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## Surveying and Dating Post-Glacial Lake Shorelines in New Zealand


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# Surveying and Dating Post-Glacial Lake Shorelines in New Zealand

Report for Royal Institution of Chartered Surveyors

**A report for Royal Institution of Chartered Surveyors**

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# Contents



## List of Figures

Executive Summary

## Background

Natural fluctuations in Earth's climate, between cold 'glacial' and warm 'interglacial' periods, produce a wide range of changes to the Earth's surface. One of these changes is related to glacial isostatic adjustment (GIA), which is a phenomenon whereby the loading and unloading of the Earth's crust and mantle due to the growth and retreat of large ice sheets induces regional deformation. The response at the surface depends on the specific properties of the crust and mantle, but typically involves changes in the elevation of the land surface over time.

Uplift from GIA caused by retreat of ice since the last glacial period, which was at its maximum ~18,000-24,000 years ago, can still be observed today in many parts of the world that were glaciated. It affects estimation of the equipotential surface (geoid models) for survey datum, causes 'new' land to emerge in regions of relative sea-level lowering, and can alter flood, earthquake, and landslide hazards in mountainous terrain. Quantifying GIA can be challenging, and has typically been limited to tectonically stable continental interiors (e.g. Fennoscandia and central North America) where the magnitude of uplift is on the order of hundreds of metres. Modern geodetic networks can detect ongoing uplift attributable to deglaciation, and natural strain markers, such as palaeo-shorelines of glacial lakes, can yield information on the timing and magnitude of uplift over longer timescales. Often, the coverage and extent of these two datasets, as well as preservation of lake-shorelines in stable continental shield settings, permits evaluation of differential uplift over hundreds of kilometres.

Differential uplift can present hazards to developed land. Lakes occupying formerly glaciated basins, and undergoing tilting, may transgress or regress based on the pattern of uplift and location of drainage, causing flooding and land emergence, respectively. In lakes dammed by unconsolidated glacial till or glacio-fluvial outwash, a tilt-induced breach of the natural dam may cause catastrophic flooding or river aggradation down-valley.

It has also been proposed, and in some cases observed, that GIA and lake level fluctuations may increase stress on earthquake faults and cause clusters of seismicity. In regions of on-going active seismicity, an increase in stress may be sufficient to cause failure on otherwise 'slow-moving' faults.

Glacial-rebound signals have not been identified or isolated from tectonic processes in the New Zealand landscape. This contrasts with other parts of the world where glacial-unloading has caused $10^1$-$10^2$ metres of uplift and increased fault activity. The aim of this research was to quantify the magnitude and timing of post-glacial lake-level changes and deformation of the Lake Wakatipu basin, New Zealand. Abandoned shorelines up to 45 m above the modern water level had previously been suggested to be tilted. Accurate measurement of the tilting rates may reveal a glacial-rebound signal from the tectonically overprinted New Zealand landscape.

## The Study

The towns of Queenstown, Glenorchy, Frankton, and Kingston are located on the shores of Lake Wakatipu. They are popular tourist destinations and have significant flood and earthquake hazards. This study was focused on identifying evidence of post-glacial rebound and a history of lake level changes that may influence ongoing hazards in the region. Palaeo-shorelines of Lake Wakatipu, an ~80 km long lake that developed as a consequence of the retreat of the Wakatipu Valley Glacier at the end of the last glacial period, were surveyed using aerial Light Detection and Ranging (LiDAR), differential global positions systems (dGPS), and real-time kinematic (RTK) GPS techniques. Survey datasets were analysed for differential tilting from one side of the lake to the other. Additionally, geomorphic mapping, exposure-age and luminescence dating, and stratigraphic logging were used to assess the history of level changes around the lake.

## Key findings

- **There is no differential, along-lake post-glacial rebound signal from the last 17,100 years.**

  From mapping and correlating shorelines from seven locations along the length of Lake Wakatipu, no progressive, or in fact any demonstrable, offset can be detected. We have dated the onset of sedimentation into the Wakatipu basin following glacier retreat from the valley to 17,100 ± 2,600 years ago. There are three possible explanations for this: (1) all glacial rebound occurred before this time; (2) rebound occurred uniformly over the length of the lake; or (3) rebound has not occurred. We consider the first hypothesis unlikely because of the time-scales over which GIA is observed in other parts of the world. Without having further palaeo-uplift data for the wider region surrounding Lake Wakatipu, we cannot rule out the second hypothesis. We believe it is also possible that the ice load (greater than 1 km in places) was not sufficient to induce rebound in this region.

- **Following deglaciation, the lake level has decreased at different rates.**

  High-resolution surveying and exposure-age dating, calibrated with optically-stimulated luminescence dating (OSL) and radiocarbon ages, reveals that decrease of lake levels progressed slowly for the first 15,000 years following deglaciation (1.3 mm/yr on average). 2,000 years ago, lake level experienced a rapid increase in lowering (~ 10 mm/yr). Finally, a few hundred years ago (< 1,000) there has been a ~5 m increase in lake level as observed by drowned shorelines near Queenstown. If lake level continues to rise, the surrounding towns may be in danger of increased frequency of flooding.

## Implications for future studies

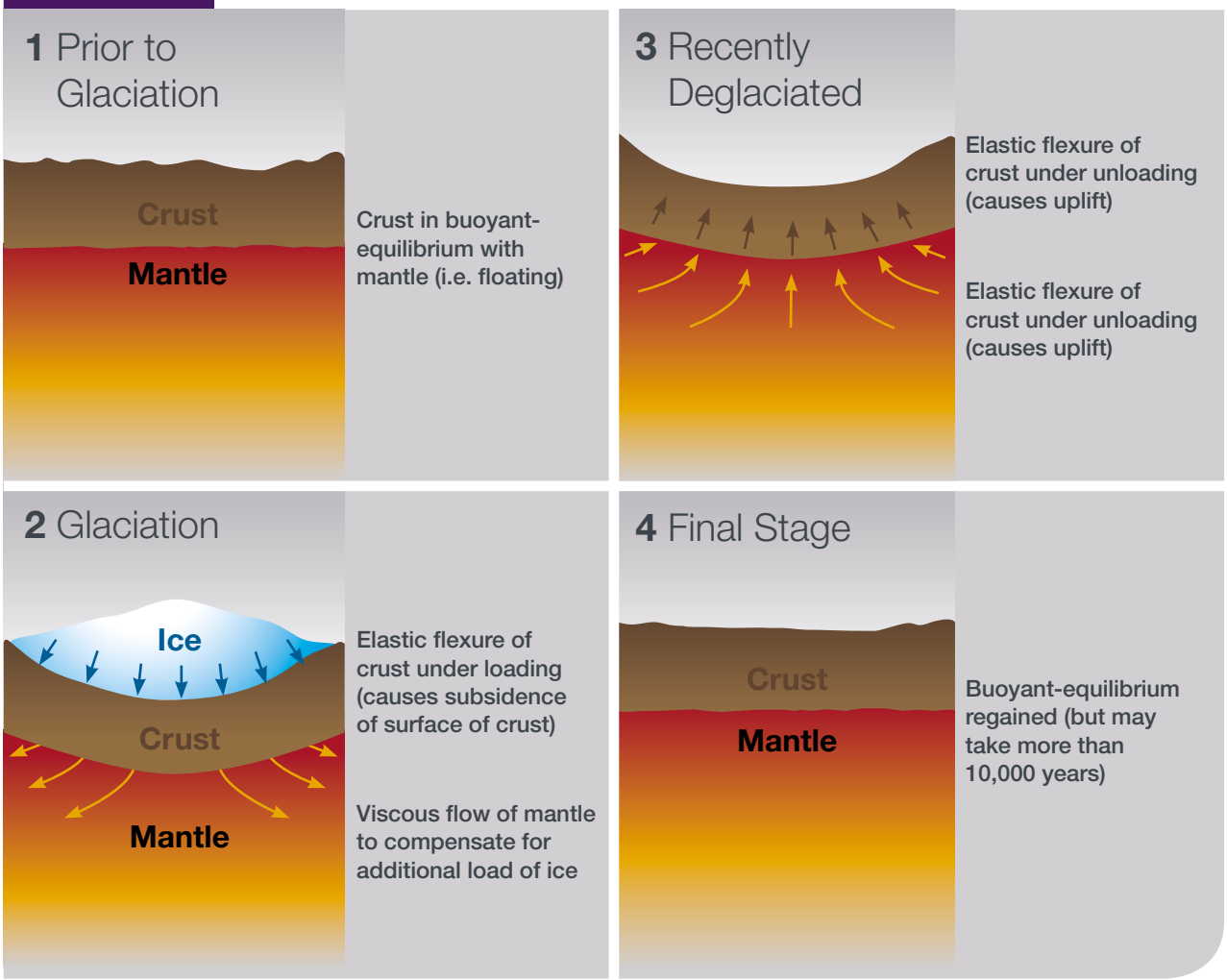
Future development of Queenstown, as well as other New Zealand and world-wide tourist destinations in formerly glaciated terrain, depends on the ability to mitigate geologic hazards. We have demonstrated that, in one specific instance, post-glacial rebound is not a concern for flooding, though unrelated lake level changes may present ongoing hazards. As tectonic activity, crust and mantle composition, ice thickness, and erosion rates differ from site to site, individual studies will have to be undertaken by qualified surveyors at other locations to assess hazards from GIA. This study provides some of the tools and a methodology for undertaking such assignments.

