be reoccupied provided the station is well marked and upon solid structure.

Intermediate stations that are only occupied once are then corrected for drift that occurred during surveying (Telford et al., 1990). Sites that have repeat measurements can be used to assess survey precision.

In this study, drift was corrected for by reoccupying the two absolute reference stations within the study area (SA80 & SA86) at the beginning and end of each daily survey. Additionally, an intermediate station was reoccupied every 1-2 hours during surveying. The meter reading is plotted against time and drift is assumed to be linear between consecutive readings (Figure 2.2) (Kearey et al., 2013). For a linear drift condition, and if the terminating reference station is the same station, then the drift rate is given by equation 2.8 (Burger et al., 2006; Telford et al., 1990):

$$\mu = \frac{g_2 - g_1}{t_2 - t_1} \quad (2.8)$$

where g_1 and g_2 are observed gravity values at the reference station at time t_1 and t_2 respectively. The drift correction applied to an observed value at an intermediate station is given by equation 2.9 (Burger et al., 2006; Telford et al., 1990):

$$\delta_s = \mu(t_s - t_1) \quad (2.9)$$

where t_s is the time of a meter reading at an intermediate station. The absolute gravity observed at an intermediate station, less tidal and drift effects, is called the observed absolute gravity (g_{obs}):

$$g_{obs} = g_{abs} - \delta_s \quad (2.10)$$

Gsolve - Accurate gravity observation reduction

Relative gravity measurements are reduced to absolute gravity values adjusted for the effects of instrumental drift, Earth's tides, and a meter calibration scaling factor. Conventionally, this is done manually using the meter's latest calibration table, then separately using equations 2.7 to 2.10.

In this study, a comprehensive Python-based computer program, Gsolve (McCubbine et al., 2016), is used to reduce raw gravity data and apply corrections simultaneously.

Figure 2.2: A gravity meter drift curve.

The curve is constructed from repeated readings at a fixed location (the base), and non-repeated readings at various locations (intermediate stations). The drift rate (μ) is found using equation 2.8. The drift correction (δ_s) is calculated using equation 2.9, then subtracted for a reading taken at time (t_s) using equation 2.10.

Gsolve reduces relative gravity observations, corrected for the meter calibration, drift and tidal gravitational effects, to absolute gravity values based on robust least squares formulae derived by Reilly (1970). Reilly's formulae transform relative gravity measurements to absolute gravity values as long as the survey includes at least one measurement at an absolute gravity reference station.

Gravity reduction using Gsolve is achieved by processing relative gravity meter readings in three key stages (McCubbine et al., 2016):

1. Relative readings are calibrated using scaling factors supplied by an input file containing the meter's latest calibration table. The gravitational effects of the Earth's tides are removed using tidal formulas following Longman (1959).
2. A least-squares absolute gravity value for each observation location is derived from drift-corrected and calibrated meter readings. Gsolve offers three methods of least squares regression, following Reilly (1970). The choice of method depends on the uncertainty of the previously recorded absolute gravity values at the designated reference station(s). For details of each method, refer to McCubbine et al. (2016). The selection process and details of the reduction method used in this study are described in Chapter 3.

3. The residuals of the least squares fit are used to reject values outside of the specified confidence interval (CI). In this study, a CI of 100% was used and outliers were manually picked and discarded based on the quality of the regression combined with geographic location, i.e. no observations were automatically excluded.

During surveying, multiple loops (repeat measurements) were made in order to correct for drift and Earth's tides, and to establish precision of the survey. For the purposes of data reduction, a single loop constitutes an entire day of surveying, that is, from the absolute gravity reference station at the beginning of the survey day to the same reference station at the end of the survey day. During this period of time, gravity observations can be affected by sudden changes in the baseline (zero point) of the gravity meter, referred to as a tare in the data (McCubbine et al., 2016; Schubert, 2015). Gsolve incorporates the tare effect into the drift function by the least squares solution allowing for any sudden change in the gravity meter's baseline to be spread out across the entire solution, limiting the effects of individual tares.

For a large-scale survey consisting of relative gravity measurements being made over several days, such as in this study, it is advantageous to compute the meter drift function and meter baseline on a daily basis, confining tare effects across individual days or loops within a day (McCubbine et al., 2016). From these daily loops, Gsolve calculates a daily drift rate (mGal per hour) based on daily meter baseline values and drift function coefficients, producing a tidal effect that is subtracted from absolute gravity values as described in stage 1.

2.2.3 Variation of gravity with latitude

Earth's gravity increases with latitude due to Earth's rotation. At latitudes nearer Earth's equator, the outward centrifugal force produced by Earth's rotation is larger than at polar latitudes. The centrifugal force acts oppositely to the force of gravity, up to a maximum of 0.3% at the equator, and thus gravitational acceleration at equatorial latitudes is reduced (Burger et al., 2006; Telford et al., 1990).

Additionally, Earth is not a perfect sphere, it is an oblate ellipsoid, a consequence of Earth's rotation and outward centrifugal force over long time-scales, forming an equatorial bulge and flattening of the polar regions (Burger et al., 2006; Telford et al., 1990). With respect to Newton's law of gravitation (equation 2.6), the increased radial

distance due to Earth's equatorial bulge means gravitational acceleration will be weaker at the equator than at Earth's poles (Telford et al., 1990).

Conversely, a larger equatorial radius means that there is increased mass between the equator and the centre of the Earth relative to the mass between the Earth's centre and the poles. This change in mass between the equator and the poles acts to increase gravitational acceleration towards the equator (Burger et al., 2006).

In combination, the effects of the surface centrifugal force due to Earth's rotation, the resulting equatorial bulge, and the change in mass between the equator and the poles result in an overall decrease of sea-level effective gravity from $\sim 9.832 \text{ m/s}^2$ at the poles to $\sim 9.780 \text{ m/s}^2$ at the equator, a difference of $\sim 5.2 \text{ Gal}$ (Burger et al., 2006; Telford et al., 1990).

The latitude correction

To correct for gravity variations with latitude, it is necessary to define a reference surface that best fits Earth's gravity field. The reference ellipsoid is the equipotential surface of the Earth's gravity field which best fits a uniform Earth. In contrast, the geoid is the equipotential surface of the Earth's gravity field which best fits global mean sea-level. The height difference between these two surfaces rarely exceeds 100 m and is more commonly $< 50 \text{ m}$ (Figure 2.3) (Burger et al., 2006; Telford et al., 1990).

Figure 2.3: Earth's topographic, ellipsoid and geoid surfaces

The shape of the geoid is dominated by broad undulations, which do not spatially correlate with the continents, and are caused by Earth's heterogeneous mass distribution (Burger et al., 2006; Telford et al., 1990). The undulating form of the geoid relative to topography and Earth's density variations are second-order effects, both low in amplitude ($< 10 \text{ m}$) and short in wavelength ($< 10^6 \text{ m}$). Therefore, the reference ellipsoid

is suitable as a first-order approximation of gravity at a given latitude (θ) (Telford et al., 1990).

The first internationally accepted reference ellipsoid was established in 1930, known as the 1930 International Gravity Formula:

$$g_{\theta} = 978049(1 + 0.0052884 \sin^2 \theta - 0.0000059 \sin^2 2\theta) \text{ mGal} \quad (2.11)$$

where g_{θ} is the normal gravity value. With the addition of satellite technology came better accuracy of various geodetic parameters, and a new ellipsoid was adopted in 1967, known as the 1967 International Gravity Formula:

$$g_{\theta} = 978031.846(1 + 0.0053024 \sin^2 \theta - 0.0000058 \sin^2 2\theta) \text{ mGal} \quad (2.12)$$

The reference ellipsoid was further updated in 1980, known as the Geodetic Reference System 1980 (GRS80), which eventually led to the current reference field, World Geodetic System 1984 (WGS84) Ellipsoidal Gravity Formula, given by equation 2.14 (Hinze et al., 2005):

$$g_{\theta} = 978032.67715 \frac{1 + 0.001931851353 \sin^2 \theta}{\sqrt{1 - 0.0066943800229 \sin^2 \theta}} \text{ mGal} \quad (2.13)$$

2.2.4 Variation of gravity with elevation

A change in elevation on Earth's surface will have a significant gravitational effect since gravitational force varies inversely with the square of radial distance (refer to equation 2.6). To correct for elevation, gravity observations are reduced to that expected on a reference datum, known as the free-air, or height correction (Burger et al., 2006; Kearey et al., 2013). The free-air correction does not account for the excess mass underlying observation points located at elevations above and below the reference datum, which also introduces a large gravitational effect that must be corrected for separately, known as the Bouguer correction (Burger et al., 2006; Kearey et al., 2013).

The free-air correction

The free-air correction accounts for the difference in gravity between the observation point and the adjacent reference point on the vertical datum, due to a difference in height (h) (Figure 2.4) (Kearey et al., 2013; Telford et al., 1990).

Figure 2.4: The free-air correction for an observation at a height (h) above the vertical datum.

The free-air correction is based on orthometric height above the geoid (i.e. height above sea level), whereby the first-order approximation for the free-air gradient is -0.3086 mGal/m and thus, the free-air correction (g_{FA}) is applied as follows (Burger et al., 2006):

$$g_{FA} = -0.3086 \times h \text{ mGal} \quad (2.14)$$

where h is the height above the geoid. Conventional gravity meters typically measure relative gravity to an accuracy of 0.01 mGal, therefore to ensure this level of accuracy, it is essential to measure station height to within 3–5 cm (Burger et al., 2006).

The Bouguer correction

The Bouguer correction accounts for the excess mass underlying observation points located at elevations higher than the vertical datum. Conversely, it accounts for a mass deficit at observation points located below the vertical datum (Figure 2.5) (Burger et al., 2006; Kearey et al., 2013).

Figure 2.5: The Bouguer correction.

The grey region corresponds to an infinite horizontal slab of rock of thickness (h) with a given density (ρ).

The Bouguer correction (g_{BC}) is calculated assuming the Earth between the observation point and the vertical datum is an infinite horizontal slab, given by equation 2.15 (Burger et al., 2006; Gerkens, 1989):

$$g_{BC} = 2\pi G\rho h = 0.04191\rho h \text{ mGal} \quad (2.15)$$

where G is the gravitational constant (equation 2.2), ρ is the density of the horizontal slab in kg/m^3 , and h is the height (km) above the geoid (Burger et al., 2006; Gerkens, 1989).

A density of 2670 kg/m^3 is generally assumed for the density of the Bouguer slab in regional gravity surveys. This value is a reasonable estimate of the mean surface rock density of the continents that are crystalline and of granitic composition (Hinze, 2003).

2.2.5 Variation of gravity with topography

The Bouguer correction does not account for the gravitational effect of topography since it assumes the Earth between the observation point and the vertical datum is an infinite horizontal slab with a planar surface (Kearey et al., 2013; Telford et al., 1990). In reality, topographic highs above the observation point introduce excess mass, exerting an upward attraction at the observation point causing gravity to decrease. Conversely, topographic lows below the observation point introduce a mass deficit, causing the Bouguer correction to overcorrect for these areas (Figure 2.6) (Kearey et al., 2013; Telford et al., 1990).

Figure 2.6: The gravitational effect of topography.

Topographic highs above the observation point introduce excess mass (+), while topographic lows below the observation point introduce a mass deficit (−).

This mass imbalance produces terrain effects responsible for errors in the gravity anomalies of tens of milligals (Gerken, 1989; Stern, 1995). To avoid a large terrain effect, gravity sites are typically selected in areas of low topographic relief, where features too small to be shown on a topographic map can be gravitationally significant (Milsom, 2003). However, in this case, the study area is surrounded by high (>1000 m a.s.l) mountainous terrain requiring a significant topographic correction, conventionally known as a terrain correction.

The terrain correction

The terrain correction accounts for variations in the observed gravitational acceleration caused by variations in topography near each observation point (Beck, 1981; Burger et al., 2006; Kearey et al., 2013; Telford et al., 1990)

Because of the assumptions made during the Bouguer slab correction, the terrain correction is positive regardless of whether the local topography consists of a mountain (mass excess) or valley (mass deficit) (Burger et al., 2006; Kearey et al., 2013). As can be appreciated from consideration of Figure 2.6, a positive topographic correction is added to the observed gravity at the observation location (Burger et al., 2006; Kearey et al., 2013; Telford et al., 1990).

Many methods for calculating terrain corrections exist in gravimetry, all of which require detailed knowledge of relief in the vicinity of each observation point and a reliable topographic source, such as a topographic map (contour interval ~10 m), and/or a high-resolution digital elevation model (DEM) (Burger et al., 2006; Telford et al., 1990). Classically, the terrain correction is applied using the Hammer (1939) method,

which uses a graticule of segmented annuli, representing sections of cylinders of different radii centred on an observation point (Figure 2.7). The traditional method is applied by outlining the outer annular segments (E to M) of the graticule on a transparent sheet overlying a topographic map, and by observing the relief of inner annular segments (A to D) in the field (Burger et al., 2006; Hammer, 1939; Telford et al., 1990).

Figure 2.7: The Hammer (1939) graticule used for the calculation of terrain corrections.

(i) Outer Hammer zones E-J extending to a radius of ~6.5 km. The outermost zones (K-M), which extend to ~22 km are not shown. (ii) Inner Hammer zones B-D extending to a radius of 170.1 m. The innermost zone (A), which is assumed to be flat is not shown. Figure modified from Kearey et al. (2013).

More recent techniques use high-resolution DEMs to compute terrain corrections. The outermost segment (M) extends almost 22 km, beyond which topographic effects are usually negligible (Kearey et al., 2013). Conventional practice involves analysing the surrounding relief within each annular segment and calculating an average elevation. The height of the gravity station is subtracted from these values, and the gravitational effect of each annular segment is determined by reference to the Hammer (1939) terrain correction chart (Appendix A; Table A.1) (Kearey et al., 2013; Milsom, 2003; Telford et al., 1990).

The chart is constructed using equation 2.16, which is a formula for the gravitational effect of an annular segment of a vertical cylinder at its axis (Kearey et al., 2013):

$$T = 0.04191 \frac{\rho}{n} \left(r_2 - r_1 + \sqrt{r_1^2 + z^2} - \sqrt{r_2^2 + z^2} \right) \text{ mGal} \quad (2.16)$$

where T is the terrain correction of a single annular segment, ρ is the Bouguer correction density (2.67 g/cc), n is the number of segments in a Hammer zone, r_1 is the inner radius of a zone (m), r_2 is the outer radius of a zone (m), and z is the modulus of elevation difference between the gravity station and the average elevation of a single annular segment (m).

The total terrain correction (g_{TC}) is the sum of the contributions of all segmented annuli in the graticule, and is added to the observed gravity at the observation location (Kearey et al., 2013; Telford et al., 1990):

$$g_{TC} = T_{inner} + T_{outer} \text{ mGal} \quad (2.17)$$

Use of the Hammer (1939) method requires skill in estimating relative distances and heights, which can be difficult in rugged terrain, introducing a large estimation error. For this study, a MATLAB-based code was used to compute both an inner and outer terrain correction for each station, incorporating equation 2.16. The code uses the New Zealand 8-m-resolution bare-earth digital elevation model (DEM) obtained from Land Information New Zealand (LINZ) to compute outer terrain corrections based on geoidal heights, covering Hammer zones E to M (170-22,000 m). To compute inner terrain corrections, the code uses a 2-m-resolution DEM, produced from a LiDAR swath of the study area (Barth et al., 2012; Langridge et al., 2014), and covers Hammer zones B (2-17 m), C (17-53 m) and D (53-170 m). Hammer zone A (0-2 m) is assumed to be level. Inner terrain corrections are based on LiDAR heights which are relative to the local geoid (NZVD2009) (Langridge et al., 2014). Inner and outer terrain corrections are then summed using equation 2.17 and added to the observed gravity for each site.

To compute an inner terrain correction for gravity stations located outside the range of the LiDAR swath, the conventional Hammer (1939) field procedure was implemented, which includes analysing the surrounding relief within each inner annular

segment (B-D) and calculating an average elevation (refer to Figure 2.7). Details of the field procedure are discussed in section 2.3.1. Average elevations are incorporated into the same MATLAB code, which are summed, converted to milligal using equation 2.16, then added to the outer terrain correction using equation 2.17.

Outer terrain corrections were also re-processed for existing gravity stations using the same method described above. Additionally, inner terrain corrections were re-processed for existing stations located within range of the LiDAR swath. Inner terrain corrections for existing stations located outside of LiDAR range were obtained from the raw dataset provided by Davy (2012).

2.2.6 The Bouguer gravity anomaly

The Bouguer gravity anomaly is the departure between the corrected gravity at the station and the expected gravity on the reference datum. The expected value of gravity (g_{exp}), also known as the Bouguer model, is the combination of the gravitational effects of latitude, elevation, topography, drift and Earth's tides following equation 2.18:

$$g_{exp} = g_{\theta} + g_{BC} + g_{FA} - g_{TC} \text{ mGal} \quad (2.18)$$

where g_{θ} is the expected gravity at latitude θ , g_{BC} is the Bouguer correction, g_{FA} is the free-air correction, and g_{TC} is the total terrain correction.

Subtracting the value of gravity expected on the reference datum with the observed gravity at the observation point resolves the Bouguer gravity anomaly (g_{BA}):

$$g_{BA} = g_{obs} - g_{exp} \text{ mGal} \quad (2.19)$$

Equating equations 2.18 and 2.19 yields:

$$g_{BA} = g_{obs} - g_{\theta} - g_{FA} - g_{BC} + g_{TC} \text{ mGal} \quad (2.20)$$

where g_{obs} is the station reading (corrected for drift and Earth's tides), g_{θ} is the expected gravity at latitude θ , g_{FA} is the free-air correction, g_{BC} is the Bouguer correction, and g_{TC} is the total terrain correction.

Since anomalies are equal to the difference between corrected values and the adjacent values on the reference datum, a positive anomaly represents a mass excess where there is a greater than expected gravitational attraction. Conversely, a negative anomaly represents a mass deficit where there is a less than expected gravitational attraction. If the Earth had no lateral variations in density, and the gravitational effects of latitude, elevation, topography, and drift had been removed, gravity readings would be identical.

The Bouguer anomaly is therefore the result of lateral variations in density, allowing for the modelling and the interpretation of the Earth's sub-surface (Kearey et al., 2013; Telford et al., 1990).

2.3 Data acquisition and reduction

2.3.1 Data acquisition

Equipment

New gravity measurements were collected using a Lacoste and Romberg gravity meter (Model G-519), which can measure relative gravity to a precision of ± 0.01 mGal (Milsom, 2003). The meter measures the difference in gravity between two observation locations or over a time interval at one site. A relative calibration is obtained at numerous points over the entire range of the meter using the meter's latest calibration table (Appendix A; Table A.2).

Coordinate and elevation data for each observation point were collected using a Trimble® R8 GNSS system and Trimble® GeoExplorer® 6000 series handheld unit. The R8 GNSS system achieves cm-level positioning accuracy by utilising real-time kinematic (RTK), and fast static corrections. In areas of rugged terrain where the R8 GNSS system was unsuitable, the more versatile GeoExplorer® handheld was used to achieve real-time decimetre (10 cm) positioning accuracy. Receiver locations were later corrected relative to the continuously operating GNSS station, Mt Price (MTPR) maintained by GeoNet, located ~11 km from Whataroa.

Post-processing of relative GNSS data produced high-precision horizontal and vertical accuracy for each observation point by using a Transverse Mercator projection (NZTM2000), which is based on the New Zealand Geodetic Datum 2000 (NZGD2000) and uses the Geodetic Reference System 1980 (GRS80) reference ellipsoid. All

horizontal positions are relative to NZGD2000 and all ground elevations are relative to NZVD2009. Additionally, existing GNSS positions recovered from past surveys were updated and corrected relative to NZGD2000 and NZVD2009 to ensure consistency across the amalgamated dataset.

Field procedure

The gravity survey was divided into four intervals. The first interval was completed by the author and Rupert Sutherland of Victoria University of Wellington (VUW) between the 30th of November and the 3rd of December 2013 during a VUW summer scholarship program designed to aid in the selection of a suitable location for the DFDP-2 drill hole (Sutherland et al., 2015). The second interval was completed between the 24th of April and the 8th of May 2015, the third interval completed between the 15th of May and the 2nd of June 2015, and the fourth interval completed between the 22nd and the 30th of September 2015. In total, 464 new gravity stations, and two absolute gravity reference stations of the GNS Science gravity network were occupied.

Station location and appropriate site spacing was planned using forward gravity models and aerial photography. Data were collected on a grid in the vicinity of the DFDP-2 borehole and the Alpine Fault, and on dense profiles of interest. Forward gravity models that aided survey design are presented in Chapter 4.

In order to constrain the regional gravity field and hence accurately model the shallow bedrock-sediment interface in the valley (240-350 m deep; expected gravity signal ~ 3 mGal), sparse regional measurements were collected on sites with small local density variation, such as schist bedrock, as far from the valley fill as possible using the various creeks and gullies located within the bounds of the study area. During the final interval of surveying, a helicopter was available and used to access otherwise inaccessible sites located on Mt Price and Adams Range. Acquisition of the regional gravity signal and its subsequent separation from Bouguer gravity anomalies is explained in more detail in Section 2.4.

As previously mentioned, the study area is surrounded by high (>1000 m a.s.l) mountainous terrain making site selection difficult, and introducing large terrain effects (>10 mGal) (Stern, 1995). During surveying, some sites were selected outside the range of the LiDAR swath, requiring an alternative method of estimating the inner terrain correction. The conventional Hammer (1939) field procedure was utilised at these sites, which involves using a truncated graticule covering Hammer zones B (2-17 m), C (17-

53 m) and D (53-170 m) (refer to Figure 2.7 (ii)). The observer stands on the observation point and estimates the average elevation of each annular segment within each Hammer zone. The inner and outer segment radii are not measured and are sometimes obscured, requiring a ‘best guess’ estimate. The observer rotates clockwise from segment to segment to maintain uniformity between sites, while estimating the segment angle.

Gravity measurements were made following the method of Milsom (2003). For specific details of the measurement procedures used in this survey refer to Appendix B.

As discussed earlier in this chapter, Earth’s tidal signal is significant and is an important consideration when modelling small amplitude signals, as expected in the valley (<3 mGal). Drift was monitored during surveying by completing internal loops in areas away from reference sites by re-occupying a relative gravity station at regular intervals (1-2 hours), allowing possible errors to be identified. No errors were identified during surveying.

The precise time of each measurement was carefully recorded at each site using the atomic clock within the GPS unit, and later converted to Coordinated Universal Time (UTC).

2.3.2 Data reduction

The objective of most gravity surveys is to estimate the location and nature of sub-surface structures. To achieve this, gravity observations are reduced to Bouguer gravity anomalies. Below is a summary of how the data were reduced.

1. Observed gravity values (g_{obs}) were adjusted for the effects of Earth’s tides, instrumental drift, and a meter calibration scaling factor. The resultant absolute gravity values were calculated for all stations using a Python-based program, known as Gsolve (McCubbine et al., 2016), introduced in section 2.2.2 and discussed further in Chapter 3.
2. Observed gravity values were corrected for latitude (g_{θ}) using the WGS84 Ellipsoidal Gravity Formula, given by equation 2.13, and GNSS-determined ellipsoidal latitudes (θ).
3. Free-air corrections (g_{FA}) were applied to each gravity value using equation 2.14, and surveyed heights (h).

4. A Bouguer correction (g_{BC}) was applied to each gravity value using equation 2.15, the surveyed height (h), and a mean rock density (ρ) of 2670 kg/m³.
5. An outer and inner terrain correction was computed for each observation point by incorporating a DEM or field observations, and equation 2.16 into a MATLAB-based code as described in section 2.2.5. The total terrain correction (g_{TC}) was applied to each gravity value using equation 2.17.
6. Bouguer gravity anomalies (g_{BA}) were calculated for all stations using equation 2.20.

2.3.3 Uncertainty in the Bouguer gravity anomaly

Potential sources of error or uncertainty in any individual gravity measurement are: reader error, instrument drift, over-simplification of the tidal model, errors in terrain corrections (density assumption, terrain measurement), as well as errors in latitude and height measurements.

Reader error

Reader error may be caused by several factors, including unstable terrain, wind, seismic activity, a faulty meter, or human error.

To reduce reader error, gravity sites were selected on solid (preferably rock) ground wherever possible. However, this is not always possible when surveying on grassy areas. To overcome this problem, top soil was removed and a metal survey plate was pushed firmly into the ground to create a solid platform for the gravity meter. Additionally, to reduce the effect of wind, each meter reading was taken while the reader had their back to the wind at each station.

During surveying, seismic events can play a role in reader error (Milsom, 2003). If the needle in the counter is fluctuating, then there is likely a current earthquake occurring. This was relatively common during this survey, and when it did occur, depending on the severity, common practice was to stop surveying and return later (~1 hr) to re-measure the last station.

Particular care must be taken of the highly sensitive gravity meter as a faulty meter will introduce a large reading error (Milsom, 2003). This includes maintaining a

constant power supply and handling the meter gently during transportation. To monitor the meter during surveying, the looping procedure previously discussed in Section 2.2.2 was implemented, allowing possible errors to be identified between repeat readings. No errors were detected during surveying.

To avoid misreading the meter dial, a consistent meter reading procedure was employed with the dial being turned only in one direction. For most gravity stations, the meter was read once, while multiple readings were made at a designated intermediate gravity station every 1-2 hours, including two readings that were made every day at each absolute gravity reference station (SA80 & SA86), once before surveying began, and again after surveying had finished.

Drift error

During a typical survey loop, it is essential to ensure that no mechanical or thermal tare occurs. A tare is a single, sudden irreversible jump in a meter reading due to instrumental effects, sometimes as large as several milligal (Schubert, 2015). Tares can be identified when repeated readings are made and compared by re-occupying an intermediate gravity station (the base) at regular intervals (1-2 hours), so that tares can be isolated from normal gravity changes (Schubert, 2015). Gsolve incorporates the tare effect into the drift function by the least squares solution as discussed in Section 2.2.2. No tares were detected for this survey.

In total, 34 primary loops were achieved in the survey, where one primary loop is equivalent to a single day of surveying. The highest recorded rate of instrumental drift was 0.04 mGal/hr on the 30th of November 2013 during the first interval of surveying. On all other survey loops, the drift rate was <0.01 mGal/hr.

The combined uncertainty associated with reader error, instrument drift, and tidal prediction is ± 0.015 mGal, which is determined from the repeatability of absolute gravity measurements. This result is described in detail in Chapter 3.

Terrain correction uncertainty

As discussed in Section 2.2.5, the inner terrain correction (2-170.1 m) was calculated using both a 2-m-resolution DEM for new and existing gravity stations located within range of the LiDAR swath, and using the traditional Hammer (1939) terrain estimation method for stations located outside the range of the LiDAR swath.

The inner terrain correction for a total of 116 new gravity stations was calculated using the traditional Hammer (1939) method, whereby 95% of corrections were <0.5 mGal, and 98% were <1.0 mGal. Of the 116 new gravity stations, 15 were located in high-relief areas, and 101 were located in low-relief areas. Uncertainties in the inner terrain corrections are quoted to one standard deviation, where stations located in high-relief areas have a standard deviation of ± 0.35 mGal, and stations located in low-relief areas have a standard deviation of ± 0.02 mGal.

The 2-m-resolution DEM of the study area is more than sufficient for calculating an inner terrain correction with relatively low uncertainty for stations located within the range of the LiDAR swath, covering Hammer zones B (2-17 m), C (17-53 m) and D (53-170 m). However, not all stations are within full range of the LiDAR swath and some are only fractionally within range (Figure 2.8). A total of 316 gravity stations, including existing stations, had LiDAR coverage of $>95\%$ within a 170 m radius (Figure 2.8a). Sites with LiDAR coverage of $<95\%$ were corrected to 100% coverage by multiplying the inner terrain correction across the missing section only when (1) the entire coverage area was considered to be flat, and (2) when the missing section was no more than 50% (Figure 2.8b). Overall, 54 gravity stations, including existing stations, satisfied these requirements. In some cases, the LiDAR coverage within the graticule was partly or entirely an area of high-relief while the missing section was either partly or entirely flat (Figure 2.8c). It was therefore inappropriate to correct these sites to 100% coverage as it would lead to a terrain overcorrection. In total, 12 gravity stations were found in this situation with an average LiDAR coverage of 80%. In total, 382 gravity stations, including existing stations, were located within full or adequate range of the LiDAR swath, where 86% of inner terrain corrections were <0.5 mGal, and 91% were <1.0 mGal.

The uncertainty in terrain corrections computed using DEMs is dependent upon the resolution of the model used to calculate them. For this reason, the uncertainty in inner terrain corrections for stations located within range of the LiDAR swath is considered to be negligible due to the high-resolution of the DEM (2 m). Additionally, the uncertainty in outer terrain corrections, which were computed for all gravity stations using the New Zealand 8-m-resolution bare-earth DEM, covering Hammer zones E to M (~ 170 -22,000 m) is also considered to be negligible.

Figure 2.8: Key examples of LiDAR inner terrain correction.

Inner terrain correction graticule (Hammer zones B-D) shown in white (radius = 170.1 m). Grey hill-shade is the LiDAR swath. (A) shows an example of a gravity station with >95% LiDAR coverage. In (B) the graticule covers an area that is considered 100% flat; however, ~50% of the graticule is outside of LiDAR range. Complications in correcting for missing sections of LiDAR arise when the missing section sits adjacent to high-relief terrain (C). Note that missing LiDAR coverage due to the Whataroa River seen in (C) is considered flat.

Height and latitude uncertainty

As previously discussed at the beginning of the chapter, a change in elevation on Earth's surface will have a significant gravitational effect since gravitational force varies inversely with the square of radial distance (refer to equation 2.6). An error in height of ± 1 m will result in a ± 0.19 mGal uncertainty in the Bouguer gravity anomaly

A total of 189 station heights were measured using the Trimble® R8 GNSS system, producing an average uncertainty in height of ± 0.03 m, and a maximum uncertainty of ± 0.9 m. In high-relief areas where the R8 GNSS system was unsuitable, the Trimble® GeoExplorer® 6000 series handheld unit was utilised. A total of 277 station heights were measured using the Trimble® GeoExplorer® 6000 series handheld unit, producing an average uncertainty in height of ± 0.4 m, and a maximum uncertainty of ± 1.9 m.

Additional error in height is introduced for stations located within range of the LiDAR swath due to a difference between the measured GPS heights of the stations and the DEM heights used to calculate inner terrain corrections. Figure 2.9 shows an empirical Cumulative Distribution Function (CDF) plot of the differences (in black) and the fitted normal distribution (in red).

Figure 2.9: Empirical CDF plot of the difference between GPS heights and LiDAR DEM heights.

The black line represents the distribution of GPS measured heights minus heights derived from the LiDAR DEM. Red line represents the fitted normal distribution.

For a total of 382 gravity stations located within adequate range of the LiDAR swath, the difference between the measured GPS heights and the DEM heights has a standard deviation of 1.67 m. A fixed estimated error with a standard deviation of 0.36 m was calculated for the measured GPS heights of both new and existing gravity stations. Therefore, the standard deviation of the LiDAR DEM can be approximated following equation 2.21:

$$H^{err} LiDAR = \sqrt{1.67^2 + 0.36^2} = 1.71 \text{ m (2. d. p)} \quad (2.21)$$

For stations located outside the range of the LiDAR swath, it is assumed that only the measurement error contributes uncertainty, and are therefore assigned a fixed estimated error in height of 0.36 m. Equation 2.22 shows that the fixed height error for gravity stations located within range of the LiDAR swath contributes 0.3 mGal, while stations located outside the range of the LiDAR swath contribute 0.07 mGal.

$$H^{unc} = h^{err}(-0.3086 + 0.04191\rho) = -0.19h^{err} \text{ mGal} \quad (2.22)$$

where H^{unc} is the resulting uncertainty in the Bouguer anomaly due to an error in height (h^{err}).

The latitude uncertainty in the Bouguer gravity anomaly is considered to be negligible compared to the height uncertainty. An uncertainty in latitude of ± 1 m results in a ± 0.0008 mGal uncertainty in the Bouguer gravity anomaly. Consequently, any uncertainty in latitude was disregarded for this study.

Total uncertainty

The total uncertainty for each Bouguer gravity anomaly (U) is the Root Mean Square (RMS) of each of the sources of error, assuming there are no correlations between sources of error:

$$U = \sqrt{U_m^2 + U_t^2 + U_h^2} \text{ mGal} \quad (2.22)$$

where U_m is the measurement uncertainty (Chapter 3), U_t is the terrain correction uncertainty, and U_h is the height uncertainty.

The average total uncertainty for the Bouguer gravity anomalies, including existing gravity stations, is ± 0.2 mGal, with a maximum total uncertainty of ± 0.3 mGal. Bouguer gravity anomalies of each gravity station, and their respective uncertainties are listed in Appendix C; Table C.1. The measured height and latitude uncertainties for each gravity station are provided in Appendix D.

2.4 Regional-residual separation

The Bouguer gravity anomaly is caused by the combined effects of deep-seated regional structure and shallow localised structure, both of which are reflected through long and short-wavelength components. In gravimetric analyses, it is often desirable to separate these components in order to observe the regional and residual anomalies individually, so that gravity signals associated with short-wavelength shallow density anomalies can be isolated and modelled (Burger et al., 2006). To accurately separate both long and short-wavelength components, gravity observations must be both extensive enough to capture the regional gravity trend and dense enough to resolve localised structure (Burger et al., 2006). However, the separation of both components is non-unique since the transition from long to short-wavelengths may be ambiguous (Kearey et al., 2013). A typical approach is to employ a combination of analytical and graphical methods to identify and remove the regional gravity trend (Burger et al., 2006).

2.4.1 Mathematical methods

A common mathematical approach to removing the regional trend involves fitting a low-degree polynomial to the Bouguer gravity data (Burger et al., 2006). Low-degree polynomials fit regional data appropriately compared to high-degree polynomials which also capture part of the residual anomaly. In this study, both first-degree (linear) and second-degree (quadratic) polynomial functions were used to fit the regional trend and subsequently separate it from a residual signal. This approach is shown in Figure 2.10.

Regional-residual separation for the Whataroa River valley

The region surrounding the Whataroa valley is affected by two broad negative gravity anomalies either side of the Alpine Fault. The anomaly east of the fault is likely due to the deep crustal root of the Southern Alps (Davey et al., 2007) and the anomaly west of the fault is due to the sub-surface presence of low-density sediments of the South Westland Basin (Davy et al., 2013). In order to capture the regional gravity trend, Bouguer anomaly points were chosen on sites with small local density variations (bedrock sites) and widespread distribution following the method of Stern (1979).

Figure 2.10: Modelling of a linear and quadratic polynomial surface fitted in x-y-g space to regional Bouguer anomaly points.

(A) shows a first degree (linear) polynomial surface. (B) & (C) show a second degree (quadratic) polynomial surface. Red points represent weighted bedrock stations. Blue points represent the remaining Bouguer gravity data.

Bouguer anomaly points located on bedrock outcrops such as schist, made accessible by the various creeks and gullies in the study area, ensured the regional fit was independent of the residual anomaly generated by the sediment-based stations in the Whataroa valley.

A surface-fitting method was used to remove the regional trend from the Bouguer gravity signature of the Whataroa River valley. As a first-order approximation, a linear polynomial surface was fitted in x - y - g space to the regional Bouguer anomaly points using the method of least squares, producing a Root Mean Square Error (RMSE) of 8.5995 mGal (Figure 2.10A). As a second-order approximation, a quadratic polynomial surface was fitted to the regional Bouguer anomaly points, producing a RMSE of 5.1433 mGal (Figure 2.10B). To further improve the surface fit, the quadratic model was re-run with outliers removed, producing an improved RMSE of 2.9866 mGal (Figure 2.10C). The second-degree polynomial surface was selected as the best fit for the data due to a reasonably low RMSE and its compatibility with the regional geological setting. As polynomial degree increases, the individual surfaces fit better with the Bouguer anomaly data; however, higher-degree surfaces are more complex and develop unrealistic curvature at their margins. Since surface-fitting methods do not consider local geological information (Burger et al., 2006), higher-degree polynomials become increasingly unreasonable. Therefore, it was appropriate to use a second-degree polynomial surface with a reasonably low RMSE and long-wavelength signature to represent the regional Bouguer anomaly signal.

Second-degree polynomials represent paraboloid surfaces, expressed in equation 2.24:

$$g_{TS} = Ax^2 + By^2 + Cxy + Dx + Ey + F \quad (2.24)$$

where g_{TS} is the gravity value of the trend surface at a spatial position x , and y . The coefficients A, B, C, D, E and F are determined through the method of least squares to reduce the residual value between the regional surface and the gravity data. The second-degree polynomial representation of the regional Bouguer anomaly was subtracted from the Whataroa Bouguer anomaly points to obtain the residual anomaly. The effect of the regional-residual separation is presented in Chapter 3.

2.5 Gravity modelling

Gravity models for this study were constructed using Geosoft® GM-SYS software by applying a simple two-dimensional technique (Northwest Geophysical Associates, 2004).

2.5.1 Two-Dimensional modelling

Two-dimensional (2-D) models assume the Earth is 2.5-dimensional in nature; i.e. density varies with depth (z direction) and in the direction of the profile (x direction). 2-D models exist but do not vary in the strike direction (y direction) and are assumed to extend to infinity. Figure 2.11 shows a schematic of a 2-D model and the relative coordinate system. The pink cross-section represents a one layer 2-D model, which extends to infinity in the y-plane. 2-D models are typically made up of different polygonal units of varying density. The gravitational response of the constructed 2-D polygonal model is calculated and compared at the location of the observed gravity to estimate the best fit of the model.

Figure 2.11: Schematic of a two-dimensional model and relative coordinate system.

Pink cross-section extends to infinity in the y-plane. Figure from Northwest Geophysical Associates (2004).

Gravity modelling of the Whataroa River valley

Two-dimensional gravity models are used in this study to define the shallow geometry surrounding the DFDP-2 drill site and nearby Alpine Fault in the Whataroa River valley. The 2-D gravity models were constructed using the GM-SYS package in Oasis montaj developed by Geosoft® following the method of Talwani et al. (1959). The models are oriented in x-z space where x is profile distance in meters and z is depth in meters. Polygons with different densities, which represent geologic units, extend to infinity in the $\pm$ y-direction and $\pm$ 30,000 km in the x-direction to eliminate edge effects. The 2-D gravity models are presented in Chapter 4.

Chapter 3 Results

3.1 Introduction

This chapter begins with an analysis of results from Gsolve’s different gravity reduction methods (first introduced in Chapter 2), followed by a detailed description of the results of the preferred reduction method. Also discussed is how existing gravity data were amalgamated with the new dataset. The combined dataset is presented as both Bouguer and residual gravity anomaly maps.

3.2 Gsolve gravity reduction results

Gsolve, a Python-based computer program (McCubbine et al., 2016), was used to transform relative gravity measurements to absolute gravity values. The transformation is based on comparisons of repeated measurements and at least one measurement at an absolute gravity reference site, where the absolute gravity value is known. Gsolve solves for absolute gravity at the observation sites by one of three methods of least squares regression, following Reilly (1970).

3.2.1 Gsolve gravity reduction methods

Gsolve’s first reduction method (Method 1) is a normal least squares solution which allows the newly-estimated absolute gravity values at reference sites to differ from previously recorded values. Method 1 is advantageous to surveys where previously recorded absolute gravity values are expected to contain significant uncertainty, for example if reference absolute gravity values were measured with imprecise instrumentation, and multiple reference sites are available in the new survey (McCubbine et al., 2016).

Method 2 is a decoupled least squares solution following Reilly (1970) which is best suited to surveys where derived absolute gravity values are required to fit

previously recorded values at reference sites precisely, while allowing gravity values at other locations surveyed to be derived with some flexibility around these observed values (McCubbine et al., 2016). Estimated variances at absolute gravity sites are non-zero, despite the attempt to fit exactly the given value. This corresponds to giving preference to the provided absolute gravity value in the solution.

Gsolve's third reduction method (Method 3) is a constrained least squares solution that is best suited to surveys where previously recorded absolute gravity values at reference sites are considered to be errorless. This method is advantageous when the history of the reference site is well known and measured regularly, usually with a highly accurate absolute gravity meter (McCubbine et al., 2016).

In order to select the best suited Gsolve gravity reduction method for this study, an experiment was conducted with the aim of testing the uncertainty of the recorded absolute gravity values at the study area reference sites.

Absolute gravity reference site uncertainty assessment

Two absolute gravity reference stations of the New Zealand gravity network (SA80 & SA86) were routinely occupied during surveying. Since being established by GNS Science in the 1980's (Stagpoole, 2013), it is possible that both reference stations have been disturbed, introducing error to recorded values of absolute gravity (e.g. caused by mass movements such as road building near the benchmarks). By estimating the uncertainty of the recorded absolute gravity values at the study area reference sites, it is possible to determine their suitability for gravity surveying and select the most appropriate Gsolve method for reducing new gravity data.

For this experiment, a sample of 10 absolute gravity reference stations of the New Zealand gravity network, including SA80 and SA86 were occupied during the course of a day. The 10 stations were hand-picked from the GNS Science database, and are spread out along State Highway 6 (SH6) from Harihari to Fox Glacier (Figure 3.1).

In total, 27 gravity readings were made across the 10 absolute gravity reference stations (2-3 readings per station) during a single loop and tied to stations SA80 and

Figure 3.1: Regional topographic map of the central West Coast.

Red triangles represent 10 absolute gravity reference stations of the New Zealand Gravity Network (Stagpoole, 2013) occupied along SH6 (black line) between Harihari and Fox Glacier. SA80 and SA86 are located near Whataroa. Inset map shows the position of the central West Coast with respect to the central South Island.

SA86 using Gsolve's Method 1, which was the preferred method since it weights all observations equally. Reference station SA47 was found to be a large outlier with a difference of -1.7 mGal between measured and recorded values of absolute gravity. SA47 was subsequently removed from the dataset, reducing the total number of reference stations to 9 and the number of gravity readings to 25 across the loop. Table 3.1 shows the calculated difference between the observed and recorded values of absolute gravity for the 9 reference stations. Figure 3.2 shows a CDF plot of the residuals.

Table 3.1: Absolute gravity difference between observed and recorded values at 9 reference stations from the New Zealand gravity network.

Survey measurements processed by Gsolve for this experiment are provided in Appendix E; Table E.1.

Station	Observed Absolute Gravity (mGal)	Gravity Readings	SE (mGal)	GNS Reference (mGal)	Observed - Reference (mGal)
SA69	980405.919	3	0.019	980405.886	0.033
SA74	980403.536	3	0.019	980403.593	-0.057
SA80	980397.201	3	0.014	980397.200	0.001
SA86	980413.737	3	0.014	980413.739	-0.002
SA90	980418.165	3	0.019	980418.252	-0.087
SA98	980425.135	3	0.019	980425.269	-0.134
SB13	980413.969	2	0.019	980414.014	-0.045
SB28	980379.123	2	0.019	980379.117	0.006
SB6	980411.166	3	0.019	980411.240	-0.074

Figure 3.2: CDF plot of the residuals from Gsolve's normal least squares solution (Method 1)

The black line represents the distribution of the residuals for 25 gravity readings across 9 reference stations.

From these results, it is reasonable to conclude that the normal distribution provides a satisfactory model for the data. Meter precision for the experiment is evaluated from the standard deviation of repeat measurements to be ± 0.015 mGal. There is no evidence that SA80 and SA86 have been disturbed and it is assumed that the recorded reference values of absolute gravity are accurate. Therefore, Gsolve's decoupled least squares solution (Method 2) was selected as the preferred reduction method for the entire survey. Sites identified as significant outliers (SA47, SA98, SA90 & SB6) may be unreliable reference stations for future surveys.

3.2.2 Survey residual analysis

Using Gsolve's decoupled least squares solution (Method 2) (McCubbine et al., 2016), residuals of the least squares fit are computed for the entire survey. The gravity measurements processed by Gsolve for the entire survey are provided in Appendix E; Table E.2.

During processing, Gsolve discards those readings with corresponding residuals that fall outside of the specified confidence interval (CI). Recall from section 2.2.2, a CI of 100% was used in this analysis so that outliers could be identified and individually evaluated. Initial results identified 4 outliers from a total of 760 gravity readings, of which 325 were repeated more than once. The 4 outliers were erroneous gravity readings (i.e. large residual values) that were subsequently removed from the dataset. Non-repeat measurements were excluded from the analysis. Figure 3.3 shows a CDF plot of the residuals.

From these results, it is reasonable to conclude that the normal distribution provides an excellent model for the data. Meter precision for the entire survey is evaluated from the standard deviation of these repeat measurements to be ± 0.015 mGal.

3.2.3 Tidal and drift analysis

In total, 34 primary loops were achieved for the survey. The tidal correction calculated for each gravity reading is provided in Appendix E; Table E.2. For additional reference, drift curves produced by Gsolve for all 34 survey loops are also provided in Appendix E; Figure E.1.

Figure 3.4 shows the distribution of tidal effects calculated by Gsolve for 325 repeat gravity readings.

Figure 3.3: CDF plot of the residuals from Gsolve's decoupled least squares solution (Method 2).

The black line represents the distribution of the residuals and the red line represents the fitted normal distribution.

Figure 3.4: CDF plot of the calculated tidal effects for repeat gravity readings.

The standard deviation of 0.056 mGal, shows that the tidal effect for the survey is at least 3 times the precision of the gravity meter, and hence highlights the importance of both tidal and drift corrections. If the magnitude of the tidal correction is wrong, but the phase correct, then a correlation might be expected with the remaining residuals. By plotting the tidal effects against the residuals for all repeat gravity readings it is hence possible to evaluate the validity of Gsolve's tidal correction (Figure 3.5). As seen in Figure 3.5, there is no correlation between the tidal effects and residuals. The tidal effect calculated using Gsolve provides a satisfactory model for the survey, or there is some remaining tidal effect that is out of phase. No time-series analysis was attempted to look for remaining signals.

Figure 3.5: Scatter plot of the calculated tidal effects and residuals for repeat gravity readings.

3.3 Existing gravity data

The primary aim of this project is to acquire new gravity data and integrate with existing gravity measurements from sediment and bedrock locations to produce gravity maps of the Whataroa River valley that spans the Alpine Fault and the DFDP-2 drill site. To

achieve this objective, existing gravity data were obtained from past surveys that overlap the study area and amalgamated with new gravity data.

3.3.1 Whataroa gravity data

In total, 134 gravity stations were acquired from Davy (2012), which span the Whataroa floodplain and have an estimated uncertainty in the Bouguer gravity anomalies of ± 0.06 mGal. The dataset from Davy (2012) includes 21 re-processed gravity stations originally established by Brikke (2007) across the Whataroa floodplain. The existing coverage of gravity stations overlapping the study area are shown in Figure 3.6.

Figure 3.6: Existing gravity stations over the Whataroa floodplain and Whataroa River valley.

Black dots represent 134 gravity stations established by Davy (2012), which include 21 gravity stations originally established by Brikke (2007). Red line represents the mapped surface trace of the Alpine Fault (NZAFD).

3.4 New gravity data

In total, 466 new gravity observations were established across the study area in the Whataroa River valley (~5x5 km), resulting in an even spread of gravity stations spanning the Alpine Fault and the DFDP-2 drill site.

3.4.1 New gravity station locations

The gravity survey was designed to collect a grid of appropriately spaced gravity stations across the study area to produce gravity maps, while also densifying station coverage over localised features of interest, such as the DFDP-2 borehole and nearby Alpine Fault. Sparse regional measurements were made on bedrock sites away from the valley fill with the aim of capturing the regional gravity trend and separating both long and short-wavelength components. The placement of localised gravity stations was planned before surveying commenced, involving the construction of forward gravity models to determine appropriate site spacing. Gravity models are presented in Chapter 4. Measurement density increases from about one measurement per 100 m² in the centre of the study area to about one measurement per 500 m² on the bounds of the study area. Figure 3.7 shows the coverage of new gravity stations across the study area.

3.5 Gravity maps

New absolute gravity data were amalgamated with existing absolute gravity data, then reduced to Bouguer and residual anomalies as described in Chapter 2. Anomaly maps were constructed with ArcGIS Spatial Analyst using an Inverse Distance Weighted (IDW) and/or an Empirical Bayesian Kriging surface interpolation function.

Figure 3.7: New gravity stations over the study area in the Whataroa River valley.

Black dots represent existing gravity stations; red dots represent new gravity stations. Red line represents the mapped surface trace of the Alpine Fault (NZAFD).

3.5.1 Amalgamation of gravity data

Before the amalgamation of existing and new gravity data, all absolute gravity values calculated by Davy (2012) were converted from the New Zealand Potsdam 1959 gravity datum to the IGSN71 gravity datum by subtracting 15.21 mGal from each existing absolute gravity value as described by Stagpoole (2013).

The amalgamation of the gravity surveys was evaluated by fitting a cubic spline surface through new values and interpolating to sites of existing measurements. Figure 3.8 shows the calculated absolute gravity difference and separation distance between new and existing gravity stations. Assuming a nominal error of 0.015 mGal for the interpolated surface, based on the Gsolve solution, and quoted precision for new measurements, agreement between new and existing measurements was evaluated. The existing gravity stations were found to have been less precisely measured than the new gravity stations.

As seen in Figure 3.8, there is no significant disagreement between new and existing gravity stations where sites are closely spaced. There appears to be an outlier at ~38 m separation distance; however, after >80 m separation, there is significant disagreement between the surveys. Therefore, for mapping purposes, it is appropriate to amalgamate the surveys and remove existing measurements at separations <80 m since they are less precise and represent ‘repeat’ measurements.

Figure 3.8: Absolute gravity difference and separation distance between existing and new gravity stations

A mean gravity difference of 0.12 ± 0.24 mGal was calculated for the 15 existing gravity stations located within 80 m of a new gravity station. To improve the fit between

surveys, 0.12 mGal was subtracted from existing gravity stations established by Davy (2012).

3.5.2 Bouguer gravity anomaly map

The Bouguer gravity anomaly map for both existing and amalgamated datasets are presented to illustrate the improvement in resolution in the Whataroa River valley, both at a regional scale (Whataroa floodplain) and local scale (study area).

Regional scale Bouguer anomaly map

Figure 3.9 shows the increased resolution in the Bouguer gravity anomaly of the Whataroa floodplain for both existing and amalgamated datasets.

Several features of interest are evident in the Bouguer gravity anomaly map constructed using the amalgamated dataset.

- A large gravity low on the Whataroa floodplain originally recognised by Brikke (2007) and later by Davy (2012).
- A prominent gravity gradient originally recognised by Davy (2012), orientated NW-SE on the floodplain becoming more defined and increasingly positive towards the southwest.
- A gravity low resembling a glacial channel appears to be dextrally offset near the range front.
- There is a regional gravity gradient towards the southeast, probably associated with a crustal root beneath the Southern Alps (Allis, 1986; Eberhart-Phillips and Bannister, 2002; Reilly, 1962; Stern, 1995; Woodward, 1979).

Figure 3.9: Bouguer gravity anomaly map of the Whataroa floodplain.

Regional-scale Bouguer gravity anomaly map based on existing data (A) and amalgamated new and existing data (B). Black dots are gravity stations. Red line represents the mapped surface trace of the Alpine Fault (NZAFD). White lines represent river systems. Gravity data has been extrapolated.

Local scale Bouguer anomaly map

Figure 3.10 shows the increased resolution in the Bouguer gravity anomaly of the study area in the Whataroa River valley for both existing and amalgamated datasets.

Several features of interest are evident in the Bouguer gravity anomaly map constructed using the amalgamated dataset.

- The resolution of the Bouguer gravity field has improved significantly in the study area, going from broad and wide contours to sharp and narrow contours revealing significant structure.
- The large gravity low along the range front appears to follow the present-day river trend.
- There is some evidence of a gravity gradient near the range front.
- A dense set of gravity stations surrounding the DFDP-2 drill site indicates a decreasing trend in the Bouguer gravity anomaly toward the centre of the valley.

3.5.3 Residual anomaly map

The residual gravity anomaly map for the amalgamated dataset is presented to illustrate the effect of applying a regional-residual separation to the Bouguer gravity anomaly, both at a regional scale (Whataroa floodplain) and local scale (study area).

Regional scale residual anomaly map

Figure 3.11 shows the quadratic surface fitted to the amalgamated Bouguer gravity data over the Whataroa River valley and the resulting residual gravity anomaly map. The quadratic surface fitted to the overall gravity trend in the Whataroa River valley is expressed in equation 3.1:

$$g_s(x, y) = (0.083x^2 - 0.024y^2 + 0.163xy + 1.692x - 1.089y - 35.874) \text{ mGal} \quad (3.1)$$

Figure 3.10: Bouguer gravity anomaly map of the study area in the Whataroa River valley.

Local-scale Bouguer gravity anomaly map based on existing data (A) and amalgamated new and existing data (B). Black dots are gravity stations. Red lines are surface tectonic lineaments mapped from LIDAR data by Barth et al. (2012). White line represents the Whataroa River. Gravity data has been extrapolated.

Figure 3.11: Regional-residual separation of the Whataroa River valley.

Regional gravity field (A) and the resulting residual gravity field of the Whataroa River valley (B). Black dots are gravity stations, white dots are weighted gravity stations used to determine the regional field. Alpine Fault (red line) (NZAFD). White lines represent river systems. Gravity data has been extrapolated.

where $g_s(x, y)$ is the surface value at some x and y relative to the surface centre at 1389340 Easting, 5203307 Northing.

The fitted surface representing the regional gravity field over the Whataroa River valley shows an increasingly negative gravity trend towards the Southern Alps, and is interpreted to be the gravitational effect of a crustal root beneath the Southern Alps (Allis, 1986; Eberhart-Phillips and Bannister, 2002; Reilly, 1962; Stern, 1995; Woodward, 1979). The residual gravity anomaly map reveals significant structure within the study area, which can be used to describe the shallow sub-surface geometry beneath Whataroa River valley, particularly near the DFDP-2 drill site and Alpine Fault.

Features of interest revealed in the regional scale residual gravity map of the Whataroa River valley (Figure 3.11) include:

- A large residual gravity low (-9 to -10 mGal) beneath the Whataroa floodplain, which is consistent with previous gravity surveys (Brikke, 2007; Davy, 2012).
- Large residual gravity highs (~2 mGal) associated with the ranges on either side of the valley.
- The gravity low along the range front is defined by -3 to -4 mGal contour intervals, which show a strong elongation towards the entrance to the Whataroa River valley.
- There is no clear evidence of a western residual gravity low extending in the northwest direction of the floodplain.

Local scale residual anomaly maps

In order to describe the interesting features discovered in the study area, Figure 3.12 and Figure 3.13 show smaller scale residual gravity maps of the DFDP-2 drill site and Alpine Fault, respectively.

Features of interest revealed in Figure 3.12 include:

- A large elongated residual gravity low defined by -3 to -4 mGal contour intervals next to the DFDP-2 drill site.
- A strong gravity trend in the -1 to -3 mGal range beneath the hillside adjacent to the DFDP-2 drill site, which becomes more negative towards the valley centre. The trend is defined by closely spaced contour lines (high gradient), indicating the presence of a steep density boundary beneath the base of the hillside.

Features of interest revealed in Figure 3.13 include:

- A strong gravity trend in the -1 to -3 mGal range beneath the NE range-front, which becomes more negative toward the floodplain. The strong gravity trend does not appear to be as well-defined on the western range front.
- The strong gravity trend observed along the range front appears to extend SW towards the Whataroa River valley, where the gravity gradient is SE of the frontal thrust (main trace), indicating that there is a moderate or steeply dipping density boundary at depth.

Figure 3.12: Residual anomaly map of the DFDP-2 drill site in the Whataroa River valley.

Black dots are gravity stations, white dots are weighted gravity stations. White line represents the trajectory of the Whataroa River. Gravity data has been extrapolated.

Figure 3.13: Residual anomaly map of the Alpine Fault at the entrance of the Whataroa River valley.

Black dots are gravity stations and white dots are weighted gravity stations. White line represents the trajectory of the Whataroa River. Red lines represent the mapped trace of the Alpine Fault provided by Barth et al. (2012). Gravity data has been extrapolated.

Chapter 4 Gravity models

4.1 Introduction

This chapter presents 2-D sub-surface gravity models constructed from the results of the gravity survey over the Whataroa River valley. Gravity models are presented to explore the sub-surface geometry surrounding the DFDP-2 drill site. A set of profiles are then constructed that cross the nearby Alpine Fault. In addition, it is described how forward gravity models were used to design the survey around these targeted features.

4.2 Gravity modelling

The modelling process involves adjusting the geometry and density of sub-surface geologic units, to fit the calculated gravity signal with the observed residual gravity anomaly. Sediment thickness is constrained by direct observation at the DFDP-2 drill site (Cox et al., 2015; Sutherland et al., 2015), and to be zero if basement rock crops out at the surface. Seismic-reflection constraints on sediment thickness were not available and not used during this study. Based on data and discussion presented in Chapter 1, densities of 2.67 g/cc and 2.1 g/cc are assumed appropriate for bedrock and sediment respectively. Because Bouguer residual anomalies are modelled, the density of the ‘air’ layer is imposed to be 2.67 g/cc.

4.3 Forward gravity models

The following sections present 2-D forward gravity models of sub-surface geometry at the DFDP-2 drill site and Alpine Fault, and were constructed using the GM-SYS package in Oasis montaj developed by Geosoft®, as described in Chapter 2.

4.3.1 DFDP-2 drill site

The DFDP-2 drill site is located on a fluvial terrace ~60 m from a steep hillslope (30-50°) (Figure 4.1). Before drilling commenced, geophysical models and slope projection into the sub-surface indicated a sediment thickness of 100 ± 40 m at the drill site. However, the observed sediment thickness at DFDP-2 was 240 m, which is more than double the value predicted from the projected angle of the adjacent hillside (Sutherland et al., 2015).

To explain how this is geologically possible, three alternative geometric hypotheses were considered before the gravity survey was undertaken:

1. The bedrock-sediment interface between the DFDP-2 drill site and the adjacent hillside is sub-vertical, interpreted as either a glacial U-shaped geometry or a fault (Figure 4.2; Model a).
2. The bedrock-sediment interface between the DFDP-2 drill site and the adjacent hillside is offset by a ~40° thrust fault that dips beneath the hillside (Figure 4.2; Model b).
3. The bedrock-sediment interface between the DFDP-2 drill site and the adjacent hillside is sub-horizontal, with sediment beneath the lower part of the hillside. This interpretation involves a low-angle thrust that is either a splay of the Alpine Fault, or related to slope instability (Figure 4.2; Model c).

Figure 4.1: Aerial photograph of the DFDP-2 drill site.

Grey topography contours (20 m intervals) show the steep hillside adjacent to the DFDP-2 drill site. Survey Zones 1 to 3 shown in white where a dense set of gravity measurements (red dots) were established at the base of the hillside. Aerial photography sourced from Land Information New Zealand (LINZ).

Survey design at the DFDP-2 drill site

Figure 4.2 shows a synthesis of the calculated gravity signals for each geometric hypothesis described above. By comparing the calculated gravity signals based on the differing hypothetical geometries, it is possible to determine the most effective placement of gravity stations at the DFDP-2 drill site.

Figure 4.2: Forward gravity models.

Synthesis of the calculated gravity response (Top) for three forward gravity models (Bottom). Zones 1, 2 and 3 indicate survey areas of interest. Topography shown on models in green. All models can apply to the hillside adjacent to DFDP-2, and the range front adjacent to the Alpine Fault.

As seen in Figure 4.2, there is a clear distinction between each calculated gravity signal across the profile, indicating that each hypothetical geometry has a unique gravity signature. The central area (Zone 2), is where there is the greatest difference in gravity between signals (Δg), indicating Zone 2 is the most useful area to make gravity measurements. Unlike peripheral areas (Zone 1 & Zone 3), where the calculated gravity signals are less distinguishable, measurements made in Zone 2 will ensure the observed gravity signal is clearly identifiable, thus falsifying the other two hypotheses. However, Zone 2 extends across the steep hillslope, which is covered in thick vegetation, making gravity surveying difficult or impossible (Figure 4.1). To address this problem, a plan was made to densify measurements at the base of the hillside, made accessible by a roadway shown in Figure 4.1. The calculated gravity signals between the hypothetical geometries are still distinguishable at the base of the hillside.

Figure 4.1 shows the measured gravity stations at the DFDP-2 survey site, where a dense coverage of gravity measurements (10-20 m site spacing) was achieved along the roadway at the base of the hillside with the addition of two sites located higher on the steep hillslope. These two sites were made accessible by a recent slip which is shown in the aerial photography (Figure 4.1).

The resulting 2-D gravity models of the DFDP-2 drill site constructed using projected gravity stations is presented in Section 4.4.1.

4.3.2 Alpine Fault

An additional aim of this project is to use the amalgamated gravity data to model the shallow structure of the Alpine Fault (<500 m), and define the location of the surface trace across the Whataroa River valley. The surface expression and shallow geometry of the Alpine Fault at the mouth of the Whataroa River valley is not well-defined due to post-glacial burial of the fault zone (Barth et al., 2012; Norris et al., 2012).

Based on the most recent measurements from the DFDP-2 borehole (Sutherland et al., 2015), a southeast dip of 30-60° is estimated on the Alpine Fault at Whataroa. The same forward modelling approach used at the DFDP-2 drill site (Figure 4.2) can also be applied to the Alpine Fault, whereby the sediment-bedrock interface beneath the range front is either sub-vertical (Model a), dipping at an angle typical of a thrust fault (Model b), or sub-horizontal such that sediment protrudes under the range front (Model

c). Just like the DFDP-2 drill site, the forward gravity models also predict a steep gravity gradient along the range front.

Survey design across the Alpine Fault

By applying the same technique used at the DFDP-2 drill site, the calculated gravity signals based on the differing hypothetical geometries across the Alpine Fault are compared, and the most effective placement of gravity stations determined.

Figure 4.3 shows an aerial photograph of the range front and mapped surface trace of the Alpine Fault in the study area. As seen in Figure 4.3, a dense coverage of gravity measurements (50-100 m site spacing) was achieved within the central area (Zone 2). The resulting 2-D gravity models constructed using observed residual anomalies projected along profile lines are presented in Section 4.4.2.

4.4 Whataroa gravity models

Two-dimensional models of the sub-surface geometry surrounding the DFDP-2 drill site and Alpine Fault are compared with the new observations below. The fit of the calculated gravity signal to the observed gravity observations is quantified as the Root Mean Square Error (RMSE, or ‘Error’).

Figure 4.3: Aerial photograph of the study area.

Grey topography contours (100 m intervals) show the steep range front orientated approximately perpendicular to the mapped surface trace of the Alpine Fault (black lines). Survey Zones 1 to 3 shown in white. A dense coverage of gravity measurements (red dots) was established through Zone 2. Aerial photography sourced from Land Information New Zealand (LINZ). Fault trace lineaments from Barth et al. (2012).

4.4.1 DFDP-2 gravity models

Profile 1 with an azimuth of 085° is orientated perpendicular to the steep gravity gradient at the hillside, as shown in Figure 4.4.

Figure 4.4: Residual gravity map of the DFDP-2 drill site showing Profile 1. Profile 1 (black line) is orientated perpendicular to the steep gravity gradient observed at the base of the hillside. Gravity stations (black dots) and the DFDP-2 drill site (yellow dot) are projected onto the profile.

Sediment thickness at the DFDP-2 drill site is constrained to 240 m based on direct observation (Sutherland et al., 2015), providing a constraint for this profile. Basement rock is assumed fixed to the base of the hillside.

Figure 4.5 shows a 2-D model (Model 1A) for Profile 1.

Figure 4.5: Gravity Model 1A for Profile 1 at the DFDP-2 drill site.

Top: observed gravity (black circles), tie point (red star), calculated gravity (black line), and RMSE of the fit (red line). Bottom: projected gravity stations (inverted triangles) extending along the profile. Red dots represent fixed constraints. Blue dot represents structurally inverted point with a confidence ellipse that was estimated by interactively moving the point until the RMSE was considered unacceptable. Zones refer to survey areas identified using forward models.

In order for the calculated signal to fit the observed gravity at the most western station on the hillside (located in Zone 2), a density of 1.8 g/cc is required for the sediment. This unreasonably low value is discussed below.

The simplest possible model was constructed with just one additional sub-surface point (blue dot) located between the base of the hillside and the observed bedrock in the DFDP-2 drill hole. The inversion mode of GM-SYS was used to find the best fitting location of this point. The structurally inverted point suggests a thrust fault may exist under the hillside, resembling pre-survey forward model (b) (Figure 4.2). Structural inversion and its relative uncertainty is discussed in Section 4.5.

Figure 4.6 shows a second 2-D model (Model 1B) for Profile 1.

Figure 4.6: Gravity Model 1B for Profile 1 at the DFDP-2 drill site.

Top: observed gravity (black circles), tie point (red star), calculated gravity (black line), and RMSE of the fit (red line). Bottom: projected gravity stations (inverted triangles) extending along the profile. Red dots represent fixed constraints. Blue dot represents structurally inverted point with confidence ellipse (Section 4.5). Note that the western most station in survey Zone 2 has been removed.

Sediment density has been increased to a value that is more realistic for the Whataroa valley (2.1 g/cc); however, this model requires that the most western gravity station be removed, since this results in a poor fit (exclusion might be justified by survey difficulties on the steep hillside). The new RMS error for the fit is reduced to 0.20 mGal. The structurally inverted point (blue dot) suggests a sub-vertical bedrock-sediment interface may exist under the hillside, resembling the calculated signal produced by pre-survey forward model (a) (Figure 4.2).

Structural inversion and the error estimation for the optimised point (blue dot) in Models 1A and 1B is discussed in Section 4.5.

4.4.2 Alpine Fault gravity models

Figure 4.7 shows gravity Profiles 2, 3, 4 and 5 extending across the mapped surface trace of the Alpine Fault in the study area. All profiles are orientated approximately perpendicular to the steep gravity gradient observed near the range front.

Figure 4.7: Residual gravity map showing all five gravity profiles.

Black symbols represent gravity stations projected to each profile (black lines). Profile 2 (triangles), Profile 3 (crosses), Profile 4 (circles) and Profile 5 (squares). Yellow dot (DFDP-2) and Profile 1 shown for reference. Mapped surface trace of the Alpine Fault (red lines) from Barth et al. (2012). Note the steep gravity gradient observed near the range front.

Sediment thickness is poorly constrained in this part of the study area, leaving only inferences to be made. Based on the modelling of Profile 1, a bulk density of 2.1 g/cc is used for the sediment, and 2.67 g/cc for basement rock. The surface trace of the

Alpine Fault mapped by Barth et al. (2012) provides a valuable constraint for the profiles. Basement rock is assumed to be fixed to the base of the range front.

Figure 4.8 shows a 2-D model (Model 2) for Profile 2.

Figure 4.8: Gravity Model 2 for Profile 2 across the Alpine Fault.

Top: observed gravity (black circles), tie point (red star), calculated gravity (black line), and RMSE of the fit (red line). Bottom: projected gravity stations (inverted triangles) extending along the profile. The profile intersects the Whataroa River and State Highway 6 (SH6).

The RMS error for Model 2 is reasonable (0.23 mGal). Increased error in the centre of the model is likely due to a station projection issue caused by a change in the gravity gradient relative to the azimuth of the profile (Figure 4.7). The steep gravity gradient observed along the range front (Zone 2) is inferred to be caused by the main thrust plane of the Alpine Fault, which is dipping moderately southeast. The fault plane is shown over-thrusting sediment in what is inferred to be a former glacial channel with a sediment thickness of ~350 m at its deepest point. Projection to the surface requires a near-surface decrease in dip, but the fault plane agrees well with the mapped surface trace of the Alpine Fault, identified by Barth et al. (2012) as a thrust fault lineament.

Figure 4.9 shows a 2-D model (Model 3) for Profile 3.

Figure 4.9: Gravity Model 3 for Profile 3 across the Alpine Fault.

Top: observed gravity (black circles), tie point (red star), calculated gravity (black line), and RMSE of the fit (red line). Bottom: projected gravity stations (inverted triangles) extending along the profile. The profile intersects the Whataroa River and State Highway 6 (SH6).

The sub-surface structure in Model 3 correlates well with Model 2. There is a steady increase in the amplitude of the observed gravity signal near the centre of the profile (Zone 2), inferred to be a continuation (NE to SW) of the main thrust plane of the Alpine Fault. The inferred glacial channel is ~50 m deeper than Model 2 at its deepest point. Model 3 is also consistent with the thrust lineament mapped by Barth et al. (2012).

Figure 4.10 shows a 2-D model (Model 4) for Profile 4.

Figure 4.10: Gravity Model 4 for Profile 4 across the Alpine Fault.

Top: observed gravity (black circles), tie point (red star), calculated gravity (black line), and RMSE of the fit (red line). Bottom: projected gravity stations (inverted triangles) extending along the profile. The profile intersects the Whataroa River and State Highway 6 (SH6).

Model 4 correlates well spatially with Models 2 and 3. However, unlike Models 2 and 3, no surface fault trace constraint is mapped. Therefore, based on the interpretation of Models 2 and 3, the observed increase in the gravity signal near the centre of the profile is inferred to be a continuation (NE to SW) of the main thrust plane of the Alpine Fault.

Figure 4.11 shows a 2-D model (Model 5) for Profile 5.

Model 5 contains little evidence of faulting. Based on a very small change in the slope angle of the bedrock-sediment interface produced by the model, and a projection of the mapped surface trace, the Alpine Fault is inferred to project to the surface with a moderately steep dip ($\sim 60^\circ$) to the southeast.

Figure 4.11: Gravity Model 5 for Profile 5 across the Alpine Fault.

Top: observed gravity (black circles), tie point (red star), calculated gravity (black line), and RMSE of the fit (red line). Bottom: projected gravity stations (inverted triangles) extending along the profile. The profile intersects State Highway 6 (SH6).

Based on the geometry of all four Models of the Alpine Fault presented above, the following inference is made about the location of the surface fault trace across the Whataroa River valley (Figure 4.12).

Figure 4.12: Inferred location of the Alpine Fault surface trace across the Whataroa River valley.

The inferred surface trace of the Alpine Fault (black line) intersects Profiles 2 to 5 based on the results of Models 2 to 5 and correlates well with the surface trace (red lines) mapped by Barth et al. (2012). Aerial photography from Land Information New Zealand (LINZ).

4.5 Gravity structural inversion and uncertainty

An inversion algorithm built into GM-SYS was used for Models 1A and 1B. A single point located between two structural constraints (hillside, DFDP-2B) is allowed to vary in the xy-plane to minimise misfit between the calculated and observed gravity. Multiple iterations were made until the inversion point could not be improved. The inversion process was then restarted with different starting points. The final result was found to be robust in both models.

A confidence region (error ellipse) was estimated by manually moving the optimized point until the visual fit to the data was considered unreasonably poor. The confidence region corresponds approximately to a contour of fit ($\text{RMSE} = 0.35 \text{ mGal}$). These alternative versions of Model 1A are shown in Figure 4.13.

Figure 4.14 shows similar sensitivity analysis for the inversion results for Model 1B on Profile 1.

Figure 4.13: Model 1A structural inversion and uncertainty.

Top: Observed and calculated gravity response to points A, B, C and D. Bottom: The optimised point (near centre of ellipse) is manually shifted to locations A, B, C and D in the xy-plane to estimate a margin of error.

Figure 4.14: Model 1B structural inversion and uncertainty.

Top: Observed and calculated gravity response to points A, B, C and D. Bottom: The optimised point (near bottom of ellipse) is manually shifted to locations A, B, C and D in the xy-plane to estimate a margin of error.

Chapter 5 Discussion and conclusions

5.1 Discussion

5.1.1 Gravity maps

The effects of extensive erosion and faulting in the Whataroa River valley is observable in the Bouguer gravity and residual gravity maps presented in Section 3.5. Below is discussion of interesting features identified in Figures 3.9 to 3.13.

Offset erosional features

A prominent gravity low beneath the Whataroa floodplain originally recognised by Brikke (2007) and later by Davy (2012) indicates the presence of a lower density material, and hence, structural low beneath the floodplain. This feature, and a steep gravity gradient refined by Davy (2012) and by this study, has previously been inferred to be a large kettle hole carved during the Waimea glaciation (~140 ka), dextrally offset by ~3.5 km from the entrance to the Whataroa River valley, suggesting a horizontal displacement rate of 25 mm/yr on the central Alpine Fault at Whataroa (Brikke, 2007). While this estimate agrees with other estimates of Quaternary horizontal displacement rates on the Alpine Fault in South Westland (Sutherland et al., 2006; Sutherland and Norris, 1995), it must be taken with caution given the sense of motion and segmentation of the Alpine Fault across the Whataroa River valley (Barth et al., 2012). Well-constrained dated offsets are required to draw such a conclusion.

In addition to the large offset gravity low beneath the Whataroa floodplain, this study has defined a dextrally offset glacial channel at the entrance to the Whataroa River valley. Given that the best estimates of Quaternary horizontal-slip rates on the central Alpine Fault range between 20-30 mm/yr (Barth et al., 2013; Cooper and Norris, 1994; Norris and Cooper, 1997; Norris and Cooper, 2001; Sutherland et al., 2006; Sutherland

and Norris, 1995; Wright, 1998), we would expect a dextral channel offset of between 340-510 m, assuming an LGM channel age of ~ 17 kyr (Barrows et al., 2013). Using gravity data and surface topography, Davy et al. (2013) measured a channel offset of 372 ± 159 m at Whataroa, and estimated a horizontal displacement rate of 20 ± 9 mm/yr, assuming a channel age of 19 ± 1 kyr. However, the uncertainties associated with this technique are significant (Davy, 2012; Davy et al., 2013).

No obvious small-scale (340-510 m) horizontal offset is observable in the new gravity maps. This study shows that the Whataroa glacier turned to the northeast and followed the trace of the Alpine Fault, which complicates the determination of an offset. Improved techniques for measuring well-constrained ages and distances of offset sub-surface features, accompanied with a joint interpretation with other geophysical methods (e.g. seismic-reflection data) are required to estimate both a reliable horizontal- and vertical-displacement rate for the Alpine Fault at Whataroa.

Local gravity gradients

The new gravity maps reveal a high gravity gradient SE of the mapped frontal thrust of the Alpine Fault (main trace), inferred to be a moderate to steeply dipping density boundary at depth, suggesting the main thrust fault plane shallows in the near surface. Additionally, the gravity maps reveal a strong gravity trend along the hillside adjacent to the DFDP-2 drill site, inferred to be a steeply dipping density boundary buried beneath the hillside.

The sub-surface geometry of the Alpine Fault and DFDP-2 drill site based on the results of the gravity models is discussed in more detail in Section 5.1.2.

Regional gravity gradient

Reduction of the regional gravity field reveals a large regional gravity gradient decreasing towards the southeast, probably associated with the South Westland Basin in the northwest (Davy et al., 2013), and the crustal root beneath the Southern Alps (Allis, 1986; Eberhart-Phillips and Bannister, 2002; Reilly, 1962; Stern, 1995; Woodward, 1979). Subtraction of the regional gravity field from the Bouguer gravity data appears to have successfully removed the large southeast regional gravity gradient, revealing significant short-wavelength structure in the study area, including a previously unknown gravity anomaly near the DFDP-2 drill site (discussed below).

Residual gravity highs (~2 mGal) associated with ranges on either side of the Whataroa valley may suggest the density used for terrain corrections was too high, but this cannot explain all of the variability. It is possible that sites used to fit the regional field were too close to the valley fill. Overall, the regional-residual separation appears to have successfully defined target features to a reasonable level of accuracy, and local DC-shift corrections were applied to individual profiles, as explained in Chapter 4.

Additional measurements with a good spatial coverage across the ranges surrounding the study area are required to improve the measurement of the regional gravity field.

Whataroa valley erosional features

After removal of the regional gravity field, a well-defined residual gravity low (-4 mGal) was observed near the DFDP-2 drill site. Based on initial interpretations, the gravity low is inferred to be the result of cyclic ice advance and subsequent glacial erosion, likely during the Otiran LGM, between 26-17 ka (Barrows et al., 2013). Following glacial retreat on the West Coast from LGM limits ~18 ka (Almond et al., 2001; Barrell et al., 2013; Newnham et al., 2003; Putnam et al., 2013; Shulmeister et al., 2005; Vandergoes and Fitzsimons, 2003; Williams, 1996), ice is inferred to have receded over the Alpine Fault at Whataroa ~16.3-14.8 ka, based on evidence from South Westland (Sutherland and Norris, 1995).

The inferred timing of ice retreat across the Alpine Fault at Whataroa is consistent with the depositional age of lacustrine sediments (16.35-15.8 ka) observed in the DFDP-2 drill core ~1 km south of the mapped fault trace (Cox et al., 2015; Sutherland et al., 2015). This implies that the residual gravity low observed beneath the DFDP-2 drill site is the remnants of a glacial over-deepening carved during ice advance, that was subsequently filled with pro-glacial lake sediments during ice retreat and melting up the Whataroa River valley.

Cox et al. (2015) imply that the lake sediments sampled in DFDP-2 may correlate to the oldest lake sediments in Lakes Wahapo and Rotokino, suggesting a substantial (~100 km²) pro-glacial lake once extended across the Whataroa floodplain. The evolution of this large ice-marginal lake likely involved a combination of dam types, and evolved through a sequence of different lake/dam configurations (Carrivick and Tweed, 2013).

A detailed history of ice advance and retreat in the Whataroa River valley, including a comprehensive interpretation of the lake sediments sampled in the DFDP-2 drill hole, will greatly improve our understanding of the interesting features identified by this study.

5.1.2 Sub-surface geometry

DFDP-2 drill site

Two-dimensional gravity models of the sub-surface geometry beneath the hillside adjacent to the DFDP-2 drill site reveal either a reverse dipping bedrock-sediment interface, based on a sediment density of 1.8 g/cc (Model 1A; Figure 4.5), or a sub-vertical bedrock-sediment interface, based on a sediment density of 2.1 g/cc (Model 1B; Figure 4.6).

Based on provisional interpretations of sediments sampled in the DFDP-2 borehole (Cox et al., 2015; Sutherland et al., 2015), which includes lake silts between 60 and 200 m, and assuming the porosity of the lake silts follow the same trend as the Taranaki mudstone compaction curve (Funnell et al., 1996), it is plausible to have a very low sediment density of 1.8 g/cc beneath the drill site. For example, if we take the quoted surface porosity (54 %) and the compaction constant (2000 m) of Taranaki mud and apply those values to the lake silts, we can calculate a porosity range between 60 and 200 m depth using equation 5.1 (Funnell et al., 1996):

$$\phi = \phi_0 \exp\left(\frac{-z}{d}\right) \quad (5.1)$$

where ϕ is porosity, z is depth in meters, ϕ_0 is the initial surface porosity (54 %), and d is the compaction constant (2000 m).

Assuming a grain density of 2.7 g/cc, the mean density of the lake silts between 60 and 200 m is 1.84 ± 0.02 g/cc (Figure 5.1).

Figure 5.1: Calculated mean density of lake silts sampled in DFDP-2.

Depth range of the lake silts shown in red.

However, approximately 30 % of sediment sampled in the DFDP-2 drill hole is gravel (Sutherland et al., 2015), introducing additional density to the lake silts, suggesting 2.1 g/cc is a better estimate of the bulk density of sediment beneath the drill site.

Modelling of the bedrock-sediment interface using a sediment density of 1.8 g/cc (Model 1A; Figure 4.5) fits the single gravity station (WDSS028) located high on the hillside within the preferred survey area (Zone 2), which has an estimated total uncertainty of ± 0.3 mGal (see Appendix C; page 142). In addition, a reasonable error of ± 0.3 mGal was estimated for the structurally inverted point in Model 1A (Figure 4.13), implying that even with a very low sediment density, Model 1A is still a plausible model for the sub-surface geometry beneath the hillside.

While maintaining all fixed constraints of Model 1A, a misfit of gravity station WDSS028 was observed after increasing the sediment density to 2.1 g/cc. Subsequent removal of WDSS028 (Model 1B; Figure 4.6), and structural inversion of the optimised point beneath the hillside, yields a reasonable error of ± 0.2 -0.3 mGal for the model (Figure 4.14), implying Model 1B is also plausible if the point on the hillside is removed.