## 1.1 Background

Glaciers were much more extensive over Earth's surface 20,000 years ago. The last major glaciation is thought to have been at its maximum about 18,000-22,000 years ago – generally referred to as the Last Glacial Maximum (LGM). At around 18,000 years ago, global temperatures increased and glaciers have thinned and retreated rapidly in response. Consequently, vast areas that were once being actively modified by ice, began being modified by other processes. For example, glacial troughs – the over-deepened valley depressions produced by glacial erosion (Cook and Swift, 2012) – are no longer filled with ice and instead are often occupied by large lakes fed by large river systems. However, the influence of past glaciers and ice caps can persist for many thousands of years after they have disappeared. The retreat of glaciers often uncovers thick deposits of sub-glacial sediments, destabilises slopes by removing buttressing support, and exposes the fresh ground surface to the effects of weathering. These processes liberate and create sediments for thousands of years following the retreat of ice (Ballantyne, 2002). Over time, these sediments are redistributed through the landscape, and often end up filling-up the valleys and lake basins left behind by the glaciers.

Another lasting impact on the landscape following deglaciation is that of glacial isostatic adjustment. Glacial isostatic adjustment (GIA) is a phenomenon whereby the loading and unloading of the Earth's crust and mantle due to the growth and retreat of large ice sheets induces regional deformation (Figure 1). The response at the surface depends on the specific properties of the crust and mantle, but typically involves horizontal deformation due to viscous mantle flow, changes to sea-level and Earth's gravitational field, modulated earthquake frequency, and, most notably, changes in the elevation of the land surface.

**Figure 1** **Conceptual diagram illustrating glacial isostatic adjustment (GIA)**



Uplift from GIA (also termed 'post-glacial rebound') caused by the retreat of ice since the last major global glaciation can still be observed today. The uplift affects the estimation of the equipotential surface (geoid models) for survey datum, causes 'new' land to emerge in regions of relative sea-level lowering, and can alter flood, earthquake, and landslide hazards in mountainous terrain. Quantifying GIA can be challenging, and has typically been limited to tectonically stable continental interiors (e.g. Fennoscandia and central North America) where the magnitude of uplift since the LGM is on the order of hundreds of metres. Modern geodetic networks can detect ongoing uplift attributable to deglaciation, while natural strain markers, such as palaeo-shorelines of glacial lakes, can yield information on the timing and magnitude of uplift in the past. Often, the coverage and extent of these two datasets, as well as preservation of lake shorelines in stable continental shield settings, permits evaluation of differential uplift over hundreds of kilometres.

Differential uplift can present hazards to developed land. Lakes occupying formerly glaciated basins, and undergoing tilting, may transgress or regress based on the pattern of uplift and location of drainage, causing flooding and land emergence, respectively. In lakes dammed by unconsolidated glacial till or glacio-fluvial outwash, a tilt-induced breach of the natural dam may cause catastrophic flooding or river aggradation down-valley. It has also been proposed, and in some cases observed, that GIA and lake level fluctuations may increase stress on earthquake faults and cause clusters of seismicity (Stewart et al., 2000). In regions of on-going active seismicity, an increase in stress may be sufficient to cause failure on otherwise 'slow-moving' faults.

Most GIA studies have been restricted to locations where strong GIA signals have been observed or are expected to be strong. These areas are typically tectonically stable continental land masses that have been extensively glaciated by kilometre-thick ice-sheets. In these locations,

**Figure 2** **Location of Lake Wakatipu, New Zealand, and of key survey sites investigated in this study.**

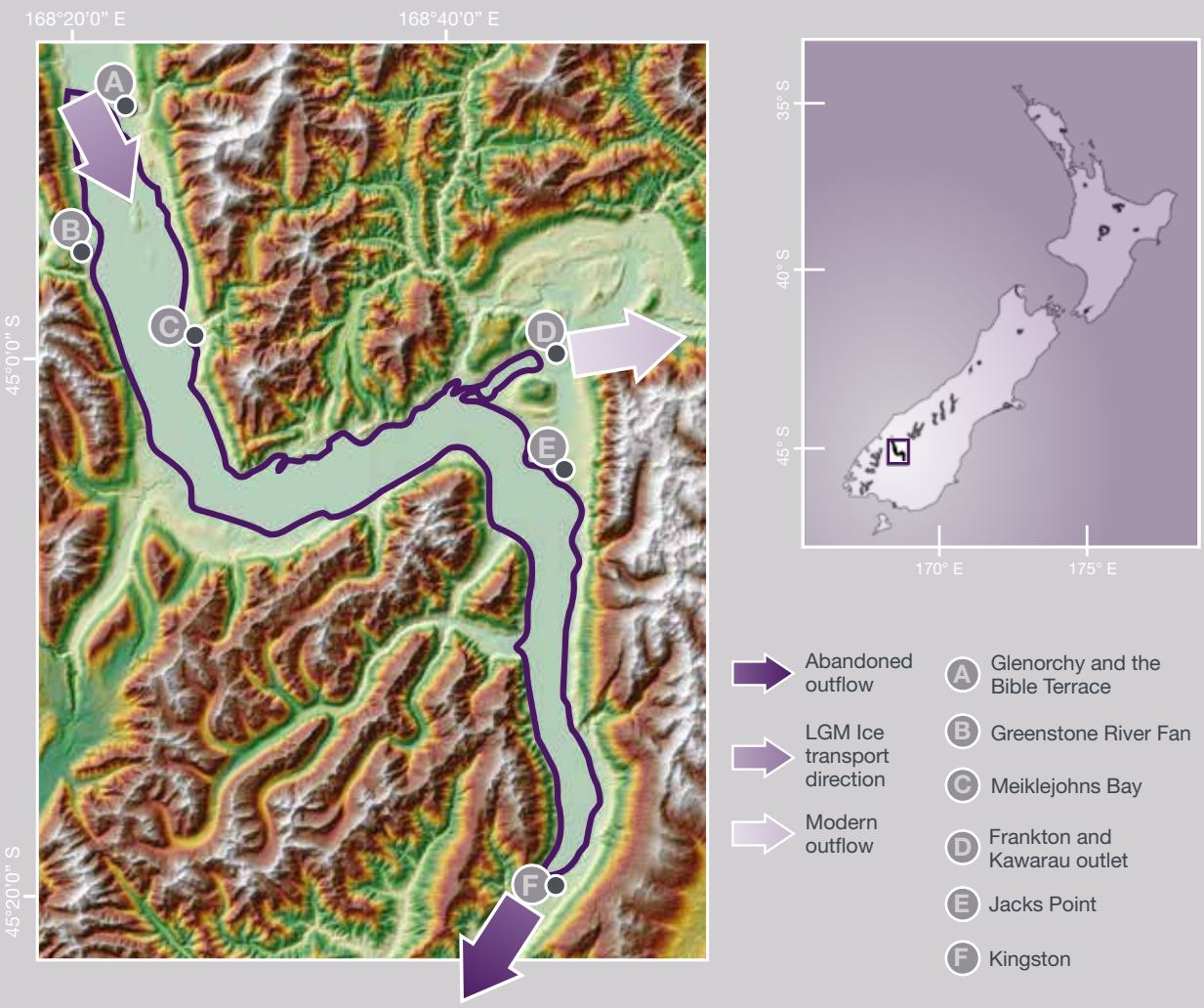
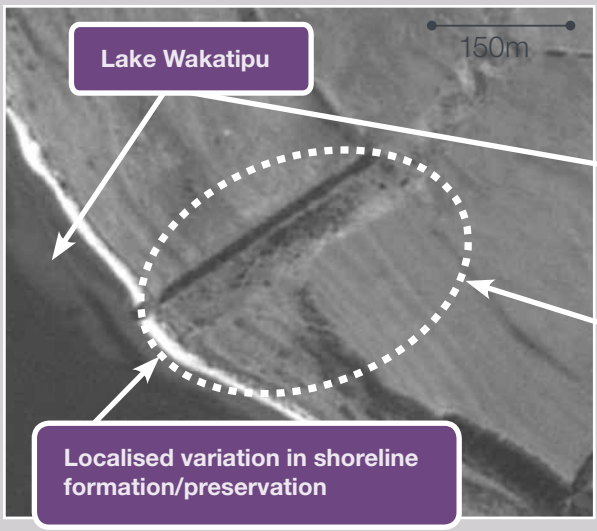
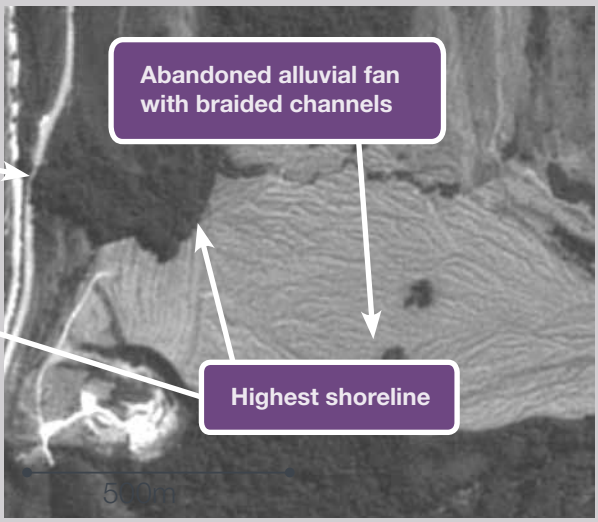


**Figure 3** Older preserved shorelines above Lake Wakatipu.




Jacks Point




Meiklejohns Bay

glacial rebound has demonstrably caused $10^1$-$10^2$ metres of uplift and increased fault activity. Fewer investigations have been carried out for landmasses affected by smaller glacial ice masses and in tectonically active settings, such as New Zealand's Southern Alps. GIA in these locations is likely to be more difficult to detect, and thus glacial-rebound signals have not previously been identified or isolated from tectonic processes in the New Zealand landscape. However, the authors considered it probable that GIA has affected the New Zealand landscape, and that the effects may be present in the landscape and able to be distinguished from background tectonic processes.