Based on these results, the bedrock-sediment interface beneath the hillside is either a thrust fault, possibly a splay of the Alpine Fault or large landslide, or a sub-vertical bedrock-sediment interface, typical of U-shaped geomorphology, possibly the steep wall of the inferred over-deepening beneath the DFDP-2 drill site. A denser coverage of gravity stations is required on the hillside to demonstrate measurement repeatability and better define the sub-surface geometry near the DFDP-2 drill site. Improved GPS technologies capable of penetrating the thick vegetation on the hillside are essential for obtaining accurate height measurements of hillside gravity stations.

To suggest a possible mechanism to explain how a steep U-shaped glacial geomorphology may exist beneath the hillside, particularly in an area of extensive fluvial erosion (Herman and Braun, 2006; Hovius et al., 1997; Korup et al., 2004; Korup et al., 2005), rapid sedimentation recorded in the DFDP-2 sequence (Cox et al., 2015) may have filled the valley vertically and buttressed the valley walls before they had a chance to fail. This is a common observation at present-day Fox and Franz Josef glaciers, where steep valley walls protrude from the sediment.

It is important to note that either a thrust fault, or a steep valley wall has been defined only at the entrance of the Whataroa valley. Additional gravity measurements are required up-valley to delineate the extent of the observed gravity anomaly beneath the DFDP-2 drill site.

Alpine Fault

Based on data and discussion presented in Chapter 1, an assumed sediment density of 2.1 g/cc was considered a reasonable value for 2-D gravity models of the sub-surface geometry beneath the range front. Comparison of Alpine Fault models (Section 4.4.2; Models 2 to 4) reveal a reverse dipping bedrock-sediment interface, inferred to be a moderate to steeply dipping density boundary at depth. The gravity gradient near the eastern range front provides a location where the basal contact of the sediment is offset. In order for the mapped frontal thrust to connect to the offset basal contact, a low-dip is required near the surface, consistent with previous studies of shallow Alpine Fault geometry (Cooper and Norris, 1994; Norris and Cooper, 1995). No significant evidence of faulting was observed in Model 5 located on the western range front, and no significant gravity gradient was observed in the gravity maps at this location, suggesting separate modes of faulting exist on either side of the valley entrance.

Assuming a constant vertical displacement rate of 6 ± 1 mm/yr calculated in the Whataroa River valley (De Pascale and Davies, 2014), and assuming a glacial channel age of 17 kyr (Barrows et al., 2013), we would expect a vertical offset of 102 m on the Alpine Fault at Whataroa. Two of the four Alpine Fault models (Models 2 and 4) suggest a vertical offset of ~100 m protrudes from the floor of the buried glacial channel.

A major limitation of the Alpine Fault models is a lack of independent geometrical constraints from seismic surveys. However, these preliminary models (seismic survey data will be available in future) are geologically reasonable, and fit well with the observed gravity signal across the range front.

5.2 Future work

The high-precision gravity data collected and processed during this study may be used for many future projects, including, but not limited to:

- Joint modelling with other geophysical data (e.g. seismic-reflection and magnetic data) and physical properties measurements (e.g. density of borehole sediments), allowing for a comprehensive joint interpretation of sub-surface structure near the Alpine Fault and DFDP-2 drill hole in the Whataroa River valley.
- Interpolation of sediment thickness determined by seismic-reflection methods and hence estimation of a sediment-volume beneath the Whataroa River valley, providing valuable insight into the erosional history of the valley.
- Constraints on the offset of sub-surface features by the Alpine Fault.

5.3 Recommendations

To make the amalgamation of existing and new gravity data as easy as possible, it is recommended that surveyors reproduce their raw datasets in a standardised manner, whereby spreadsheets are provided with required header information (e.g. Appendix C), similar to the SEG-Y (Society of Exploration Geophysics) standard used for seismic

data. Such a standard will increase efficiency and prevent data from being lost or misinterpreted.

5.4 Conclusions

The collection of 466 high-precision (0.015 mGal) gravity observations has allowed production of high-quality gravity anomaly maps at the DFDP-2 drill site and nearby Alpine Fault. Key findings of this study based on interpretation of those maps are listed below:

- A buried dextrally-offset glacial channel extending along the northeast range front, interpreted to be at least 350-450 m at its deepest point.
- Evidence of thrust faulting along the northeast range front based on interpretation of a well-defined steep gravity gradient.
- An inferred location of the near-surface trace of the Alpine Fault across the Whataroa River valley, consistent with structural lineaments mapped by Barth et al. (2012) along the range front.
- A large gravity low beneath the DFDP-2 drill site, interpreted to be a glacial over-deepening in the Whataroa River valley, consistent with lake sediments sampled in the DFDP-2 drill hole (Sutherland et al., 2015).
- A steep gravity gradient along the hillside adjacent to the DFDP-2 drill site, interpreted to be either a reverse fault, or a steep valley wall, depending on the density of the sediment assumed.

Appendix A Gravity Charts

Zone:	B	C	D	E	F	G
R (m): 2	166	53.3	170	390	895	1530
N	4	6	6	8	8	12
1	0.5	1.9	3.3	7.6	11.5	24.9
2	0.7	2.6	4.7	10.7	16.3	35.1
3	0.8	3.2	5.8	13.1	19.9	43.3
4	1.0	3.8	6.7	15.2	23.0	49.8
5	1.1	4.2	7.5	17.0	25.7	55.6
6	1.2	4.6	8.2	18.6	28.2	60.9
7	1.3	5.0	8.9	20.1	30.4	65.8
8	1.4	5.4	9.5	21.5	32.6	70.4
9	1.5	5.7	10.1	22.9	34.5	74.7
10	1.6	6.0	10.6	24.1	36.4	78.7
20	2.4	8.7	15.1	34.2	51.6	111.6
30	3.2	10.9	18.6	42.1	63.3	136.9
40	3.9	12.9	21.7	48.8	73.2	158.3
50	4.6	14.7	24.4	54.8	82.0	177.4
60	5.3	16.5	26.9	60.2	90.0	194.7
70	6.1	18.2	29.3	65.3	97.3	210.7
80	6.9	19.9	31.5	70.1	104.2	225.6
90	7.8	21.6	33.7	74.7	110.8	239.8
100	8.7	23.4	35.7	79.1	117.0	253.2

Effect (μGal):

Height differences (metres)

Continued on next page

Zone:	H	I	J	K	L	M
R(km): 1.53	2.61	4.47	6.65	9.9	14.7	21.9
N:	12	12	16	16	16	16
1	32	42	72	88	101	125
2	46	60	101	124	148	182
3	56	74	125	153	186	225
4	65	85	144	176	213	262
5	73	95	161	197	239	291
6	80	104	176	216	261	319
7	86	112	191	233	282	346
8	92	120	204	249	303	370
9	96	127	216	264	322	391
10	103	134	228	278	338	413
20	146	190	322	394	479	586
30	179	233	396	483	587	717
40	206	269	457	557	679	828
50	231	301	511	624	759	926
60	253	330	561	683	832	1015
70	274	357	606	738	899	1097
80	293	382	648	790	962	1173
90	311	405	688	838	1020	1244
100	328	427	726	884	1076	1312

Effect (μGal):

Height differences (metres)

Table A.1: Hammer terrain correction chart.

Terrain corrections are shown for Hammer zones B to M, in μGal , and per compartment. Note that $1 \mu\text{Gal} = 0.001 \text{ mGal}$. Inner and outer radii of the zones are listed in row R, in meters for zones B-G and in kilometres for zones H-M. The number of compartments within a zone are listed in row N. The table lists the exact height differences that, assuming a density of 2670 kg/m^3 , will produce the tabulated terrain effects (Milsom, 2003).

MILLIGAL VALUES FOR LACOSTE & ROMBERG, INC. MODEL G GRAVITY METER #G- 519					
COUNTER READING*	VALUE IN MILLIGALS	FACTOR FOR INTERVAL	COUNTER READING*	VALUE IN MILLIGALS	FACTOR FOR INTERVAL
000	000.00	1.01235			
100	101.24	1.01223	3600	3644.52	1.01326
200	202.46	1.01213	3700	3745.85	1.01327
300	303.67	1.01205	3800	3847.18	1.01330
400	404.88	1.01199	3900	3948.51	1.01332
500	506.08	1.01194	4000	4049.84	1.01334
600	607.27	1.01192	4100	4151.17	1.01335
700	708.46	1.01189	4200	4252.51	1.01336
800	809.65	1.01187	4300	4353.84	1.01336
900	910.84	1.01187	4400	4455.18	1.01334
1000	1012.02	1.01187	4500	4556.51	1.01332
1100	1113.21	1.01188	4600	4657.85	1.01329
1200	1214.40	1.01189	4700	4759.17	1.01324
1300	1315.59	1.01191	4800	4860.50	1.01317
1400	1416.78	1.01192	4900	4961.82	1.01307
1500	1517.97	1.01196	5000	5063.12	1.01295
1600	1619.17	1.01202	5100	5164.42	1.01284
1700	1720.37	1.01207	5200	5265.70	1.01270
1800	1821.58	1.01214	5300	5366.97	1.01254
1900	1922.79	1.01221	5400	5468.23	1.01236
2000	2024.01	1.01228	5500	5569.46	1.01217
2100	2125.24	1.01235	5600	5670.68	1.01194
2200	2226.47	1.01243	5700	5771.87	1.01167
2300	2327.72	1.01251	5800	5873.04	1.01140
2400	2428.97	1.01260	5900	5974.18	1.01110
2500	2530.23	1.01269	6000	6075.29	1.01081
2600	2631.50	1.01276	6100	6176.37	1.01050
2700	2732.77	1.01283	6200	6277.42	1.01019
2800	2834.06	1.01289	6300	6300.44	1.00086
2900	2935.35	1.01295	6400	6400.53	1.00953
3000	3036.64	1.01301	6500	6500.48	1.00922
3100	3137.94	1.01307	6600	6600.40	1.00882
3200	3239.25	1.01312	6700	6700.28	1.00835
3300	3340.56	1.01317	6800	6800.32	1.00781
3400	3441.88	1.01322	6900	6900.10	1.00722
3500	3543.20	1.01324	7000	7000.82	

* Note: Right-hand wheel on counter indicates approximately 0.1 milligal.

Table A.2: Calibration table for a Lacoste & Romberg model G-519 gravity meter.

Appendix B Detailed Gravity Meter Technique

The general procedure for taking a gravity measurement requires great care and patience. Firstly, to avoid problems with levelling the meter, it is essential to select a site that is as cemented as possible, such as exposed rock. In soft grassy areas, a spade is used to remove loose material and create a solid platform for the plate. The meter is then placed on the plate and levelled using both bubble levels and electronic levellers. The meter's internal beam is then released by turning the knurled arrestment knob, or clamp, counter-clockwise to its limit. The position of the beam is determined by assessing the crosshair in the microscope. Each meter model has a unique reading line, such as the G-model used in this study (reading line 2.2). To balance the beam, the left side of the crosshair is brought to the reading line by turning the nulling dial either left or right. For uniformity, it is essential to approach the reading line from the same direction, whereby each reading is made by approaching the reading line from left to right (turning clockwise). The slack in the gears and universal joint will cause an error if the reading line is not approached always from the same direction. The meter reading is then obtained from the counter and nulling dial, which is later converted to milligal using the meter's latest calibration table (Appendix A). Finally, the internal beam is stabilised by turning the knurled arrestment knob, or clamp, clockwise to its limit, and the meter is ready for transport to the next station.

Appendix C Gravity Data

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
SA80	-43.27747	170.41729	1390433	5205133.1	97.747	13.30	980397.20	980431.59	-34.39	-0.77	0.34
SA86	-43.26583	170.37515	1386972.7	5206319.2	70.667	3.81	980413.74	980445.37	-31.63	-2.51	0.07
WAD001	-43.28881	170.46064	1393989	5203980.7	1449.472	23.18	980119.08	980156.86	-37.79	-0.30	0.31
WAD002	-43.2895	170.46033	1393966.1	5203903.7	1438.522	23.05	980121.92	980159.20	-37.28	0.39	0.31
WAFS001	-43.28436	170.39429	1388590.4	5204309.5	86.64	9.88	980404.95	980437.82	-32.88	0.58	0.34
WAFS002	-43.28398	170.39443	1388600.8	5204351.9	87.508	9.43	980404.96	980438.07	-33.11	0.30	0.34
WAFS003	-43.28361	170.39456	1388609.9	5204393.3	87.545	9.12	980405.00	980438.34	-33.35	0.01	0.34
WAFS004	-43.28323	170.39469	1388619.1	5204435.9	87.997	8.83	980404.88	980438.50	-33.63	-0.33	0.34
WAFS005	-43.28286	170.39482	1388628.6	5204477.4	87.454	8.59	980404.90	980438.82	-33.92	-0.68	0.34
WAFS006	-43.28249	170.39495	1388637.8	5204519.5	85.866	8.38	980405.10	980439.31	-34.21	-1.02	0.34
WAFS007	-43.2821	170.39508	1388646.8	5204563.1	88.091	8.17	980404.70	980439.05	-34.34	-1.21	0.34
WAFS008	-43.28172	170.39522	1388656.4	5204605.4	87.252	7.98	980404.91	980439.37	-34.46	-1.38	0.34
WAFS009	-43.28135	170.39534	1388665.2	5204646.7	86.139	7.81	980405.17	980439.72	-34.55	-1.52	0.34
WAFS010	-43.28095	170.39548	1388674.8	5204691.3	85.659	7.65	980405.27	980439.94	-34.66	-1.70	0.34
WAFS011	-43.28054	170.39561	1388684.7	5204736.9	85.491	7.50	980405.30	980440.08	-34.79	-1.88	0.34
WAFS012	-43.27974	170.39589	1388704.4	5204826.9	85.229	7.24	980405.30	980440.33	-35.03	-2.24	0.09
WAFS013	-43.27896	170.3962	1388726.9	5204914	85.451	7.03	980405.22	980440.43	-35.20	-2.53	0.09
WAFS014	-43.28413	170.39212	1388413.6	5204329.1	88.947	9.49	980405.06	980437.74	-32.68	0.56	0.34
WAFS015	-43.28034	170.40385	1389352	5204780.3	84.246	8.16	980402.99	980439.66	-36.67	-3.23	0.34
WAFS016	-43.27996	170.40346	1389319.7	5204821	84.953	7.98	980403.16	980439.66	-36.50	-3.15	0.34
WAFS017	-43.27959	170.40314	1389292	5204861.7	84.925	7.82	980403.53	980439.79	-36.26	-3.00	0.34
WAFS018	-43.27924	170.40278	1389262	5204899.5	84.919	7.69	980403.79	980439.89	-36.10	-2.92	0.34
WAFS019	-43.27892	170.40246	1389234.8	5204934.7	83.645	7.59	980404.28	980440.22	-35.94	-2.84	0.34
WAFS020	-43.2786	170.40218	1389210.9	5204968.9	84.023	7.49	980404.39	980440.21	-35.82	-2.80	0.34
WAFS021	-43.27825	170.40188	1389184.9	5205007.9	82.482	7.40	980404.82	980440.57	-35.76	-2.82	0.34
WAFS022	-43.2779	170.40155	1389157.2	5205045.4	81.402	7.29	980405.19	980440.86	-35.67	-2.82	0.34
WAFS023	-43.27922	170.40533	1389468.6	5204908.3	84.132	8.11	980402.67	980439.63	-36.95	-3.62	0.34
WAFS024	-43.27884	170.40502	1389441.9	5204950	83.115	7.95	980403.39	980439.95	-36.56	-3.32	0.34
WAFS025	-43.27848	170.40475	1389418.6	5204989.4	83.958	7.82	980403.58	980439.89	-36.30	-3.15	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom Res Anom (mGal)	Error (mGal)	
WAFS026	-43.27812	170.40437	1389386.6	5205028.2	83.073	7.67	980404.08	980440.17	-36.09	-3.02	0.34
WAFS027	-43.27776	170.40411	1389364.1	5205067.9	81.949	7.56	980404.44	980440.48	-36.04	-3.05	0.34
WAFS028	-43.2774	170.40382	1389339.6	5205106.4	83.152	7.44	980404.40	980440.32	-35.93	-3.02	0.34
WAFS029	-43.27715	170.40348	1389311.3	5205133.7	83.15	7.35	980404.51	980440.39	-35.88	-3.04	0.34
WAFS030	-43.27685	170.40315	1389283.4	5205166	81.42	7.24	980404.99	980440.82	-35.83	-3.06	0.34
WAFS031	-43.2765	170.40278	1389252.1	5205203.6	83.42	7.11	980404.76	980440.52	-35.76	-3.08	0.34
WAFS032	-43.27614	170.40249	1389227.1	5205243.1	81.58	7.00	980405.26	980440.96	-35.71	-3.11	0.34
WAFS033	-43.27588	170.40228	1389209.8	5205271.8	80.147	6.91	980405.61	980441.31	-35.70	-3.16	0.34
WAFS034	-43.2789	170.40764	1389655	5204949.8	80.284	8.56	980402.69	980439.90	-37.21	-3.80	0.34
WAFS035	-43.27857	170.40719	1389616.8	5204984.8	82.958	8.34	980402.47	980439.57	-37.10	-3.78	0.34
WAFS036	-43.27819	170.40683	1389586.8	5205026.7	82.896	8.17	980402.99	980439.72	-36.72	-3.49	0.34
WAFS037	-43.27776	170.40653	1389560.4	5205073.7	81.265	8.00	980403.74	980440.17	-36.42	-3.29	0.34
WAFS038	-43.27732	170.40621	1389533.7	5205121.3	81.569	7.84	980403.99	980440.23	-36.24	-3.21	0.34
WAFS039	-43.27695	170.40594	1389510.4	5205162.3	80.927	7.70	980404.30	980440.46	-36.16	-3.21	0.34
WAFS040	-43.2766	170.40553	1389475.8	5205199.9	82.119	7.54	980404.28	980440.35	-36.07	-3.21	0.34
WAFS041	-43.27619	170.40518	1389445.6	5205244.4	81.672	7.39	980404.56	980440.55	-35.99	-3.23	0.34
WAFS042	-43.27581	170.4049	1389421.4	5205286.1	80.727	7.27	980404.89	980440.83	-35.94	-3.26	0.34
WAFS043	-43.27543	170.40453	1389390.7	5205327.6	81.89	7.13	980404.81	980440.70	-35.89	-3.30	0.34
WAFS044	-43.27496	170.40418	1389360.3	5205378	81.691	6.99	980405.11	980440.84	-35.73	-3.24	0.34
WAFS045	-43.27433	170.40633	1389532.5	5205453.6	79.335	7.21	980405.00	980441.02	-36.03	-3.53	0.34
WAFS046	-43.27485	170.40672	1389566	5205397	80.01	7.40	980404.64	980440.75	-36.12	-3.51	0.34
WAFS047	-43.278	170.40927	1389783.9	5205053.8	79.234	8.77	980402.81	980439.82	-37.02	-3.68	0.34
WAFS048	-43.27754	170.40882	1389745.5	5205103.3	81.281	8.51	980402.59	980439.63	-37.05	-3.83	0.34
WAFS049	-43.27714	170.40851	1389719.5	5205147.8	80.953	8.32	980402.92	980439.85	-36.93	-3.81	0.34
WAFS050	-43.27669	170.40823	1389694.9	5205197	80.282	8.14	980403.52	980440.12	-36.60	-3.57	0.34
WAFS051	-43.27628	170.40792	1389668.6	5205240.9	80.382	7.98	980403.77	980440.23	-36.45	-3.52	0.34
WAFS052	-43.27584	170.40767	1389646.4	5205289.3	81.139	7.82	980403.83	980440.20	-36.37	-3.52	0.34
WAFS053	-43.27523	170.40709	1389597.8	5205355.4	80.826	7.55	980404.17	980440.47	-36.30	-3.61	0.34
WAFS054	-43.275	170.40911	1389760.4	5205386	79.322	8.00	980403.83	980440.30	-36.47	-3.71	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
WAFS055	-43.27547	170.40934	1389780.9	5205335.2	77.926	8.16	980403.94	980440.46	-36.52	-3.66	0.34
WAFS056	-43.276	170.40983	1389822.1	5205277.8	79.453	8.42	980403.15	980439.94	-36.79	-3.81	0.34
057	-43.27638	170.41032	1389863.7	5205236.9	79.343	8.68	980402.70	980439.74	-37.04	-3.96	0.34
058	-43.27673	170.41068	1389894.4	5205198.3	79.313	8.90	980402.52	980439.56	-37.04	-3.88	0.34
059	-43.2761	170.41153	1389961.1	5205270.2	78.765	9.04	980402.44	980439.47	-37.02	-3.93	0.34
060	-43.28566	170.40086	1389127.8	5204182	89.051	11.47	980400.37	980435.88	-35.51	-1.30	0.34
061	-43.28558	170.40186	1389209	5204193.1	92.461	10.92	980400.35	980435.76	-35.41	-1.14	0.34
062	-43.28458	170.40098	1389133.8	5204302.4	91.978	9.83	980401.61	980436.84	-35.23	-1.21	0.34
063	-43.28377	170.40108	1389139.4	5204392	93.462	9.25	980401.97	980437.07	-35.09	-1.21	0.34
064	-43.28288	170.40116	1389143.1	5204491.8	91.571	8.82	980402.38	980437.79	-35.41	-1.68	0.34
065	-43.28189	170.40109	1389133.7	5204601.2	92.813	8.44	980402.73	980437.83	-35.10	-1.56	0.34
066	-43.28118	170.40076	1389104.8	5204679.4	88.411	8.07	980403.07	980439.00	-35.94	-2.55	0.34
067	-43.28023	170.40054	1389083.1	5204784.5	87.678	7.77	980403.77	980439.36	-35.59	-2.39	0.34
068	-43.27945	170.40057	1389083.4	5204870.3	87.606	7.59	980403.96	980439.48	-35.52	-2.45	0.34
069	-43.27852	170.40059	1389081.4	5204973.9	87.962	7.36	980404.34	980439.56	-35.22	-2.32	0.34
070	-43.28499	170.40094	1389131.8	5204256.7	91.617	10.21	980401.39	980436.57	-35.18	-1.09	0.34
071	-43.28418	170.40103	1389137	5204346.4	91.59	9.52	980401.72	980437.20	-35.48	-1.53	0.34
072	-43.27762	170.40072	1389088.6	5205074.6	86.252	7.16	980404.51	980440.02	-35.51	-2.76	0.34
073	-43.27668	170.40041	1389060.6	5205178.2	85.342	6.88	980404.84	980440.39	-35.55	-2.98	0.09
074	-43.27585	170.40084	1389092.2	5205270.7	85.764	6.73	980404.89	980440.38	-35.49	-3.04	0.09
075	-43.27522	170.40167	1389157.6	5205343.2	83.499	6.70	980404.88	980440.80	-35.92	-3.54	0.09
076	-43.27324	170.40037	1389045.2	5205560	78.197	6.19	980406.65	980442.17	-35.53	-3.56	0.09
077	-43.27258	170.40293	1389250.5	5205640.1	82.696	6.39	980406.06	980441.03	-34.97	-2.98	0.09
078	-43.27218	170.40498	1389415.4	5205689.4	79.825	6.59	980405.95	980441.35	-35.40	-3.37	0.09
079	-43.27247	170.40687	1389570.1	5205661.9	81.205	6.95	980404.91	980440.75	-35.84	-3.66	0.34
080	-43.27263	170.40905	1389747.6	5205649.8	79.335	7.43	980404.42	980440.65	-36.24	-3.92	0.34
081	-43.27276	170.41175	1389967.3	5205641.4	77.229	8.21	980403.83	980440.30	-36.47	-4.01	0.34
082	-43.2727	170.41538	1390261.3	5205657.8	76.701	9.86	980401.68	980438.75	-37.07	-4.46	0.34
083	-43.2741	170.40357	1389307.6	5205473	84.736	6.80	980404.88	980440.36	-35.48	-3.18	0.09

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom Res Anom (mGal)	Error (mGal)	
WAFS084	-43.27341	170.40558	1389468.6	5205554.2	83.906	7.05	980404.55	980440.21	-35.66	-3.38	0.34
WAFS085	-43.2736	170.40778	1389647.5	5205538.5	81.694	7.40	980404.20	980440.31	-36.11	-3.68	0.34
WAFS086	-43.27395	170.4099	1389820.8	5205505.6	79.833	7.94	980403.74	980440.17	-36.43	-3.83	0.34
WAFS087	-43.27469	170.41031	1389857.2	5205424.3	76.795	8.30	980403.98	980440.47	-36.49	-3.73	0.34
WAFS088	-43.27499	170.41319	1390092	5205398	74.876	9.40	980402.74	980439.77	-37.03	-4.08	0.34
WAFS089	-43.27375	170.41244	1390026.8	5205533.6	77.33	8.72	980403.39	980439.86	-36.47	-3.79	0.34
WAFS090	-43.27414	170.41464	1390206.3	5205495.4	77.173	9.82	980402.10	980438.82	-36.72	-3.86	0.34
WAFS091	-43.27326	170.41378	1390133.9	5205591.6	77.18	9.13	980402.82	980439.43	-36.61	-3.96	0.34
WAFS092	-43.2725	170.41339	1390099.3	5205675.5	76.575	8.74	980403.50	980439.87	-36.37	-3.88	0.34
WAFS093	-43.28119	170.40486	1389436.7	5204688.3	85.878	8.59	980402.24	980438.98	-36.73	-3.07	0.34
WAFS094	-43.28192	170.40552	1389492.8	5204609.1	86.421	8.90	980401.83	980438.63	-36.80	-2.95	0.34
WAFS095	-43.28258	170.40624	1389554	5204537.1	87.815	9.16	980401.19	980438.15	-36.96	-2.94	0.34
WAFS096	-43.28325	170.40686	1389606.4	5204464.9	87.675	9.43	980400.85	980437.97	-37.12	-2.94	0.34
WAFS097	-43.28034	170.40665	1389579.7	5204787.7	86.038	8.67	980401.59	980438.79	-37.21	-3.59	0.34
WAFS098	-43.28106	170.40746	1389647.6	5204709.9	85.412	8.96	980401.60	980438.69	-37.09	-3.29	0.34
WAFS099	-43.2816	170.40829	1389716.7	5204650.9	87.11	9.27	980401.05	980438.10	-37.05	-3.09	0.34
WAFS100	-43.27977	170.40836	1389715.8	5204854.9	85.056	8.90	980401.73	980438.70	-36.97	-3.35	0.34
WAFS101	-43.28048	170.40894	1389765.8	5204778	85.621	9.16	980401.46	980438.39	-36.94	-3.16	0.34
WAFS102	-43.27916	170.41032	1389872.9	5204927.4	82.871	9.36	980401.73	980438.62	-36.89	-3.28	0.34
WAFS103	-43.27983	170.41091	1389923.1	5204854.4	91.454	9.63	980400.23	980436.72	-36.50	-2.73	0.34
WAFS104	-43.28129	170.40976	1389835.3	5204689.3	91.704	9.62	980399.98	980436.81	-36.83	-2.84	0.34
WAFS105	-43.28335	170.40964	1389832.8	5204460.8	93.87	10.03	980399.07	980436.16	-37.10	-2.72	0.34
WAFS106	-43.28453	170.40823	1389721.8	5204325.5	91.694	10.01	980399.42	980436.72	-37.30	-2.78	0.34
WAFS107	-43.27825	170.41208	1390013.1	5205033	89.473	9.96	980400.14	980436.64	-36.50	-2.97	0.34
WAFS108	-43.27893	170.41278	1390072.3	5204959.4	90.203	10.36	980399.96	980436.15	-36.19	-2.49	0.34
WAFS109	-43.27796	170.41342	1390120.6	5205068.6	88.642	10.60	980399.98	980436.13	-36.15	-2.61	0.34
WAFS110	-43.27856	170.41416	1390183.1	5205003.5	89.029	11.14	980399.75	980435.57	-35.83	-2.13	0.34
WAFS111	-43.28529	170.40589	1389535.1	5204235.3	92.299	10.09	980399.46	980436.59	-37.13	-2.63	0.34
WAFS112	-43.28541	170.40434	1389409.4	5204218.7	92.652	10.29	980399.81	980436.32	-36.52	-2.10	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
WAFS113	-43.28439	170.4033	1389321.2	5204328.8	83.714	9.62	980402.14	980438.66	-36.52	-2.37	0.34
WAFS114	-43.28683	170.40481	1389452.7	5204061.7	84.744	11.21	980400.34	980437.09	-36.75	-2.03	0.34
WAFS115	-43.28513	170.4086	1389753.8	5204260	94.406	10.21	980398.58	980436.04	-37.45	-2.80	0.34
WAFS116	-43.28601	170.40879	1389772.9	5204163.2	94.189	10.51	980398.04	980435.86	-37.82	-2.98	0.34
WAFS117	-43.28673	170.40915	1389804.3	5204084.2	94.293	10.71	980397.64	980435.70	-38.06	-3.06	0.34
WAFS118	-43.28749	170.40955	1389839.5	5204000.3	95.555	10.96	980397.06	980435.27	-38.21	-3.03	0.34
WAFS119	-43.2883	170.40988	1389868.8	5203911.4	95.464	11.17	980396.53	980435.16	-38.63	-3.27	0.34
WAFS120	-43.28903	170.41025	1389901.8	5203831.5	93.089	11.42	980396.67	980435.44	-38.77	-3.25	0.34
WAFS121	-43.28939	170.40896	1389798	5203787.6	92.827	11.47	980396.65	980435.47	-38.82	-3.30	0.34
WAFS122	-43.28778	170.40824	1389734.2	5203965.3	90.003	10.92	980398.21	980436.43	-38.22	-3.08	0.34
WAFS123	-43.28626	170.40753	1389671.5	5204132	90.163	10.44	980399.03	980436.75	-37.72	-2.92	0.34
WAFS124	-43.28422	170.40989	1389855.4	5204364.3	94.336	10.28	980398.40	980435.90	-37.50	-2.94	0.34
WAFS125	-43.28498	170.41021	1389884.6	5204280.5	96.001	10.52	980397.84	980435.40	-37.55	-2.82	0.34
WAFS126	-43.28606	170.41078	1389933.9	5204162.8	96.936	10.88	980397.10	980434.95	-37.85	-2.87	0.34
WAFS127	-43.28689	170.41122	1389972.7	5204070.8	97.534	11.15	980396.50	980434.65	-38.15	-2.98	0.34
WAFS128	-43.28779	170.41168	1390013.6	5203972	98.338	11.45	980395.76	980434.26	-38.51	-3.13	0.34
WAFS129	-43.28869	170.41217	1390055.9	5203873.5	101.147	11.71	980394.75	980433.53	-38.78	-3.19	0.34
WAFS130	-43.28897	170.41456	1390250.8	5203848.5	124.935	12.19	980389.87	980428.40	-38.53	-2.72	0.34
WAFS131	-43.28718	170.41038	1389905.5	5204036.5	96.285	10.97	980396.99	980435.10	-38.11	-2.94	0.34
WAFS132	-43.28505	170.40943	1389821.3	5204271.4	94.316	10.34	980398.43	980435.92	-37.50	-2.80	0.34
WAFS133	-43.28102	170.41145	1389971.4	5204723.4	92.059	10.16	980400.00	980436.18	-36.19	-2.15	0.34
WAFS134	-43.28186	170.41193	1390013.1	5204631.6	92.939	10.60	980399.38	980435.64	-36.26	-2.04	0.34
WAFS135	-43.28268	170.41224	1390041.1	5204541	93.591	10.98	980398.67	980435.21	-36.54	-2.13	0.34
WAFS136	-43.28303	170.41114	1389952.8	5204500	93.664	10.47	980398.74	980435.73	-36.99	-2.59	0.34
WAFS137	-43.28357	170.41271	1390082.1	5204443.4	95.394	11.46	980397.66	980434.45	-36.79	-2.19	0.34
WAFS138	-43.28468	170.41318	1390124.4	5204322.2	99.009	11.94	980396.29	980433.36	-37.07	-2.22	0.34
WAFS139	-43.28482	170.41187	1390018.2	5204302.8	96.446	11.12	980397.19	980434.70	-37.50	-2.70	0.34
WAFS140	-43.28583	170.41377	1390176.1	5204195.2	103.843	12.32	980394.70	980432.13	-37.43	-2.31	0.34
WAFS141	-43.28659	170.41248	1390073.9	5204107.8	101.922	11.60	980395.33	980433.30	-37.97	-2.77	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom Res Anom (mGal)	Error (mGal)
WAFS142	-43.28529	170.41645	1390392	5204262.3	125.674	16.32	980389.20	980423.79	-34.59	0.58
WAFS143	-43.28459	170.41477	1390252.8	5204335.4	101.839	13.79	980395.51	980430.95	-35.43	0.34
WAFS144	-43.28329	170.41437	1390215.8	5204478.7	97.038	13.28	980397.14	980432.29	-35.14	0.34
WAFS145	-43.28232	170.41397	1390180.4	5204586.1	93.974	12.51	980398.42	980433.57	-35.15	0.34
WAFS146	-43.28134	170.41359	1390146.4	5204693.2	93.979	11.64	980399.53	980434.35	-34.82	0.34
WAFS147	-43.28014	170.41329	1390117.3	5204825.9	91.108	10.97	980399.88	980435.48	-35.60	0.34
WAFS148	-43.27963	170.41476	1390234.8	5204886.5	92.758	12.03	980399.02	980434.05	-35.03	0.34
WAFS149	-43.2803	170.41506	1390261.5	5204813	93.738	12.94	980398.77	980433.01	-34.24	0.34
WAFS150	-43.27891	170.41585	1390321	5204968.7	92.09	12.95	980398.62	980433.20	-34.58	0.34
WAFS151	-43.28311	170.3868	1387978.6	5204429.6	80.999	8.84	980407.33	980439.87	-32.54	0.34
WAFS152	-43.28163	170.38411	1387754.9	5204587.4	79.196	7.81	980408.19	980441.12	-32.93	0.34
WAFS153	-43.27993	170.38322	1387676.7	5204773.8	78.852	7.02	980408.52	980441.82	-33.30	0.09
WAFS154	-43.27798	170.38267	1387625.7	5204988.6	78.604	6.32	980409.10	980442.39	-33.29	0.09
WAFS155	-43.27596	170.38215	1387576	5205211.2	76.182	5.72	980409.94	980443.29	-33.35	0.09
WAFS156	-43.27263	170.38125	1387491.9	5205579	75.879	5.00	980410.87	980443.76	-32.89	0.09
WAFS157	-43.27758	170.39835	1388896.5	5205072.3	84.609	6.86	980405.09	980440.63	-2.95	0.09
WAFS158	-43.27709	170.39565	1388675.6	5205120.8	82.89	6.55	980405.92	980441.24	-35.32	0.09
WAFS159	-43.27661	170.39306	1388463.8	5205167.3	81.888	6.30	980406.65	980441.64	-34.99	0.09
WAFS160	-43.27828	170.39125	1388322.9	5204977	81.748	6.67	980406.71	980441.45	-34.74	0.09
WAFS161	-43.27601	170.38989	1388204.3	5205225.8	79.546	6.01	980407.88	980442.33	-34.45	0.09
WAFS162	-43.27553	170.38731	1387993.8	5205272.7	77.855	5.83	980408.69	980442.81	-34.12	0.09
WAFS163	-43.27509	170.38496	1387801.4	5205315.6	76.432	5.63	980409.40	980443.25	-33.84	0.09
WAFS164	-43.27343	170.38493	1387793	5205499.5	75.711	5.27	980409.85	980443.60	-33.75	0.09
WAFS165	-43.27605	170.39918	1388958.7	5205244.5	86.532	6.58	980405.53	980440.40	-34.87	0.09
WAFS166	-43.27453	170.39813	1388868.4	5205411.2	82.331	6.18	980406.41	980441.49	-35.08	0.09
WAFS167	-43.2727	170.39752	1388811.8	5205612.8	80.72	5.83	980407.64	980441.99	-34.35	0.09
WAFS168	-43.27104	170.39673	1388742	5205794.6	78.668	5.55	980408.88	980442.52	-33.65	0.09
WAFS169	-43.27182	170.39109	1388287.2	5205694.2	78.597	5.24	980409.17	980442.92	-33.74	0.09
WAFS170	-43.27387	170.38913	1388135.2	5205461.2	78.583	5.52	980408.75	980442.82	-34.07	0.09

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
WAFS171	-43.27413	170.39215	1388381.6	5205440.8	80.069	5.71	980407.96	980442.37	-34.41	-2.83	0.09
WAFS172	-43.27269	170.39447	1388564.6	5205605.9	80.432	5.59	980408.22	980442.28	-34.07	-2.56	0.09
WAFS173	-43.27456	170.39518	1388629.1	5205400.5	82.164	5.96	980407.05	980441.74	-34.68	-2.82	0.09
WAFS174	-43.28059	170.38694	1387980.9	5204709.9	80.608	7.36	980407.53	980441.19	-33.66	-1.44	0.09
WAFS175	-43.2786	170.38763	1388030	5204932	80.211	6.66	980407.51	980441.79	-34.28	-2.31	0.09
WAFS176	-43.27726	170.3854	1387844.7	5205076	77.994	6.17	980408.57	980442.60	-34.03	-2.45	0.09
WAFS177	-43.27977	170.38501	1387821.4	5204795.7	79.002	6.99	980408.16	980441.80	-33.65	-1.71	0.09
WAFS178	-43.28445	170.38627	1387940.2	5204279.7	81.584	9.78	980406.46	980438.93	-32.47	0.32	0.34
WAFS179	-43.28213	170.38149	1387544.2	5204525.3	79.952	7.94	980408.20	980440.88	-32.69	-0.70	0.34
WAFS180	-43.28128	170.37703	1387179	5204607.3	76.43	7.40	980409.74	980442.04	-32.30	-0.87	0.09
WAFS181	-43.28051	170.37284	1386836.8	5204682.3	80.158	6.82	980410.54	980441.81	-31.27	-0.37	0.09
WAFS182	-43.27537	170.37795	1387233.1	5205266.5	73.778	5.45	980411.36	980443.98	-32.62	-1.96	0.09
WAFS183	-43.27853	170.36228	1385973.1	5204875.8	91.455	5.74	980413.06	980440.49	-27.44	2.09	0.09
WAFS184	-43.27962	170.36834	1386468.1	5204769.8	87.143	6.25	980411.52	980440.93	-29.42	0.91	0.09
WAFS185	-43.27632	170.37191	1386746.7	5205145.8	75.565	5.46	980412.74	980443.70	-30.96	-0.72	0.09
WAFS186	-43.28131	170.39792	1388874.6	5204657.3	86.917	7.93	980404.27	980439.45	-35.18	-1.97	0.34
WAFS187	-43.28041	170.39314	1388483.5	5204745.2	82.472	7.40	980406.20	980440.77	-34.57	-1.88	0.34
WAFS188	-43.2843	170.38014	1387441.9	5204280.1	97.632	9.13	980403.70	980436.41	-32.71	-0.53	0.34
WAFS189	-43.28644	170.37913	1387367.6	5204040.3	132.731	10.59	980395.71	980428.23	-32.52	-0.11	0.34
WAFS190	-43.28613	170.37645	1387148.9	5204068.1	114.853	10.28	980399.57	980432.03	-32.47	-0.38	0.34
WAFS191	-43.28827	170.37891	1387356.2	5203836.5	159.074	12.50	980387.55	980421.31	-33.76	-1.09	0.34
WAFS193	-43.29057	170.37817	1387303.8	5203578.6	229.992	15.51	980374.24	980404.56	-30.32	2.62	0.34
WDF001	-43.28477	170.40667	1389596.6	5204295.3	88.953	9.89	980400.12	980437.40	-37.28	-2.83	0.34
WDF002	-43.28383	170.40604	1389542.2	5204398.4	88.612	9.51	980400.74	980437.76	-37.02	-2.79	0.34
WDF003	-43.28285	170.40548	1389493	5204505.2	87.326	9.14	980401.49	980438.29	-36.81	-2.79	0.34
WDF004	-43.28309	170.40412	1389383.5	5204475.2	85.463	9.07	980402.18	980438.75	-36.57	-2.60	0.34
WDF005	-43.28392	170.40437	1389406.8	5204384.3	86.451	9.39	980401.61	980438.31	-36.71	-2.57	0.34
WDF006	-43.28484	170.40481	1389445.9	5204282.4	86.124	9.81	980401.19	980438.05	-36.85	-2.51	0.34
WDF007	-43.28484	170.40541	1389494.5	5204284.7	87.332	9.83	980400.82	980437.78	-36.97	-2.59	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom Res Anom (mGal)	Error (mGal)	
WDF008	-43.28442	170.40526	1389480.5	5204330.2	86.454	9.66	980401.16	980438.09	-36.94	-2.64	0.34
WDF009	-43.28388	170.40505	1389461.8	5204390.2	87.058	9.43	980401.32	980438.15	-36.84	-2.66	0.34
WDF010	-43.2834	170.40491	1389448.7	5204442.8	86.659	9.25	980401.61	980438.37	-36.76	-2.68	0.34
WDSS001	-43.29135	170.40648	1389603.8	5203564.3	92.668	13.19	980395.74	980433.96	-38.22	-2.51	0.34
WDSS002	-43.29133	170.40627	1389586.5	5203565.5	92.811	13.50	980395.64	980433.62	-37.99	-2.30	0.34
WDSS003	-43.29134	170.40605	1389568.7	5203564.6	93.11	13.86	980395.41	980433.20	-37.79	-2.12	0.34
WDSS004	-43.29083	170.40576	1389543	5203619.8	91.114	14.42	980395.70	980432.99	-37.29	-1.73	0.34
WDSS005	-43.29082	170.40588	1389553.4	5203621.3	92.596	13.85	980395.64	980433.27	-37.63	-2.07	0.34
WDSS006	-43.29082	170.40604	1389565.8	5203622.1	92.832	13.52	980395.73	980433.55	-37.82	-2.25	0.34
WDSS007	-43.2908	170.40626	1389583.6	5203624.1	93.801	13.19	980395.71	980433.69	-37.98	-2.39	0.34
WDSS008	-43.29079	170.4065	1389603.1	5203626.1	93.811	12.85	980395.84	980434.02	-38.18	-2.58	0.34
WDSS009	-43.29024	170.4065	1389601.7	5203687.8	91.235	12.57	980396.57	980434.76	-38.19	-2.69	0.34
WDSS010	-43.29016	170.40616	1389573.8	5203695	91.202	12.92	980396.55	980434.42	-37.87	-2.41	0.34
WDSS011	-43.29014	170.40598	1389559	5203697.5	91.293	13.20	980396.45	980434.11	-37.66	-2.23	0.34
WDSS012	-43.29013	170.40588	1389550.5	5203698.3	89.434	13.39	980396.68	980434.29	-37.61	-2.18	0.34
WDSS013	-43.29141	170.40554	1389527.3	5203555.5	96.423	15.56	980394.25	980430.86	-36.60	-0.96	0.34
WDSS014	-43.29141	170.40556	1389529.3	5203555.5	96.176	15.43	980394.32	980431.04	-36.72	-1.07	0.34
WDSS015	-43.29141	170.40559	1389531.8	5203555.6	96.397	15.22	980394.42	980431.21	-36.79	-1.14	0.34
WDSS018	-43.29095	170.4055	1389523	5203606.1	96.027	15.39	980394.55	980431.07	-36.52	-0.97	0.34
WDSS019	-43.29095	170.40553	1389525.4	5203606.2	96.111	15.22	980394.60	980431.22	-36.62	-1.06	0.34
WDSS020	-43.29095	170.40556	1389527.6	5203606.6	95.967	15.02	980394.71	980431.45	-36.74	-1.18	0.34
WDSS021	-43.29053	170.40545	1389517.1	5203652.1	96.084	15.13	980394.80	980431.28	-36.48	-1.01	0.34
WDSS022	-43.29053	170.40548	1389519.7	5203652.7	96.224	14.90	980394.86	980431.48	-36.62	-1.15	0.34
WDSS023	-43.29053	170.40551	1389522	5203652.2	96.075	14.78	980394.96	980431.62	-36.67	-1.19	0.34
WDSS024	-43.29096	170.40544	1389518	5203605.1	98.271	15.52	980393.80	980430.49	-36.69	-1.14	0.34
WDSS025	-43.29132	170.4058	1389548.4	5203565.8	91.566	14.52	980395.44	980432.85	-37.41	-1.76	0.34
WDSS026	-43.2908	170.40566	1389535.4	5203623.2	91.326	14.62	980395.49	980432.75	-37.26	-1.72	0.34
WDSS027	-43.2924	170.4054	1389519.2	5203444.3	105.617	15.71	980392.21	980428.99	-36.78	-0.95	0.34
WDSS028	-43.29252	170.40465	1389459.6	5203429.4	143.338	16.65	980385.74	980420.64	-34.90	0.89	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom Res Anom (mGal)	Error (mGal)	
WDSS032	-43.29724	170.41421	1390251.2	5202929.2	99.73	12.92	980392.06	980433.37	-41.31	-3.82	0.34
WDSS033	-43.2972	170.41299	1390152.2	5202931.3	100.22	12.80	980392.14	980433.40	-41.26	-3.87	0.34
WDSS034	-43.29711	170.41177	1390052.9	5202937.5	98.799	12.82	980392.59	980433.64	-41.05	-3.77	0.34
WDSS035	-43.29705	170.41059	1389956.9	5202941.8	99.022	13.00	980392.93	980433.42	-40.49	-3.32	0.34
WDSS036	-43.29694	170.40902	1389829.3	5202949.1	103.067	13.49	980392.84	980432.12	-39.28	-2.25	0.34
WDSS037	-43.29745	170.40819	1389763.7	5202890.7	103.55	14.06	980392.95	980431.50	-38.55	-1.50	0.34
WDSS038	-43.29767	170.40717	1389681.6	5202864.3	108.345	14.67	980392.34	980429.97	-37.63	-0.62	0.34
WDSS039	-43.29735	170.40649	1389624.8	5202898.2	123.992	15.17	980390.50	980426.36	-35.86	1.03	0.34
WDSS040	-43.29681	170.4056	1389550.7	5202955.5	145.507	15.56	980386.00	980421.69	-35.69	1.02	0.34
WDSS041	-43.29677	170.40495	1389498.4	5202957.7	164.343	15.90	980382.69	980417.65	-34.96	1.69	0.34
WDSS042	-43.29684	170.40408	1389428.1	5202948.5	187.851	16.37	980378.14	980412.55	-34.41	2.18	0.34
WDSS044	-43.29631	170.40257	1389303.3	5203003.5	249.819	14.95	980367.66	980401.74	-34.08	2.27	0.31
WDSS045	-43.29623	170.40176	1389237.5	5203010.2	277.638	14.62	980360.56	980396.59	-36.03	0.23	0.31
WDSS046	-43.28955	170.40553	1389520	5203762.1	86.177	13.67	980397.27	980434.60	-37.33	-2.04	0.34
WDSS047	-43.29009	170.4056	1389527.8	5203701.8	92.755	14.01	980396.24	980433.01	-36.77	-1.37	0.34
WDSS048	-43.28986	170.40623	1389578	5203728.8	89.592	12.73	980397.03	980434.89	-37.86	-2.46	0.34
WDSS049	-43.29017	170.40689	1389632.9	5203696.2	89.982	12.28	980396.74	980435.29	-38.55	-3.04	0.34
WDSS050	-43.29052	170.4077	1389699.5	5203659.1	90.896	12.09	980396.39	980435.34	-38.94	-3.30	0.34
WDSS051	-43.29102	170.40721	1389661.7	5203602.7	92.424	12.44	980395.94	980434.73	-38.78	-3.08	0.34
WDSS052	-43.29233	170.40805	1389734.4	5203459.5	92.829	12.54	980395.24	980434.67	-39.43	-3.40	0.34
WDSS053	-43.29202	170.40685	1389636	5203490.3	92.505	13.11	980395.43	980434.13	-38.70	-2.83	0.34
WDSS054	-43.28925	170.40502	1389477.9	5203793.9	96.878	14.44	980395.85	980431.69	-35.84	-0.65	0.34
WDSS055	-43.28987	170.40531	1389503.5	5203725.6	99.981	14.45	980395.31	980431.13	-35.81	-0.48	0.34
WDSS057	-43.29193	170.40603	1389569.3	5203498.6	91.48	14.25	980395.39	980433.19	-37.80	-2.01	0.34
WFW001	-43.2684	170.41737	1390408.1	5206140.1	113.761	8.58	980396.02	980432.35	-36.33	-4.48	0.34
WFW002	-43.26833	170.41865	1390512.1	5206151.1	122.826	8.87	980393.80	980430.27	-36.47	-4.60	0.34
WFW003	-43.26847	170.41987	1390611.6	5206139	143.209	9.30	980389.53	980425.84	-36.31	-4.38	0.34
WFW004	-43.26913	170.42243	1390821.1	5206071.8	161.215	10.08	980386.48	980421.58	-35.10	-2.96	0.34
WFW005	-43.26917	170.42347	1390905.9	5206069.9	166.954	10.65	980385.41	980419.89	-34.47	-2.30	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
WFW006	-43.26885	170.42448	1390986.5	5206107.9	175.024	11.04	980383.74	980417.88	-34.14	-2.00	0.34
WFW007	-43.2685	170.42347	1390904	5206144.8	163.869	10.38	980385.89	980420.70	-34.81	-2.77	0.34
WFW008	-43.2681	170.42226	1390804	5206185.6	159.51	9.50	980386.76	980422.40	-35.64	-3.72	0.34
WFW009	-43.26698	170.42225	1390799.2	5206310.2	157.563	9.13	980387.24	980423.06	-35.82	-4.11	0.34
WFW010	-43.26754	170.42322	1390880.4	5206250.5	160.839	9.78	980386.57	980421.81	-35.24	-3.40	0.34
WFW011	-43.26812	170.42452	1390987.6	5206189.1	171.459	10.70	980384.44	980418.85	-34.41	-2.42	0.34
WKG001	-43.28457	170.39556	1388693.9	5204289.3	87.226	10.22	980404.37	980437.39	-33.02	0.58	0.34
WKG002	-43.28372	170.39576	1388707.3	5204384.4	88.363	9.22	980404.47	980438.09	-33.62	-0.15	0.34
WKG003	-43.28288	170.39603	1388726.7	5204478.2	88.602	8.61	980404.30	980438.58	-34.28	-0.94	0.34
WKG004	-43.28208	170.39634	1388748.5	5204567.7	86.677	8.18	980404.60	980439.31	-34.71	-1.48	0.34
WKG005	-43.28106	170.39672	1388776	5204681.7	86.57	7.74	980404.83	980439.68	-34.85	-1.77	0.34
WKG006	-43.28213	170.39763	1388853.6	5204565.4	89.26	8.27	980403.86	980438.72	-34.86	-1.53	0.34
WKG007	-43.28316	170.39727	1388828.1	5204450.6	89.675	8.82	980403.81	980438.18	-34.37	-0.89	0.34
WKG008	-43.28395	170.397	1388808.7	5204362.2	89.713	9.44	980403.75	980437.62	-33.87	-0.27	0.34
WKG009	-43.28476	170.39671	1388788.3	5204271	87.971	10.52	980403.60	980436.96	-33.36	0.37	0.34
WKG010	-43.28505	170.39826	1388915.1	5204243.1	88.789	10.91	980402.65	980436.43	-33.79	0.11	0.34
WKG011	-43.28431	170.39848	1388930.4	5204326.3	90.595	9.71	980402.89	980437.21	-34.32	-0.54	0.34
WKG012	-43.28352	170.39869	1388944.7	5204413.8	89.799	9.08	980403.32	980437.93	-34.60	-0.95	0.34
WKG013	-43.28273	170.39894	1388962.1	5204502.1	89.092	8.62	980403.50	980438.46	-34.96	-1.42	0.34
WKG014	-43.28154	170.39908	1388969.1	5204635.4	88.667	8.08	980403.68	980438.97	-35.29	-1.95	0.34
WIC001	-43.26508	170.39641	1388695.6	5206456.3	75.475	4.72	980410.07	980443.44	-33.37	-2.99	0.09
WIC002	-43.26582	170.39333	1388448.6	5206365.8	75.738	4.61	980410.33	980443.56	-33.23	-2.90	0.09
WIC003	-43.26682	170.38946	1388137.6	5206245.1	75.681	4.52	980410.75	980443.76	-33.02	-2.76	0.09
WIC004	-43.26773	170.38593	1387854.3	5206135.7	75.223	4.42	980410.97	980444.03	-33.07	-2.90	0.09
WLC001	-43.29755	170.42119	1390818.5	5202912.8	143.295	15.25	980382.95	980422.51	-39.56	-1.49	0.31
WLC002	-43.29597	170.42056	1390761.7	5203086.3	153.763	14.75	980382.04	980420.80	-38.76	-1.08	0.31
WMTPO01	-43.30824	170.37415	1387039.7	5201606	1240.912	27.51	980160.56	980195.31	-34.76	0.48	0.31
WMTPO02	-43.30703	170.37409	1387030.4	5201740	1258.024	30.64	980152.94	980188.70	-35.76	-0.73	0.31
WRS001	-43.24972	170.39254	1388328.1	5208152	64.28	3.15	980411.59	980445.83	-34.24	-6.38	0.09

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
WRS002	-43.25394	170.39446	1388498.5	5207688	67.669	3.53	980412.14	980445.16	-33.02	-4.47	0.09
WRS003	-43.25833	170.39598	1388637.1	5207205	71.328	3.98	980411.66	980444.38	-32.73	-3.44	0.09
WRS004	-43.26037	170.39108	1388246.7	5206965.6	71.261	3.90	980411.87	980444.66	-32.79	-3.42	0.09
WRS005	-43.26177	170.38569	1387813.9	5206796.3	71.494	3.79	980412.57	980444.86	-32.28	-3.01	0.09
WRS006	-43.24858	170.38653	1387836.8	5208263.5	62.592	2.84	980412.34	980446.36	-34.03	-6.56	0.09
WRS007	-43.24778	170.38235	1387494.1	5208341.3	61.335	2.67	980413.72	980446.71	-32.99	-5.80	0.09
WRS008	-43.28352	170.38946	1388195.7	5204391	85.111	8.97	980406.25	980438.96	-32.71	0.20	0.34
WRS009	-43.28393	170.38946	1388196.8	5204345.1	87.166	9.29	980405.71	980438.27	-32.57	0.42	0.34
WRS010	-43.28436	170.38946	1388198.8	5204296.9	90.615	9.67	980404.93	980437.25	-32.33	0.73	0.34
WRS011	-43.28479	170.38945	1388198.9	5204249.7	95.461	10.09	980403.84	980435.92	-32.08	1.05	0.34
WRS013	-43.28566	170.38963	1388217	5204153.3	110.034	10.95	980400.91	980432.27	-31.36	1.93	0.34
WRS014	-43.28601	170.38956	1388212.3	5204114.8	106.714	11.39	980399.16	980432.52	-33.35	-0.01	0.34
WRS015	-43.29838	170.41293	1390151.1	5202799.2	99.968	12.99	980392.00	980433.36	-41.36	-3.72	0.34
WRS016	-43.30514	170.41411	1390270.4	5202051.6	102.999	14.05	980390.55	980432.32	-41.76	-2.60	0.34
WRS017	-43.31497	170.42101	1390863.8	5200977.8	109.849	15.07	980386.04	980430.84	-44.80	-2.81	0.09
WRS018	-43.3174	170.41437	1390333.5	5200690.9	154.272	17.30	980377.97	980420.09	-42.12	-0.23	0.31
WRS020	-43.301	170.41798	1390569.5	5202521.5	97.196	14.71	980390.77	980432.42	-41.65	-3.06	0.34
WRS021	-43.31204	170.42105	1390856.9	5201302.4	101.482	14.99	980387.64	980432.30	-44.66	-3.34	0.09
WRS022	-43.31027	170.4264	1391284	5201513.1	190.93	13.08	980373.68	980416.45	-42.77	-1.42	0.31
WRS023	-43.30622	170.42964	1391533.2	5201970.6	260.739	12.66	980363.47	980402.78	-39.31	1.33	0.31
WRS024	-43.26453	170.41769	1390421.3	5206570.8	82.918	8.07	980402.36	980438.57	-36.22	-5.10	0.34
WRS025	-43.26361	170.42037	1390635.4	5206679.7	88.764	8.50	980400.51	980436.91	-36.40	-5.40	0.34
WRS026	-43.26286	170.42269	1390820.6	5206769.4	95.909	9.22	980398.79	980434.72	-35.94	-5.04	0.34
WRS027	-43.26315	170.42572	1391067.6	5206744.7	109.314	11.13	980395.50	980430.20	-34.71	-3.71	0.34
WRS028	-43.26367	170.42618	1391106.9	5206687.4	114.913	12.31	980393.77	980427.97	-34.20	-3.08	0.34
WRS029	-43.26364	170.42705	1391177.5	5206693	121.551	12.44	980392.66	980426.53	-33.87	-2.75	0.34
WRS030	-43.26385	170.42793	1391249.6	5206672.2	132.651	12.98	980390.47	980423.82	-33.35	-2.17	0.34
WRS031	-43.264	170.42853	1391298.8	5206657	141.739	13.30	980388.74	980421.73	-33.00	-1.78	0.34
WRS032	-43.26413	170.42945	1391373.8	5206644.5	154.325	13.64	980386.43	980418.92	-32.49	-1.24	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
WRS033	-43.2647	170.43136	1391530.7	5206586.4	179.976	14.97	980380.76	980412.60	-31.84	-0.45	0.34
WRS034	-43.2648	170.4371	1391997.3	5206589.1	258.824	18.12	980362.65	980393.95	-31.30	0.16	0.34
WRS035	-43.28305	170.36447	1386166.2	5204379.1	106.092	7.33	980408.15	980436.43	-28.27	2.07	0.09
WRS036	-43.28648	170.35727	1385594.1	5203980.3	138.046	8.38	980401.11	980429.40	-28.29	1.62	0.34
WRS037	-43.29262	170.35819	1385690.8	5203300.5	207.573	13.14	980379.88	980411.52	-31.64	-0.85	0.34
WRS038	-43.29395	170.35805	1385683.6	5203152.5	229.095	14.76	980374.46	980405.79	-31.33	-0.38	0.34
WRS039	-43.29441	170.35769	1385656.4	5203100.1	238.992	15.50	980372.13	980403.15	-31.02	-0.06	0.34
WRS040	-43.29497	170.35777	1385664.6	5203037.6	247.577	16.03	980369.93	980400.98	-31.05	-0.01	0.34
WRS041	-43.29568	170.35832	1385711.5	5202960.8	268.207	16.37	980365.85	980396.65	-30.79	0.41	0.34
WRS042	-43.29674	170.35887	1385760.3	5202844.8	293.297	18.00	980359.61	980390.18	-30.57	0.86	0.34
WRS044	-43.29335	170.35825	1385697.8	5203218.9	220.064	13.97	980376.73	980408.30	-31.57	-0.68	0.34
WRS045	-43.27412	170.38186	1387546.1	5205414.9	75.617	5.30	980410.40	980443.65	-33.24	-2.43	0.09
WRS046	-43.27265	170.38783	1388025.3	5205593.2	78.531	5.23	980409.30	980443.01	-33.71	-2.67	0.09
WRS047	-43.27115	170.39374	1388499.9	5205775.4	80.645	5.33	980408.98	980442.37	-33.39	-2.18	0.09
WRS048	-43.27097	170.39956	1388972	5205809.5	79.379	5.76	980408.17	980442.17	-34.00	-2.47	0.09
WRS049	-43.27081	170.40069	1389062.7	5205830.3	79.442	5.84	980407.87	980442.06	-34.19	-2.63	0.09
WRS050	-43.27062	170.40207	1389174.6	5205855.1	79.924	5.96	980407.41	980441.83	-34.43	-2.82	0.09
WRS051	-43.27046	170.40329	1389272.8	5205875.7	78.74	6.11	980407.31	980441.89	-34.59	-2.95	0.09
WRS052	-43.27047	170.40397	1389328.2	5205877.2	80.165	6.17	980406.77	980441.55	-34.78	-3.10	0.09
WRS053	-43.27048	170.40453	1389373.7	5205877	79.121	6.26	980406.80	980441.67	-34.87	-3.16	0.09
WRS054	-43.2705	170.40512	1389421.5	5205876.1	79.16	6.35	980406.58	980441.57	-35.00	-3.26	0.09
WRS055	-43.27052	170.40571	1389469.1	5205876	79.386	6.44	980406.33	980441.44	-35.11	-3.34	0.09
WRS056	-43.27054	170.40629	1389516.1	5205874.7	79.715	6.53	980406.03	980441.29	-35.25	-3.45	0.09
WRS057	-43.2706	170.40699	1389573.8	5205870.3	79.94	6.68	980405.70	980441.10	-35.40	-3.56	0.09
WRS058	-43.27061	170.4076	1389622.8	5205870	78.882	6.76	980405.71	980441.23	-35.51	-3.64	0.09
WRS059	-43.27065	170.40873	1389714.9	5205868.9	76.956	7.01	980405.65	980441.36	-35.72	-3.78	0.34
WRS060	-43.27071	170.41091	1389892	5205867.4	77.763	7.51	980404.62	980440.71	-36.10	-4.05	0.34
WRS061	-43.27073	170.413	1390061.7	5205870.6	73.719	8.18	980404.51	980440.84	-36.33	-4.19	0.34
WRS062	-43.28297	170.3897	1388213.1	5204452	84.789	8.57	980406.47	980439.37	-32.91	-0.06	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
WRS063	-43.28225	170.38995	1388230.7	5204533.2	84.702	8.13	980406.59	980439.77	-33.18	-0.44	0.34
WRS064	-43.28046	170.39058	1388275.6	5204733.6	83.64	7.33	980406.66	980440.61	-33.96	-1.46	0.09
WRS065	-43.28664	170.38974	1388229.4	5204044.8	124.358	12.02	980396.48	980428.48	-31.99	1.47	0.34
WRS066	-43.28698	170.39011	1388260.2	5204008.5	137.973	12.03	980394.61	980425.82	-31.21	2.34	0.34
WRS067	-43.28746	170.39056	1388298.6	5203955.6	148.323	12.64	980391.50	980423.21	-31.72	1.96	0.34
WRS071	-43.26461	170.41581	1390268.5	5206556.9	79.725	7.49	980403.55	980439.79	-36.24	-5.17	0.34
WRS072	-43.26434	170.413	1390039.9	5206580.2	75.105	6.71	980405.78	980441.46	-35.68	-4.74	0.09
WRS073	-43.26543	170.41038	1389830.8	5206452.9	72.111	6.38	980407.23	980442.47	-35.24	-4.19	0.09
WRS074	-43.26598	170.40727	1389579.9	5206384	71.273	5.99	980408.52	980443.08	-34.56	-3.53	0.09
WRS075	-43.26421	170.37606	1387040.9	5206501	68.229	3.67	980414.26	980445.84	-31.58	-2.61	0.09
WRS076	-43.26365	170.3782	1387213	5206569	69.004	3.67	980413.90	980445.63	-31.73	-2.68	0.09
WRS077	-43.26291	170.38117	1387450.9	5206658.7	70.221	3.73	980413.56	980445.26	-31.71	-2.55	0.09
WRS078	-43.26735	170.39843	1388867.6	5206209.6	77.485	5.18	980409.28	980442.79	-33.52	-2.66	0.09
WRS079	-43.26703	170.40094	1389070.4	5206251.5	77.262	5.36	980408.87	980442.62	-33.76	-2.83	0.09
WRS080	-43.26687	170.40301	1389237.4	5206274.5	76.621	5.55	980408.49	980442.55	-34.06	-3.06	0.09
WRS081	-43.26671	170.40519	1389413.8	5206297	76.317	5.80	980408.07	980442.34	-34.27	-3.20	0.09
WRS082	-43.25102	170.39915	1388869.5	5208025	65.967	3.60	980411.31	980445.16	-33.85	-5.59	0.09
WRS083	-43.25205	170.40472	1389325.1	5207923.9	66.042	4.06	980410.44	980444.78	-34.33	-5.77	0.09
WRS084	-43.25326	170.41125	1389859.7	5207806	61.605	4.88	980409.69	980444.94	-35.25	-6.34	0.09
WRS085	-43.25733	170.41002	1389773.5	5207351.7	66.688	5.24	980410.25	980443.95	-33.70	-4.11	0.09
WRS086	-43.25455	170.41786	1390400.6	5207679.2	63.001	6.11	980407.51	980443.56	-36.05	-6.81	0.09
WRS087	-43.29813	170.41987	1390713	5202845.3	119.684	14.79	980386.84	980427.66	-40.82	-2.72	0.31
WRS088	-43.29731	170.42219	1390898.9	5202941.6	159.144	15.16	980380.24	980419.45	-39.21	-1.13	0.31
WRS089	-43.29707	170.42302	1390965	5202970.1	178.324	15.12	980377.01	980415.70	-38.69	-0.61	0.31
WRS090	-43.26916	170.39529	1388618.7	5206000.1	78.865	5.19	980409.62	980442.67	-33.05	-2.07	0.09
WRS091	-43.26952	170.39266	1388406.4	5205953.2	78.794	5.04	980409.82	980442.87	-33.05	-2.17	0.09
WRS092	-43.27017	170.38926	1388133.1	5205873.2	77.1	4.90	980409.91	980443.41	-33.50	-2.74	0.09
WRS093	-43.27101	170.38445	1387745.7	5205766.9	75.707	4.85	980410.40	980443.80	-33.41	-2.86	0.09
WRS094	-43.26036	170.40204	1389136.2	5206994.8	72.683	4.67	980410.41	980443.61	-33.20	-3.34	0.09

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom Res Anom (mGal)	Error (mGal)	
WRS095	-43.25651	170.40379	1389265.3	5207426.3	69.046	4.44	980411.17	980444.21	-33.04	-3.76	0.09
WRS096	-43.25483	170.38862	1388027.7	5207574.8	66.838	3.36	980412.73	980445.57	-32.84	-4.41	0.09
WRS097	-43.25637	170.38281	1387561.2	5207389.5	69.346	3.22	980414.29	980445.36	-31.07	-2.72	0.09
WRS098	-43.25804	170.37671	1387072.3	5207188.4	65.259	3.15	980416.08	980446.38	-30.31	-2.10	0.09
WRS099	-43.26021	170.37216	1386710.7	5206935.4	67.9	3.19	980416.62	980446.02	-29.41	-1.24	0.09
WRS100	-43.27818	170.37911	1387337.5	5204957.2	75.534	6.21	980410.49	980443.12	-32.63	-1.46	0.09
WRS101	-43.26353	170.36822	1386402.2	5206556.8	65.382	3.37	980415.55	980446.64	-31.08	-2.81	0.09
WRS102	-43.25172	170.37366	1386802.6	5207882.1	61.574	2.66	980417.94	980447.03	-29.09	-1.86	0.09
WRS103	-43.25568	170.36622	1386212.9	5207423.4	61.313	2.72	980417.99	980447.38	-29.38	-2.19	0.09
WRS104	-43.2751	170.3575	1385572.9	5205244.3	68.576	4.89	980415.66	980445.53	-29.87	-1.28	0.09
WRS105	-43.27446	170.36767	1386395.9	5205340.9	72.907	4.87	980413.60	980444.65	-31.05	-1.47	0.09
WRS106	-43.27025	170.3661	1386253.4	5205805	68.148	4.13	980414.08	980445.94	-31.86	-2.96	0.09
WRS107	-43.26891	170.41556	1390263.2	5206079.3	95.02	8.36	980399.83	980436.30	-36.47	-4.59	0.34
WRS108	-43.26893	170.41662	1390349.1	5206079.7	101.644	8.77	980398.25	980434.59	-36.33	-4.41	0.34
WRS109	-43.26907	170.4178	1390445.3	5206067.1	113.41	9.01	980395.98	980432.05	-36.07	-4.08	0.34
WRS110	-43.26939	170.41919	1390559.5	5206035.1	125.945	9.50	980393.22	980429.12	-35.90	-3.81	0.34
WRS111	-43.26979	170.42044	1390662.3	5205993.5	135.203	9.97	980390.99	980426.87	-35.88	-3.67	0.34
WRS112	-43.26876	170.41437	1390165.9	5206093.3	83.446	8.12	980402.47	980438.81	-36.34	-4.52	0.34
WRS113	-43.27228	170.42187	1390786.8	5205720.1	167.973	11.18	980385.31	980419.43	-34.12	-1.36	0.34
WRS114	-43.27347	170.42605	1391129.9	5205599.3	222.012	16.21	980371.65	980403.88	-32.23	0.90	0.34
WRS115	-43.27594	170.42845	1391333	5205330.2	272.716	18.75	980358.40	980391.60	-33.19	0.54	0.34
WRS116	-43.28803	170.41609	1390371.5	5203956.8	137.229	13.03	980387.53	980425.06	-37.52	-1.81	0.34
WRS117	-43.29003	170.41886	1390603.8	5203741.7	191.802	13.25	980376.99	980414.28	-37.29	-1.00	0.31
DFDP2-S5	-43.29318	170.40945	1389850.6	5203368.3	95.288	12.39	980394.44	980434.42	-39.98	-3.68	0.34
WE01	-43.29259	170.41424	1390237.5	5203445.9	93.17	13.58	980393.00	980433.58	-40.58	-4.05	0.34
WE02	-43.29773	170.41704	1390482.2	5202881.7	92.33	13.86	980392.55	980433.93	-41.39	-3.57	0.34
WE03	-43.29807	170.41761	1390529.8	5202845.6	95.424	14.23	980391.88	980432.99	-41.11	-3.18	0.34
WE06	-43.29713	170.41748	1390515.7	5202949.5	96.37	14.09	980391.66	980432.85	-41.19	-3.48	0.34
WE08	-43.29479	170.41729	1390492.1	5203209.6	95.648	15.21	980391.31	980431.67	-40.36	-3.16	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
WE09	-43.29366	170.41602	1390385.7	5203331.9	97.951	14.84	980391.55	980431.48	-39.93	-3.06	0.34
WE10	-43.29152	170.41313	1390143.7	5203561.8	95.174	12.51	980393.66	980434.16	-40.50	-4.27	0.34
WE11	-43.29018	170.41156	1390011.7	5203707.2	95.011	11.82	980395.05	980434.77	-39.72	-3.87	0.34
WS01	-43.29254	170.40599	1389568.3	5203431.1	94.224	14.55	980394.93	980432.40	-37.48	-1.57	0.34
WS02	-43.29268	170.40656	1389615.1	5203417	94.1655	13.66	980395.05	980433.32	-38.27	-2.29	0.34
WS03	-43.29278	170.40715	1389662.9	5203406.8	95.419	13.19	980394.89	980433.55	-38.66	-2.62	0.34
WS04	-43.29289	170.40775	1389712	5203396.1	95.9185	12.88	980394.80	980433.77	-38.97	-2.86	0.34
WS05	-43.293	170.40835	1389760.7	5203385.3	94.992	12.64	980394.82	980434.20	-39.38	-3.20	0.34
WS06	-43.29315	170.40893	1389808.7	5203370.6	95.06	12.50	980394.72	980434.35	-39.63	-3.38	0.34
WS07	-43.29335	170.40949	1389854.3	5203350	95.5065	12.42	980394.35	980434.36	-40.01	-3.67	0.34
WS08	-43.29355	170.41004	1389899.9	5203328.5	95.858	12.37	980394.18	980434.36	-40.18	-3.76	0.34
WS09	-43.29375	170.41058	1389944.3	5203307.8	95.9405	12.34	980394.01	980434.38	-40.37	-3.87	0.34
WS10	-43.29396	170.41113	1389989.9	5203286.2	96.214	12.34	980393.77	980434.35	-40.57	-3.99	0.34
WS11	-43.29416	170.41169	1390035.7	5203264.7	96.057	12.37	980393.56	980434.37	-40.81	-4.14	0.34
WS12	-43.2944	170.41218	1390076.5	5203240.1	95.978	12.43	980393.43	980434.35	-40.92	-4.17	0.34
WS13	-43.29475	170.41257	1390109.3	5203202.3	97.251	12.50	980393.15	980434.06	-40.91	-4.06	0.34
WS14	-43.29528	170.41331	1390171.4	5203145.1	97.193	12.64	980392.82	980433.97	-41.15	-4.13	0.34
WS15	-43.29588	170.41413	1390239.6	5203080.5	98.252	12.83	980392.31	980433.63	-41.32	-4.12	0.34
WS16	-43.29649	170.41492	1390305.7	5203014.8	98.816	13.05	980392.05	980433.35	-41.30	-3.92	0.34
WS17	-43.29702	170.41551	1390356	5202956.8	98.918	13.27	980391.87	980433.16	-41.29	-3.75	0.34
WS18	-43.29701	170.41591	1390387.8	5202958.6	93.705	13.45	980392.74	980434.01	-41.27	-3.69	0.34
WS19	-43.29748	170.41566	1390369.6	5202906.9	92.758	13.41	980392.90	980434.28	-41.39	-3.73	0.34
WS20	-43.29729	170.41615	1390408.6	5202928.6	92.709	13.49	980393.01	980434.19	-41.18	-3.53	0.34
WS21	-43.29745	170.41549	1390355.4	5202909.6	101.098	13.26	980391.47	980432.78	-41.31	-3.68	0.34
WS22	-43.29736	170.41505	1390319.3	5202917.9	101.298	13.12	980391.70	980432.88	-41.18	-3.60	0.34
WT01	-43.2904	170.40542	1389514.3	5203666.6	95.692	14.97	980394.95	980431.50	-36.56	-1.11	0.34
WT02	-43.29046	170.40624	1389580.9	5203662.7	92.976	13.03	980395.96	980433.98	-38.02	-2.51	0.34
WT03	-43.2905	170.40683	1389629.1	5203658.8	93.426	12.41	980396.06	980434.52	-38.46	-2.88	0.34
WT04	-43.29064	170.4077	1389699.8	5203645.5	93.092	12.09	980395.99	980434.91	-38.93	-3.26	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom Res Anom (mGal)	Error (mGal)
WT05	-43.29115	170.40899	1389806.7	5203593.1	93.757	11.98	980395.45	980434.94	-39.49	0.34
WT06	-43.29141	170.40554	1389527.7	5203555	98.679	15.47	980394.26	980430.50	-36.24	0.34
WT06B	-43.29143	170.40597	1389562.8	5203553.8	92.04	14.11	980395.48	980433.17	-37.69	0.34
WT06C	-43.29146	170.40631	1389590	5203551.7	93.051	13.50	980395.47	980433.59	-38.12	0.34
WT07	-43.2915	170.40725	1389666.7	5203549	93.923	12.61	980395.51	980434.31	-38.79	0.34
WT08	-43.29168	170.40799	1389727.1	5203530.8	94.105	12.35	980395.31	980434.55	-39.24	0.34
WT09	-43.29189	170.40889	1389801	5203510.7	95.273	12.16	980395.07	980434.53	-39.46	0.34
WT10	-43.29218	170.40989	1389883.3	5203480.1	95.393	12.08	980394.68	980434.62	-39.94	0.34
WT11	-43.29227	170.41058	1389939.3	5203472	93.978	12.05	980394.52	980434.92	-40.40	0.34
WT12	-43.29229	170.41145	1390010.3	5203471.6	92.846	12.10	980394.73	980435.10	-40.37	0.34
WT13	-43.29241	170.40581	1389553.2	5203444.1	93.63	14.97	980394.72	980432.09	-37.36	0.34
WT17	-43.29296	170.41004	1389898	5203394.6	93.645	12.23	980394.39	980434.87	-40.48	0.34
WT18	-43.29301	170.41091	1389968.3	5203391.3	95.442	12.18	980394.08	980434.57	-40.49	0.34
WT19	-43.2931	170.41197	1390055.1	5203383.6	95.837	12.26	980393.63	980434.43	-40.80	0.34
WT20B	-43.29365	170.40599	1389571.4	5203307.3	95.639	15.05	980394.57	980431.72	-37.15	0.34
WT21	-43.29374	170.40741	1389687.5	5203300.8	97.717	13.31	980394.35	980433.06	-38.71	0.34
WT22	-43.29383	170.40824	1389754.7	5203293.1	96.963	12.92	980394.29	980433.61	-39.32	0.34
WT23	-43.29391	170.40936	1389845.9	5203286.7	96.872	12.59	980394.00	980433.97	-39.97	0.34
WT27	-43.29501	170.40656	1389622.5	5203157.7	101.42	14.56	980393.49	980431.20	-37.71	0.34
WT28	-43.29482	170.40731	1389683.2	5203181.2	96.564	13.80	980394.13	980432.90	-38.77	0.34
WT29	-43.29473	170.40828	1389761.5	5203193.4	96.977	13.19	980394.07	980433.42	-39.35	0.34
WT30	-43.29487	170.40923	1389838.8	5203180.4	97.297	12.86	980393.84	980433.70	-39.86	0.34
WT31	-43.29505	170.41015	1389913.9	5203161.9	97.77	12.66	980393.51	980433.82	-40.30	0.34
WT32	-43.29525	170.41091	1389976.3	5203141.7	97.954	12.59	980393.23	980433.88	-40.65	0.34
WW01	-43.28869	170.40474	1389453.4	5203854.7	96.338	14.14	980396.62	980432.05	-35.43	0.34
WW02	-43.28723	170.40367	1389361.6	5204014.8	97.868	13.08	980398.51	980432.68	-34.17	0.34
WW03	-43.28622	170.40189	1389213.5	5204122.2	102.848	12.22	980399.62	980432.47	-32.84	0.34
WW04	-43.28562	170.40008	1389064.5	5204184.1	93.285	11.70	980400.61	980434.82	-34.21	0.34
WW05	-43.28517	170.39756	1388858.7	5204227.9	89.546	11.36	980402.64	980435.85	-33.21	0.34

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
WW06	-43.28371	170.39388	1388554.8	5204380.8	87.525	9.18	980405.23	980438.29	-33.06	0.25	0.34
WW07	-43.28448	170.39397	1388564.7	5204295.8	87.099	10.06	980404.90	980437.56	-32.66	0.79	0.34
B	-43.24494	170.3685	1386360.1	5208621.8	55.801	2.18	980418.84	980448.03	-29.19	-3.03	0.14
N1	-43.28359	170.32266	1382776.1	5204211.6	91.04	5.15	980414.91	980441.62	-26.72	-2.12	0.14
N11	-43.25831	170.34332	1384362.6	5207072.8	53.16	2.39	980418.98	980449.54	-30.57	-5.15	0.14
N13	-43.25712	170.34827	1384760.7	5207217.8	56.09	2.43	980417.02	980448.83	-31.81	-5.99	0.14
N14	-43.25038	170.3634	1385965	5208004.8	53.301	2.34	980419.20	980448.85	-29.65	-3.23	0.14
N17	-43.24728	170.38016	1387315.2	5208391.7	55.595	2.58	980414.22	980447.89	-33.67	-6.64	0.14
N19	-43.24297	170.39567	1388559.4	5208909.6	55.167	2.87	980409.53	980447.29	-37.76	-10.80	0.14
N2	-43.2829	170.30777	1381565	5204248.7	79.634	3.55	980420.42	980445.40	-24.98	-2.99	0.14
N21	-43.23952	170.40364	1389194.5	5209313.6	52.794	3.03	980407.32	980447.28	-39.96	-13.40	0.14
N22	-43.23714	170.41058	1389749.6	5209594.6	51.426	3.25	980407.14	980447.12	-39.97	-13.78	0.14
N23	-43.23672	170.4157	1390163.6	5209654.6	49.946	3.57	980407.86	980447.05	-39.19	-13.10	0.14
N24	-43.23587	170.41903	1390431.6	5209757.5	50.006	3.74	980407.81	980446.79	-38.99	-13.09	0.14
N25	-43.23144	170.42614	1390993.8	5210267.5	47.912	3.89	980409.50	980446.65	-37.16	-12.20	0.14
N26	-43.23023	170.43085	1391371.8	5210413.5	57.152	4.15	980406.64	980444.47	-37.83	-13.26	0.14
N27	-43.22839	170.43691	1391857.9	5210632.5	72.112	4.28	980402.75	980441.23	-38.48	-14.51	0.14
N28	-43.23223	170.44388	1392436.9	5210223.4	87.799	5.49	980398.35	980437.28	-38.92	-14.53	0.14
N29	-43.23473	170.44974	1392920.9	5209960.3	105.769	6.84	980394.34	980432.62	-38.27	-13.66	0.14
N3	-43.27137	170.30173	1381034	5205513.9	68.229	2.61	980421.66	980447.55	-25.89	-5.44	0.14
N30	-43.24044	170.45877	1393673.9	5209348.2	143.473	11.67	980384.66	980420.89	-36.22	-10.82	0.14
N5	-43.2659	170.31177	1381829.2	5206147.9	61.928	2.19	980420.91	980448.71	-27.81	-5.94	0.14
N7	-43.26182	170.32149	1382603.4	5206625.9	57.818	2.17	980419.99	980449.17	-29.18	-6.12	0.14
N9	-43.25725	170.33195	1383436.5	5207160.9	54.605	2.15	980418.74	980449.41	-30.67	-6.58	0.14
W001	-43.28458	170.41372	1390167.7	5204334.2	105.0656	12.35	980395.91	980431.75	-35.84	-0.98	0.36
W002	-43.28484	170.41273	1390088.2	5204302.8	102.2076	11.62	980396.57	980433.07	-36.50	-1.64	0.36
W003	-43.28517	170.41176	1390010.7	5204263.7	101.5656	11.13	980396.82	980433.71	-36.89	-2.02	0.36
W004	-43.2855	170.41068	1389924.2	5204224.3	101.3576	10.76	980397.20	980434.15	-36.95	-2.09	0.36
W005	-43.28579	170.40948	1389827.8	5204189.1	99.6696	10.52	980397.85	980434.75	-36.90	-2.06	0.36