Lake Wakatipu, New Zealand, is situated in a glacial trough that was occupied by a kilometre-thick glacier at the LGM (Figure 2). Since the time when the lake formed shortly after deglaciation, the lake level has dropped episodically by a total of some 45 metres, and in doing so has left behind a series of shorelines that demark older lake levels (Figure 3). Like with other formerly glaciated lake basins in the New Zealand Southern Alps, these abandoned shorelines have previously been suggested to be tilted upwards towards the head of the lake (Wellman, 1979). Existing explanations for this tilting have been the existence of an uplift gradient that increases (typically north-west) towards the tectonic plate boundary and axis of the Southern Alps. These lakes are generally oriented in the direction of this uplift gradient, so that the head of a lake, which is closer to the mountains, is uplifted more so than its distal, down-valley end. However, it is also possible that part of this tilting can be explained by GIA. Ice thickness and therefore GIA is generally assumed to be greatest nearer the mountains, where snow and ice accumulate and less towards the glacier boundaries, where the ice melts. One way to differentiate between these two sources of tilting is to explore how the tilting of the shorelines has changed through time. For example, if the rate of tilting reduced over time, GIA may have been involved because GIA has been shown in other parts of the world to gradually lessen with time since ice unloading. If on the other hand, the total amount of tilting accumulated approximately constantly over time, then a GIA process is unlikely. Assessing the rate of tilting requires that the elevations and ages of the shorelines along the length of the lake are accurately known. Lake Wakatipu was chosen as a suitable site to search for a GIA signal in New Zealand.

## 1.2 Aims and Objectives

The aim of this research was to identify and quantify any glacial-isostatic uplift signal present in the abandoned shorelines above Lake Wakatipu. This aim was separated into the following objectives:

**Objective 1:** Quantify the magnitude of deformation of the Lake Wakatipu basin, New Zealand, by measuring shoreline elevations along the length of the lake.

**Objective 2:** Determine the timing of lake level changes by measuring the age of the abandoned shorelines;

**Objective 3:** Based on information from Objectives 1 and 2, calculate the rate of shoreline deformation to assess for a rate-change consistent with GIA.

# 2.0 Site Description and Previous Studies

At ~80 km in length, Lake Wakatipu is New Zealand's longest lake, and third largest by surface area (~290 km$^2$). The unique shape of the basin in which the lake sits is a result of a long history of tectonic, hillslope, fluvial, and, most notably, glacial processes. The Wakatipu trough has been deepened and widened during at least four major glaciations (Barrell, 1994), during which the Wakatipu Glacier probably exceeded 1 km in thickness (Barrell, 2011). Lake Wakatipu formed when the Wakatipu Glacier retreated from its LGM extent. The newly formed lake is thought to have established a stable level at approximately 43 m above the present level, where it would have existed for a considerable length of time. During this time a prominent shoreline, of which the remains can be seen around many parts of the lake (Figure 3), was etched into the landscape through the erosion and reworking of sediments by wave action (Thomson, 1996). Tributary rivers entering the lake were dropping their sediments into the lake, building up great fans of material, of which some remnants can be seen around the lake. At the time that the lake was forming this prominent shoreline and fans, the lake outflow was situated in the southern-most part of the lake at Kingston. This outflow was eventually abandoned when the lake became connected to the Kawarau catchment farther to the north (Figure 2) (Thomson, 1996). This switch in outlet location probably occurred as a result of a breach of sediments previously separating the lake from the Kawarau catchment. The Kawarau River at that time, must have been lower in elevation than the river draining the lake at Kingston, and thus became the more favourable outlet for the lake. It was after this drainage switch that the lake began to drop, abandoning the prominent high-stand shoreline. The lake continued to lower but with short episodes of relative stability that allowed a series of lower but less well-defined shorelines to be formed below the prominent high-stand shoreline and the modern day lake level. The tributary streams around the lake had to adjust to lower lake levels by cutting into their fan surfaces. In places this process can be identified in the landscape by the preservation of the oldest fan surface and below this a series of river terraces, that are equivalent to the lake shorelines.

Both Glenorchy and Kingston (Figure 2) have a history of flooding. Small (<2-3 m) changes in lake level are enough to inundate parts of both townships. Since Lake Wakatipu has several inflowing rivers but only one outflow along the Kawarau, moderate to heavy rain can cause prolonged periods of flooding. Differential tilting of the lake basin would exacerbate the problem by causing local transgressions of the shoreline. Thus, determining the rate at which tilting and lake lowering has occurred in the past is critical to determining ongoing flood hazards.

Assessment of shoreline tilt and tilt rate through time required accurate measurement of the elevations of abandoned shorelines along the length of the lake, and determining the age of each shoreline.

## 3.1 Shoreline surveying

Shoreline elevations were measured at six locations along the length of the lake. The selection of surveying locations was based on the degree of preservation of the shoreline features and ease of access; some places along the lake have little to no preservation of the abandoned shorelines. Three surveying techniques were used to measure the elevation of shorelines; differential GPS, Real Time Kinematic (RTK) GPS, and Light Detection and Ranging (LiDAR), the details of which are provided below and in Table 1.

**Table 1** **Survey data collection techniques, correction methods, error and transformations**

| Survey Method and Site | Vertical accuracy (mm) | Geodetic (calibration) mark accuracy* (mm) (95% CI) |
|---|---|---|
| **RTK (Greenstone River fan)** | 15–30 | 200 |
| **RTK (Bible Tce and Blanket Bay)** | 15–30 | 400; 30 |
| **RTK (Jacks Point)** | 15–30 | 350; 10 |
| **RTK (Glen Nevis)** | 15–30 | 250; 10 |
| **LiDAR (Bible Terrace)** | 26 | – |
| **LiDAR (Queenstown)** | 32 | – |
| **LiDAR (Kingston)** | 48 | – |
| **dGPS† (All sites)** | 200-1000 | – |

*Mark accuracy given as Tier (relative to datum); Class (relative to surrounding marks) confidence intervals (CI).
† Estimated accuracy stated is 2× that of the horizontal accuracy following differential correction.

A single lake shoreline can consist of a few different landform components (Figure 4). For each technique, the elevation of the shoreline assumed to be most representative of the elevation of the lake at the time of shoreline formation was selected. In being consistent with previous literature and observations of the modern lake shoreline, this was chosen to be the 'inner edge' of each shoreline (Figure 4). This landform feature is the best approximation of a mean lake level (MLL) that existed when the shoreline was being actively formed. The only exception to this was where the inner edge had an obvious drape of material from subsequent depositional processes (e.g. slope wash).

### 3.1.1 Real-Time Kinematic GPS (RTK)

A Trimble R8 GNSS base station and receiver with 15-30 mm vertical accuracy was used for surveying shorelines at five locations (Bible Terrace, Greenstone River Fan, Jacks Point, and Kingston; Figure 2). Surface elevations were measured at 1-5 m increments along transects perpendicular to the shoreline. High-order geodetic marks were used to calibrate the base/receiver data where available. For one location, where there were insufficient geodetic marks available, site calibration was achieved by differential correction of the base station to PositioNZ continuous GPS stations (Table 1). Positions were recorded in New Zealand Geodetic Datum 2000 (NZGD2000) with a New Zealand Transverse Mercator (NZTM) projection. Normal-orthometric heights were recorded in New Zealand Vertical Datum 2009 (NZVD09) which uses the New Zealand Geoid 2009 (NZG09). Site calibrations were conducted using Trimble Business Center version 2.8.

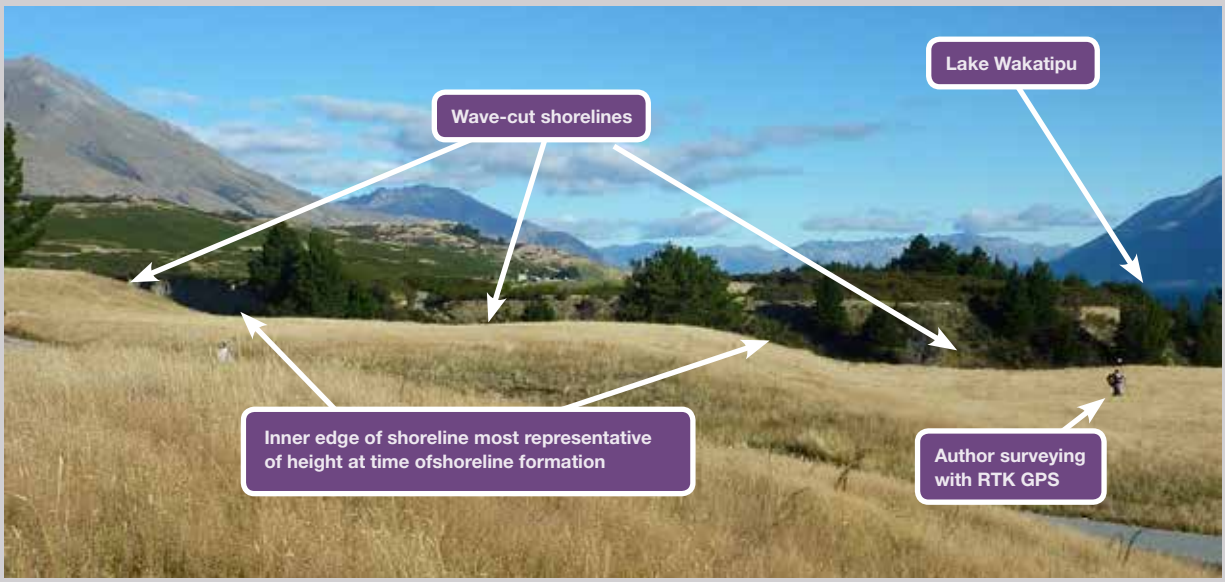
### 3.1.2 Differential GPS (dGPS)

At the Greenstone River fan, Jacks Point and Meiklejohns Bay (Figure 2), a Trimble GeoXH 2008 GPS handheld receiver was used to map shorelines and collect continuous points (at approximately 1 second intervals) while walking along the terrace transect. At the former two sites, the GeoXH dGPS was used synchronously with the RTK in order to compare the instrument accuracy and ability to recognize terraces in the continuous lines (dGPS) versus point profiles (RTK). Data from the receiver were differentially corrected in Trimble Pathfinder against PositioNZ stations, with an estimated vertical accuracy of 200-1000 mm (Table 1).