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
W006	-43.28597	170.40875	1389769.2	5204167.3	99.5406	10.51	980397.98	980434.80	-36.82	-1.99	0.36
W007	-43.28633	170.40789	1389700.7	5204125.1	95.7606	10.48	980398.69	980435.61	-36.93	-2.09	0.36
W008	-43.28671	170.40706	1389634.7	5204080.8	95.6386	10.57	980398.82	980435.57	-36.76	-1.90	0.36
W009	-43.28709	170.40618	1389564.6	5204036.4	92.9446	10.81	980399.15	980435.91	-36.75	-1.89	0.36
W010	-43.28746	170.40544	1389505.8	5203993.5	95.1316	11.32	980398.79	980435.00	-36.21	-1.33	0.36
what01	-43.24511	170.36844	1386355.7	5208602.6	55.801	2.19	980418.75	980448.04	-29.29	-3.11	0.14
what02	-43.22042	170.35147	1384890.8	5211302	40.59	2.03	980412.25	980448.96	-36.71	-13.52	0.14
what03	-43.22273	170.36227	1385776.8	5211072.7	42.15	1.48	980412.80	980449.41	-36.61	-12.85	0.14
what04	-43.22699	170.38609	1387726.2	5210660.2	49.071	1.86	980409.07	980448.06	-38.99	-14.30	0.14
what05	-43.22586	170.41232	1389852.1	5210852.4	47.164	2.61	980407.95	980447.58	-39.62	-15.24	0.14
what06	-43.22659	170.40602	1389343.2	5210755.5	49.31	2.40	980407.52	980447.43	-39.91	-15.31	0.14
what07	-43.22681	170.39896	1388770.7	5210712.8	49.473	2.18	980408.18	980447.64	-39.46	-14.75	0.14
what08	-43.2268	170.39154	1388167.6	5210695.7	49.504	1.98	980408.49	980447.84	-39.35	-14.64	0.14
what09	-43.22021	170.38308	1387457.9	5211406.1	45.078	1.59	980408.53	980448.50	-39.97	-16.08	0.14
what10	-43.20314	170.38938	1387910.1	5213317.3	36.023	1.23	980408.16	980449.10	-40.94	-18.98	0.14
what11	-43.18798	170.38163	1387227.8	5214981.1	29.08	0.85	980406.96	980449.47	-42.51	-21.76	0.14
what12	-43.18016	170.36873	1386152	5215817.5	26.407	0.67	980406.92	980449.48	-42.56	-21.90	0.14
what13	-43.16242	170.33764	1383562.9	5217707.7	17.048	0.39	980409.59	980449.99	-40.40	-19.40	0.14
what14	-43.21341	170.37658	1386905.7	5212144.6	40.184	1.32	980409.21	980449.11	-39.90	-16.74	0.14
what15	-43.24286	170.35577	1385319.5	5208820.8	51.843	1.94	980419.83	980448.86	-29.04	-3.86	0.14
whata01	-43.28473	170.40791	1389696.8	5204302.9	90.686	10.01	980399.47	980436.93	-37.46	-2.93	0.36
whata02	-43.27557	170.41555	1390285.2	5205339.4	78.088	11.01	980401.58	980437.59	-36.00	-2.83	0.36
whata03	-43.27596	170.4146	1390209.4	5205293.7	78.115	10.50	980401.91	980438.12	-36.22	-3.01	0.36
whata04	-43.27647	170.41368	1390136.5	5205234.8	79.189	10.20	980401.65	980438.26	-36.61	-3.35	0.36
whata05	-43.27681	170.41272	1390059.8	5205194.6	79.95	9.85	980401.76	980438.49	-36.73	-3.45	0.36
whata06	-43.27722	170.41172	1389980.1	5205146.5	79.624	9.51	980402.06	980438.93	-36.87	-3.56	0.36
whata07	-43.27763	170.41082	1389908.5	5205098.7	80.222	9.25	980402.06	980439.11	-37.06	-3.71	0.36
whata08	-43.27811	170.40984	1389830.6	5205043	80.318	9.00	980402.35	980439.38	-37.03	-3.65	0.36
whata09	-43.27858	170.40897	1389761.6	5204988.6	80.337	8.84	980402.54	980439.58	-37.04	-3.61	0.36

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
whata10	-43.27901	170.40792	1389677.9	5204938.2	79.243	8.65	980402.80	980440.03	-37.23	-3.78	0.36
whata11	-43.27942	170.40696	1389601.4	5204890.2	79.893	8.51	980402.71	980440.08	-37.36	-3.90	0.36
whata12	-43.28	170.40625	1389545.8	5204824	80.536	8.52	980402.62	980440.00	-37.38	-3.85	0.36
whata13	-43.28041	170.4053	1389470.1	5204776.1	80.76	8.47	980402.90	980440.04	-37.14	-3.59	0.36
whata14	-43.28091	170.40447	1389404.5	5204718.5	81.473	8.47	980403.10	980439.94	-36.85	-3.26	0.36
whata15	-43.28151	170.40388	1389358.7	5204650.3	82.725	8.54	980403.05	980439.68	-36.63	-2.97	0.36
whata16	-43.28227	170.40344	1389325.6	5204564.8	84.265	8.73	980402.83	980439.25	-36.43	-2.65	0.36
whata17	-43.2832	170.40313	1389303.7	5204460.8	84.231	9.04	980402.67	980439.04	-36.37	-2.45	0.36
whata18	-43.27319	170.36147	1385888.3	5205466.5	68.067	4.52	980414.74	980445.84	-31.10	-2.30	0.14
whata19	-43.27238	170.37066	1386631.3	5205580	72.52	4.57	980412.85	980444.84	-31.99	-2.39	0.14
whata20	-43.27049	170.37551	1387018.3	5205802.3	70.405	4.44	980412.47	980445.21	-32.73	-2.96	0.14
whata21	-43.2822	170.4011	1389135.5	5204566.7	89.811	8.49	980402.58	980438.40	-35.82	-2.22	0.36
whata22	-43.28288	170.40003	1389051	5204488.5	90.156	8.70	980402.87	980438.18	-35.31	-1.67	0.36
whata23	-43.28351	170.39931	1388994.8	5204416.7	90.605	9.06	980402.92	980437.79	-34.87	-1.17	0.36
whata24	-43.28388	170.39841	1388923.1	5204373.3	90.6	9.35	980403.15	980437.53	-34.38	-0.68	0.36
whata25	-43.2843	170.39757	1388856.4	5204324.6	90.451	9.76	980403.32	980437.19	-33.87	-0.15	0.36
whata26	-43.16882	170.37143	1386332.2	5217083.3	23.657	0.60	980408.17	980449.06	-40.89	-21.03	0.14
whata27	-43.15919	170.35503	1384965.2	5218110.8	20.506	0.43	980408.94	980448.98	-40.04	-19.73	0.14
whata28	-43.16573	170.34851	1384458.1	5217367.7	19.637	0.45	980408.78	980449.72	-40.94	-20.20	0.14
whata29	-43.15346	170.3254	1382535.9	5218670.7	14.879	0.28	980410.64	980449.72	-39.08	-17.73	0.14
whata30	-43.2632	170.4033	1389248.4	5206682.4	75.641	5.14	980409.36	980442.82	-33.45	-3.07	0.14
whata31	-43.2639	170.40117	1389078	5206599.3	74.163	5.00	980409.90	980443.32	-33.42	-3.01	0.14
whata32	-43.26475	170.39917	1388918.6	5206499.8	75.109	4.91	980409.91	980443.29	-33.38	-2.92	0.14
whata33	-43.20515	170.36256	1385738.3	5213025.9	34.551	1.12	980410.38	980449.68	-39.30	-16.88	0.14
whata34	-43.25081	170.30627	1381328.6	5207809.1	55.23	2.46	980420.30	980448.39	-28.09	-7.53	0.14
whata35	-43.25445	170.304	1381157.4	5207398.9	59.277	2.05	980420.14	980448.34	-28.20	-7.87	0.14
whata36	-43.25887	170.30529	1381277.9	5206911.4	62.249	2.06	980420.88	980448.14	-27.26	-6.62	0.14
whata37	-43.26329	170.30662	1381401.7	5206424	66.376	2.20	980421.62	980447.59	-25.98	-5.00	0.14
whata38	-43.2677	170.30722	1381466.2	5205935.7	68.924	2.31	980420.86	980447.37	-26.51	-5.28	0.14

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
whata39	-43.27191	170.30906	1381630.6	5205473	73.018	2.55	980421.13	980446.71	-25.58	-3.88	0.14
whata40	-43.27665	170.30864	1381613.5	5204945.5	76.947	2.92	980421.57	980446.00	-24.43	-2.59	0.14
whats01	-43.22183	170.35711	1385354.1	5211159.4	41.103	1.55	980412.80	980449.47	-36.67	-13.15	0.14
whats02	-43.22394	170.3689	1386319.1	5210955.3	44.013	1.55	980411.95	980449.08	-37.13	-13.07	0.14
whats03	-43.21987	170.37611	1386890.5	5211425.7	43.594	1.49	980410.00	980448.86	-38.87	-15.07	0.14
whats04	-43.20798	170.37651	1386881.5	5212747.2	37.427	1.19	980408.96	980449.30	-40.34	-17.69	0.14
whats05	-43.18863	170.36925	1386224.1	5214877.7	28.81	0.78	980407.17	980449.65	-42.49	-21.29	0.14
whats06	-43.17319	170.35492	1385005.4	5216555.7	23.436	0.55	980407.50	980449.55	-42.05	-21.29	0.14
whats07	-43.17383	170.3811	1387135.7	5216551.6	24.749	0.70	980407.61	980449.20	-41.59	-21.95	0.14
whats08	-43.18185	170.38222	1387254.6	5215663.7	25.923	0.77	980407.41	980449.62	-42.21	-22.00	0.14
whats09	-43.19619	170.38426	1387470.2	5214076.3	32.045	1.02	980407.40	980449.46	-42.06	-20.66	0.14
whats10	-43.2115	170.38666	1387718.3	5212382.1	37.607	1.40	980408.79	980449.37	-40.58	-17.66	0.14
whats11	-43.22963	170.37348	1386710.9	5210335	47.843	1.73	980412.07	980448.67	-36.60	-11.85	0.14
whats12	-43.24136	170.34731	1384627	5208965.2	48.583	1.89	980420.06	980449.42	-29.36	-4.92	0.14
whats13	-43.24457	170.36518	1386089.2	5208654.6	55.083	2.11	980419.02	980448.21	-29.19	-3.26	0.14
whats14	-43.25586	170.33585	1383747.9	5207325.2	56.977	2.15	980419.44	980448.82	-29.38	-4.94	0.14
whats15	-43.25967	170.34969	1384884.7	5206937.8	57.2	2.62	980418.54	980448.65	-30.11	-3.93	0.14
whats16	-43.26186	170.36091	1385803.1	5206723.4	62.086	3.03	980417.11	980447.48	-30.36	-2.91	0.14
whats17	-43.25908	170.39602	1388643.3	5207121.6	71.406	4.06	980411.43	980444.36	-32.93	-3.53	0.14
whats18	-43.2622	170.38411	1387687.4	5206744.9	71.034	3.77	980412.78	980445.01	-32.23	-2.99	0.14
whats19	-43.21212	170.40282	1389033.2	5212354.1	41.6	1.73	980408.29	980448.31	-40.02	-17.38	0.14
whats20	-43.20299	170.376	1386822.7	5213300.1	34.282	1.08	980408.28	980449.58	-41.30	-19.10	0.14
whats21	-43.23421	170.39009	1388075.7	5209868.6	53.384	2.23	980408.98	980447.49	-38.51	-12.86	0.14
whats22	-43.24969	170.39251	1388325.8	5208155.6	64.315	3.15	980411.55	980445.82	-34.27	-6.43	0.14
whats23	-43.24745	170.38058	1387349.5	5208374	61.26	2.60	980414.64	980446.77	-32.13	-5.06	0.14
whats24	-43.26444	170.39872	1388881	5206533.1	76.636	4.83	980409.69	980443.05	-33.36	-2.97	0.14
whats25	-43.26508	170.39637	1388692.5	5206456.1	75.583	4.72	980410.03	980443.42	-33.39	-3.01	0.14
whats26	-43.26592	170.39305	1388425.9	5206354.4	75.489	4.61	980410.39	980443.63	-33.24	-2.90	0.14
whats27	-43.26681	170.38959	1388148.2	5206246.8	75.758	4.52	980410.73	980443.74	-33.01	-2.75	0.14

Continued on next page

Station (ID)	Latitude (WGS84)	Longitude (WGS84)	Easting (NZTM)	Northing (NZTM)	Height (m) (NZVD2009)	Total TC (mGal)	g Abs (mGal)	Boug Mod (mGal)	Boug Anom (mGal)	Res Anom (mGal)	Error (mGal)
whats28	-43.2677	170.38611	1387868.8	5206139.1	75.484	4.42	980410.93	980443.97	-33.04	-2.86	0.14
whats29	-43.26856	170.38254	1387582.1	5206034.5	74.353	4.41	980411.36	980444.29	-32.93	-2.88	0.14
whats30	-43.26964	170.37925	1387318.8	5205906.2	72.749	4.43	980411.91	980444.68	-32.77	-2.82	0.14
whats31	-43.2769	170.35436	1385324.4	5205036.2	67.55	5.65	980416.94	980445.14	-28.20	0.24	0.14
whats32	-43.2684	170.3563	1385451.9	5205985.2	62.751	3.62	980416.59	980447.34	-30.76	-3.03	0.14
whats33	-43.2612	170.41007	1389791	5206921.6	70.698	5.71	980408.91	980443.04	-34.14	-3.86	0.14
whats34	-43.26038	170.41297	1390023.6	5207019.9	70.676	6.06	980407.70	980442.62	-34.91	-4.70	0.14
whats35	-43.25954	170.41581	1390251.2	5207120.4	69.545	6.47	980406.79	980442.36	-35.57	-5.44	0.14
whats36	-43.25881	170.41824	1390446	5207207.5	68.406	6.95	980405.97	980442.04	-36.07	-6.03	0.14
whats37	-43.2585	170.42178	1390732.2	5207250.8	90.048	7.48	980400.76	980437.22	-36.46	-6.43	0.36
whats38	-43.2462	170.43076	1391419.2	5208639.3	84.026	7.04	980402.12	980437.73	-35.61	-7.98	0.14
whats39	-43.23577	170.43158	1391450.1	5209799.7	75.223	4.75	980403.97	980440.81	-36.84	-11.25	0.14
whats40	-43.20028	170.43962	1391982.3	5213761.3	37.05	2.46	980407.69	980447.40	-39.72	-21.13	0.14
whats41	-43.2067	170.43802	1391874.1	5213044.3	41.363	2.73	980406.86	980446.87	-40.01	-20.14	0.14
whats42	-43.21277	170.43443	1391603.2	5212361.2	48.22	2.87	980405.49	980445.92	-40.43	-19.22	0.14
whats43	-43.21871	170.43256	1391471.5	5211696.9	53.351	3.12	980404.75	980445.20	-40.45	-18.06	0.14
whats44	-43.22372	170.43244	1391478.9	5211140.2	61.704	3.47	980404.45	980443.67	-39.21	-15.91	0.14
whats45	-43.22818	170.43711	1391873.3	5210656.5	76.308	4.46	980402.40	980440.21	-37.80	-13.88	0.14
whats46	-43.21642	170.44567	1392528.6	5211983.8	56.842	3.91	980404.07	980443.52	-39.45	-18.34	0.14
whats47	-43.21076	170.44992	1392854.6	5212622.9	49.218	3.89	980405.89	980444.53	-38.64	-19.00	0.14

Table C.1: Gravity data collected during this study.

Appendix D Position survey data

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WAFS001	-43.28436465	170.3942906	0.011	99.168	0.021
WAFS002	-43.28398658	170.3944353	0.009	100.036	0.017
WAFS003	-43.28361673	170.3945634	0.009	100.073	0.019
WAFS004	-43.28323558	170.3946928	0.008	100.525	0.017
WAFS005	-43.28286509	170.3948253	0.009	99.982	0.018
WAFS006	-43.28248911	170.3949553	0.009	98.394	0.019
WAFS007	-43.28209974	170.3950828	0.009	100.619	0.018
WAFS008	-43.28172149	170.3952173	0.009	99.78	0.017
WAFS009	-43.28135284	170.395341	0.008	98.667	0.015
WAFS010	-43.28095364	170.3954762	0.009	98.187	0.016
WAFS011	-43.28054678	170.3956159	0.01	98.019	0.019
WAFS012	-43.27974247	170.3958934	0.01	97.757	0.016
WAFS013	-43.27896547	170.3962039	0.01	97.979	0.016
WAFS014	-43.28413846	170.3921211	0.01	101.475	0.014
WAFS015	-43.28034291	170.4038486	0.01	96.774	0.01
WAFS016	-43.27996766	170.4034658	0.01	97.481	0.01
WAFS017	-43.27959447	170.4031409	0.01	97.453	0.01
WAFS018	-43.27924563	170.4027859	0.01	97.447	0.01
WAFS019	-43.27892111	170.4024641	0.009	96.173	0.01
WAFS020	-43.27860715	170.4021828	0.009	96.551	0.011
WAFS021	-43.27824921	170.4018783	0.009	95.01	0.011
WAFS022	-43.27790397	170.4015511	0.009	93.93	0.011
WAFS023	-43.27922401	170.4053333	0.008	96.66	0.011
WAFS024	-43.27884164	170.4050202	0.008	95.643	0.011
WAFS025	-43.278481	170.4047485	0.008	96.486	0.011
WAFS026	-43.27812299	170.4043694	0.009	95.601	0.011
WAFS027	-43.27775944	170.4041074	0.008	94.477	0.011
WAFS028	-43.27740651	170.4038202	0.008	95.68	0.011
WAFS029	-43.27715298	170.4034826	0.011	95.678	0.035
WAFS030	-43.2768545	170.4031516	0.011	93.948	0.033
WAFS031	-43.27650697	170.4027806	0.012	95.948	0.033
WAFS032	-43.27614521	170.4024871	0.012	94.108	0.032
WAFS033	-43.27588216	170.4022854	0.012	92.675	0.031
WAFS034	-43.27890281	170.4076436	0.008	92.812	0.01
WAFS035	-43.27857783	170.4071872	0.009	95.486	0.011
WAFS036	-43.27819266	170.4068338	0.009	95.424	0.011
WAFS037	-43.27776249	170.4065262	0.009	93.793	0.011
WAFS038	-43.27732648	170.4062153	0.008	94.097	0.01
WAFS039	-43.27695135	170.405944	0.009	93.455	0.01
WAFS040	-43.27660323	170.4055331	0.01	94.647	0.011
WAFS041	-43.27619457	170.4051778	0.01	94.2	0.012
WAFS042	-43.27581249	170.4048965	0.008	93.255	0.01
WAFS043	-43.27543028	170.4045345	0.008	94.418	0.01
WAFS044	-43.27496892	170.4041786	0.009	94.091	0.01

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WAFS045	-43.27433712	170.4063284	0.008	91.735	0.012
WAFS046	-43.27485572	170.4067185	0.008	92.41	0.012
WAFS047	-43.27800334	170.4092705	0.008	91.86	0.011
WAFS048	-43.27754707	170.4088168	0.009	93.907	0.011
WAFS049	-43.27714008	170.408513	0.008	93.579	0.011
WAFS050	-43.27669065	170.4082289	0.008	92.81	0.011
WAFS051	-43.27628852	170.4079218	0.008	92.91	0.011
WAFS052	-43.27584699	170.4076671	0.008	93.667	0.01
WAFS053	-43.27523865	170.4070946	0.008	93.354	0.011
WAFS054	-43.27500827	170.4091084	0.009	91.948	0.009
WAFS055	-43.27547113	170.4093408	0.008	90.552	0.008
WAFS056	-43.27599908	170.4098265	0.009	92.079	0.009
WAFS057	-43.27637896	170.4103231	0.009	91.969	0.009
WAFS058	-43.27673452	170.4106855	0.008	91.939	0.008
WAFS059	-43.27610655	170.411534	0.008	91.391	0.009
WDSS001	-43.29135226	170.4064836	0.015	105.196	0.032
WDSS002	-43.29133599	170.4062711	0.015	105.339	0.031
WDSS003	-43.29133927	170.406051	0.014	105.638	0.029
WDSS004	-43.2908354	170.4057563	0.014	103.642	0.028
WDSS005	-43.29082486	170.4058851	0.013	105.124	0.026
WDSS006	-43.29082096	170.4060375	0.013	105.36	0.026
WDSS007	-43.29080843	170.4062576	0.013	106.329	0.025
WDSS008	-43.29079589	170.4064986	0.013	106.339	0.024
WDSS009	-43.29024005	170.4065046	0.012	103.763	0.023
WDSS010	-43.29016777	170.4061637	0.011	103.73	0.021
WDSS011	-43.29014151	170.4059826	0.012	103.821	0.022
WDSS012	-43.29013168	170.4058785	0.011	101.962	0.019
WDSS013	-43.29140928	170.4055381	0.028	108.951	0.028
WDSS014	-43.29141036	170.4055623	0.03	108.704	0.039
WDSS015	-43.29141025	170.405593	0.022	108.925	0.029
WDSS018	-43.2909535	170.4055048	0.012	108.555	0.017
WDSS019	-43.29095275	170.4055337	0.012	108.639	0.017
WDSS020	-43.2909501	170.4055618	0.012	108.495	0.016
WDSS021	-43.29053825	170.4054494	0.025	108.612	0.027
WDSS022	-43.2905336	170.4054818	0.014	108.752	0.02
WDSS023	-43.29053831	170.4055104	0.015	108.603	0.021
WDSS025	-43.29132311	170.4058016	0.011	104.094	0.015
WDSS026	-43.2908028	170.4056633	0.033	103.854	0.024
WRS001	-43.24972661	170.3925371	0.01	76.562	0.012
WRS002	-43.25394783	170.3944565	0.008	79.951	0.009
WRS003	-43.258332	170.3959767	0.008	83.61	0.009
WRS004	-43.26037544	170.39108	0.008	83.57	0.009
WRS005	-43.26177654	170.3856879	0.009	83.803	0.013
WRS006	-43.24858516	170.3865344	0.01	74.786	0.013

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WRS007	-43.24778881	170.382347	0.009	73.529	0.01
WRS008	-43.28352038	170.3894622	0.01	97.557	0.013
WRS009	-43.28393393	170.3894582	0.009	99.612	0.01
WRS010	-43.28436769	170.3894643	0.008	103.061	0.009
WRS011	-43.28479289	170.3894473	0.007	107.907	0.008
WRS015	-43.29838667	170.4129309	0.003	112.701	0.007
WRS016	-43.30514504	170.4141158	0.006	115.732	0.008
WRS017	-43.31497005	170.4210156	0.009	122.694	0.014
WRS018	-43.31740264	170.4143738	0.017	167.117	0.021
WRS020	-43.30100185	170.4179781	0.014	109.929	0.023
WRS021	-43.31204757	170.421054	0.012	114.327	0.025
WRS022	-43.31027141	170.4263961	0.026	203.858	0.038
WRS023	-43.30622447	170.4296392	0.011	273.6	0.033
WRS024	-43.26453518	170.4176956	0.013	95.424	0.018
WRS025	-43.26361504	170.4203725	0.013	101.27	0.021
WRS026	-43.26285962	170.4226863	0.02	108.415	0.035
WRS027	-43.26314992	170.4257165	0.016	121.961	0.032
WRS028	-43.26367639	170.4261787	0.015	127.56	0.043
WRS029	-43.26364557	170.4270494	0.025	134.198	0.055
WRS030	-43.26385272	170.4279301	0.02	145.298	0.038
WRS031	-43.26400325	170.4285291	0.016	154.386	0.025
WRS032	-43.26413611	170.4294477	0.017	166.972	0.037
WRS033	-43.26470222	170.4313568	0.034	192.623	0.093
WRS034	-43.26480683	170.4371021	0.024	271.471	0.033
WRS035	-43.28305393	170.3644693	0.009	118.461	0.016
WRS036	-43.28647932	170.3572698	0.009	150.345	0.016
WRS037	-43.29262139	170.3581958	0.01	220.036	0.032
WRS038	-43.29395095	170.3580497	0.029	241.558	0.069
WRS039	-43.29441421	170.3576942	0.04	251.455	0.035
WRS040	-43.29497832	170.3577704	0.02	260.04	0.046
WRS041	-43.29568242	170.3583184	0.015	280.67	0.021
WRS042	-43.29674024	170.3588735	0.064	305.843	0.137
WRS044	-43.29335702	170.3582504	1.1	232.527	0.266
WRS045	-43.27412766	170.3818591	0.015	87.926	0.023
WRS046	-43.27265855	170.3878264	0.015	90.84	0.025
WRS047	-43.27115299	170.3937389	0.015	93.045	0.023
WRS048	-43.27097823	170.3995636	0.009	91.779	0.013
WRS049	-43.27081698	170.4006883	0.009	91.842	0.013
WRS050	-43.27062479	170.4020752	0.009	92.324	0.015
WRS051	-43.27046702	170.4032929	0.009	91.14	0.016
WRS052	-43.27046961	170.4039748	0.01	92.565	0.02
WRS053	-43.27048345	170.4045347	0.008	91.521	0.017
WRS054	-43.27050514	170.4051235	0.008	91.56	0.017
WRS055	-43.27051928	170.4057087	0.01	91.786	0.019

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WRS056	-43.2705445	170.4062877	0.008	92.115	0.014
WRS057	-43.27059983	170.4069958	0.008	92.34	0.014
WRS058	-43.27061683	170.4075983	0.011	91.282	0.019
WRS059	-43.27065206	170.4087319	0.012	89.462	0.019
WRS060	-43.27071492	170.4109123	0.011	90.269	0.017
WRS061	-43.27073355	170.4130015	0.022	86.225	0.034
WRS062	-43.28297665	170.3897002	0.008	97.235	0.013
WRS063	-43.28225159	170.3899473	0.009	97.148	0.013
WRS064	-43.28046108	170.3905778	0.018	96.086	0.025
WAD001	-43.28881498	170.4606411	0.009	1462.65	0.015
WAD002	-43.28950085	170.4603303	0.009	1451.7	0.015
WDF001	-43.28477034	170.406673	0.014	101.576	0.022
WDF002	-43.28382751	170.4060426	0.012	101.235	0.017
WDF003	-43.28285341	170.4054785	0.012	99.949	0.016
WDF004	-43.28309275	170.4041181	0.013	98.086	0.016
WDF005	-43.28391653	170.4043699	0.012	99.074	0.015
WDF006	-43.28484416	170.404813	0.014	98.747	0.016
WDF007	-43.28483707	170.4054118	0.012	99.955	0.015
WDF008	-43.28442381	170.4052567	0.012	99.077	0.015
WDF009	-43.28387921	170.4050497	0.011	99.681	0.014
WDF010	-43.28340168	170.4049086	0.01	99.282	0.015
WFW001	-43.26840127	170.4173683	0.007	126.362	0.016
WFW002	-43.26833151	170.4186518	0.004	135.427	0.011
WFW003	-43.26846822	170.419873	0.014	155.81	0.018
WFW004	-43.26913057	170.4224262	0.011	173.816	0.013
WFW005	-43.26917179	170.4234693	0.01	179.555	0.012
WFW006	-43.26885205	170.4244763	0.011	187.625	0.013
WFW007	-43.26849691	170.4234739	0.01	176.47	0.013
WFW008	-43.26810248	170.4222582	0.01	172.111	0.012
WFW009	-43.26697978	170.4222468	0.01	170.164	0.012
WFW010	-43.2675395	170.4232242	0.01	173.44	0.014
WFW011	-43.26812138	170.4245197	0.009	184.06	0.014
WGK001	-43.28457184	170.3955563	0.017	99.849	0.057
WGK002	-43.28372013	170.3957579	0.016	100.986	0.049
WGK003	-43.28288112	170.3960323	0.015	101.225	0.029
WGK004	-43.28208217	170.3963355	0.014	99.3	0.021
WGK005	-43.28106449	170.3967178	0.013	99.193	0.017
WGK006	-43.28213272	170.3976281	0.013	101.883	0.018
WGK007	-43.28315794	170.3972702	0.013	102.298	0.016
WGK008	-43.28394831	170.3969979	0.013	102.336	0.015
WGK009	-43.28476268	170.3967114	0.01	100.594	0.014
WGK010	-43.28504909	170.3982625	0.01	101.412	0.014
WGK011	-43.28430511	170.3984828	0.01	103.218	0.014
WGK012	-43.28352167	170.3986918	0.009	102.422	0.012

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WGK013	-43.28273246	170.3989398	0.009	101.715	0.013
WGK014	-43.28153521	170.3990776	0.016	101.29	0.017
WIC001	-43.26507893	170.3964086	0.008	87.97	0.01
WIC002	-43.26582389	170.3933337	0.008	88.233	0.01
WIC003	-43.26682229	170.3894592	0.008	88.085	0.011
WIC004	-43.26772664	170.3859302	0.008	87.627	0.012
WLC001	-43.29754669	170.4211937	0.033	156.123	0.051
WLC002	-43.29597068	170.42056	0.052	166.591	0.067
WMTP001	-43.30824237	170.3741494	0.008	1253.553	0.012
WMTP002	-43.30703421	170.3740868	0.009	1270.665	0.013
WRS087	-43.29812511	170.4198685	0.019	132.512	0.022
WRS088	-43.29731024	170.4221941	0.14	171.972	0.111
WRS089	-43.29707211	170.4230194	1.033	191.152	0.968
SA86	-43.26582325	170.3751545	0.3	81.802	0.4
SA80	-43.27746724	170.4172908	0.5	110.468	0.5
WAFS060	-43.28565865	170.400857	0.1	101.674	0.5
WAFS061	-43.28558135	170.4018621	0.3	105.084	0.9
WAFS062	-43.2845767	170.4009778	0.5	104.601	1.7
WAFS063	-43.28377299	170.4010806	0.6	106.085	1.5
WAFS064	-43.28287568	170.4011644	0.2	104.194	0.6
WAFS065	-43.28188868	170.4010908	0.3	105.436	1.3
WAFS066	-43.28117762	170.4007645	0.3	101.034	1.2
WAFS067	-43.28022585	170.4005387	0.2	100.301	0.8
WAFS068	-43.27945445	170.4005743	0.1	100.229	0.4
WAFS069	-43.27852216	170.4005898	0.2	100.585	0.5
WAFS070	-43.28498757	170.4009357	0.5	104.24	1.9
WAFS071	-43.28418245	170.401034	0.5	104.213	0.6
WAFS072	-43.27761828	170.4007164	0.1	98.875	0.3
WAFS073	-43.27667864	170.4004114	0.3	97.965	0.5
WAFS074	-43.27585481	170.4008369	0.5	98.387	1.1
WAFS075	-43.27522108	170.4016689	0.2	96.122	0.6
WAFS076	-43.2732394	170.4003685	0.2	90.692	0.5
WAFS077	-43.2725768	170.4029273	0.1	95.191	0.4
WAFS078	-43.27217927	170.4049754	0.1	92.32	0.2
WAFS079	-43.27246936	170.4068699	0.1	93.7	0.3
WAFS080	-43.27262824	170.40905	0.1	91.936	0.2
WAFS081	-43.27276462	170.4117509	0.1	89.83	0.2
WAFS082	-43.27269953	170.4153768	0.1	89.302	0.1
WAFS083	-43.27409557	170.4035658	0.1	97.231	0.3
WAFS084	-43.27341056	170.4055786	0.2	96.401	0.3
WAFS085	-43.27360129	170.4077753	0.1	94.189	0.1
WAFS086	-43.27394552	170.4098957	0.1	92.434	0.1
WAFS087	-43.27468737	170.4103136	0.2	89.396	0.3
WAFS088	-43.27498944	170.4131933	0.2	87.477	0.2

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WAFS089	-43.27375131	170.4124429	0.1	89.931	0.2
WAFS090	-43.27414443	170.4146377	0.1	89.774	0.2
WAFS091	-43.2732596	170.4137833	0.4	89.781	0.4
WAFS092	-43.27249508	170.4133891	0.2	89.176	0.7
WAFS093	-43.2811902	170.4048551	0.1	98.501	0.2
WAFS094	-43.28191873	170.4055152	0.1	99.044	0.2
WAFS095	-43.2825835	170.4062415	0.1	100.438	0.2
WAFS096	-43.28324756	170.4068591	0.1	100.298	0.1
WAFS097	-43.28033666	170.4066539	0.1	98.661	0.2
WAFS098	-43.2810551	170.4074601	0.1	98.035	0.3
WAFS099	-43.28160478	170.4082878	0.1	99.733	0.3
WAFS100	-43.27976974	170.4083554	0.1	97.679	0.2
WAFS101	-43.28047558	170.4089417	0.1	98.342	0.2
WAFS102	-43.2791618	170.4103169	0.1	95.592	0.2
WAFS103	-43.27983215	170.4109068	0.1	104.175	0.2
WAFS104	-43.28129233	170.4097636	0.2	104.425	0.2
WAFS105	-43.28334709	170.4096448	0.1	106.591	0.3
WAFS106	-43.28453399	170.4082266	0.1	104.317	0.3
WAFS107	-43.2782505	170.4120837	0.1	102.194	0.2
WAFS108	-43.27892937	170.4127842	0.1	102.924	0.2
WAFS109	-43.27796014	170.4134199	0.1	101.363	0.1
WAFS110	-43.27856316	170.4141645	0.1	101.75	0.2
WAFS111	-43.28529321	170.4058926	0.1	104.922	0.2
WAFS112	-43.28540675	170.404339	0.1	105.275	0.2
WAFS113	-43.28439162	170.4032957	0.5	96.337	0.5
WAFS114	-43.28683122	170.4048124	0.5	97.367	0.6
WAFS115	-43.28513196	170.4085951	0.2	107.127	0.3
WAFS116	-43.28600748	170.4087938	0.1	106.91	0.2
WAFS117	-43.2867275	170.4091496	0.1	107.014	0.4
WAFS118	-43.28749204	170.4095511	0.1	108.276	0.3
WAFS119	-43.28830003	170.4098785	0.3	108.185	0.6
WAFS120	-43.28902736	170.4102546	0.2	105.81	0.4
WAFS121	-43.28939345	170.4089591	0.2	105.548	0.4
WAFS122	-43.28777686	170.4082418	0.1	102.626	0.2
WAFS123	-43.28625977	170.4075336	0.1	102.786	0.3
WAFS124	-43.28422213	170.4098861	0.2	107.057	0.5
WAFS125	-43.28498391	170.4102143	0.2	108.722	0.3
WAFS126	-43.28605637	170.4107762	0.2	109.657	0.2
WAFS127	-43.28689463	170.411219	0.3	110.255	0.2
WAFS128	-43.28779499	170.4116846	0.2	111.059	0.2
WAFS129	-43.28869233	170.412168	0.2	113.868	0.3
WAFS130	-43.28897175	170.4145588	0.2	137.656	0.4
WAFS131	-43.28718465	170.4103776	0.1	109.006	0.2
WAFS132	-43.28504833	170.4094315	0.1	107.037	0.2

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WAFS133	-43.28102375	170.4114518	0.1	104.78	0.1
WAFS134	-43.28186142	170.4119297	0.1	105.66	0.1
WAFS135	-43.28268419	170.4122401	0.1	106.312	0.2
WAFS136	-43.28302832	170.4111372	0.1	106.385	0.2
WAFS137	-43.28357391	170.4127081	0.1	108.115	0.1
WAFS138	-43.28467514	170.4131822	0.1	111.73	0.1
WAFS139	-43.2848201	170.4118677	0.1	109.167	0.2
WAFS140	-43.28583221	170.4137701	0.2	116.564	0.4
WAFS141	-43.28659046	170.4124785	0.2	114.643	0.4
WAFS142	-43.28528885	170.4164542	1	138.395	0.9
WAFS143	-43.28459302	170.4147687	0.5	114.56	0.5
WAFS144	-43.28329328	170.4143681	0.3	109.759	0.5
WAFS145	-43.28231742	170.4139732	0.2	106.695	0.7
WAFS146	-43.28134461	170.4135944	0.1	106.7	0.2
WAFS147	-43.28014286	170.4132877	0.1	103.829	0.2
WAFS148	-43.27963059	170.4147568	0.1	105.479	0.2
WAFS149	-43.28029908	170.4150581	0.1	106.459	0.2
WAFS150	-43.27891453	170.41585	0.1	104.811	0.2
WAFS151	-43.2831086	170.3868024	0.1	93.54	0.1
WAFS152	-43.28162578	170.3841088	0.1	91.737	0.1
WAFS153	-43.27992759	170.383218	0.1	91.393	0.1
WAFS154	-43.27798079	170.3826739	0.4	91.145	0.6
WAFS155	-43.27596468	170.3821476	0.1	88.723	0.4
WAFS156	-43.2726324	170.3812542	0.3	88.283	0.7
WAFS157	-43.27758484	170.3983505	0.1	97.232	0.1
WAFS158	-43.27708635	170.3956506	0.1	95.513	0.1
WAFS159	-43.2766091	170.3930603	0.2	94.511	0.2
WAFS160	-43.27828149	170.3912528	0.2	94.289	0.3
WAFS161	-43.27601028	170.3898882	0.1	92.087	0.1
WAFS162	-43.27552849	170.3873145	0.1	90.396	0.2
WAFS163	-43.27508896	170.384962	0.2	88.973	0.3
WAFS164	-43.27343184	170.3849303	0.1	88.115	0.2
WAFS165	-43.27605316	170.3991834	0.3	99.155	0.5
WAFS166	-43.27452849	170.3981346	0.1	94.826	0.2
WAFS167	-43.27269926	170.3975161	0.1	93.215	0.2
WAFS168	-43.27104409	170.3967262	0.1	91.163	0.2
WAFS169	-43.27182017	170.3910885	0.1	91.001	0.2
WAFS170	-43.2738733	170.3891283	0.1	90.987	0.2
WAFS171	-43.27412559	170.3921538	0.1	92.564	0.2
WAFS172	-43.27269173	170.3944698	0.2	92.927	0.2
WAFS173	-43.27455814	170.3951846	0.1	94.659	0.1
WAFS174	-43.28058811	170.3869385	0.1	93.149	0.2
WAFS175	-43.27860352	170.387629	0.1	92.752	0.2
WAFS176	-43.27725659	170.3854037	0.1	90.535	0.1

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WAFS177	-43.27977076	170.3850083	0.1	91.543	0.1
WAFS178	-43.2844461	170.3862718	0.1	94.125	0.3
WAFS179	-43.2821255	170.3814911	0.3	92.493	0.4
WAFS180	-43.28128492	170.3770261	0.4	88.971	0.5
WAFS181	-43.28051288	170.3728421	0.2	92.622	0.3
WAFS182	-43.27537064	170.3779478	0.1	86.319	0.2
WAFS183	-43.27852763	170.362284	0.1	103.919	0.3
WAFS184	-43.27962166	170.3683365	0.1	99.607	0.2
WAFS185	-43.27631876	170.3719128	0.1	88.029	0.2
WAFS186	-43.28131196	170.3979219	0.1	99.54	0.2
WAFS187	-43.28041129	170.393141	0.1	95.095	0.1
WAFS188	-43.28430241	170.3801367	0.3	110.173	0.3
WAFS189	-43.28643818	170.3791291	0.2	145.272	0.2
WAFS190	-43.28612639	170.3764475	0.3	127.394	0.3
WAFS191	-43.28826845	170.3789104	1.2	171.615	1.4
WAFS193	-43.29057281	170.3781651	0.6	242.533	1.7
WDSS024	-43.29095724	170.4054409	0.9	110.894	0.9
WDSS027	-43.29240407	170.4053951	0.4	118.381	0.6
WDSS028	-43.29252081	170.4046546	0.2	156.102	0.4
WDSS032	-43.29724157	170.4142121	0.1	112.558	0.1
WDSS033	-43.29719542	170.4129944	0.1	113.048	0.1
WDSS034	-43.29711119	170.4117738	0.1	111.627	0.1
WDSS035	-43.29704652	170.4105935	0.1	111.85	0.1
WDSS036	-43.29694464	170.4090241	0.1	115.895	0.2
WDSS037	-43.29745177	170.408194	0.1	116.314	0.1
WDSS038	-43.29766662	170.4071731	0.1	121.109	0.2
WDSS039	-43.29734559	170.4064864	1.4	136.756	1.8
WDSS040	-43.29680965	170.4055954	1.1	158.271	1.1
WDSS041	-43.2967748	170.4049525	1	177.107	1
WDSS042	-43.29683847	170.4040833	1.8	200.615	1.9
WDSS044	-43.2963086	170.4025666	1.3	262.583	1.7
WDSS045	-43.29623016	170.4017588	0.5	290.402	0.8
WDSS046	-43.2895452	170.4055257	0.9	98.8	0.9
WDSS047	-43.29008988	170.4055991	0.5	105.378	0.7
WDSS048	-43.28986112	170.4062279	0.2	102.215	0.6
WDSS049	-43.29016942	170.4068907	0.1	102.605	0.2
WDSS050	-43.29052195	170.4076976	0.1	103.519	0.1
WDSS051	-43.29101883	170.4072108	0.1	105.047	0.2
WDSS052	-43.292327	170.4080511	0.3	105.593	0.4
WDSS053	-43.29202271	170.4068503	0.5	105.269	0.5
WDSS054	-43.28924775	170.4050197	0.7	109.501	1
WDSS055	-43.28986913	170.405309	0.8	112.604	1.6
WDSS056	-43.29186	170.4055981	1.3	110.974	2.6
WDSS057	-43.29192903	170.4060325	0.1	104.244	0.3

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WRS013	-43.28566068	170.3896313	0.3	122.575	0.6
WRS014	-43.28600623	170.3895591	0.4	119.255	1.3
WRS065	-43.28664076	170.3897421	0.7	136.899	0.9
WRS066	-43.28697534	170.3901078	0.5	150.514	0.9
WRS067	-43.28746239	170.3905599	0.5	160.864	1
WRS071	-43.26461386	170.4158078	0.1	92.326	0.2
WRS072	-43.26433986	170.4130035	0.1	87.706	0.2
WRS073	-43.26542737	170.4103805	0.1	84.712	0.2
WRS074	-43.26597666	170.4072659	0.1	83.768	0.3
WRS075	-43.26421132	170.376059	0.1	80.633	0.2
WRS076	-43.26364825	170.3782026	0.1	81.408	0.3
WRS077	-43.26290813	170.3811654	0.6	82.625	0.6
WRS078	-43.26734644	170.3984311	0.2	89.98	0.3
WRS079	-43.26702671	170.400944	0.2	89.757	0.2
WRS080	-43.26686659	170.4030078	0.1	89.116	0.2
WRS081	-43.2667131	170.4051886	0.2	88.812	0.3
WRS082	-43.25101641	170.3991503	0.1	78.344	0.2
WRS083	-43.25205339	170.4047182	0.1	78.419	0.4
WRS084	-43.25326351	170.4112531	0.1	74.086	0.3
WRS085	-43.25732568	170.4100182	0.1	79.169	0.2
WRS086	-43.25455413	170.4178611	0.1	75.482	0.2
WRS087	-43.29810703	170.419916	1.3	134.972	1.6
WRS088	-43.29730604	170.4222028	2.1	175.946	1.5
WRS089	-43.29725803	170.4229735	13.1	211.362	9.2
WRS090	-43.2691612	170.395287	0.2	91.36	0.4
WRS091	-43.26952335	170.3926555	0.1	91.289	0.2
WRS092	-43.27016594	170.3892608	0.1	89.504	0.3
WRS093	-43.27101321	170.3844509	0.2	88.111	0.4
WRS094	-43.26035836	170.4020388	0.4	85.178	1.7
WRS095	-43.2565128	170.4037918	0.3	81.423	0.6
WRS096	-43.25483067	170.3886178	0.3	79.127	0.8
WRS097	-43.25636613	170.3828053	0.2	81.635	0.6
WRS098	-43.25803724	170.3767106	0.1	77.548	0.3
WRS099	-43.26021048	170.3721627	0.3	80.227	0.8
WRS100	-43.27818182	170.3791126	0.1	88.075	0.1
WRS101	-43.26352823	170.3682187	0.2	77.709	0.2
WRS102	-43.25172099	170.3736602	0.1	73.787	0.2
WRS103	-43.25567996	170.3662246	0.2	73.526	0.3
WRS104	-43.27509882	170.3575006	0.2	80.97	0.3
WRS105	-43.27446372	170.3676697	0.2	85.234	0.3
WRS106	-43.27024925	170.3660954	0.2	80.475	0.3
WRS107	-43.26890785	170.4155613	0.4	107.621	0.5
WRS108	-43.26892813	170.4166187	0.2	114.245	0.2
WRS109	-43.26906851	170.4177985	0.5	126.011	0.5

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WRS110	-43.26938789	170.4191912	1.2	138.546	1.3
WRS111	-43.2697909	170.4204413	0.5	147.804	0.4
WRS112	-43.26875509	170.4143686	0.1	96.047	0.1
WRS113	-43.27228482	170.4218696	0.3	180.574	0.5
WRS114	-43.27346705	170.4260479	0.6	234.754	1.5
WRS115	-43.27594418	170.4284465	0.1	285.59	0.4
WRS116	-43.28803113	170.4160862	0.5	149.95	1.5
WRS117	-43.29003043	170.4188648	1.1	204.523	1.4
DFDP2-S5	-43.29317979	170.409447	0.4	108.116	0.6
WE01	-43.29258946	170.4142411	1.1	105.998	1.1
WE02	-43.29773298	170.4170399	0.6	105.158	0.5
WE03	-43.29807064	170.4176115	0.6	108.252	0.5
WE06	-43.29713241	170.4174773	0.6	109.198	0.8
WE08	-43.29478668	170.4172869	0.7	108.476	0.7
WE09	-43.29365685	170.4160222	0.7	110.779	0.7
WE10	-43.29152104	170.4131307	0.5	107.895	0.9
WE11	-43.29017675	170.4115598	0.9	107.732	1.8
WS01	-43.29253649	170.4059947	0.4	106.988	0.5
WS02	-43.29267576	170.4065647	0.4	106.9295	0.6
WS03	-43.29278131	170.4071498	0.4	108.183	0.5
WS04	-43.29289088	170.4077511	0.3	108.6825	0.4
WS05	-43.29300214	170.4083467	0.3	107.756	0.4
WS06	-43.29314795	170.4089311	0.3	107.888	0.4
WS07	-43.29334579	170.4094856	0.3	108.3345	0.4
WS08	-43.29355181	170.4100387	0.3	108.686	0.5
WS09	-43.29375071	170.4105775	0.3	108.7685	0.4
WS10	-43.29395731	170.4111314	0.3	109.042	0.4
WS11	-43.29416305	170.4116865	0.5	108.885	0.7
WS12	-43.29439594	170.4121794	0.4	108.806	0.5
WS13	-43.2947452	170.4125693	0.8	110.079	1.1
WS14	-43.2952773	170.4133127	1.2	110.021	1.6
WS15	-43.29587701	170.4141271	0.6	111.08	0.9
WS16	-43.2964865	170.4149168	0.6	111.644	1.1
WS17	-43.29702275	170.4155138	0.6	111.746	1.2
WS18	-43.29701472	170.4159059	0.4	106.533	0.7
WS19	-43.29747523	170.4156629	0.8	105.586	1.4
WS20	-43.29729063	170.4161508	0.7	105.537	1.2
WS21	-43.29744709	170.4154886	0.2	113.926	0.2
WS22	-43.29736232	170.4150476	0.5	114.126	0.6
WT01	-43.29040311	170.4054197	1	108.315	0.9
WT02	-43.29045608	170.4062378	0.4	105.599	0.5
WT03	-43.29050465	170.4068306	0.1	106.049	0.1
WT04	-43.29064455	170.4076963	0.1	105.715	0.1
WT05	-43.29114541	170.4089924	0.5	106.478	0.5

Station	Latitude	Longitude	Horizontal error (m)	Height (WGS84)	Height error (m)
WT06	-43.29141016	170.4055416	0.6	111.302	0.5
WT06B	-43.29143125	170.4059735	0.2	104.663	0.2
WT06C	-43.29145746	170.4063078	0.4	105.674	0.5
WT07	-43.29150312	170.4072517	0.4	106.546	0.5
WT08	-43.29168354	170.4079883	0.4	106.869	0.6
WT09	-43.29188527	170.4088909	0.3	108.101	0.5
WT10	-43.29218378	170.4098926	0.3	108.221	0.5
WT11	-43.29227163	170.4105788	0.4	106.806	0.8
WT12	-43.29229482	170.4114531	0.4	105.674	0.6
WT13	-43.29241482	170.4058134	6.8	106.394	0.8
WT17	-43.29295697	170.4100407	0.3	106.473	0.6
WT18	-43.29300624	170.4109052	0.3	108.27	0.6
WT19	-43.29309892	170.4119711	0.3	108.665	0.6
WT20B	-43.29365065	170.4059857	0.5	108.403	0.7
WT21	-43.29374178	170.4074122	0.4	110.481	0.5
WT22	-43.29382996	170.4082372	0.4	109.727	0.5
WT23	-43.29391234	170.4093578	0.4	109.7	0.5
WT27	-43.29501059	170.406557	0.4	114.184	0.6
WT28	-43.29481644	170.407314	0.5	109.328	0.5
WT29	-43.2947284	170.4082831	0.2	109.741	0.3
WT30	-43.29486643	170.40923	0.1	110.125	0.1
WT31	-43.29505428	170.410148	0.1	110.598	0.1
WT32	-43.29525312	170.4109087	0.1	110.782	0.1
WW01	-43.28869355	170.4047416	0.7	108.961	0.6
WW02	-43.28722806	170.403673	1.1	110.491	0.9
WW03	-43.28622001	170.4018905	1.2	115.471	1.6
WW04	-43.28562171	170.4000784	0.3	105.908	0.5
WW05	-43.28517021	170.3975616	0.3	102.169	0.5
WW06	-43.2837095	170.393878	0.3	100.148	0.5
WW07	-43.28447706	170.3939674	0.4	99.722	0.5

Table D.1: Site survey GPS data.

Appendix E Gsolve Data

Station Name	Latitude	Longitude	Height (m)	Dial (mGal)	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
SA80	-43.27747	170.41729	97.75	3975.2	4024.708	26	9	2015	3	36	0.081226109	1	0.012393531
SA86	-43.26583	170.37515	70.67	3991.53	4041.255	26	9	2015	3	47	0.08526557	1	0.020119044
SA47	-43.13956	170.63179	78.42	3970.65	4020.097	27	9	2015	1	14	-0.030116762	1	0.000721581
SA47	-43.13956	170.63179	78.42	3970.65	4020.097	27	9	2015	1	17	-0.028725482	1	-0.000721586
SB13	-43.39347	170.12878	154.61	3991.71	4041.438	27	9	2015	2	54	0.030126947	1	0.001396657
SB13	-43.39347	170.12878	154.61	3991.71	4041.438	27	9	2015	2	58	0.032851078	1	-0.001396657
SB28	-43.45825	170.04258	285.66	3957.34	4006.61	27	9	2015	3	29	0.053516332	1	-0.004069349
SB28	-43.45825	170.04258	285.66	3957.35	4006.62	27	9	2015	3	32	0.055458946	1	0.00406935
SA86	-43.26583	170.37515	70.67	3991.44	4041.164	27	9	2015	21	25	0.014153215	1	-0.043172283
SA80	-43.27747	170.41729	97.75	3975.12	4024.627	27	9	2015	21	37	0.004890826	1	-0.035939471
SB6	-43.36863	170.18574	122.13	3988.99	4038.681	28	9	2015	21	19	0.037183539	1	-0.002311044
SB6	-43.36863	170.18574	122.13	3988.99	4038.681	28	9	2015	21	22	0.034825451	1	-4.84336E-06
SB6	-43.36863	170.18574	122.13	3988.99	4038.681	28	9	2015	21	25	0.032452832	1	0.002315888
SA98	-43.2885	170.23141	85.77	4002.76	4052.635	28	9	2015	21	49	0.012765418	1	0.00587934
SA98	-43.2885	170.23141	85.77	4002.75	4052.625	28	9	2015	21	55	0.007875021	1	0.000532561
SA98	-43.2885	170.23141	85.77	4002.74	4052.615	28	9	2015	21	59	0.0046169	1	-0.006411901
SA90	-43.28696	170.31819	82.92	3995.84	4045.623	28	9	2015	22	36	-0.025082697	1	0.000178568
SA90	-43.28696	170.31819	82.92	3995.84	4045.623	28	9	2015	22	41	-0.028872149	1	0.003881542
SA90	-43.28696	170.31819	82.92	3995.83	4045.612	28	9	2015	22	44	-0.031115584	1	-0.004060111
SA74	-43.23582	170.43287	76.68	3981.37	4030.96	28	9	2015	23	22	-0.057519592	1	-0.001542542
SA74	-43.23582	170.43287	76.68	3981.37	4030.96	28	9	2015	23	24	-0.058724628	1	-0.000372098
SA74	-43.23582	170.43287	76.68	3981.37	4030.96	28	9	2015	23	28	-0.061080549	1	0.00191464
SA69	-43.19686	170.44761	47.38	3983.72	4033.341	28	9	2015	23	44	-0.069958776	1	0.008415834
SA69	-43.19686	170.44761	47.38	3983.7	4033.321	28	9	2015	23	48	-0.071921763	1	-0.009956762
SA69	-43.19686	170.44761	47.38	3983.71	4033.331	28	9	2015	23	51	-0.073338146	1	0.001540934
SA86	-43.26583	170.37515	70.67	3991.46	4041.184	29	9	2015	2	46	-0.06065098	1	0.021440426
SA80	-43.27747	170.41729	97.75	3975.14	4024.647	29	9	2015	2	36	-0.066018376	1	0.025158753

Table E.1: Survey measurements processed using Gsolve for 10 absolute gravity reference stations of the New Zealand gravity network.

Note that time has been converted to UTC.

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
SA86	-43.265827	170.37515	83.071	3893.41	4071.038	30	11	2013	3	18	0.037459147	1	-0.006538452
SA80	-43.277467	170.41729	110.468	3877.67	4054.554	30	11	2013	3	52	0.055344847	1	0.007907687
WT13	-43.292415	170.40581	106.394	3875.33	4052.103	30	11	2013	4	27	0.069107034	1	-0.002650392
WT06	-43.29141	170.40554	111.302	3874.91	4051.663	30	11	2013	4	45	0.074216238	1	6.36646E-12
WT01	-43.290403	170.40542	108.315	3875.57	4052.354	30	11	2013	4	55	0.076455538	1	2.66527E-09
WW01	-43.288694	170.40474	108.961	3877.18	4054.041	30	11	2013	5	11	0.079146484	1	-2.75259E-09
WW02	-43.287228	170.40367	110.491	3878.99	4055.936	30	11	2013	5	23	0.080453439	1	7.61702E-10
WW03	-43.28622	170.40189	115.471	3880.06	4057.057	30	11	2013	5	31	0.080993166	1	-2.84672E-10
WW04	-43.285622	170.40008	105.908	3881.01	4058.052	30	11	2013	5	44	0.08132226	1	-2.5193E-10
WW05	-43.28517	170.39756	102.169	3882.96	4060.094	30	11	2013	5	56	0.081046735	1	4.41105E-10
WW06	-43.28371	170.39388	100.148	3885.44	4062.691	30	11	2013	6	7	0.08033123	1	3.13321E-10
WW07	-43.284477	170.39397	99.722	3885.13	4062.367	30	11	2013	6	16	0.079435608	1	-3.74712E-10
SA80	-43.277467	170.41729	110.468	3877.79	4054.679	30	11	2013	6	28	0.077812797	1	0.010394062
WT13	-43.292415	170.40581	106.394	3875.43	4052.208	30	11	2013	6	36	0.076530297	1	0.011367267
SA86	-43.265827	170.37515	83.071	3893.56	4071.195	30	11	2013	6	45	0.074845952	1	-0.020480173
SA86	-43.265827	170.37515	83.071	3893.41	4071.038	30	11	2013	21	47	-0.1165765	2	-0.032754783
SA80	-43.277467	170.41729	110.468	3877.65	4054.533	30	11	2013	22	14	-0.128285	2	0.015319698
WT13	-43.292415	170.40581	106.394	3875.28	4052.051	30	11	2013	22	41	-0.13544846	2	0.019894056
WS01	-43.292536	170.40599	106.988	3875.45	4052.229	30	11	2013	22	55	-0.13734684	2	6.82758E-09
WS02	-43.292676	170.40656	106.9295	3875.59	4052.375	30	11	2013	23	9	-0.13794559	2	0.024766431
WS03	-43.292781	170.40715	108.183	3875.41	4052.187	30	11	2013	23	19	-0.13757367	2	4.45652E-11
WS04	-43.292891	170.40775	108.6825	3875.33	4052.103	30	11	2013	23	3	-0.13784781	2	-2.77396E-11
WS05	-43.293002	170.40835	107.756	3875.35	4052.124	30	11	2013	23	34	-0.13577312	2	4.09273E-11
WS06	-43.293148	170.40893	107.888	3875.25	4052.019	30	11	2013	23	39	-0.13484489	2	-8.6402E-12
WS08	-43.293552	170.41004	108.686	3874.78	4051.527	30	11	2013	23	49	-0.13250515	2	0.042011711
WS09	-43.293751	170.41058	108.7685	3874.58	4051.318	30	11	2013	23	55	-0.13079764	2	-9.09495E-12
WS10	-43.293957	170.41113	109.042	3874.35	4051.077	1	12	2013	0	0	-0.12920364	2	-3.9563E-11
WT13	-43.292415	170.40581	106.394	3875.25	4052.019	1	12	2013	0	13	-0.12437172	2	-0.012284128
WS02	-43.292676	170.40656	106.9295	3875.55	4052.334	1	12	2013	0	17	-0.12267872	2	-0.024766423
WT19	-43.293099	170.41197	108.665	3874.23	4050.951	1	12	2013	0	52	-0.10419327	2	-2.72848E-12
WT11	-43.292272	170.41058	106.806	3875.09	4051.852	1	12	2013	1	3	-0.09716946	2	2.00089E-11
WT12	-43.292295	170.41145	105.674	3875.29	4052.061	1	12	2013	1	13	-0.09034016	2	1.40972E-11

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WT18	-43.293006	170.41091	108.27	3874.68	4051.422	1	12	2013	1	24	-0.08240169	2	-5.09317E-11
WT17	-43.292957	170.41004	106.473	3874.98	4051.737	1	12	2013	1	32	-0.07638093	2	-1.77351E-11
WS08	-43.293552	170.41004	108.686	3874.75	4051.496	1	12	2013	1	44	-0.06700378	2	-0.042011711
WS07	-43.293346	170.40949	108.3345	3874.98	4051.737	1	12	2013	2	45	-0.01584686	2	-0.01082467
WT10	-43.292184	170.40989	108.221	3875.33	4052.103	1	12	2013	3	21	0.014091761	2	-3.18323E-12
WT09	-43.291885	170.40889	108.101	3875.71	4052.501	1	12	2013	3	31	0.021999532	2	1.04592E-11
WT08	-43.291684	170.40799	106.869	3875.95	4052.752	1	12	2013	3	44	0.031897755	2	1.36424E-12
WS07	-43.293346	170.40949	108.3345	3875.06	4051.82	1	12	2013	4	21	0.057053951	2	0.010824668
WT07	-43.291503	170.40725	106.546	3876.18	4052.993	1	12	2013	5	9	0.081167602	2	-5.72982E-11
WT06C	-43.291457	170.40631	105.674	3876.14	4052.951	1	12	2013	5	19	0.084808896	2	-2.27374E-12
WT06B	-43.291431	170.40597	104.663	3876.15	4052.962	1	12	2013	5	25	0.086755168	2	-2.95586E-11
WT02	-43.290456	170.40624	105.599	3876.61	4053.444	1	12	2013	5	36	0.089856423	2	-5.18412E-11
WT03	-43.290505	170.40683	106.049	3876.71	4053.548	1	12	2013	5	47	0.092351737	2	5.45697E-11
WT04	-43.290645	170.4077	105.715	3876.64	4053.475	1	12	2013	5	56	0.093945974	2	1.10049E-10
WT05	-43.291145	170.40899	106.478	3876.13	4052.941	1	12	2013	6	4	0.095029323	2	-4.63842E-11
DFDP2-S5	-43.29318	170.40945	108.116	3875.18	4051.946	1	12	2013	6	18	0.096184899	2	0.02089514
WT13	-43.292415	170.40581	106.394	3875.41	4052.187	1	12	2013	6	26	0.096434475	2	-0.023691355
WS11	-43.294163	170.41169	108.885	3874.32	4051.045	1	12	2013	6	45	0.095891827	2	-6.72526E-09
WS12	-43.294396	170.41218	108.806	3874.19	4050.909	1	12	2013	6	52	0.09531022	2	-1.33241E-10
SA80	-43.277467	170.41729	110.468	3877.81	4054.7	1	12	2013	7	7	0.093410425	2	0.020966817
SA86	-43.265827	170.37515	83.071	3893.57	4071.206	1	12	2013	7	21	0.090954745	2	-0.00834544
SA86	-43.265827	170.37515	83.071	3893.45	4071.08	1	12	2013	21	4	-0.07281801	3	-0.040585271
SA80	-43.277467	170.41729	110.468	3877.68	4054.564	1	12	2013	21	51	-0.11214335	3	0.031497601
WT13	-43.292415	170.40581	106.394	3875.32	4052.093	1	12	2013	22	1	-0.11926051	3	0.045575475
WS13	-43.294745	170.41257	110.079	3873.75	4050.448	1	12	2013	23	21	-0.15596161	3	0.029609384
WS14	-43.295277	170.41331	110.021	3873.42	4050.103	1	12	2013	23	3	-0.1513492	3	1.63709E-11
WS15	-43.295877	170.41413	111.08	3872.92	4049.579	1	12	2013	23	36	-0.15802566	3	3.18323E-12
WS16	-43.296486	170.41492	111.644	3872.69	4049.338	1	12	2013	23	45	-0.1584756	3	0.027714923
WS17	-43.297023	170.41551	111.746	3872.49	4049.129	1	12	2013	23	57	-0.15815186	3	4.72937E-11
WS18	-43.297015	170.41591	106.533	3873.32	4049.998	2	12	2013	0	6	-0.15721898	3	-8.04903E-11
WS19	-43.297475	170.41566	105.586	3873.47	4050.155	2	12	2013	0	15	-0.15569659	3	5.82077E-11
WS20	-43.297291	170.41615	105.537	3873.58	4050.27	2	12	2013	0	24	-0.15359593	3	5.54792E-11

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WS16	-43.296486	170.41492	111.644	3872.64	4049.286	2	12	2013	0	33	-0.15092999	3	-0.022092676
WS21	-43.297447	170.41549	113.926	3872.11	4048.731	2	12	2013	0	42	-0.14769768	3	1.67847E-09
WS22	-43.297362	170.41505	114.126	3872.33	4048.961	2	12	2013	0	5	-0.15735077	3	-3.63798E-12
WS16	-43.296486	170.41492	111.644	3872.66	4049.307	2	12	2013	0	56	-0.1416134	3	-0.005622247
WS13	-43.294745	170.41257	110.079	3873.69	4050.386	2	12	2013	1	3	-0.13811194	3	-0.029609393
DFDP2-S5	-43.29318	170.40945	108.116	3874.95	4051.705	2	12	2013	1	42	-0.11341418	3	-0.015142826
WT23	-43.293912	170.40936	109.7	3874.55	4051.286	2	12	2013	1	57	-0.10190302	3	-3.00133E-11
WT22	-43.29383	170.40824	109.727	3874.84	4051.59	2	12	2013	2	4	-0.09622234	3	-3.63798E-11
WT21	-43.293742	170.40741	110.481	3874.9	4051.653	2	12	2013	2	12	-0.08951244	3	-3.63798E-11
DFDP2-S5	-43.29318	170.40945	108.116	3874.97	4051.726	2	12	2013	2	19	-0.08346208	3	-0.01636119
WT20B	-43.293651	170.40599	108.403	3875.12	4051.883	2	12	2013	2	26	-0.07728794	3	-1.07775E-10
WT27	-43.295011	170.40656	114.184	3874.09	4050.804	2	12	2013	2	39	-0.0654804	3	5.43423E-10
DFDP2-S5	-43.29318	170.40945	108.116	3874.98	4051.737	2	12	2013	2	55	-0.05052827	3	-0.031244739
WT13	-43.292415	170.40581	106.394	3875.33	4052.103	2	12	2013	5	5	0.0626254	3	-0.036594194
WT28	-43.294816	170.40731	109.328	3874.82	4051.569	2	12	2013	6	5	0.093961669	3	-2.1505E-09
WT29	-43.294728	170.40828	109.741	3874.76	4051.506	2	12	2013	6	18	0.09821904	3	2.22872E-09
WT30	-43.294866	170.40923	110.125	3874.54	4051.276	2	12	2013	6	32	0.101767374	3	3.87899E-10
WT31	-43.295054	170.41015	110.598	3874.23	4050.951	2	12	2013	6	38	0.102962162	3	2.63753E-11
WT32	-43.295253	170.41091	110.782	3873.96	4050.668	2	12	2013	6	44	0.103963406	3	-6.65295E-10
DFDP2-S5	-43.29318	170.40945	108.116	3875.15	4051.915	2	12	2013	6	58	0.105560852	3	0.04185362
WT13	-43.292415	170.40581	106.394	3875.38	4052.155	2	12	2013	7	9	0.106112375	3	-0.001616728
SA80	-43.277467	170.41729	110.468	3877.76	4054.648	2	12	2013	7	36	0.105006005	3	0.021262664
SA86	-43.265827	170.37515	83.071	3893.53	4071.164	2	12	2013	7	45	0.103942389	3	0.001355595
SA80	-43.277467	170.41729	110.468	3877.67	4054.554	2	12	2013	21	48	-0.08327014	4	0.007433693
WE01	-43.292589	170.41424	105.998	3873.63	4050.323	2	12	2013	22	1	-0.09520672	4	-0.012222079
WE02	-43.297733	170.41704	105.158	3873.19	4049.862	2	12	2013	22	26	-0.11659958	4	1.40972E-11
WE03	-43.298071	170.41761	108.252	3872.54	4049.181	2	12	2013	22	34	-0.1228892	4	-3.72893E-11
WE04	-43.298449	170.41864	117.589	3870.3	4046.835	2	12	2013	22	43	-0.1295925	4	1.04592E-11
WE05	-43.297145	170.4183	111.403	3871.46	4048.05	2	12	2013	22	53	-0.13654113	4	-1.37425E-09
WE06	-43.297132	170.41748	109.198	3872.32	4048.951	2	12	2013	23	0	-0.14106593	4	1.25283E-09
WE07	-43.295221	170.41897	131.879	3868.13	4044.563	2	12	2013	23	12	-0.14815362	4	7.36236E-10
WE08	-43.294787	170.41729	108.476	3871.97	4048.584	2	12	2013	23	24	-0.15431421	4	-1.05501E-10

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WE09	-43.293657	170.41602	110.779	3872.21	4048.836	2	12	2013	23	3	-0.14292691	4	-2.77396E-11
WE01	-43.292589	170.41424	105.998	3873.59	4050.281	2	12	2013	23	36	-0.15951349	4	0.012222082
WE10	-43.291521	170.41313	107.895	3874.21	4050.93	2	12	2013	23	41	-0.16138502	4	-1.8872E-10
WE11	-43.290177	170.41156	107.732	3875.53	4052.313	2	12	2013	23	54	-0.16540607	4	2.93312E-10
WE12	-43.288426	170.40918	93.325	3877.95	4054.847	3	12	2013	0	9	-0.16849612	4	-2.4238E-10
SA80	-43.277467	170.41729	110.468	3877.57	4054.449	3	12	2013	0	22	-0.16984301	4	-0.007433694
SA86	-43.265827	170.37515	70.667	3991.48	4041.205	24	4	2015	22	25	0.029683335	5	0.010427746
SA86	-43.265827	170.37515	70.667	3991.48	4041.205	24	4	2015	22	32	0.032021678	5	0.00903885
SA86	-43.265827	170.37515	70.667	3991.48	4041.205	24	4	2015	22	36	0.033329242	5	0.008273828
SA80	-43.277467	170.41729	97.747	3975.15	4024.657	24	4	2015	22	57	0.03989036	5	-0.004168546
SA80	-43.277467	170.41729	97.747	3975.15	4024.657	24	4	2015	23	0	0.040764138	5	-0.004635418
SA80	-43.277467	170.41729	97.747	3975.14	4024.647	24	4	2015	23	3	0.041623897	5	-0.015221471
WRS001	-43.249723	170.39254	64.28	3989.34	4039.036	25	4	2015	1	31	0.064422226	5	-0.019306164
WRS002	-43.253944	170.39446	67.669	3989.9	4039.603	25	4	2015	1	43	0.064616549	5	7.00311E-11
WRS003	-43.258328	170.39598	71.328	3989.42	4039.117	25	4	2015	1	54	0.064608049	5	-2.04636E-11
WRS004	-43.260371	170.39108	71.261	3989.63	4039.33	25	4	2015	2	6	0.064403591	5	-5.77529E-11
WRS005	-43.261773	170.38569	71.494	3990.32	4040.029	25	4	2015	2	26	0.063656853	5	-1.68257E-11
WRS001	-43.249723	170.39254	64.28	3989.36	4039.056	25	4	2015	3	25	0.059179686	5	0.021665214
WRS007	-43.247785	170.38235	61.335	3991.43	4041.154	25	4	2015	3	59	0.055727342	5	-4.8658E-11
WRS006	-43.248581	170.38653	62.592	3990.06	4039.766	25	4	2015	4	25	0.052972357	5	5.50699E-10
WRS001	-43.249723	170.39254	64.28	3989.32	4039.016	25	4	2015	4	34	0.052029996	5	-0.002359052
SA86	-43.265827	170.37515	70.667	3991.45	4041.174	25	4	2015	4	47	0.050746792	5	0.010777419
SA80	-43.277467	170.41729	97.747	3975.1	4024.606	25	4	2015	5	3	0.049190779	5	-0.014492402
SA86	-43.265827	170.37515	70.667	3991.37	4041.093	26	4	2015	20	43	-0.03201806	6	0.005742404
SA86	-43.265827	170.37515	70.667	3991.37	4041.093	26	4	2015	20	46	-0.03150361	6	0.00454217
SA86	-43.265827	170.37515	70.667	3991.37	4041.093	26	4	2015	20	49	-0.03097095	6	0.003323735
SA80	-43.277467	170.41729	97.747	3975.05	4024.556	26	4	2015	21	7	-0.02733264	6	-0.003025642
SA80	-43.277467	170.41729	97.747	3975.05	4024.556	26	4	2015	21	10	-0.02667554	6	-0.004368526
SA80	-43.277467	170.41729	97.747	3975.05	4024.556	26	4	2015	21	13	-0.02600147	6	-0.005728373
WDSS001	-43.291348	170.40648	92.668	3973.64	4023.127	26	4	2015	22	19	-0.0073508	6	-0.007324433
WDSS002	-43.291332	170.40627	92.811	3973.55	4023.036	26	4	2015	22	28	-0.00434453	6	5.82077E-11
WDSS003	-43.291335	170.40605	93.11	3973.33	4022.813	26	4	2015	22	36	-0.00160285	6	-2.27374E-12

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WDSS004	-43.290831	170.40576	91.114	3973.63	4023.117	26	4	2015	22	52	0.004043684	6	-4.54747E-12
WDSS005	-43.290821	170.40588	92.596	3973.57	4023.056	26	4	2015	23	4	0.00839146	6	5.45697E-12
WDSS006	-43.290817	170.40604	92.832	3973.67	4023.157	26	4	2015	23	17	0.01317261	6	2.91038E-11
WDSS007	-43.290804	170.40626	93.801	3973.66	4023.147	26	4	2015	23	27	0.016877756	6	-3.81988E-11
WDSS001	-43.291348	170.40648	92.668	3973.67	4023.157	26	4	2015	23	39	0.021329038	6	-0.023892088
WDSS008	-43.290792	170.4065	93.811	3973.8	4023.289	26	4	2015	23	51	0.025753376	6	-3.53066E-09
WDSS009	-43.290236	170.4065	91.235	3974.53	4024.029	27	4	2015	0	3	0.030122204	6	4.03406E-09
WDSS010	-43.290164	170.40616	91.202	3974.51	4024.008	27	4	2015	0	11	0.032988636	6	-1.4943E-09
WDSS011	-43.290138	170.40598	91.293	3974.42	4023.917	27	4	2015	0	20	0.036156535	6	-1.5275E-09
WDSS012	-43.290128	170.40588	89.434	3974.65	4024.15	27	4	2015	0	30	0.039590586	6	1.7676E-09
WDSS001	-43.291348	170.40648	92.668	3973.76	4023.248	27	4	2015	0	41	0.043246469	6	0.031216533
WDSS013	-43.291405	170.40554	96.423	3972.29	4021.759	27	4	2015	1	28	0.056893885	6	0.004529837
WDSS014	-43.291406	170.40556	96.176	3972.36	4021.83	27	4	2015	1	40	0.05975024	6	1.64619E-10
WDSS015	-43.291406	170.40559	96.397	3972.46	4021.931	27	4	2015	1	52	0.062308525	6	-3.4197E-10
WDSS016	-43.29139	170.4055	102.608	3971.91	4021.374	27	4	2015	2	9	0.065388947	6	-4.3924E-09
WDSS017	-43.29139	170.40552	99.5099	3971.63	4021.09	27	4	2015	2	18	0.066749445	6	-1.58252E-09
WDSS018	-43.29095	170.4055	96.027	3972.6	4022.073	27	4	2015	2	30	0.068261257	6	2.38151E-09
WDSS013	-43.291405	170.40554	96.423	3972.32	4021.789	27	4	2015	2	39	0.069165125	6	0.006428114
WDSS019	-43.290949	170.40553	96.111	3972.66	4022.134	27	4	2015	2	47	0.069799186	6	9.29504E-10
WDSS020	-43.290946	170.40556	95.967	3972.77	4022.245	27	4	2015	2	56	0.070322266	6	2.73803E-09
WDSS021	-43.290534	170.40545	96.084	3972.86	4022.336	27	4	2015	3	6	0.070665484	6	-6.63022E-10
WDSS022	-43.29053	170.40548	96.224	3972.92	4022.397	27	4	2015	3	14	0.070760899	6	-3.06773E-09
WDSS023	-43.290534	170.40551	96.075	3973.02	4022.499	27	4	2015	3	27	0.070578771	6	1.07912E-09
WDSS013	-43.291405	170.40554	96.423	3972.34	4021.81	27	4	2015	3	35	0.070263305	6	0.012795141
SA80	-43.277467	170.41729	97.747	3975.22	4024.728	27	4	2015	4	1	0.068175129	6	-0.0209064
SA86	-43.265827	170.37515	70.667	3991.56	4041.286	27	4	2015	4	13	0.066720882	6	-0.003332466
SA86	-43.265827	170.37515	70.667	3991.46	4041.184	27	4	2015	20	57	-0.03077508	7	0.007328319
SA86	-43.265827	170.37515	70.667	3991.47	4041.194	27	4	2015	20	59	-0.03065928	7	0.017483312
SA86	-43.265827	170.37515	70.667	3991.47	4041.194	27	4	2015	21	2	-0.03046704	7	0.017497457
SA80	-43.277467	170.41729	97.747	3975.12	4024.627	27	4	2015	21	18	-0.02901106	7	-0.011853777
SA80	-43.277467	170.41729	97.747	3975.12	4024.627	27	4	2015	21	20	-0.02879008	7	-0.01193716
SA80	-43.277467	170.41729	97.747	3975.13	4024.637	27	4	2015	21	22	-0.02855917	7	-0.001897276

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WDSS013	-43.291405	170.40554	96.423	3972.21	4021.678	27	4	2015	21	41	-0.02583916	7	-0.013996646
WDSS024	-43.290957	170.40544	98.271	3971.78	4021.242	27	4	2015	21	58	-0.02269834	7	1.45519E-11
WDSS025	-43.291319	170.4058	91.566	3973.4	4022.884	27	4	2015	22	11	-0.01983975	7	5.00222E-12
WDSS026	-43.290799	170.40566	91.326	3973.45	4022.934	27	4	2015	22	27	-0.0158137	7	5.91172E-12
WAFS001	-43.284361	170.39429	86.64	3982.84	4032.449	28	4	2015	3	37	0.074174842	7	-0.013705286
WAFS002	-43.283983	170.39443	87.508	3982.86	4032.47	28	4	2015	3	48	0.074113997	7	3.91083E-11
WAFS003	-43.283613	170.39456	87.545	3982.9	4032.51	28	4	2015	3	58	0.07373581	7	-2.72848E-12
WAFS004	-43.283232	170.39469	87.997	3982.78	4032.389	28	4	2015	4	6	0.073213761	7	-4.45652E-11
WAFS005	-43.282861	170.39482	87.454	3982.8	4032.409	28	4	2015	4	19	0.071956745	7	2.09184E-11
WAFS006	-43.282485	170.39495	85.866	3983	4032.612	28	4	2015	4	27	0.070937002	7	-4.3201E-11
WAFS001	-43.284361	170.39429	86.64	3982.84	4032.449	28	4	2015	4	41	0.068721124	7	-0.003848583
WAFS007	-43.282096	170.39508	88.091	3982.6	4032.206	28	4	2015	4	51	0.066809014	7	8.74934E-10
WAFS008	-43.281718	170.39522	87.252	3982.8	4032.409	28	4	2015	5	14	0.061473205	7	-1.96951E-09
WAFS009	-43.281349	170.39534	86.139	3983.05	4032.662	28	4	2015	5	25	0.058499683	7	1.10367E-09
WAFS010	-43.28095	170.39548	85.659	3983.15	4032.764	28	4	2015	5	35	0.055587724	7	-1.74532E-09
WAFS011	-43.280543	170.39561	85.491	3983.17	4032.784	28	4	2015	5	43	0.053128769	7	-6.88033E-10
WAFS012	-43.279739	170.39589	85.229	3983.17	4032.784	28	4	2015	5	48	0.051537642	7	1.13096E-09
WAFS013	-43.278962	170.3962	85.451	3983.09	4032.703	28	4	2015	5	56	0.048915712	7	2.15596E-09
WAFS001	-43.284361	170.39429	86.64	3982.83	4032.439	28	4	2015	6	12	0.043445967	7	0.017553868
SA80	-43.277467	170.41729	97.747	3975.15	4024.657	28	4	2015	6	22	0.039842954	7	-0.012882816
SA86	-43.265827	170.37515	70.667	3991.49	4041.215	28	4	2015	6	32	0.036252316	7	0.010258588
SA86	-43.265827	170.37515	70.667	3991.45	4041.174	28	4	2015	22	11	-0.02366625	8	0.02380222
SA86	-43.265827	170.37515	70.667	3991.44	4041.164	28	4	2015	22	13	-0.02342083	8	0.013361822
SA86	-43.265827	170.37515	70.667	3991.45	4041.174	28	4	2015	22	14	-0.02329376	8	0.02333707
SA80	-43.277467	170.41729	97.747	3975.09	4024.596	28	4	2015	22	28	-0.02114475	8	-0.018373588
SA80	-43.277467	170.41729	97.747	3975.09	4024.596	28	4	2015	22	30	-0.02080089	8	-0.018779228
SA80	-43.277467	170.41729	97.747	3975.09	4024.596	28	4	2015	22	31	-0.02062473	8	-0.018986271
WAFS014	-43.284135	170.39212	88.947	3982.95	4032.561	29	4	2015	2	15	0.058172121	8	4.46562E-10
WRS008	-43.283516	170.38946	85.111	3984.12	4033.746	29	4	2015	2	35	0.064348035	8	-0.008061695
WRS009	-43.28393	170.38946	87.166	3983.6	4033.22	29	4	2015	2	49	0.068076918	8	-2.13231E-09
WRS010	-43.284364	170.38946	90.615	3982.83	4032.439	29	4	2015	2	56	0.069736524	8	2.10593E-09
WRS011	-43.284789	170.38945	95.461	3981.76	4031.355	29	4	2015	3	5	0.07165618	8	-1.53568E-09