### 3.1.3 Light Detection and Ranging (LiDAR)

LiDAR data were acquired by New Zealand Aerial Mapping for Queenstown Lakes District Council in October 2011. Data were collected using an Optech ALTM3100EA system at a height of 1200 m with a 42° field of view. The pulse repetition frequency (PRF) was set at 70 kHz. The accuracy of the dataset was verified on the ground using dGPS and a regional network of geodetic reference marks. The standard deviations of vertical accuracy from ground surveying range from 2.5 to 5 cm for the datasets presented herein. Ground returns were manually processed to remove vegetation and hydrologic features. The processed LiDAR point clouds were gridded into 1x1 m digital elevation models (DEMs). Elevation profiles and contours were constructed in ArcGIS 10 3D Analyst.

**Figure 4** Wave-cut shoreline features



## 3.2 Shoreline correlation

To test for any differences in shoreline elevation between sites, it was necessary to be able to match shorelines confidently. Shoreline matching, or correlation, is difficult because shorelines are often sporadically preserved along the length of a lake, and the shorelines at any one site can look different because of variable beach materials and wave energies. However, at Lake Wakatipu the uppermost shoreline was clearly defined and recognisable at most surveyed sites, and at other locations along the lake (Figure 3). Additionally, the density of high accuracy survey data obtained in this study allowed 'wiggle- matching' of breaks in slope from site to site, as opposed to elevations alone. This is important because small breaks in slope at one site (i.e. departures towards a slope of zero) can correspond to well-defined palaeo-shorelines elsewhere. Correlation using only an elevation profile is often difficult in such circumstances. The shoreline elevations measured at each site were plotted on an elevation and slope graph with lines of best fit plotted to match-up the shorelines. Shoreline elevations were artificially shifted in some cases to see whether a better fit could be achieved.

## 3.3 Shoreline age estimation

The ages of the shorelines were assessed by dating river terraces cut into the Greenstone River fan (Figures 2 & 5). The fan was built up by the deposition of gravels and sands transported by the Greenstone River as it reached the lake. Evidence that this fan was formed into a lake (as opposed to building up against the side of a glacier) is shown in the arrangement of the sediment layers that were deposited. In an exposure of these sediments in a road cutting, it can be seen that the sediments are arranged in layers that dip steeply towards the lake (Figure 6B). Such layers are termed foreset beds and are formed when a river deposits its sediments into a standing water body (e.g. lake or sea) – the sands and gravels transported by the river drop out of suspension as they enter the still water, and avalanche down the submerged leading edge of the delta. As the delta continues to build, the river floodplain and channels advance over the older foreset beds, partially eroding and burying them with more sand and gravels. These new sediments, however, are not deposited at the leading edge of the delta in still water but are instead deposited by the flowing river and come to rest at the same gradient as the river (i.e. close to horizontal) – the layers they form are referred to as topset beds. It is assumed that the delta was building out and forming these foreset and topset beds at a time when the lake was at its highest elevation and when the lake level must have been relatively stable. A remnant of the aggradation surface of this fan is thought to be seen at the Greenstone River Fan (T1 shown in Figure 5), and at other locations around the lake (Figures 3 & 7). The subsequent lowering of the lake caused the river to cut down into this fan material, forming a series of terraces that step down incrementally towards the level of the modern river floodplain (Figure 5). The heights and ages of these terraces are assumed to correlate directly with the heights and ages of the shorelines around the lake, since each would have been formed during a period of relative lake level stability; however, a slight adjustment in elevation was made to account for a slight gradient between terrace and lake.

**Figure 5** **Terraces mapped at Greenstone River Fan**

**Figure 6** Sampling


OSL sampling in terrace sediments overlaying forest beds


Foreset beds (immediately left and above of person) capped with younger, flat-laying river gravels

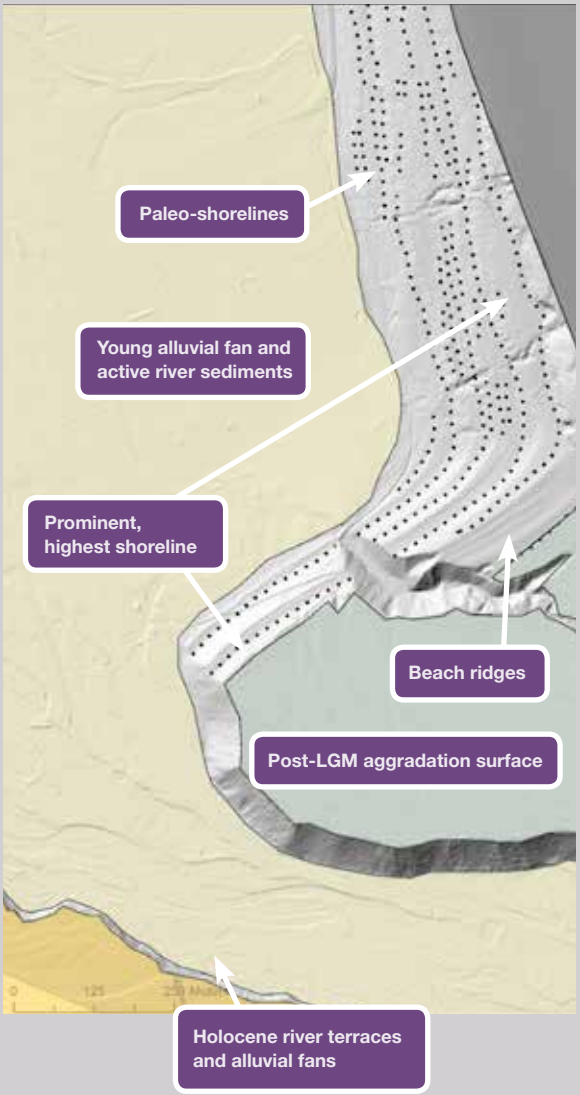

OSL samples from foreset sand bed


Author using Schmidt hammer measurement on boulder (not from this study)


Gravel deposits in terrace exposure


Soil pit with beach gravels at base.

**Figure 7** Shorelines (dotted lines) mapped onto LiDAR data at Bible Terrace



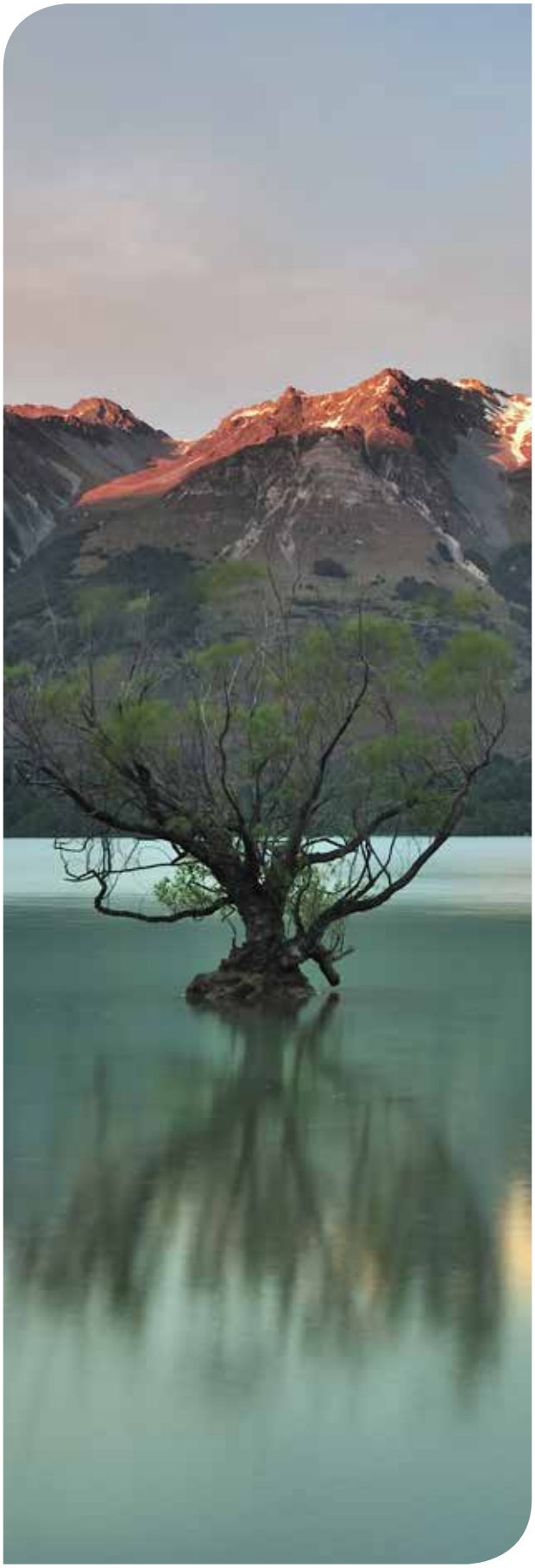

The age of the fan, and by inference the (minimum) age for the formation of Lake Wakatipu, was assessed by dating the time of deposition of the original fan sediments (the foreset beds). This was achieved using a technique that measures the time since last exposure to sunlight of fine sediments: Optically Stimulated Luminescence (OSL) dating. OSL measures the amount of energy stored in the lattice of quartz or feldspar crystals that naturally builds up when the grains are stored away from heat or light energy. When the grains are exposed to sunlight or heat for several seconds, this signal is fully 'bleached' from the grains, and the clock starts again. A sample is taken in the field by very carefully not allowing sunlight to touch the grains: (i) the researcher digs approximately 0.2 to 0.5 m into an outcrop to remove potentially sunlit cover material; (ii) hammers a metal or plastic tube, covered on one end, into the free face; (iii) extracts a tube filled with material; and (iv) covers the tube in foil and opaque tape. In the laboratory, the material is exposed to a controlled amount of light and the energy emitted is a function of the time since burial. Incomplete bleaching during transport and deposition may cause an inherited signal of stored energy, and the age will be skewed towards the penultimate bleaching event (i.e. an older age than the age of deposition).

In New Zealand, two methods of OSL dating, Multiple Aliquot Additive Dose (MAAD) and Single Aliquot Regenerative dose (SAR), are available and applicable to quartz or feldspar grains. New Zealand quartz has been shown to be an unreliable 'clock' for retaining and identifying a luminescence signal using SAR (Preusser et al., 2006). MAAD and SAR applied to feldspar grains are generally accepted as being reliable. Two OSL samples were taken from the foreset beds (Figure 6) and sent to

Victoria University of Wellington, New Zealand. Samples were processed using MAAD on fine-grained feldspar.

The terrace surfaces, which must be younger than the foreset beds, were dated using a Schmidt hammer, following the methodology of Stahl et al. (2013) (Figure 6D), and by taking one OSL sample of sediments at the top of one terrace surface (Figure 6A). The Schmidt hammer (SH) is a tool to measure the hardness of rocks and other surfaces; in this case it was used to measure the hardness of river boulders exposed at the surface of the terraces. The SH is essentially a spring-loaded piston that records the percentage rebound in controlled impact with a rock surface. The rebound value (R-value) of the impact relates to the rock type, surface roughness, and the amount of weathering (chemical alteration from exposure to atmosphere and water), which in turn are related to the length of time the boulder has been sitting at the surface. The rate of weathering of the boulders, and thus boulder age, was calibrated using the OSL data, knowledge of the boulder rock type, regional climate data, and statistical methods described in Stahl et al. (2013). Fifty to one hundred boulders were tested per terrace to develop a large inventory of possible exposure ages and calculate uncertainty.

# 4.0 Results



## 4.1 Shoreline correlations and elevation differences

From our data, we cannot detect any significant difference in elevation of correlative shorelines along the length of the lake. Figures 8-11 show the heights and slopes of shorelines at different sites along the lake as measured by the three different techniques (dGPS, RTK GPS and LiDAR). The best shoreline correlations (lines of equal elevation drawn through the mapped shorelines that typically correspond to areas of low slope) are shown in Figures 8-11 by the highlighted envelopes. These lines are all horizontal, suggesting that there has not been any significant tilting of the lake shorelines.

Of particular note is the very good correlation of the 'most' prominent shoreline at a height of 351.5 m. This shoreline is the most well-developed and best preserved of all shorelines, and is observed along many parts of the lake (e.g. Figures 3, 7 & 12). This is assumed to represent the maximum height of the lake and is considered to have formed over a long period to become so well-defined and be so well-preserved. This shoreline does not appear to be tilted, thus supporting the observation that the younger, lower shorelines are also not tilted. There are other (assumed) shoreline features higher than this prominent shoreline in several locations (Figure 10). None of these features seem to correlate with one another on either geomorphological grounds (i.e. appearance of feature in the field), or by elevation – some features that are very close to one another along the lake (i.e. at Bible Terraces and Blanket Bay) are not at similar elevations, strongly suggesting that they did not form under the same conditions. We therefore interpreted these surfaces not to be wave-cut features formed by lake Wakatipu, but to be produced prior to the formation of the lake. Possible origins include: (i) Incision by rivers draining the fans where some of these surfaces formed; (ii) kame terraces – which are river channels that can develop between a glacier and the valley side; or (iii) formation at the margins of a proto-lake which could have formed in the early part of the recession of the Wakatipu glacier.