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WRS008	-43.283516	170.38946	85.111	3984.13	4033.757	29	4	2015	4	5	0.077584587	8	-0.013945047
WRS012	-43.28525	170.38951	101.195	3980.61	4030.19	29	4	2015	4	20	0.077067928	8	1.93859E-09
WRS013	-43.285661	170.38963	110.034	3978.88	4028.437	29	4	2015	4	39	0.075240556	8	-2.62935E-09
WRS014	-43.286006	170.38956	106.714	3977.15	4026.684	29	4	2015	4	56	0.072519787	8	-2.7967E-10
WRS008	-43.283516	170.38946	85.111	3984.15	4033.777	29	4	2015	5	19	0.067287609	8	0.014332552
SA80	-43.277467	170.41729	97.747	3975.18	4024.687	29	4	2015	5	33	0.063254603	8	-0.024701922
SA86	-43.265827	170.37515	70.667	3991.55	4041.275	29	4	2015	5	45	0.059430326	8	0.028014088
SA86	-43.265827	170.37515	70.667	3991.5	4041.225	29	4	2015	20	44	-0.00880868	9	0.017831519
SA86	-43.265827	170.37515	70.667	3991.49	4041.215	29	4	2015	20	46	-0.00930489	9	0.007925999
SA86	-43.265827	170.37515	70.667	3991.48	4041.205	29	4	2015	20	49	-0.01003386	9	-0.001881012
SA80	-43.277467	170.41729	97.747	3975.15	4024.657	29	4	2015	20	59	-0.01232506	9	-0.009662011
SA80	-43.277467	170.41729	97.747	3975.15	4024.657	29	4	2015	21	1	-0.01275494	9	-0.009500655
SA80	-43.277467	170.41729	97.747	3975.15	4024.657	29	4	2015	21	3	-0.0131754	9	-0.009348715
WRS015	-43.298383	170.41293	99.968	3970.03	4019.469	29	4	2015	22	1	-0.02058268	9	2.06774E-09
WRS016	-43.305141	170.41411	102.999	3968.62	4018.04	29	4	2015	23	23	-0.01306036	9	-1.5325E-09
WRS017	-43.314966	170.42101	109.849	3964.19	4013.551	30	4	2015	0	6	-0.00088293	9	0.00806182
WRS018	-43.317399	170.41437	154.272	3956.25	4005.505	30	4	2015	1	7	0.022898852	9	-1.50067E-11
WRS019	-43.318694	170.41216	188.472	3949.69	3998.858	30	4	2015	2	19	0.0532947	9	5.89353E-10
WRS017	-43.314966	170.42101	109.849	3964.28	4013.642	30	4	2015	3	42	0.077439268	9	-0.008061819
SA80	-43.277467	170.41729	97.747	3975.33	4024.839	30	4	2015	5	6	0.077176466	9	0.017849249
SA86	-43.265827	170.37515	70.667	3991.62	4041.346	30	4	2015	5	18	0.074825765	9	-0.013214374
SA86	-43.265827	170.37515	70.667	3991.53	4041.255	30	4	2015	20	34	0.014023338	10	0.014943371
SA80	-43.277467	170.41729	97.747	3975.18	4024.687	30	4	2015	20	44	0.010477379	10	-0.010844572
WRS020	-43.300998	170.41798	97.196	3968.83	4018.253	30	4	2015	21	54	-0.00907304	10	2.48747E-10
WRS021	-43.312044	170.42105	101.482	3965.73	4015.112	30	4	2015	22	34	-0.01428675	10	-0.007061932
WRS022	-43.310267	170.4264	190.93	3951.97	4001.168	1	5	2015	0	18	-0.00196645	10	-5.45697E-12
WRS023	-43.306221	170.42964	260.739	3941.94	3991.005	1	5	2015	1	58	0.037027798	10	1.10913E-09
WRS021	-43.312044	170.42105	101.482	3965.85	4015.233	1	5	2015	4	12	0.081766695	10	0.007061932
SA80	-43.277467	170.41729	97.747	3975.28	4024.789	1	5	2015	5	23	0.080519626	10	0.002908057
SA86	-43.265827	170.37515	70.667	3991.59	4041.316	1	5	2015	5	33	0.078559839	10	-0.007006858
SA86	-43.265827	170.37515	70.667	3991.64	4041.367	2	5	2015	20	25	0.061760131	11	0.023649258
SA80	-43.277467	170.41729	97.747	3975.29	4024.799	2	5	2015	20	35	0.058003833	11	-0.001880916

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WRS024	-43.264531	170.41769	82.918	3980.37	4029.947	2	5	2015	21	6	0.045738662	11	-0.002189835
WRS025	-43.263611	170.42037	88.764	3978.54	4028.092	2	5	2015	21	27	0.037224807	11	2.36469E-11
WRS026	-43.262856	170.42269	95.909	3976.83	4026.359	2	5	2015	21	50	0.028168641	11	-6.32099E-11
WRS027	-43.263146	170.42572	109.314	3973.57	4023.056	2	5	2015	22	20	0.017463502	11	-0.002528927
WRS024	-43.264531	170.41769	82.918	3980.33	4029.906	2	5	2015	22	47	0.00955461	11	-0.009472346
WRS028	-43.263672	170.42618	114.913	3971.86	4021.323	2	5	2015	23	26	0.001990429	11	-7.04858E-11
WRS029	-43.263642	170.42705	121.551	3970.76	4020.209	2	5	2015	23	53	-6.9301E-05	11	2.50111E-11
WRS030	-43.263849	170.42793	132.651	3968.6	4018.02	3	5	2015	0	16	0.000368797	11	5.45697E-11
WRS031	-43.263999	170.42853	141.739	3966.87	4016.267	3	5	2015	0	40	0.002969992	11	-0.024637006
WRS027	-43.263146	170.42572	109.314	3973.57	4023.056	3	5	2015	1	4	0.007641914	11	0.002528927
WRS032	-43.264132	170.42945	154.325	3964.64	4014.007	3	5	2015	2	2	0.026030312	11	9.09495E-13
WRS033	-43.264698	170.43136	179.976	3959.06	4008.353	3	5	2015	2	31	0.037737626	11	-2.45564E-11
WRS034	-43.264803	170.4371	258.824	3941.22	3990.275	3	5	2015	3	45	0.06810753	11	1.82354E-10
WRS031	-43.263999	170.42853	141.739	3967.01	4016.409	3	5	2015	5	5	0.087863284	11	0.024637006
WRS024	-43.264531	170.41769	82.918	3980.44	4030.017	3	5	2015	5	48	0.087656425	11	0.011662186
SA80	-43.277467	170.41729	97.747	3975.32	4024.829	3	5	2015	6	0	0.085982885	11	-0.01587201
SA86	-43.265827	170.37515	70.667	3991.65	4041.377	3	5	2015	6	8	0.084504424	11	-0.005896327
SA86	-43.265827	170.37515	70.667	3991.71	4041.438	3	5	2015	20	33	0.076884244	12	0.017955162
WRS035	-43.28305	170.36447	106.092	3986.16	4035.814	3	5	2015	21	29	0.057239651	12	-3.09819E-09
WRS036	-43.286475	170.35727	138.046	3979.17	4028.731	3	5	2015	22	12	0.040338836	12	-0.024516473
WRS037	-43.292617	170.35819	207.573	3958.22	4007.501	3	5	2015	23	12	0.020074039	12	2.31921E-11
WRS038	-43.293947	170.35805	229.095	3952.86	4002.07	3	5	2015	23	43	0.013059163	12	6.36646E-11
WRS039	-43.29441	170.35769	238.992	3950.56	3999.739	4	5	2015	0	9	0.009629114	12	0.003224573
WRS040	-43.294974	170.35777	247.577	3948.38	3997.53	4	5	2015	0	36	0.00867819	12	4.09273E-12
WRS041	-43.295678	170.35832	268.207	3944.33	3993.426	4	5	2015	1	5	0.010687873	12	-0.034085386
WRS039	-43.29441	170.35769	238.992	3950.58	3999.76	4	5	2015	1	26	0.014023311	12	0.021537039
WRS041	-43.295678	170.35832	268.207	3944.38	3993.477	4	5	2015	1	42	0.017556664	12	0.010884417
WRS042	-43.296736	170.35887	293.297	3938.21	3987.225	4	5	2015	2	7	0.024568767	12	3.54703E-11
WRS043	-43.298424	170.35945	346	3929.18	3978.075	4	5	2015	2	48	0.039053137	12	6.71662E-10
WRS041	-43.295678	170.35832	268.207	3944.43	3993.528	4	5	2015	3	40	0.059645736	12	0.023200969
WRS039	-43.29441	170.35769	238.992	3950.58	3999.76	4	5	2015	3	54	0.065012336	12	-0.024761612
WRS044	-43.293353	170.35825	220.064	3955.15	4004.391	4	5	2015	4	10	0.070806949	12	-8.2764E-11

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WRS036	-43.286475	170.35727	138.046	3979.25	4028.812	4	5	2015	5	2	0.085365096	12	0.024516476
SA86	-43.265827	170.37515	70.667	3991.67	4041.397	4	5	2015	5	54	0.090040828	12	-0.017955164
SA86	-43.265827	170.37515	70.667	3991.72	4041.448	4	5	2015	20	46	0.085685899	13	0.019373599
SA80	-43.277467	170.41729	97.747	3975.36	4024.87	4	5	2015	20	56	0.083478173	13	-0.016672686
WAFS015	-43.280339	170.40385	84.246	3981.05	4030.636	4	5	2015	21	43	0.069682481	13	-0.018725332
WAFS016	-43.279964	170.40346	84.953	3981.24	4030.828	4	5	2015	21	53	0.066203374	13	3.7744E-11
WAFS017	-43.279591	170.40314	84.925	3981.6	4031.193	4	5	2015	22	2	0.062978208	13	-3.13776E-11
WAFS018	-43.279242	170.40278	84.919	3981.85	4031.446	4	5	2015	22	14	0.05858829	13	-5.09317E-11
WAFS019	-43.278917	170.40246	83.645	3982.33	4031.933	4	5	2015	22	22	0.05563328	13	6.36646E-12
WAFS020	-43.278603	170.40218	84.023	3982.43	4032.034	4	5	2015	22	31	0.052309065	13	-8.59472E-11
WAFS021	-43.278245	170.40188	82.482	3982.85	4032.46	4	5	2015	22	37	0.050105358	13	-5.77529E-11
WAFS022	-43.27779	170.40155	81.402	3983.22	4032.834	4	5	2015	22	44	0.047559219	13	5.82077E-11
WAFS015	-43.280339	170.40385	84.246	3981.04	4030.625	4	5	2015	22	55	0.043644383	13	0.003480927
WAFS023	-43.27922	170.40533	84.132	3980.72	4030.301	4	5	2015	23	16	0.036581966	13	3.45608E-11
WAFS024	-43.278838	170.40502	83.115	3981.42	4031.011	4	5	2015	23	26	0.033484521	13	-3.91083E-11
WAFS025	-43.278477	170.40475	83.958	3981.61	4031.203	4	5	2015	23	35	0.030875533	13	3.00133E-11
WAFS026	-43.278119	170.40437	83.073	3982.1	4031.7	4	5	2015	23	47	0.027695334	13	3.9563E-11
WAFS015	-43.280339	170.40385	84.246	3981.03	4030.615	4	5	2015	23	56	0.025566251	13	0.016764514
WAFS027	-43.277755	170.40411	81.949	3982.44	4032.044	5	5	2015	0	13	0.022153103	13	-4.54747E-12
WAFS028	-43.277403	170.40382	83.152	3982.4	4032.004	5	5	2015	0	21	0.020858512	13	1.54614E-11
WAFS029	-43.277149	170.40348	83.15	3982.51	4032.115	5	5	2015	0	30	0.019651245	13	-3.36513E-11
WAFS030	-43.276851	170.40315	81.42	3982.98	4032.591	5	5	2015	0	39	0.018715261	13	-2.6721E-09
WAFS031	-43.276503	170.40278	83.42	3982.75	4032.358	5	5	2015	0	48	0.01805721	13	1.96087E-09
WAFS032	-43.276141	170.40249	81.58	3983.24	4032.855	5	5	2015	0	55	0.017740317	13	8.6402E-12
WAFS033	-43.275878	170.40228	80.147	3983.59	4033.209	5	5	2015	1	3	0.017589903	13	1.86901E-10
WAFS015	-43.280339	170.40385	84.246	3981	4030.585	5	5	2015	1	18	0.017937348	13	0.001170369
WAFS034	-43.278899	170.40764	80.284	3980.71	4030.291	5	5	2015	1	44	0.020351981	13	3.01497E-10
WAFS035	-43.278574	170.40719	82.958	3980.53	4030.109	5	5	2015	4	53	0.077777186	13	-1.57797E-10
WAFS015	-43.280339	170.40385	84.246	3981.04	4030.625	5	5	2015	5	13	0.082897943	13	-0.00269048
SA80	-43.277467	170.41729	97.747	3975.33	4024.839	5	5	2015	5	53	0.089233866	13	-0.005830318
SA86	-43.265827	170.37515	70.667	3991.66	4041.387	5	5	2015	6	2	0.089791414	13	0.003129405
0.023574475	SA86	-43.265827	170.37515	70.667	3991.72	4041.448	6	6	5	2015	20	25	0.078511258

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
SA80	-43.277467	170.41729	97.747	3975.36	4024.87	6	5	2015	20	36	0.081121635	14	-0.017451803
WRS045	-43.274124	170.38186	75.617	3988.41	4038.094	6	5	2015	20	54	0.084167123	14	2.19416E-09
WRS046	-43.272655	170.38783	78.531	3987.31	4036.979	6	5	2015	21	5	0.085370525	14	-0.009353275
WRS047	-43.271149	170.39374	80.645	3987	4036.665	6	5	2015	21	16	0.086073644	14	-1.09139E-11
WRS048	-43.270974	170.39956	79.379	3986.2	4035.854	6	5	2015	21	26	0.086294917	14	-4.8658E-11
WRS049	-43.270813	170.40069	79.442	3985.91	4035.56	6	5	2015	21	34	0.086197138	14	-3.7744E-11
WRS050	-43.270621	170.40207	79.924	3985.45	4035.094	6	5	2015	21	42	0.085866098	14	-1.50067E-11
WRS051	-43.270463	170.40329	78.74	3985.35	4034.993	6	5	2015	21	51	0.085228362	14	1.54614E-11
WRS052	-43.270466	170.40397	80.165	3984.82	4034.456	6	5	2015	21	58	0.084548423	14	-2.04636E-11
WRS046	-43.272655	170.38783	78.531	3987.31	4036.979	6	5	2015	22	10	0.083046161	14	-0.00281396
WRS053	-43.27048	170.40453	79.121	3984.84	4034.476	6	5	2015	22	33	0.079051749	14	-5.54792E-11
WRS054	-43.270501	170.40512	79.16	3984.62	4034.253	6	5	2015	22	42	0.077165601	14	-6.50289E-11
WRS055	-43.270515	170.40571	79.386	3984.37	4034	6	5	2015	22	48	0.075822587	14	1.90994E-11
WRS056	-43.270541	170.40629	79.715	3984.08	4033.706	6	5	2015	22	55	0.074179702	14	3.63798E-12
WRS046	-43.272655	170.38783	78.531	3987.3	4036.969	6	5	2015	23	10	0.070455934	14	0.003533793
WRS057	-43.270596	170.40699	79.94	3983.74	4033.361	6	5	2015	23	22	0.067267435	14	2.13731E-11
WRS058	-43.270613	170.4076	78.882	3983.75	4033.372	6	5	2015	23	29	0.065376497	14	7.36691E-11
WRS059	-43.270648	170.40873	76.956	3983.68	4033.301	6	5	2015	23	46	0.060724358	14	1.226E-09
WRS060	-43.270711	170.41091	77.763	3982.66	4032.267	6	5	2015	23	56	0.057993217	14	-2.01999E-09
WRS061	-43.27073	170.413	73.719	3982.55	4032.156	7	5	2015	0	6	0.055304034	14	1.40972E-10
WRS046	-43.272655	170.38783	78.531	3987.26	4036.928	7	5	2015	3	31	0.041748141	14	0.008633439
WRS062	-43.282973	170.3897	84.789	3984.47	4034.101	7	5	2015	4	40	0.057452047	14	-0.000201188
WRS063	-43.282248	170.38995	84.702	3984.59	4034.223	7	5	2015	5	6	0.064162003	14	4.502E-11
WRS064	-43.280457	170.39058	83.64	3984.66	4034.294	7	5	2015	5	14	0.066183605	14	3.07409E-10
WRS062	-43.282973	170.3897	84.789	3984.48	4034.111	7	5	2015	5	32	0.070554834	14	0.000201187
SA80	-43.277467	170.41729	97.747	3975.32	4024.829	7	5	2015	6	3	0.077056117	14	-0.017151735
SA86	-43.265827	170.37515	70.667	3991.67	4041.397	7	5	2015	6	11	0.078390078	14	0.011029068
SA86	-43.265827	170.37515	70.667	3991.75	4041.478	15	5	2015	20	58	0.034214633	15	0.02562503
SA80	-43.277467	170.41729	97.747	3975.37	4024.88	15	5	2015	21	24	0.024383969	15	-0.02536341
WAFS036	-43.278189	170.40683	82.896	3981.1	4030.686	15	5	2015	22	46	0.006066566	15	0.000328416
WAFS037	-43.277759	170.40653	81.265	3981.84	4031.436	15	5	2015	22	55	0.005587873	15	5.91172E-12
WAFS038	-43.277323	170.40621	81.569	3982.08	4031.679	15	5	2015	23	4	0.005448367	15	-4.22915E-11

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WAFS039	-43.276947	170.40594	80.927	3982.39	4031.993	15	5	2015	23	15	0.005742763	15	2.27374E-11
WAFS040	-43.276599	170.40553	82.119	3982.37	4031.973	15	5	2015	23	26	0.006547154	15	-2.04636E-11
WAFS041	-43.276191	170.40518	81.672	3982.65	4032.257	15	5	2015	23	36	0.007715549	15	-3.63798E-11
WAFS036	-43.278189	170.40683	82.896	3981.11	4030.696	15	5	2015	23	51	0.010244326	15	0.002725094
WAFS042	-43.275809	170.4049	80.727	3982.98	4032.591	16	5	2015	0	3	0.012877879	15	-5.22959E-11
WAFS043	-43.275426	170.40453	81.89	3982.91	4032.52	16	5	2015	0	16	0.016339338	15	-4.54747E-12
WAFS044	-43.274965	170.40418	81.691	3983.21	4032.824	16	5	2015	0	25	0.019074009	15	6.82121E-12
WAFS045	-43.274333	170.40633	79.335	3983.1	4032.713	16	5	2015	0	36	0.022766531	15	-3.54703E-11
WAFS046	-43.274852	170.40672	80.01	3982.75	4032.358	16	5	2015	0	49	0.027576274	15	-4.6839E-11
WAFS036	-43.278189	170.40683	82.896	3981.13	4030.717	16	5	2015	1	1	0.032396293	15	-0.002992985
WAFS047	-43.277999	170.40927	79.234	3980.96	4030.544	16	5	2015	1	29	0.044647021	15	-3.63798E-12
WAFS048	-43.277543	170.40882	81.281	3980.75	4030.332	16	5	2015	1	39	0.049248852	15	3.22871E-11
WAFS049	-43.277136	170.40851	80.953	3981.08	4030.666	16	5	2015	1	47	0.052973351	15	-3.09228E-11
WAFS050	-43.276687	170.40823	80.282	3981.68	4031.274	16	5	2015	1	56	0.057180728	15	1.12459E-09
WAFS036	-43.278189	170.40683	82.896	3981.16	4030.747	16	5	2015	2	5	0.061379872	15	-0.005080976
WAFS051	-43.276285	170.40792	80.382	3981.94	4031.537	16	5	2015	2	15	0.065989986	15	8.34461E-10
WAFS052	-43.275843	170.40767	81.139	3982	4031.598	16	5	2015	2	26	0.070951838	15	-9.0904E-10
WAFS053	-43.275235	170.40709	80.826	3982.34	4031.943	16	5	2015	2	37	0.075742202	15	6.32099E-10
WAFS054	-43.275004	170.40911	79.322	3982.01	4031.608	16	5	2015	2	47	0.079907475	15	4.96584E-10
WAFS055	-43.275467	170.40934	77.926	3982.12	4031.72	16	5	2015	2	55	0.083076646	15	3.48336E-10
WAFS056	-43.275995	170.40983	79.453	3981.35	4030.94	16	5	2015	3	4	0.086443152	15	-3.18323E-12
WAFS057	-43.276375	170.41032	79.343	3980.91	4030.494	16	5	2015	3	14	0.089903615	15	6.68933E-10
WAFS058	-43.276731	170.41068	79.313	3980.73	4030.311	16	5	2015	3	23	0.092737262	15	2.93767E-10
WAFS059	-43.276103	170.41153	78.765	3980.66	4030.24	16	5	2015	3	36	0.096308166	15	-2.45564E-11
WAFS036	-43.278189	170.40683	82.896	3981.21	4030.798	16	5	2015	3	50	0.099391082	15	0.001825046
WAFS036	-43.278189	170.40683	82.896	3981.21	4030.798	16	5	2015	5	33	0.092381463	15	0.003195397
SA80	-43.277467	170.41729	97.747	3975.46	4024.971	16	5	2015	6	16	0.072947432	15	-0.011855167
SA86	-43.265827	170.37515	70.667	3991.8	4041.529	16	5	2015	6	25	0.067868768	15	0.011593545
SA86	-43.265827	170.37515	70.667	3991.74	4041.468	16	5	2015	21	11	0.05901235	16	0.000592553
SA80	-43.277467	170.41729	97.747	3975.4	4024.91	16	5	2015	21	21	0.054787274	16	-0.013351257
WAFS060	-43.285659	170.40086	89.051	3978.54	4028.092	16	5	2015	21	32	0.050292048	16	-1.13491E-08
WAFS061	-43.285581	170.40186	92.461	3978.51	4028.062	16	5	2015	21	37	0.048254759	16	4.51746E-09

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WAFS062	-43.284577	170.40098	91.978	3979.76	4029.328	16	5	2015	22	0	0.03931557	16	0.011909814
WAFS063	-43.283773	170.40108	93.462	3980.1	4029.673	16	5	2015	22	8	0.036423871	16	4.91127E-11
WAFS064	-43.282876	170.40116	91.571	3980.5	4030.078	16	5	2015	22	15	0.034009751	16	3.22871E-11
WAFS065	-43.281889	170.40109	92.813	3980.84	4030.423	16	5	2015	22	22	0.031716519	16	-1.22782E-11
WAFS066	-43.281178	170.40076	88.411	3981.17	4030.757	16	5	2015	22	33	0.028387074	16	1.81899E-12
WAFS067	-43.280226	170.40054	87.678	3981.86	4031.456	16	5	2015	22	40	0.026453587	16	-4.09273E-11
WAFS068	-43.279454	170.40057	87.606	3982.05	4031.649	16	5	2015	22	47	0.024677287	16	1.10049E-10
WAFS069	-43.278522	170.40059	87.962	3982.42	4032.024	16	5	2015	22	56	0.022637445	16	1.04592E-11
WAFS062	-43.284577	170.40098	91.978	3979.74	4029.308	16	5	2015	23	8	0.020403337	16	0.015274265
WAFS070	-43.284988	170.40094	91.617	3979.5	4029.065	16	5	2015	23	19	0.018810081	16	-1.81899E-12
WAFS071	-43.284182	170.40103	91.59	3979.83	4029.399	16	5	2015	23	33	0.017467052	16	2.77396E-11
WAFS072	-43.277618	170.40072	86.252	3982.58	4032.186	16	5	2015	23	51	0.01688745	16	0.004667564
WAFS073	-43.276679	170.40041	85.342	3982.9	4032.51	16	5	2015	23	58	0.01703135	16	4.63842E-11
WAFS074	-43.275855	170.40084	85.764	3982.95	4032.561	17	5	2015	0	5	0.017378297	16	5.91172E-12
WAFS075	-43.275221	170.40167	83.499	3982.94	4032.551	17	5	2015	0	18	0.018558922	16	-4.6839E-11
WAFS062	-43.284577	170.40098	91.978	3979.7	4029.268	17	5	2015	0	32	0.020632153	16	-0.01965847
WAFS076	-43.273239	170.40037	78.197	3984.7	4034.334	17	5	2015	1	25	0.034581198	16	2.26009E-09
WAFS077	-43.272577	170.40293	82.696	3984.12	4033.746	17	5	2015	1	39	0.039646104	16	-0.001011353
WAFS078	-43.272179	170.40498	79.825	3984.02	4033.645	17	5	2015	1	52	0.044716146	16	1.90994E-11
WAFS079	-43.272469	170.40687	81.205	3983	4032.612	17	5	2015	2	4	0.049640417	16	-1.40972E-11
WAFS080	-43.272628	170.40905	79.335	3982.51	4032.115	17	5	2015	2	18	0.055585831	16	-0.006238518
WAFS081	-43.272765	170.41175	77.229	3981.94	4031.537	17	5	2015	2	38	0.064240434	16	-1.40972E-11
WAFS082	-43.2727	170.41538	76.701	3979.83	4029.399	17	5	2015	2	57	0.07236314	16	8.18545E-12
WAFS080	-43.272628	170.40905	79.335	3982.55	4032.156	17	5	2015	3	42	0.089470482	16	0.006238513
WAFS077	-43.272577	170.40293	82.696	3984.17	4033.797	17	5	2015	4	20	0.099461423	16	0.001011351
WAFS062	-43.284577	170.40098	91.978	3979.77	4029.339	17	5	2015	5	34	0.100387906	16	-0.007525607
SA80	-43.277467	170.41729	97.747	3975.41	4024.92	17	5	2015	5	57	0.094750511	16	-0.00737531
SA86	-43.265827	170.37515	70.667	3991.75	4041.478	17	5	2015	6	7	0.09146547	16	0.015466446
SA86	-43.265827	170.37515	70.667	3991.77	4041.498	17	5	2015	20	41	0.091606977	17	0.011566233
SA80	-43.277467	170.41729	97.747	3975.43	4024.941	17	5	2015	20	52	0.08831042	17	-0.002420682
WAFS083	-43.274096	170.40357	84.736	3982.99	4032.601	17	5	2015	21	27	0.076142406	17	-7.50333E-10
WAFS084	-43.273411	170.40558	83.906	3982.65	4032.257	17	5	2015	21	36	0.072706175	17	-0.014135904

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WAFS085	-43.273601	170.40778	81.694	3982.3	4031.902	17	5	2015	22	8	0.060198044	17	-4.82032E-11
WAFS086	-43.273946	170.4099	79.833	3981.83	4031.426	17	5	2015	22	35	0.050012451	17	1.36424E-11
WAFS084	-43.273411	170.40558	83.906	3982.62	4032.226	17	5	2015	22	51	0.044473043	17	-0.00553423
WAFS087	-43.274687	170.41031	76.795	3982.05	4031.649	17	5	2015	23	12	0.038037728	17	4.17913E-09
WAFS088	-43.274989	170.41319	74.876	3980.82	4030.403	17	5	2015	23	33	0.032811469	17	-3.46427E-09
WAFS089	-43.273751	170.41244	77.33	3981.46	4031.051	17	5	2015	23	52	0.02930867	17	3.53293E-09
WAFS090	-43.274144	170.41464	77.173	3980.18	4029.754	18	5	2015	0	14	0.026881797	17	-2.85127E-10
WAFS091	-43.27326	170.41378	77.18	3980.89	4030.473	18	5	2015	0	29	0.026277317	17	3.94266E-10
WAFS092	-43.272495	170.41339	76.575	3981.56	4031.152	18	5	2015	0	47	0.026703761	17	-2.35468E-09
WAFS084	-43.273411	170.40558	83.906	3982.61	4032.216	18	5	2015	1	5	0.02837456	17	0.019670135
WAFS093	-43.28119	170.40486	85.878	3980.31	4029.886	18	5	2015	2	19	0.046558674	17	-0.012945255
WAFS094	-43.281919	170.40552	86.421	3979.92	4029.491	18	5	2015	2	28	0.049712405	17	-3.9563E-11
WAFS095	-43.282584	170.40624	87.815	3979.29	4028.852	18	5	2015	2	39	0.053735654	17	-4.91127E-11
WAFS096	-43.283248	170.40686	87.675	3978.95	4028.508	18	5	2015	2	48	0.057134433	17	-2.27374E-12
WAFS093	-43.28119	170.40486	85.878	3980.34	4029.916	18	5	2015	3	1	0.062139168	17	0.00790401
WAFS097	-43.280337	170.40665	86.038	3979.69	4029.257	18	5	2015	3	17	0.068370791	17	-2.4238E-10
WAFS098	-43.281055	170.40746	85.412	3979.7	4029.268	18	5	2015	3	29	0.072996128	17	-1.00044E-11
WAFS099	-43.281605	170.40829	87.11	3979.16	4028.72	18	5	2015	3	37	0.076015994	17	5.316E-10
WAFS093	-43.28119	170.40486	85.878	3980.35	4029.926	18	5	2015	3	57	0.083175346	17	0.005041246
SA80	-43.277467	170.41729	97.747	3975.35	4024.86	18	5	2015	4	58	0.098823959	17	-0.024222258
SA86	-43.265827	170.37515	70.667	3991.71	4041.438	18	5	2015	5	8	0.100089949	17	0.015076704
SA86	-43.265827	170.37515	70.667	3991.71	4041.438	18	5	2015	20	41	0.098396993	18	0.012292862
SA80	-43.277467	170.41729	97.747	3975.36	4024.87	18	5	2015	21	23	0.091035132	18	-0.01020053
WAFS100	-43.27977	170.40836	85.056	3979.83	4029.399	18	5	2015	21	51	0.083267206	18	-0.008224459
WAFS101	-43.280476	170.40894	85.621	3979.56	4029.126	18	5	2015	22	1	0.080108019	18	-3.27418E-11
WAFS102	-43.279162	170.41032	82.871	3979.83	4029.399	18	5	2015	22	13	0.07613008	18	-4.09273E-12
WAFS100	-43.27977	170.40836	85.056	3979.83	4029.399	18	5	2015	22	43	0.065754456	18	0.008224455
WAFS103	-43.279832	170.41091	91.454	3978.33	4027.879	18	5	2015	23	2	0.05921031	18	0.003895822
WAFS104	-43.281292	170.40976	91.704	3978.08	4027.626	18	5	2015	23	13	0.055563832	18	1.63709E-11
WAFS105	-43.283347	170.40964	93.87	3977.17	4026.704	18	5	2015	23	41	0.047078287	18	9.09495E-12
WAFS106	-43.284534	170.40823	91.694	3977.52	4027.059	18	5	2015	23	51	0.044427433	18	-7.32143E-11
WAFS103	-43.279832	170.41091	91.454	3978.31	4027.859	19	5	2015	0	14	0.039254295	18	0.002112434

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WAFS107	-43.278251	170.41208	89.473	3978.22	4027.768	19	5	2015	0	49	0.034439546	18	4.46562E-09
WAFS108	-43.278929	170.41278	90.203	3978.04	4027.585	19	5	2015	0	56	0.033966471	18	-2.68756E-10
WAFS109	-43.277796	170.41342	88.642	3978.06	4027.606	19	5	2015	1	10	0.03351836	18	-2.14823E-09
WAFS110	-43.278563	170.41416	89.029	3977.83	4027.373	19	5	2015	1	18	0.033573503	18	2.69711E-09
WAFS103	-43.279832	170.41091	91.454	3978.3	4027.849	19	5	2015	1	45	0.035380069	18	-0.006008253
WAFS111	-43.285293	170.40589	92.299	3977.55	4027.089	19	5	2015	2	5	0.038278728	18	-7.64857E-05
WAFS112	-43.285407	170.40434	92.652	3977.9	4027.444	19	5	2015	2	10	0.03918857	18	1.00954E-10
WAFS113	-43.284392	170.4033	83.714	3980.2	4029.774	19	5	2015	2	20	0.041218075	18	-4.72937E-11
WAFS114	-43.286831	170.40481	84.744	3978.43	4027.981	19	5	2015	2	42	0.046609468	18	4.1382E-11
WAFS111	-43.285293	170.40589	92.299	3977.55	4027.089	19	5	2015	3	0	0.051777206	18	-0.014700175
WAFS115	-43.285132	170.4086	94.406	3976.71	4026.238	19	5	2015	3	24	0.059428351	18	4.36557E-11
WAFS116	-43.286007	170.40879	94.189	3976.18	4025.701	19	5	2015	3	37	0.063783045	18	6.20275E-10
WAFS117	-43.286727	170.40915	94.293	3975.79	4025.306	19	5	2015	3	47	0.067167763	18	2.57478E-09
WAFS118	-43.287492	170.40955	95.555	3975.22	4024.728	19	5	2015	3	55	0.069869847	18	-3.43334E-10
WAFS119	-43.2883	170.40988	95.464	3974.7	4024.201	19	5	2015	4	6	0.073536621	18	8.06267E-10
WAFS120	-43.289027	170.41025	93.089	3974.84	4024.343	19	5	2015	4	16	0.076783315	18	-7.80346E-10
WAFS121	-43.289393	170.40896	92.827	3974.83	4024.333	19	5	2015	4	30	0.081111435	18	1.29194E-09
WAFS122	-43.287777	170.40824	90.003	3976.37	4025.893	19	5	2015	4	45	0.085364031	18	-5.70708E-10
WAFS123	-43.28626	170.40753	90.163	3977.18	4026.714	19	5	2015	4	54	0.087674954	18	-8.02629E-10
WAFS111	-43.285293	170.40589	92.299	3977.62	4027.16	19	5	2015	5	7	0.09063456	18	0.014776657
WAFS124	-43.284222	170.40989	94.336	3976.57	4026.096	19	5	2015	5	25	0.093873635	18	2.76486E-10
WAFS125	-43.284984	170.41021	96.001	3976.02	4025.539	19	5	2015	5	34	0.095066224	18	3.9563E-10
WAFS126	-43.286056	170.41078	96.936	3975.29	4024.799	19	5	2015	5	39	0.095595748	18	-8.78117E-10
WAFS127	-43.286895	170.41122	97.534	3974.69	4024.191	19	5	2015	5	45	0.096099254	18	-1.51431E-10
WAFS128	-43.287795	170.41168	98.338	3973.96	4023.451	19	5	2015	5	53	0.096538725	18	3.7744E-10
SA80	-43.277467	170.41729	97.747	3975.37	4024.88	19	5	2015	6	21	0.095846554	18	-0.015885362
SA86	-43.265827	170.37515	70.667	3991.72	4041.448	19	5	2015	6	29	0.0950005	18	0.013793026
SA86	-43.265827	170.37515	70.667	3991.74	4041.468	19	5	2015	20	37	0.091921046	19	-0.008561697
SA80	-43.277467	170.41729	97.747	3975.42	4024.931	19	5	2015	20	48	0.092971998	19	-0.009162804
WAFS130	-43.288972	170.41456	124.935	3968.2	4017.614	19	5	2015	21	16	0.093289826	19	1.50067E-11
WAFS131	-43.287185	170.41038	96.285	3975.22	4024.728	19	5	2015	21	38	0.091423695	19	-1.59162E-11
WAFS132	-43.285048	170.40943	94.316	3976.64	4026.167	19	5	2015	21	54	0.089051252	19	-1.45519E-11

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WAFS129	-43.288692	170.41217	101.147	3973.03	4022.509	19	5	2015	22	16	0.084631996	19	0.017530461
WAFS133	-43.281024	170.41145	92.059	3978.18	4027.727	19	5	2015	23	3	0.072131092	19	-2.22826E-11
WAFS134	-43.281861	170.41193	92.939	3977.57	4027.109	19	5	2015	23	16	0.068305399	19	-9.14042E-11
WAFS135	-43.282684	170.41224	93.591	3976.87	4026.4	19	5	2015	23	27	0.065049992	19	-3.00133E-11
WAFS136	-43.283028	170.41114	93.664	3976.93	4026.461	19	5	2015	23	39	0.061534705	19	5.27507E-11
WAFS137	-43.283574	170.41271	95.394	3975.86	4025.376	19	5	2015	23	52	0.057828724	19	4.59295E-11
WAFS138	-43.284675	170.41318	99.009	3974.51	4024.008	20	5	2015	0	7	0.05377765	19	-4.54747E-13
WAFS139	-43.28482	170.41187	96.446	3975.4	4024.91	20	5	2015	0	16	0.051499616	19	-3.63798E-12
WAFS140	-43.285832	170.41377	103.843	3972.94	4022.418	20	5	2015	0	34	0.047374261	19	1.40972E-11
WAFS141	-43.28659	170.41248	101.922	3973.56	4023.046	20	5	2015	0	48	0.044638514	19	-4.3201E-11
WAFS129	-43.288692	170.41217	101.147	3973	4022.478	20	5	2015	0	59	0.042822653	19	0.014807291
WAFS142	-43.285289	170.41645	125.674	3967.51	4016.915	20	5	2015	1	56	0.038700966	19	-2.35877E-09
WAFS143	-43.284593	170.41477	101.839	3973.74	4023.228	20	5	2015	2	12	0.039257782	19	1.98224E-09
WAFS144	-43.283293	170.41437	97.038	3975.35	4024.86	20	5	2015	2	33	0.041104953	19	-2.02499E-09
WAFS145	-43.282317	170.41397	93.974	3976.61	4026.136	20	5	2015	2	46	0.042847346	19	2.93176E-09
WAFS146	-43.281345	170.41359	93.979	3977.71	4027.251	20	5	2015	2	57	0.044651081	19	-2.07592E-09
WAFS147	-43.280143	170.41329	91.108	3978.06	4027.606	20	5	2015	3	13	0.047762805	19	2.40743E-09
WAFS148	-43.279631	170.41476	92.758	3977.22	4026.755	20	5	2015	3	26	0.050665017	19	-1.06957E-09
WAFS149	-43.280299	170.41506	93.738	3976.97	4026.501	20	5	2015	3	36	0.053089716	19	-1.94814E-09
WAFS150	-43.278915	170.41585	92.09	3976.83	4026.359	20	5	2015	3	48	0.05616875	19	2.27919E-09
WAFS129	-43.288692	170.41217	101.147	3972.99	4022.468	20	5	2015	4	13	0.063013731	19	-0.032337754
WAFS151	-43.283109	170.3868	80.999	3985.44	4035.084	20	5	2015	4	33	0.068547907	19	-2.05046E-09
WAFS152	-43.281626	170.38411	79.196	3986.29	4035.945	20	5	2015	4	43	0.071280346	19	1.90539E-10
WAFS153	-43.279928	170.38322	78.852	3986.62	4036.28	20	5	2015	4	50	0.073148509	19	1.84173E-10
WAFS154	-43.277981	170.38267	78.604	3987.2	4036.868	20	5	2015	5	3	0.076480679	19	7.23958E-10
WAFS155	-43.275965	170.38215	76.182	3988.03	4037.709	20	5	2015	5	17	0.079792635	19	9.3678E-11
WAFS156	-43.272632	170.38125	75.879	3988.95	4038.641	20	5	2015	5	29	0.082334246	19	2.7012E-10
SA80	-43.277467	170.41729	97.747	3975.47	4024.981	20	5	2015	5	46	0.085393048	19	0.002434864
SA86	-43.265827	170.37515	70.667	3991.81	4041.539	20	5	2015	6	17	0.088713238	19	0.01528962
SA86	-43.265827	170.37515	70.667	3991.84	4041.569	21	5	2015	20	45	0.058082335	20	0.016701543
SA80	-43.277467	170.41729	97.747	3975.5	4025.012	21	5	2015	20	55	0.061754959	20	-0.006182066
WDSS013	-43.291405	170.40554	96.423	3972.59	4022.063	21	5	2015	21	45	0.07470241	20	-0.021423733