**Figure 8** Shoreline correlation between Glenorchy (Bible Terrace) and Greenstone River

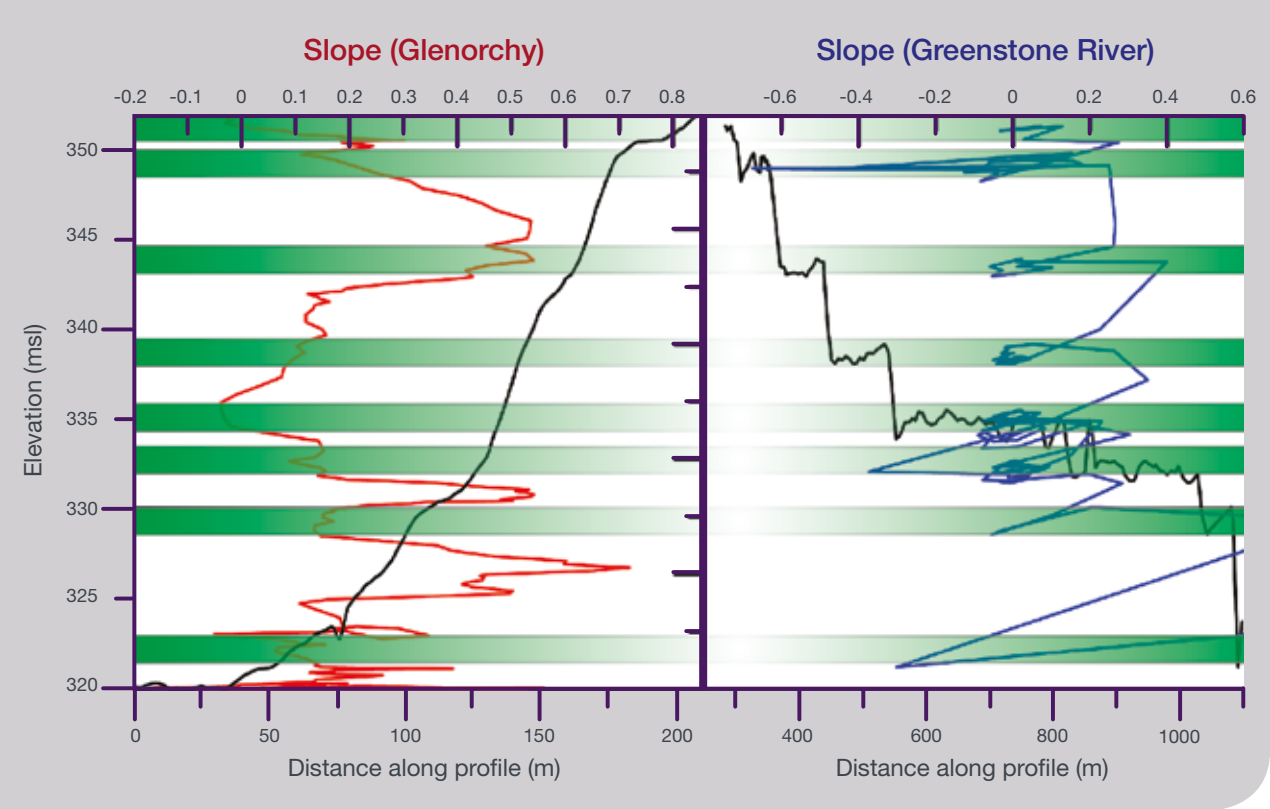



**Figure 9** Shoreline correlation between Glenorchy (Bible Terrace) and Kingston

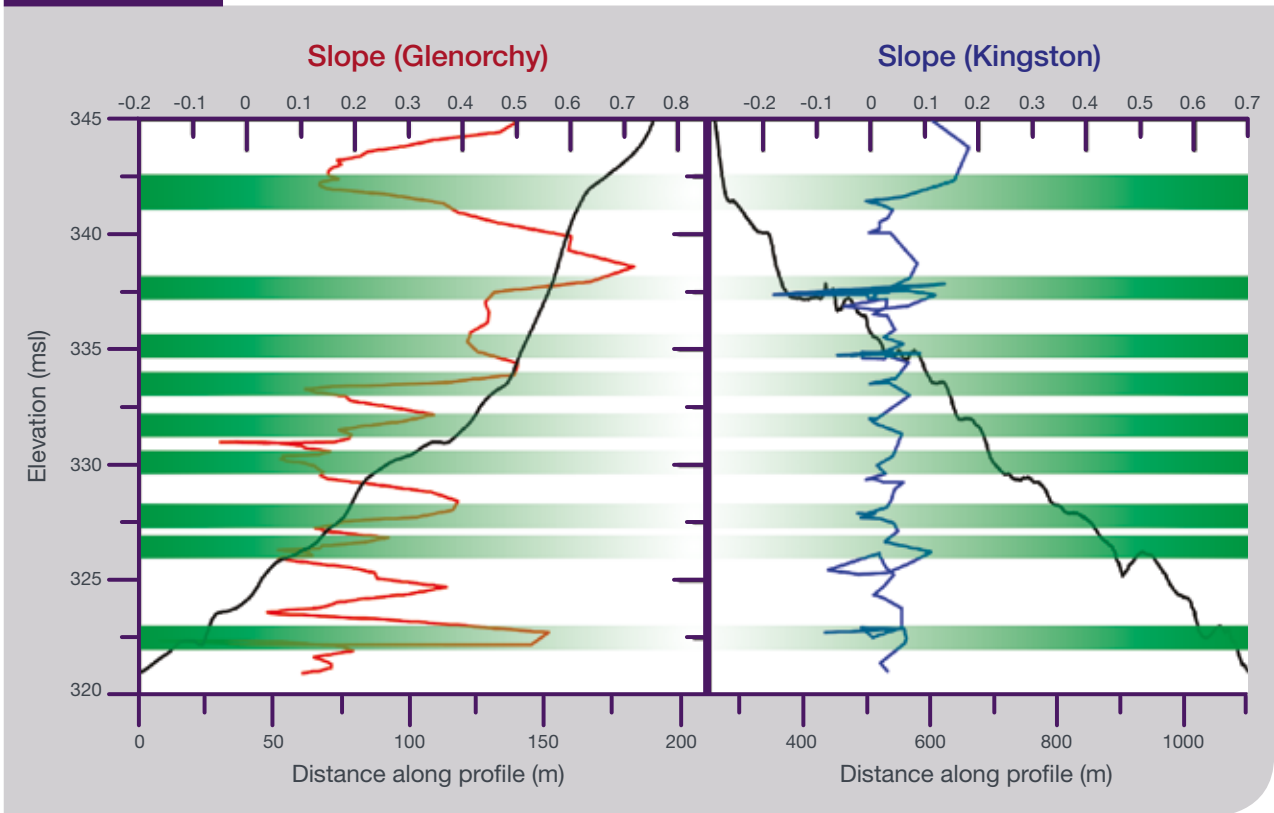


**Figure 10** Shoreline correlation between Glenorchy and Queenstown

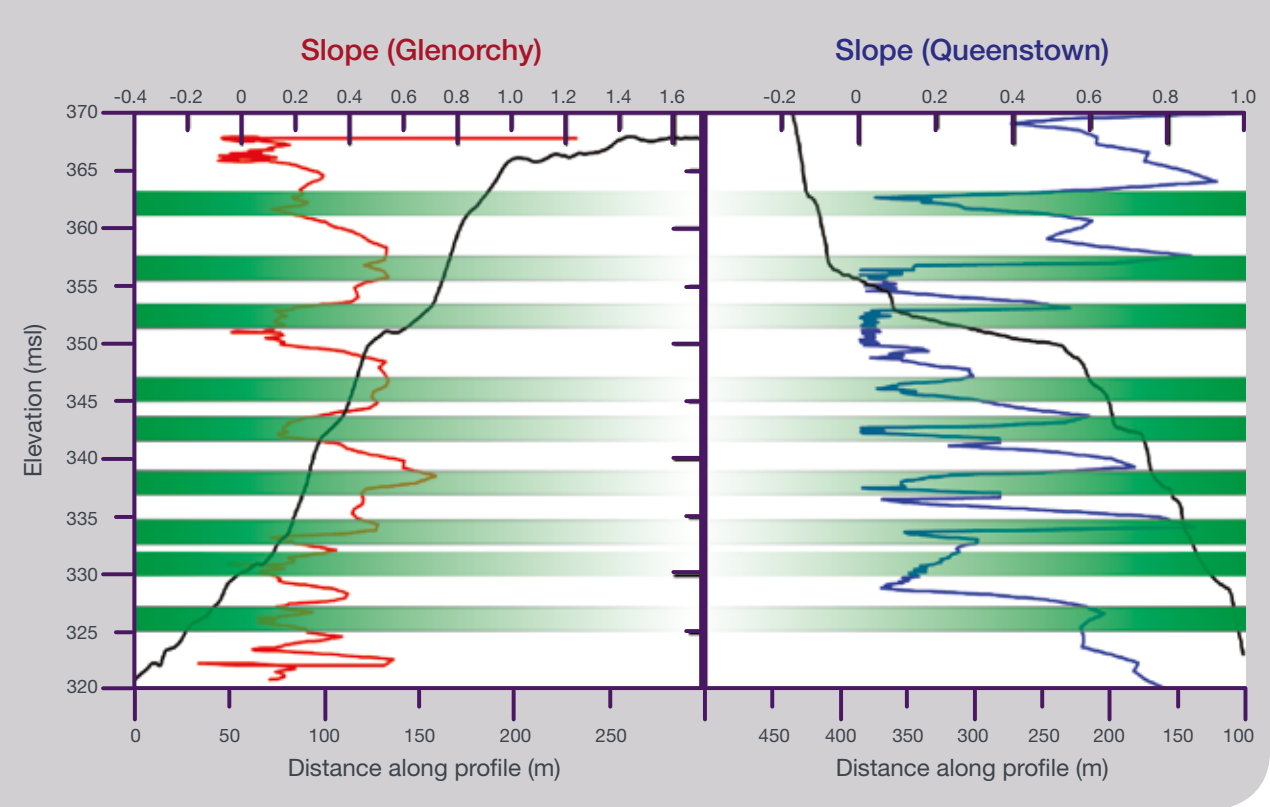



**Figure 11** Shoreline correlation between Jacks Point and Meiklejohns Bay

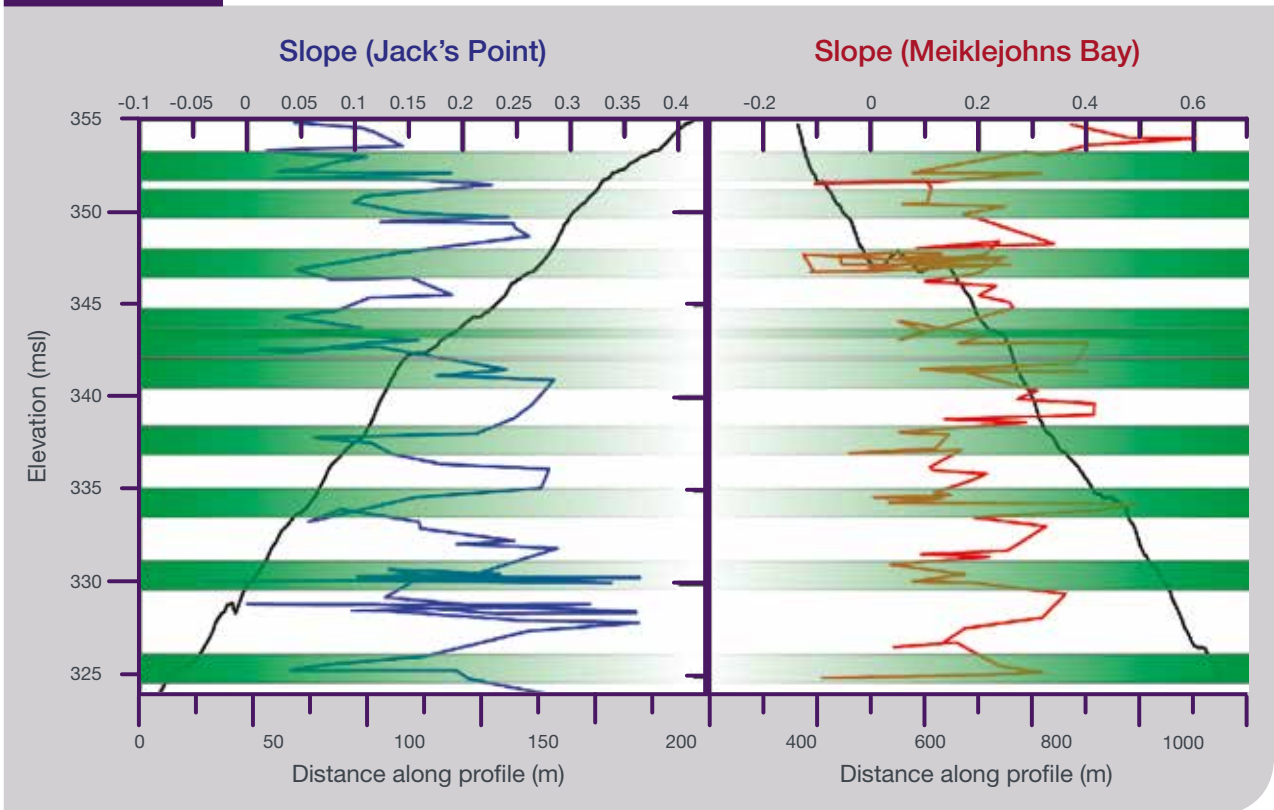
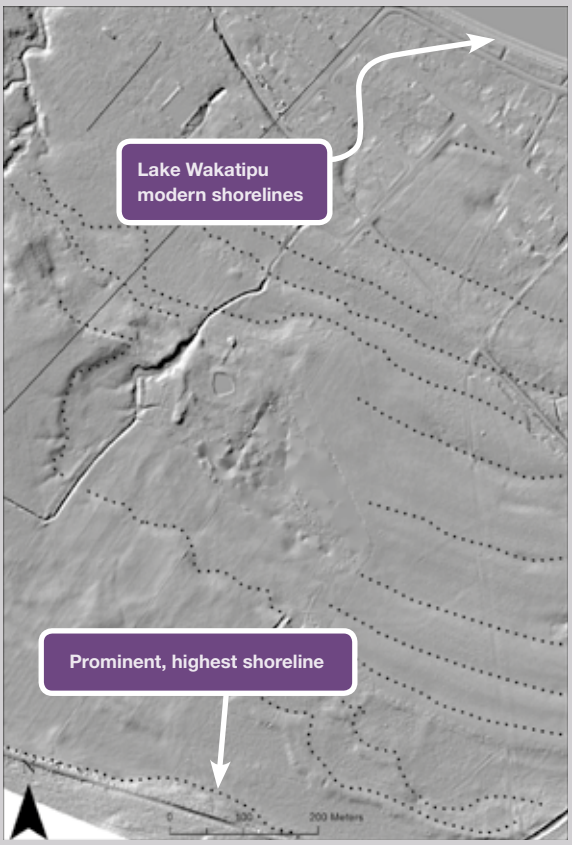