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WDSS027	-43.292404	170.4054	105.617	3970.6	4020.046	21	5	2015	22	35	0.079308083	20	2.19416E-09
WDSS028	-43.292521	170.40465	143.338	3964.22	4013.581	21	5	2015	23	30	0.076154989	20	2.66891E-09
WDSS013	-43.291405	170.40554	96.423	3972.62	4022.093	22	5	2015	0	11	0.069906068	20	0.008688714
WDSS029	-43.29097	170.40471	148.37	3964.68	4014.048	22	5	2015	1	58	0.050014783	20	-3.97176E-09
WDSS030	-43.29109	170.40443	166.952	3960.46	4009.771	22	5	2015	2	45	0.044465261	20	8.72706E-09
WDSS031	-43.29087	170.40504	126.483	3967.49	4016.895	22	5	2015	3	27	0.042732334	20	-1.83945E-09
WDSS013	-43.291405	170.40554	96.423	3972.61	4022.083	22	5	2015	3	51	0.043192712	20	0.01760881
SA80	-43.277467	170.41729	97.747	3975.51	4025.022	22	5	2015	4	56	0.048882096	20	7.63206E-05
SA86	-43.265827	170.37515	70.667	3991.82	4041.549	22	5	2015	5	20	0.052055569	20	-0.015469596
SA86	-43.265827	170.37515	70.667	3991.82	4041.549	22	5	2015	21	6	0.045997562	21	0.007389612
SA80	-43.277467	170.41729	97.747	3975.5	4025.012	22	5	2015	21	15	0.049475515	21	0.004780156
WDSS013	-43.291405	170.40554	96.423	3972.59	4022.063	22	5	2015	21	48	0.060148497	21	-0.008408163
WDSS032	-43.297242	170.41421	99.73	3970.45	4019.894	22	5	2015	23	20	0.073987312	21	-0.008278052
WDSS033	-43.297195	170.41299	100.22	3970.53	4019.975	22	5	2015	23	29	0.074124669	21	5.27507E-11
WDSS034	-43.297111	170.41177	98.799	3970.98	4020.431	22	5	2015	23	35	0.074108832	21	4.82032E-11
WDSS035	-43.297047	170.41059	99.022	3971.31	4020.766	22	5	2015	23	44	0.073930684	21	4.54747E-11
WDSS036	-43.296945	170.40902	103.067	3971.23	4020.685	22	5	2015	23	58	0.073305819	21	2.09184E-11
WDSS037	-43.297452	170.40819	103.55	3971.33	4020.786	23	5	2015	0	5	0.072845924	21	-2.45564E-11
WDSS032	-43.297242	170.41421	99.73	3970.46	4019.905	23	5	2015	1	29	0.061834813	21	0.006337842
WDSS038	-43.297667	170.40717	108.345	3970.72	4020.168	23	5	2015	1	43	0.059457733	21	-0.003087517
WDSS039	-43.297346	170.40649	123.992	3968.91	4018.334	23	5	2015	1	52	0.057910787	21	-5.27507E-11
WDSS040	-43.29681	170.4056	145.507	3964.47	4013.835	23	5	2015	2	7	0.055346497	21	-1.77351E-11
WDSS041	-43.296775	170.40495	164.343	3961.2	4010.521	23	5	2015	2	18	0.053506154	21	-4.54747E-13
WDSS042	-43.296838	170.40408	187.851	3956.71	4005.971	23	5	2015	2	30	0.051564469	21	-8.91305E-11
WDSS043	-43.296703	170.40344	231.699	3952.71	4001.918	23	5	2015	2	42	0.049715106	21	-2.72848E-11
WDSS044	-43.296309	170.40257	249.819	3946.36	3995.484	23	5	2015	3	3	0.046769892	21	-5.86624E-11
WDSS045	-43.29623	170.40176	277.638	3939.35	3988.38	23	5	2015	3	24	0.044284195	21	3.13776E-11
WDSS038	-43.297667	170.40717	108.345	3970.72	4020.168	23	5	2015	5	16	0.040618605	21	0.003087516
WDSS032	-43.297242	170.41421	99.73	3970.45	4019.894	23	5	2015	5	35	0.041473108	21	0.001940209
WDSS013	-43.291405	170.40554	96.423	3972.61	4022.083	23	5	2015	5	59	0.042920683	21	-0.00010677
SA80	-43.277467	170.41729	97.747	3975.51	4025.022	23	5	2015	6	7	0.043445507	21	-0.010687147
SA86	-43.265827	170.37515	70.667	3991.85	4041.579	23	5	2015	6	16	0.044053747	21	0.007032311

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
SA86	-43.265827	170.37515	70.667	3991.82	4041.549	23	5	2015	21	18	0.032662118	22	0.007220523
SA80	-43.277467	170.41729	97.747	3975.49	4025.002	23	5	2015	21	27	0.036262892	22	-0.00285987
WRS008	-43.283516	170.38946	85.111	3984.44	4034.071	23	5	2015	21	55	0.046305451	22	0.01646615
WRS065	-43.286641	170.38974	124.358	3974.79	4024.292	23	5	2015	22	25	0.055413241	22	5.41149E-11
WRS066	-43.286975	170.39011	137.973	3972.94	4022.418	23	5	2015	22	43	0.059933725	22	-8.41283E-11
WRS067	-43.287462	170.39056	148.323	3969.87	4019.307	23	5	2015	22	59	0.063322275	22	-5.41149E-11
WRS068	-43.288214	170.3908	177.883	3965.33	4014.706	23	5	2015	23	15	0.066103054	22	0.014678918
WRS069	-43.289494	170.39053	201.642	3957.42	4006.691	23	5	2015	23	39	0.069125955	22	3.54703E-11
WRS070	-43.290163	170.38941	244.334	3951.08	4000.266	24	5	2015	0	3	0.070792407	22	-1.31877E-11
WRS068	-43.288214	170.3908	177.883	3965.28	4014.656	24	5	2015	0	56	0.070044682	22	-0.014678918
WRS008	-43.283516	170.38946	85.111	3984.38	4034.01	24	5	2015	1	28	0.067096872	22	-0.011874911
WRS008	-43.283516	170.38946	85.111	3984.36	4033.99	24	5	2015	1	53	0.063814853	22	-0.022609343
WDSS013	-43.291405	170.40554	96.423	3972.51	4021.982	24	5	2015	2	4	0.062166098	22	-0.03099934
WDSS046	-43.289545	170.40553	86.177	3975.5	4025.012	24	5	2015	2	38	0.056508333	22	-6.28415E-09
WDSS047	-43.29009	170.4056	92.755	3974.48	4023.978	24	5	2015	2	54	0.053687813	22	5.4265E-09
WDSS048	-43.289861	170.40623	89.592	3975.26	4024.768	24	5	2015	3	4	0.051909286	22	-3.51247E-09
WDSS049	-43.290169	170.40689	89.982	3974.97	4024.475	24	5	2015	3	16	0.049785895	22	9.19499E-10
WDSS050	-43.290522	170.4077	90.896	3974.62	4024.12	24	5	2015	3	24	0.048386903	22	-5.316E-10
WDSS051	-43.291019	170.40721	92.424	3974.17	4023.664	24	5	2015	3	37	0.046161934	22	-5.36738E-09
WDSS052	-43.292327	170.40805	92.829	3973.47	4022.955	24	5	2015	3	54	0.043379598	22	3.40788E-09
WDSS053	-43.292023	170.40685	92.505	3973.65	4023.137	24	5	2015	4	3	0.041979374	22	2.44199E-10
WDSS013	-43.291405	170.40554	96.423	3972.51	4021.982	24	5	2015	4	18	0.039782448	22	0.024884033
SA80	-43.277467	170.41729	97.747	3975.41	4024.92	24	5	2015	4	28	0.038380305	22	0.01920625
SA86	-43.265827	170.37515	70.667	3991.71	4041.438	24	5	2015	4	36	0.037350026	22	0.000566512
SA86	-43.265827	170.37515	70.667	3991.74	4041.468	24	5	2015	21	46	0.028078951	23	0.023283216
SA80	-43.277467	170.41729	97.747	3975.39	4024.9	24	5	2015	21	58	0.032525632	23	-0.010101248
WAFS072	-43.277618	170.40072	86.252	3982.61	4032.216	24	5	2015	22	36	0.045290501	23	-0.012438684
WAFS157	-43.277585	170.39835	84.609	3983.2	4032.814	24	5	2015	22	48	0.048914524	23	2.09184E-11
WAFS158	-43.277086	170.39565	82.89	3984.02	4033.645	24	5	2015	23	1	0.052575589	23	-1.23828E-09
WAFS159	-43.276609	170.39306	81.888	3984.75	4034.385	24	5	2015	23	19	0.057150532	23	-9.9908E-10
WAFS072	-43.277618	170.40072	86.252	3982.63	4032.237	24	5	2015	23	36	0.060909497	23	-0.007500198
WAFS160	-43.278281	170.39125	81.748	3984.82	4034.456	25	5	2015	0	23	0.068110704	23	-3.11047E-09

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WAFS161	-43.27601	170.38989	79.546	3985.98	4035.631	25	5	2015	0	47	0.069908893	23	3.86899E-09
WAFS162	-43.275528	170.38731	77.855	3986.78	4036.442	25	5	2015	1	3	0.070399374	23	-3.78077E-09
WAFS163	-43.275089	170.38496	76.432	3987.48	4037.151	25	5	2015	1	18	0.070355708	23	1.49157E-10
WAFS164	-43.273432	170.38493	75.711	3987.92	4037.597	25	5	2015	1	34	0.069788474	23	-6.15728E-10
WAFS072	-43.277618	170.40072	86.252	3982.65	4032.257	25	5	2015	2	6	0.067161825	23	0.007241581
WAFS165	-43.276053	170.39918	86.532	3983.65	4033.27	25	5	2015	2	41	0.062307739	23	2.18461E-09
WAFS166	-43.274528	170.39813	82.331	3984.51	4034.142	25	5	2015	3	5	0.058033739	23	1.10185E-09
WAFS167	-43.272699	170.39752	80.72	3985.72	4035.368	25	5	2015	3	19	0.055269541	23	-1.07502E-09
WAFS168	-43.271044	170.39673	78.668	3986.94	4036.604	25	5	2015	3	31	0.052779014	23	7.04404E-10
WAFS169	-43.27182	170.39109	78.597	3987.23	4036.898	25	5	2015	3	49	0.048901818	23	-8.80391E-10
WAFS170	-43.273873	170.38913	78.583	3986.81	4036.472	25	5	2015	4	10	0.044247756	23	5.79348E-10
WAFS171	-43.274126	170.39215	80.069	3986.02	4035.672	25	5	2015	4	32	0.039350453	23	-2.46473E-10
WAFS172	-43.272692	170.39447	80.432	3986.27	4035.925	25	5	2015	4	55	0.034366442	23	-1.8872E-10
WAFS173	-43.274558	170.39518	82.164	3985.12	4034.76	25	5	2015	5	13	0.03066941	23	-3.84716E-10
WAFS072	-43.277618	170.40072	86.252	3982.61	4032.216	25	5	2015	5	33	0.026845101	23	0.008029739
SA80	-43.277467	170.41729	97.747	3975.38	4024.89	25	5	2015	5	49	0.024033678	23	-0.009457496
SA86	-43.265827	170.37515	70.667	3991.71	4041.438	25	5	2015	5	59	0.022411201	23	0.000943094
SA86	-43.265827	170.37515	70.667	3991.69	4041.417	25	5	2015	21	24	0.008427893	24	-7.83436E-05
SA80	-43.277467	170.41729	97.747	3975.37	4024.88	25	5	2015	21	34	0.011856814	24	-0.001953107
WRS008	-43.283516	170.38946	85.111	3984.31	4033.939	25	5	2015	22	9	0.023797937	24	-0.00113184
WAFS174	-43.280588	170.38694	80.608	3985.58	4035.226	25	5	2015	22	28	0.030282817	24	-8.86757E-09
WAFS175	-43.278604	170.38763	80.211	3985.57	4035.216	25	5	2015	22	44	0.035643713	24	-7.50333E-10
WAFS176	-43.277257	170.3854	77.994	3986.62	4036.28	25	5	2015	23	2	0.041471097	24	4.95947E-09
WAFS177	-43.279771	170.38501	79.002	3986.22	4035.874	25	5	2015	23	24	0.048184858	24	-1.10686E-09
WRS008	-43.283516	170.38946	85.111	3984.34	4033.969	26	5	2015	0	10	0.060081138	24	-0.005193686
WAFS178	-43.284446	170.38627	81.584	3984.56	4034.192	26	5	2015	0	42	0.066108955	24	-3.23098E-09
WRS008	-43.283516	170.38946	85.111	3984.36	4033.99	26	5	2015	0	55	0.067943218	24	0.007888146
WAFS179	-43.282125	170.38149	79.952	3986.28	4035.935	26	5	2015	1	14	0.069930968	24	-1.50067E-11
WAFS180	-43.281285	170.37703	76.43	3987.8	4037.475	26	5	2015	1	27	0.070807176	24	1.17325E-09
WAFS181	-43.280513	170.37284	80.158	3988.59	4038.276	26	5	2015	1	41	0.071301952	24	-1.53204E-09
WAFS182	-43.275371	170.37795	73.778	3989.4	4039.097	26	5	2015	2	3	0.071127161	24	2.61207E-09
WRS008	-43.283516	170.38946	85.111	3984.35	4033.98	26	5	2015	2	23	0.069986138	24	-0.002963062

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WAFS183	-43.278528	170.36228	91.455	3991.07	4040.789	26	5	2015	2	37	0.068643449	24	1.14505E-09
WAFS184	-43.279622	170.36834	87.143	3989.55	4039.249	26	5	2015	2	52	0.066724312	24	-2.14732E-09
WAFS185	-43.276319	170.37191	75.565	3990.75	4040.465	26	5	2015	3	10	0.063806622	24	3.28328E-10
WRS008	-43.283516	170.38946	85.111	3984.35	4033.98	26	5	2015	3	32	0.059427351	24	0.008634577
WAFS186	-43.281312	170.39792	86.917	3982.38	4031.983	26	5	2015	3	58	0.053259521	24	-2.46018E-10
WAFS187	-43.280411	170.39314	82.472	3984.28	4033.909	26	5	2015	4	13	0.049320773	24	1.31149E-09
WRS008	-43.283516	170.38946	85.111	3984.34	4033.969	26	5	2015	4	44	0.040554589	24	0.018458158
SA80	-43.277467	170.41729	97.747	3975.37	4024.88	26	5	2015	5	5	0.034287926	24	-0.017594043
SA86	-43.265827	170.37515	70.667	3991.7	4041.427	26	5	2015	5	14	0.031625786	24	-0.006066801
SA86	-43.265827	170.37515	70.667	3991.69	4041.417	26	5	2015	21	33	0.004121503	25	0.025040376
SA80	-43.277467	170.41729	97.747	3975.34	4024.85	26	5	2015	21	44	0.007120247	25	-0.008271029
WAFS188	-43.284302	170.38014	97.632	3981.78	4031.375	26	5	2015	22	25	0.019172678	25	-2.70302E-09
WAFS189	-43.286438	170.37913	132.731	3973.88	4023.37	26	5	2015	22	43	0.0248928	25	-0.024935128
WAFS190	-43.286126	170.37645	114.853	3977.72	4027.261	26	5	2015	23	13	0.034631355	25	2.54659E-11
WAFS191	-43.288268	170.37891	159.074	3965.89	4015.274	27	5	2015	0	6	0.051171669	25	0.006972829
WAFS192	-43.289243	170.37839	197.494	3960.47	4009.781	27	5	2015	0	42	0.060737042	25	-7.09406E-11
WAFS193	-43.290573	170.37817	229.992	3952.77	4001.979	27	5	2015	1	10	0.066640699	25	3.72893E-11
WAFS191	-43.288268	170.37891	159.074	3965.91	4015.294	27	5	2015	1	46	0.071696108	25	-0.00525486
WAFS194	-43.291993	170.37796	241.354	3944.52	3993.619	27	5	2015	2	38	0.073104515	25	5.90262E-10
WAFS191	-43.288268	170.37891	159.074	3965.92	4015.304	27	5	2015	3	45	0.064048535	25	-0.001717969
WAFS189	-43.286438	170.37913	132.731	3974	4023.492	27	5	2015	4	12	0.057240795	25	0.024935131
SA80	-43.277467	170.41729	97.747	3975.43	4024.941	27	5	2015	4	38	0.049236296	25	-0.008742626
SA86	-43.265827	170.37515	70.667	3991.75	4041.478	27	5	2015	4	48	0.045919828	25	-0.008026722
SA86	-43.265827	170.37515	70.667	3991.58	4041.306	27	5	2015	20	51	-0.00266106	26	0.00166661
SA80	-43.277467	170.41729	97.747	3975.26	4024.768	27	5	2015	21	1	-0.0018612	26	0.000981947
WRS071	-43.264614	170.41581	79.725	3981.54	4031.132	27	5	2015	21	52	0.005178577	26	-2.95586E-10
WRS072	-43.26434	170.413	75.105	3983.74	4033.361	27	5	2015	22	5	0.007808291	26	-5.02041E-10
WRS073	-43.265427	170.41038	72.111	3985.19	4034.831	27	5	2015	22	34	0.01474696	26	1.73395E-09
WRS074	-43.265977	170.40727	71.273	3986.47	4036.128	27	5	2015	23	1	0.022310764	26	1.43336E-09
SA86	-43.265827	170.37515	70.667	3991.65	4041.377	27	5	2015	23	46	0.036366332	26	0.011024708
WRS075	-43.264211	170.37606	68.229	3992.17	4041.904	28	5	2015	0	23	0.048263961	26	-1.14005E-09
SA86	-43.265827	170.37515	70.667	3991.67	4041.397	28	5	2015	0	47	0.055570742	26	0.00422749

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WRS076	-43.263648	170.3782	69.004	3991.83	4041.559	28	5	2015	0	56	0.058148565	26	1.37152E-09
WRS077	-43.262908	170.38117	70.221	3991.5	4041.225	28	5	2015	1	18	0.06394423	26	4.70664E-10
WRS078	-43.267346	170.39843	77.485	3987.28	4036.949	28	5	2015	1	37	0.068252637	26	9.12678E-10
WRS079	-43.267027	170.40094	77.262	3986.88	4036.543	28	5	2015	1	48	0.070376366	26	4.93856E-10
WRS080	-43.266867	170.40301	76.621	3986.51	4036.168	28	5	2015	2	1	0.072506681	26	-2.57933E-09
WRS081	-43.266713	170.40519	76.317	3986.1	4035.753	28	5	2015	2	16	0.074411341	26	6.98947E-10
SA86	-43.265827	170.37515	70.667	3991.67	4041.397	28	5	2015	2	45	0.076250744	26	-0.031655568
WRS082	-43.251016	170.39915	65.967	3989.31	4039.006	28	5	2015	3	10	0.0757399	26	-1.74123E-09
WRS083	-43.252053	170.40472	66.042	3988.45	4038.134	28	5	2015	3	33	0.073494975	26	9.10404E-10
WRS084	-43.253264	170.41125	61.605	3987.71	4037.384	28	5	2015	3	57	0.069331537	26	-7.97627E-10
WRS085	-43.257326	170.41002	66.688	3988.26	4037.942	28	5	2015	4	20	0.063676307	26	8.15817E-10
WRS086	-43.254554	170.41786	63.001	3985.55	4035.196	28	5	2015	4	48	0.054751514	26	2.94676E-10
SA80	-43.277467	170.41729	97.747	3975.36	4024.87	28	5	2015	5	58	0.025212719	26	0.006053242
SA86	-43.265827	170.37515	70.667	3991.68	4041.407	28	5	2015	6	7	0.021001226	26	0.00770158
SA86	-43.265827	170.37515	70.667	3991.67	4041.397	28	5	2015	21	12	0.004975166	27	-0.007429147
SA80	-43.277467	170.41729	97.747	3975.33	4024.839	28	5	2015	21	22	0.00493287	27	-0.025344079
WRS087	-43.298125	170.41987	119.684	3965.12	4014.493	28	5	2015	22	46	0.013730737	27	-0.016943296
WRS088	-43.29731	170.42219	159.144	3958.65	4007.937	28	5	2015	23	11	0.019377185	27	0.025309095
WRS089	-43.297072	170.42302	178.324	3955.47	4004.715	28	5	2015	23	30	0.024422984	27	0.03321144
WRS087	-43.298125	170.41987	119.684	3965.14	4014.514	29	5	2015	0	17	0.038853436	27	-0.013558891
SA86	-43.265827	170.37515	70.667	3991.74	4041.468	29	5	2015	1	43	0.065617975	27	0.027401443
WRS090	-43.269161	170.39529	78.865	3987.65	4037.323	29	5	2015	2	16	0.073346247	27	-1.29512E-09
WRS091	-43.269523	170.39266	78.794	3987.85	4037.526	29	5	2015	2	33	0.076275111	27	-9.91349E-10
WRS092	-43.270166	170.38926	77.1	3987.94	4037.617	29	5	2015	2	53	0.078643168	27	-4.32783E-09
WRS093	-43.271013	170.38445	75.707	3988.42	4038.104	29	5	2015	3	15	0.079752755	27	1.97269E-09
SA86	-43.265827	170.37515	70.667	3991.71	4041.438	29	5	2015	3	31	0.079499465	27	-0.00709947
WRS094	-43.260358	170.40204	72.683	3988.43	4038.114	29	5	2015	3	48	0.07819702	27	2.1887E-09
WRS095	-43.256513	170.40379	69.046	3989.18	4038.874	29	5	2015	4	5	0.075825391	27	2.97405E-10
WRS096	-43.254831	170.38862	66.838	3990.71	4040.424	29	5	2015	4	24	0.071921101	27	1.04001E-09
WRS097	-43.256366	170.38281	69.346	3992.24	4041.975	29	5	2015	4	38	0.068203136	27	-1.10231E-09
WRS098	-43.258037	170.37671	65.259	3994	4043.758	29	5	2015	4	51	0.06413743	27	9.52241E-10
WRS099	-43.26021	170.37216	67.9	3994.53	4044.295	29	5	2015	5	4	0.059505643	27	8.20819E-10

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
SA86	-43.265827	170.37515	70.667	3991.69	4041.417	29	5	2015	5	15	0.055161609	27	0.006389934
SA80	-43.277467	170.41729	97.747	3975.33	4024.839	29	5	2015	5	34	0.046765135	27	-0.022622205
SA86	-43.265827	170.37515	70.667	3991.67	4041.397	29	5	2015	5	42	0.043045009	27	0.000685178
SA86	-43.265827	170.37515	70.667	3991.58	4041.306	29	5	2015	21	37	0.0132263	28	-0.00599396
SA80	-43.277467	170.41729	97.747	3975.26	4024.768	29	5	2015	21	50	0.012334997	28	-0.002827514
WRS100	-43.278182	170.37911	75.534	3988.38	4038.063	29	5	2015	22	3	0.011855516	28	-1.68257E-11
WRS101	-43.263528	170.36822	65.382	3993.37	4043.12	29	5	2015	22	28	0.012120355	28	-4.54747E-11
SA86	-43.265827	170.37515	70.667	3991.57	4041.296	29	5	2015	22	42	0.013051346	28	-0.011594494
WRS102	-43.251721	170.37366	61.574	3995.73	4045.511	29	5	2015	23	3	0.015376218	28	3.45608E-11
WRS103	-43.25568	170.36622	61.313	3995.78	4045.562	29	5	2015	23	19	0.017968768	28	-2.00089E-11
SA86	-43.265827	170.37515	70.667	3991.57	4041.296	29	5	2015	23	39	0.02211409	28	-0.016835861
WRS104	-43.275099	170.3575	68.576	3993.49	4043.241	30	5	2015	0	14	0.031301985	28	1.77351E-11
WRS105	-43.274464	170.36767	72.907	3991.46	4041.184	30	5	2015	0	33	0.037113898	28	2.72848E-11
SA86	-43.265827	170.37515	70.667	3991.62	4041.346	30	5	2015	0	54	0.043939342	28	0.017033015
WRS106	-43.270249	170.3661	68.148	3991.94	4041.671	30	5	2015	1	7	0.048291432	28	-4.72937E-11
SA86	-43.265827	170.37515	70.667	3991.65	4041.377	30	5	2015	1	44	0.06055615	28	0.034167892
WDSS054	-43.289248	170.40502	96.878	3973.97	4023.461	30	5	2015	2	0	0.065595221	28	3.63798E-11
WDSS055	-43.289869	170.40531	99.981	3973.44	4022.924	30	5	2015	2	13	0.069349526	28	2.45291E-09
WDSS056	-43.29186	170.4056	98.21	3972.4	4021.87	30	5	2015	2	31	0.074014643	28	1.7626E-09
WDSS057	-43.291929	170.40603	91.48	3973.52	4023.005	30	5	2015	2	49	0.077910522	28	-1.04046E-09
SA86	-43.265827	170.37515	70.667	3991.65	4041.377	30	5	2015	3	6	0.080714134	28	0.019507328
WRS107	-43.268908	170.41556	95.02	3977.91	4027.454	30	5	2015	3	32	0.083254121	28	0.007449887
WRS108	-43.268928	170.41662	101.644	3976.35	4025.873	30	5	2015	3	45	0.083591154	28	9.27685E-11
WRS109	-43.269069	170.4178	113.41	3974.1	4023.593	30	5	2015	3	57	0.083319003	28	-4.18368E-11
WRS110	-43.269388	170.41919	125.945	3971.38	4020.837	30	5	2015	4	12	0.082162038	28	6.82121E-12
WRS111	-43.269791	170.42044	135.203	3969.15	4018.577	30	5	2015	4	26	0.080243427	28	-0.020783403
WRS107	-43.268908	170.41556	95.02	3977.88	4027.423	30	5	2015	4	56	0.0733858	28	-0.007449888
WRS112	-43.268755	170.41437	83.446	3980.49	4030.068	30	5	2015	5	11	0.06857087	28	1.43064E-09
SA80	-43.277467	170.41729	97.747	3975.27	4024.779	30	5	2015	5	35	0.059041023	28	-0.008225946
SA86	-43.265827	170.37515	70.667	3991.59	4041.316	30	5	2015	5	45	0.054528956	28	-0.004447062
SA86	-43.265827	170.37515	70.667	3991.57	4041.296	30	5	2015	21	9	0.032378308	29	0.000612292
SA80	-43.277467	170.41729	97.747	3975.23	4024.738	30	5	2015	21	31	0.027278781	29	-0.014810518

Continued on next page

Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WRS111	-43.269791	170.42044	135.203	3969.11	4018.537	30	5	2015	22	15	0.019987256	29	0.002432759
WRS113	-43.272285	170.42187	167.973	3963.51	4012.862	30	5	2015	22	47	0.017848824	29	-2.46018E-10
WRS114	-43.273467	170.42605	222.012	3950.04	3999.213	30	5	2015	23	55	0.023271048	29	1.62891E-09
WRS115	-43.275944	170.42845	272.716	3936.98	3985.979	31	5	2015	0	45	0.03513414	29	-2.45882E-09
WRS111	-43.269791	170.42044	135.203	3969.19	4018.618	31	5	2015	2	21	0.066578332	29	0.018350642
SA80	-43.277467	170.41729	97.747	3975.33	4024.839	31	5	2015	2	56	0.076777138	29	0.012507239
WRS116	-43.288031	170.41609	137.229	3965.79	4015.172	31	5	2015	3	38	0.085130931	29	7.69887E-10
WRS117	-43.29003	170.41886	191.802	3955.39	4004.634	31	5	2015	4	49	0.084585697	29	-8.13998E-11
SA80	-43.277467	170.41729	97.747	3975.3	4024.809	31	5	2015	5	51	0.06593928	29	-0.020255365
SA86	-43.265827	170.37515	70.667	3991.64	4041.367	31	5	2015	5	58	0.062855728	29	0.001162953
SA86	-43.265827	170.37515	70.667	3991.69	4041.417	22	9	2015	22	0	0.037561437	30	0.026047181
SA80	-43.277467	170.41729	97.747	3975.32	4024.829	22	9	2015	22	14	0.03842105	30	-0.022697139
WFW001	-43.268401	170.41737	113.761	3974.18	4023.674	22	9	2015	22	40	0.040442928	30	3.40651E-09
WFW002	-43.268332	170.41865	122.826	3971.99	4021.455	22	9	2015	22	50	0.041383392	30	-8.48559E-10
WFW003	-43.268468	170.41987	143.209	3967.77	4017.179	22	9	2015	23	4	0.042804299	30	5.53428E-10
WFW004	-43.269131	170.42243	161.215	3964.76	4014.129	22	9	2015	23	30	0.045632197	30	-0.003104581
WFW005	-43.269172	170.42347	166.954	3963.71	4013.065	22	9	2015	23	39	0.04662499	30	-1.36424E-12
WFW006	-43.268852	170.42448	175.024	3962.06	4011.393	22	9	2015	23	50	0.047817955	30	-2.50111E-11
WFW007	-43.268497	170.42347	163.869	3964.18	4013.541	22	9	2015	23	58	0.048658297	30	1.04592E-11
WFW008	-43.268102	170.42226	159.51	3965.04	4014.412	23	9	2015	0	8	0.049661936	30	1.45519E-11
WFW004	-43.269131	170.42243	161.215	3964.76	4014.129	23	9	2015	0	20	0.050776638	30	-0.00332869
WFW009	-43.26698	170.42225	157.563	3965.51	4014.889	23	9	2015	0	57	0.053237741	30	-1.06866E-10
WFW010	-43.26754	170.42322	160.839	3964.85	4014.22	23	9	2015	1	7	0.053573112	30	1.81899E-11
WFW011	-43.268121	170.42452	171.459	3962.75	4012.092	23	9	2015	1	17	0.053735593	30	1.31877E-11
WFW004	-43.269131	170.42243	161.215	3964.76	4014.129	23	9	2015	1	34	0.053573059	30	0.001156981
WFW004	-43.269131	170.42243	161.215	3964.73	4014.098	23	9	2015	3	17	0.038021551	30	-0.003555227
WFW004	-43.269131	170.42243	161.215	3964.72	4014.088	23	9	2015	4	8	0.02052035	30	0.008831513
SA80	-43.277467	170.41729	97.747	3975.24	4024.748	23	9	2015	5	24	-0.01406993	30	-0.008956898
SA86	-43.265827	170.37515	70.667	3991.57	4041.296	23	9	2015	5	34	-0.01892003	30	0.005606861
SA86	-43.265827	170.37515	70.667	3991.54	4041.265	23	9	2015	21	26	0.021671509	31	0.003126
SA80	-43.277467	170.41729	97.747	3975.22	4024.728	23	9	2015	21	37	0.020818775	31	0.005419094
WGK001	-43.284572	170.39556	87.226	3982.27	4031.872	23	9	2015	22	15	0.020188426	31	-0.017592966

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Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WKG002	-43.28372	170.39576	88.363	3982.39	4031.993	23	9	2015	22	23	0.020519268	31	1.86446E-11
WKG003	-43.282881	170.39603	88.602	3982.22	4031.821	23	9	2015	22	33	0.021158767	31	5.54792E-11
WKG004	-43.282082	170.39634	86.677	3982.52	4032.125	23	9	2015	22	42	0.02194202	31	-7.00311E-11
WKG005	-43.281064	170.39672	86.57	3982.75	4032.358	23	9	2015	22	51	0.022914064	31	-4.54747E-11
WKG006	-43.282133	170.39763	89.26	3981.79	4031.385	23	9	2015	23	5	0.024792244	31	4.59295E-11
WKG007	-43.283158	170.39727	89.675	3981.74	4031.335	23	9	2015	23	14	0.026213278	31	6.36646E-12
WKG008	-43.283948	170.397	89.713	3981.69	4031.284	23	9	2015	23	26	0.028341294	31	-1.81899E-12
WKG009	-43.284763	170.39671	87.971	3981.54	4031.132	23	9	2015	23	31	0.029302098	31	-4.6839E-11
WKG001	-43.284572	170.39556	87.226	3982.3	4031.902	23	9	2015	23	40	0.031122306	31	0.002156812
WKG001	-43.284572	170.39556	87.226	3982.33	4031.933	24	9	2015	0	53	0.048486515	31	0.015436158
WKG010	-43.285049	170.39826	88.789	3980.62	4030.2	24	9	2015	1	5	0.051371712	31	-5.68434E-10
WKG011	-43.284305	170.39848	90.595	3980.86	4030.443	24	9	2015	1	11	0.052768961	31	1.39607E-10
WKG012	-43.283522	170.39869	89.799	3981.29	4030.879	24	9	2015	1	18	0.054353223	31	3.36513E-11
WKG013	-43.282732	170.39894	89.092	3981.47	4031.061	24	9	2015	1	29	0.056721457	31	2.31921E-11
WKG014	-43.281535	170.39908	88.667	3981.65	4031.244	24	9	2015	1	56	0.061694561	31	1.65528E-10
SA80	-43.277467	170.41729	97.747	3975.26	4024.768	24	9	2015	2	45	0.066337887	31	0.001462073
SA86	-43.265827	170.37515	70.667	3991.57	4041.296	24	9	2015	3	0	0.066320453	31	-0.010007166
SA86	-43.265827	170.37515	70.667	3991.51	4041.235	24	9	2015	23	9	0.00098348	32	0.004803705
SA80	-43.277467	170.41729	97.747	3975.18	4024.687	24	9	2015	23	20	0.002563014	32	-0.004510505
WMT001	-43.308242	170.37415	1240.912	3741.68	3788.082	25	9	2015	1	46	0.050766688	32	1.27329E-11
WMT002	-43.307034	170.37409	1258.024	3734.17	3780.472	25	9	2015	2	11	0.06034816	32	-7.9126E-11
WAD001	-43.288815	170.46064	1449.472	3700.76	3746.619	25	9	2015	2	42	0.070778282	32	1.60071E-10
WAD002	-43.289501	170.46033	1438.522	3703.57	3749.466	25	9	2015	2	52	0.073590499	32	5.96629E-10
SA80	-43.277467	170.41729	97.747	3975.23	4024.738	25	9	2015	3	46	0.08272934	32	-0.009951753
SA86	-43.265827	170.37515	70.667	3991.57	4041.296	25	9	2015	3	59	0.083157653	32	0.009658553
SA86	-43.265827	170.37515	70.667	3991.44	4041.164	25	9	2015	22	20	-0.01800332	33	-0.000602428
SA80	-43.277467	170.41729	97.747	3975.11	4024.616	25	9	2015	22	34	-0.02105403	33	-0.005494616
WDF001	-43.28477	170.40667	88.953	3978	4027.545	25	9	2015	22	54	-0.02381509	33	0.007428634
WDF002	-43.283828	170.40604	88.612	3978.6	4028.153	25	9	2015	23	6	-0.02457917	33	-3.09228E-11
WDF003	-43.282853	170.40548	87.326	3979.34	4028.903	25	9	2015	23	17	-0.02466119	33	4.77485E-11
WDF004	-43.283093	170.40412	85.463	3980.02	4029.592	25	9	2015	23	27	-0.02421555	33	2.31921E-11
WDF005	-43.283917	170.40437	86.451	3979.46	4029.024	25	9	2015	23	36	-0.02339451	33	3.41061E-11

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Station Name	Latitude	Longitude	Height (m)	Dial	Calibrated Dial (mGal)	Day	Month	Year	Hour	Minute	Tidal Effect (mGal)	Loop	Sample (Residuals)
WDF006	-43.284844	170.40481	86.124	3979.05	4028.609	25	9	2015	23	47	-0.02186311	33	-1.68257E-11
WDF007	-43.284837	170.40541	87.332	3978.68	4028.234	25	9	2015	23	57	-0.01998194	33	-5.22959E-11
WDF001	-43.28477	170.40667	88.953	3978	4027.545	26	9	2015	0	4	-0.01839278	33	0.005939847
WDF001	-43.28477	170.40667	88.953	3978.01	4027.555	26	9	2015	0	59	0.0010093	33	-0.000238411
WDF008	-43.284424	170.40526	86.454	3979.04	4028.599	26	9	2015	1	11	0.006596529	33	5.46606E-10
WDF009	-43.283879	170.40505	87.058	3979.2	4028.761	26	9	2015	1	19	0.010525238	33	-2.26646E-09
WDF010	-43.283402	170.40491	86.659	3979.49	4029.055	26	9	2015	1	29	0.015631876	33	-3.76531E-10
WDF001	-43.28477	170.40667	88.953	3978.02	4027.565	26	9	2015	1	50	0.026900016	33	-0.013130073
WIC001	-43.265079	170.39641	75.475	3987.87	4037.546	26	9	2015	2	21	0.044044286	33	-4.09273E-10
WIC002	-43.265824	170.39333	75.738	3988.13	4037.81	26	9	2015	2	30	0.04901194	33	-5.62977E-10
WIC003	-43.266822	170.38946	75.681	3988.55	4038.235	26	9	2015	2	51	0.060267447	33	1.09594E-09
WIC004	-43.267727	170.38593	75.223	3988.77	4038.458	26	9	2015	3	1	0.06536452	33	-8.75843E-10
SA80	-43.277467	170.41729	97.747	3975.2	4024.708	26	9	2015	3	36	0.081226109	33	0.000394392
SA86	-43.265827	170.37515	70.667	3991.53	4041.255	26	9	2015	3	47	0.08526557	33	0.005702656
SA86	-43.265827	170.37515	70.667	3991.44	4041.164	27	9	2015	21	25	0.014153215	34	-0.001738394
SA80	-43.277467	170.41729	97.747	3975.12	4024.627	27	9	2015	21	37	0.004890826	34	0.007262914
WRS087	-43.298125	170.41987	119.684	3964.89	4014.26	27	9	2015	22	43	-0.04049495	34	0.032818395
WLC001	-43.297547	170.42119	143.295	3961	4010.319	27	9	2015	23	17	-0.05770739	34	-6.74845E-10
WRS088	-43.29731	170.42219	159.144	3958.3	4007.583	27	9	2015	23	42	-0.06651563	34	-0.025309095
WRS089	-43.297072	170.42302	178.324	3955.1	4004.34	28	9	2015	0	18	-0.07264617	34	-0.03321144
WRS087	-43.298125	170.41987	119.684	3964.85	4014.22	28	9	2015	1	12	-0.06656294	34	-0.002316201
WLC002	-43.295971	170.42056	153.763	3960.13	4009.437	28	9	2015	1	50	-0.05191197	34	-3.24553E-09
SA80	-43.277467	170.41729	97.747	3975.14	4024.647	28	9	2015	2	36	-0.02504627	34	0.015988128
SA86	-43.265827	170.37515	70.667	3991.46	4041.184	28	9	2015	2	46	-0.01835468	34	0.006505696

Table E.2: Survey measurements processed using Gsolve for the entire gravity survey.

Note that time has been converted to UTC.

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Figure E.1: Drift curves for all 34 survey loops produced using Gsolve.

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