**Figure 12** Shorelines (dotted lines) mapped onto LiDAR data at Kingston




## 4.2 Shoreline ages

The OSL dating of the foreset beds at the Greenstone fan gave an average age of 17,100 ± 2,600 years old. This age fits well with our expected age for the initial formation of the Greenstone fan, which probably began to form soon after retreat of the Wakatipu glacier, commencing around ~18,000 years ago (based on evidence elsewhere in New Zealand, e.g. Barrell, 2011). The OSL dating of the river terrace, however, yielded an age inconsistent with the stratigraphy of ~24,000 years. We rejected this age on the assumption that the sand grains sampled had not been adequately exposed to sunlight when they were transported and deposited by the Greenstone River, and thus have an 'inherited' age representing an earlier sunlight exposure event. Nevertheless, independently derived Schmidt hammer ages provide a reasonable and consistent spread of ages for the river terraces – these ages and their errors for each terrace are shown in Table 2.

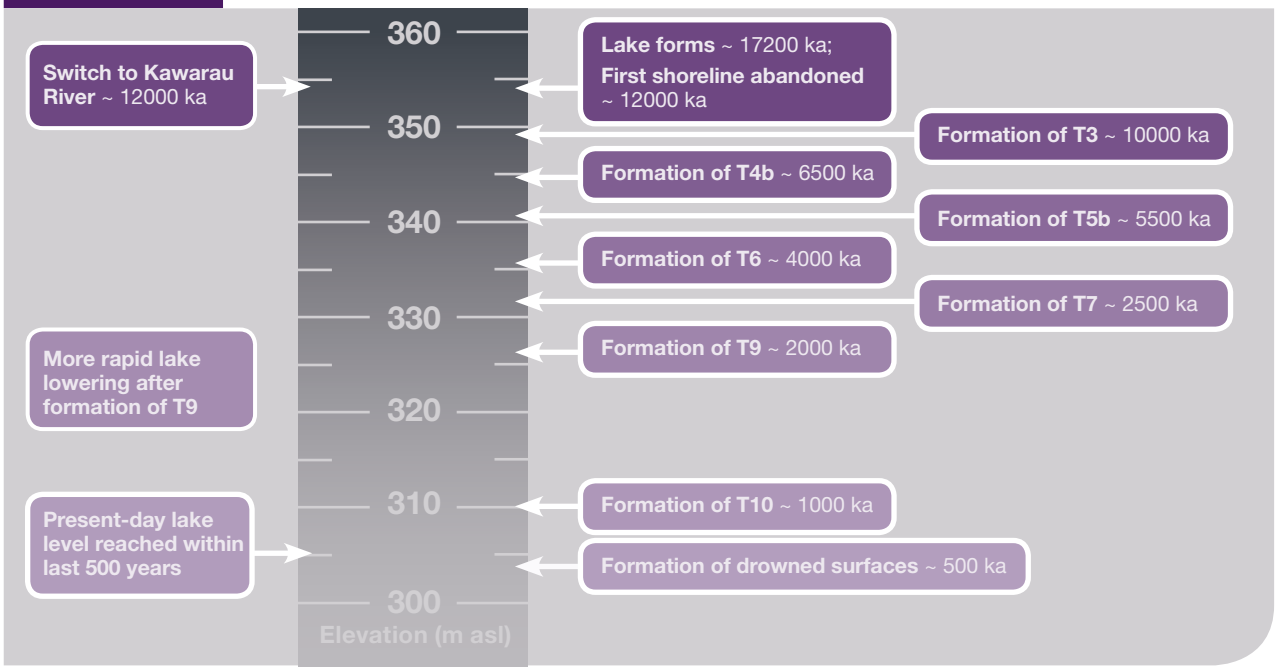
**Table 2** Schmidt hammer median rebound values and inferred exposure ages for correlated shoreline terraces

| Terrace | $SH_R$ [1] | SH Exposure Age (2σ) |
|---|---|---|
| 3 | 34.4 | 10201 ± 3916 |
| 4b | 37.8 | 6247 ± 2378 |
| 5b | 37.6 | 6419 ±2446 |
| 6 | 41.2 | 3945 ± 1444 |
| 7 | 47.2 | 1911 ± 702 |
| 8 | 45.3 | 2384 ± 890 |
| 9 | 46.3 | 2119 ±800 |
| 10 | 55.9 | 784 ± 284 |

1 Median Schmidt Hammer rebound value for 50-100 tests on each terrace

# 5.0 Discussion

**Figure 13** **Shorelines (dotted lines) mapped onto LiDAR data at Kingston**




## 5.1 Lake level reconstruction

We used the shoreline correlations and elevation data, along with our new terrace and fan ages and existing age data to reconstruct the history of formation and subsequent lake level changes at Wakatipu (Figure 13). The glacial basin would have begun filling in phase with retreat of the glacier, which is thought to have commenced about 18,000 years ago (Barrell, 2011). Lake level was initially stable and this is when the uppermost prominent shoreline is thought to have been formed. At about 12,000 years ago, the lake switched drainage to the Kawarau River, and following this, the lake level began to drop. The drop in level was slow at first but became quite rapid about 3000 years ago. Within the last few years, the lake level stopped decreasing and began to increase, resulting in the drowning of at least two shorelines near Queenstown. We do not know if the lowering trend over the past few thousand years will resume, but the lake level appears to have remained relatively stable in the last few hundred years.

## 5.2 Glacial Isostatic Adjustment (GIA) implications

From mapping and correlating shorelines from seven locations along the length of Lake Wakatipu, no progressive, or in fact any demonstrable, offset can be detected. Therefore, the shorelines do not record any evidence of either glacial rebound or faulting. With respect to the former, we propose three possible scenarios to explain this finding:

- **Rapid onset and short-lived glacial rebound**: Glacial rebound could have begun and ended prior to abandonment of the uppermost prominent shoreline at around 12,000 years ago. Based on the extent and definition of the uppermost shoreline around the lake, we believe that no deformation occurred during the ~5000 years it took to form the shoreline. This requires that glacial rebound must have begun and ended within the narrow time interval between deglaciation (~18,000 years ago) and formation of the lake (~17,000 years ago). There would have been no reliable landscape marker features (e.g. a lake shoreline) to record any such deformation, however we think it unlikely that glacial rebound would have occurred and diminished so quickly after the retreat of the Wakatipu glacier. Studies of GIA from other locations around the world indicate that there is a considerable delay time, between maximum ice unloading and maximum glacial rebound signal and that the rebound signal can continue for thousands of years after ice unloading. This delayed and drawn-out response is related to the long response time of the viscous upper mantle and lower crust; we have no reason to believe that the crust and mantle under Otago would behave any differently. Further, based on response time at other locations around the world, we reject any notion that GIA is yet to occur at Lake Wakatipu. We suggest that a scenario of a rapid (or very delayed) response is the least likely of those presented here.

- **Glacial rebound occurred uniformly over the length of the lake:** If glacial rebound occurred uniformly over the length of the lake (i.e. every part of the lake was uplifted to the same extent) then there would be no differential tilting of the shorelines. There are two possible reasons to explain why glacial rebound could have occurred approximately uniformly over the length of the lake. The first reason is that the ice thickness, and therefore unloading, could have been uniform along the length of the lake. According to a glacier thickness reconstructions by Barrell (2011), the thickness of ice decreased down valley towards Kingston. Although, this ice thickness reconstruction is uncertain, particularly in the northern half of the lake, it is consistent with the basic observation that glacier thicknesses is generally thicker towards the source area for the glacier and thinner towards the terminal region where it is melting. Therefore, this reason is unlikely to apply here. The second reason could be that the wavelength of isostatic adjustment in the crust is too long to cause sufficient tilting over the length of Lake Wakatipu. In other words, the crust was too stiff, causing the unloading response to spread very far from the point of unloading, providing a sufficiently low angle of rebound tilt that was undetectable across the ~80 km length of Lake Wakatipu. In other locations around the world where GIA has been detected, tilting angles are sufficiently large to expect a significant amount of differential tilting across distances of tens of kilometres, making this scenario unlikely.
- **Glacial rebound has not occurred at Lake Wakatipu:** This may be because of sufficiently small volumes of ice relative to the thickness and strength of the crust and viscosity of the upper mantle. However, given that ice thicknesses were approximately 1 km in the Wakatipu basin, and that there appears to be nothing anomalous about the crustal and mantle structure in Otago, we also consider this scenario unlikely.

It is possible that relatively small ice volumes and unresponsive crust and mantle, in combination with the previous scenario (ice thickness gradient and GIA wavelength), did produce glacial rebound at Lake Wakatipu but that the magnitude and gradient of tilting were both sufficiently small to produce negligible shoreline tilting. This situation is our preferred explanation of why no tilting has been detected in this study. This hypothesis could be tested using numerical modelling of the expected glacial rebound pattern for Otago, similar to that undertaken for other parts of the world (Dietrich et al., 2010, Ivins and James, 1999, Norton and Hampel, 2010), but is beyond the scope of the research presented here. We also suggest that other lake basins in different tectonic settings in the central South Island for which Wellman (1979) also measured tilting warrant further examination to check whether or not this tilting is demonstrable. If it is, then similar approaches to that taken here could be used to quantify the magnitude and rates of tilting and explore whether there is a gradual decay in uplift rates (i.e. a glacial-rebound signal).

# 6.0 Implications for flood hazards at Lake Wakatipu and elsewhere

High-resolution surveying and age dating are required to detect subtle deformation of the earth and calculate rates of surface processes. In areas that have undergone or are undergoing deglaciation, it is critical that the rates of rebound or tilting are accurately quantified. Our results indicate that townships around Lake Wakatipu that are prone to flooding have not had flood frequency increased or decreased due to lake basin tilting. However, regions in the Northern Hemisphere that have had substantially larger ice coverage than New Zealand are still rebounding. Decisions for future land divisions and construction on lake fronts in these regions should take into account ongoing uplift, subsidence, lake transgressions, and related geomorphic impacts (e.g. sediment aggradation or removal at river deltas, change in lake outlets, etc.). We suggest that a more cross-disciplinary approach than is usually taken – an incorporation of engineering geomorphologic, geologic, and survey data to inform land development plans – should be the norm in formerly glaciated landscapes. The increasing usage and widespread availability of LiDAR to local governments, geologists, and professional surveyors will continue to assist in this process. Field campaigns to ascertain ages of landforms and conduct additional surveying are equally important.

This study provides some basic tools to carry out future research in these areas.

# 7.0 Conclusions

The aim of this research was to identify and quantify any glacial-isostatic uplift signal present in the abandoned shorelines above Lake Wakatipu. GIA is a phenomenon that has affected post-glacial and present day uplift and seismic activity in many parts of the world, but had not previously been investigated in the New Zealand landscape. Lake Wakatipu provided an opportunity to study this phenomenon because of a suite of well-preserved shorelines. The aim of the project was achieved by undertaking an extensive surveying and dating campaign of these shorelines. The shorelines were shown to have formed between the present day and when the lake first formed, soon after retreat of the Wakatipu glacier at the end of the last glaciation. The first shoreline to form is the most prominent and widespread shoreline, and is thought to have formed over approximately 5000 years, between about 17,200 and 12,000 years ago. At 12,000 years ago, the shoreline was abandoned when drainage switched to a new outlet (the Kawarau River). This abandonment was followed by the progressive, but probably episodic, lowering of the lake. The lowering took place slowly at first but accelerated about 3000 years ago. At about 500 years ago the lowering reversed, possibly rapidly, causing drowning of the lowest preserved shorelines. As far as our data indicate, the lake level has been relatively stable since that time. We were able to confidently correlate shoreline fragments across the length of the lake and show that, despite previous suggestions, there has been no significant tilting of the shorelines since they began forming nearly 17,000 years ago. Although this does not rule out that uplift from GIA has been a feature of the landscape, it suggests that GIA uplift gradients were insignificant. Further, we detected no evidence of fault activity or tectonically driven uplift in this area, which is somewhat surprising given the tectonically active setting of Lake Wakatipu. This research provides the first attempt to explore the GIA signal in New Zealand. The somewhat surprising and challenging results invite investigation of these processes in other parts of New Zealand, to draw further inferences about the nature of GIA processes in tectonically active settings.

# 8.0 References


Ballantyne, C. K. 2002. Paraglacial geomorphology. *Quaternary Science Reviews*, 21, 1935–2017.

Barrell, D. J. A. 1994. Surficial geology of the Wakatipu Basin, Central Otago, New Zealand. *Institute of Geological and Nuclear Sciences science report*. Lower Hutt: Institute of Geological and Nuclear Sciences report 94/39.

Barrell, D. J. A. 2011. Quaternary glaciers of New Zealand. *In:* EHLERS, J., GIBBARD, P. L. & HUGHES, P. D. (eds.) *Developments in Quaternary Science*. Amsterdam: The Netherlands.

Cook, S. J. & SWIFT, D. A. 2012. Subglacial basins: Their origin and importance in glacial systems and landscapes. *Earth-Science Reviews*, 115, 332-372.

Dietrich, R., IVINS, E. R., CASASSA, G., LANGE, H., WENDT, J. & FRITSCHE, M. 2010. Rapid crustal uplift in Patagonia due to enhanced ice loss. *Earth and Planetary Science Letters*, 289, 22-29.

Ivins, E. R. & JAMES, T. S. 1999. Simple models for late Holocene and present-day Patagonian glacier fluctuations and predictions of a geodetically detectable isostatic response. *Geophysical Journal International*, 138, 601-624.

Norton, K. P. & HAMPEL, A. 2010. Postglacial rebound promotes glacial re-advances – a case study from the European Alps. *Terra Nova*, 0, 1-6.

Preusser, F., RAMSEYER, K. & SCHLÜCHTER, C. 2006. Characterisation of low OSL intensity quartz from the New Zealand Alps. *Radiation Measurements*, 41, 871-877.

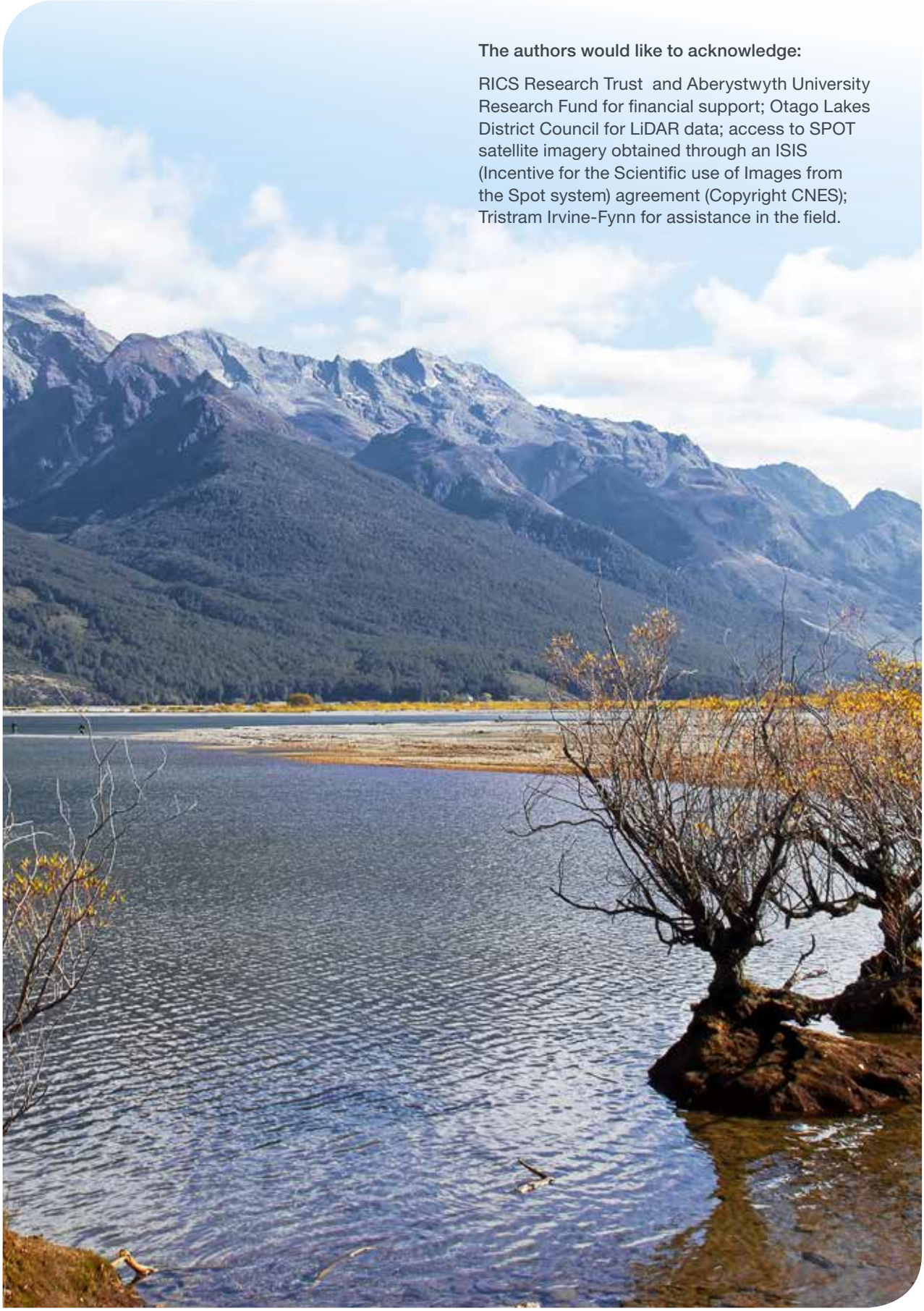
Stahl, T., WINKLER, S., QUIGLEY, M., BEBBINGTON, M., DUFFY, B. & DUKE, D. 2013. Schmidt hammer exposure-age dating (SHD) of late Quaternary fluvial terraces in New Zealand. *Earth Surface Processes and Landforms*, n/a-n/a.

Stewart, I. S., SAUBER, J. & ROSE, J. 2000. Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. *Quaternary Science Reviews*, 19, 1367-1389.

Thomson, R. 1996. Prehistoric changes in the level of Lake Wakatipu. *An unpublished outline study prepared for the Otago Regional Council*, 4pp.

Wellman, H. W. 1979. An uplift map for the South Island of New Zealand, and a model for uplift of the Southern Alps. In: WALCOTT, R. I. & CRESSWELL, M. M. (eds.) *The Origin of the Southern Alps*. Bulletin of the Royal Society of New Zealand.


# 9.0 Acknowledgements



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