Relative Age dating of the Wahianoa Moraines, Mount Ruapehu, New Zealand.

Erin Nolan

Thesis submitted in partial fulfilment of the degree of Master of Science in Quaternary Science, at Massey University, Palmerston North, New Zealand.

January 2008

Abstract

This study attempts to determine a relative age of the Wahianoa moraines, Mt Ruapehu using three relative age dating techniques: Lichenometry, Schmidt hammer and Boulder roundness. There were three study areas used, termed the Wahianoa 'A', 'B' and 'C' moraines. Upon determining a relative age for these moraines, their timing of their formation was placed within New Zealand's glacial timescale. This is the first study of its kind conducted on Mt Ruapehu and has left the door open for more research in this field.

The species of lichens measured on the Wahianoa moraines were *Rhizocarpon* subgenus, which the largest diameters were measured using callipers. A total of 606 lichens were measured in the Wahianoa Valley and were processed using the growth curve and size frequency methods. A lichenometric growth curve was constructed from lichens growing in the Ohakune cemetery. The dates derived from both methods placed the formation of the Wahianoa moraines during the Little Ice Age.

An L-type Schmidt hammer was used on the boulders in the Wahianoa Valley. A total of 280 measurements were taken off the boulders on the Wahianoa moraines. The results of this method, when compared to Winkler's (2005) study in the South Island placed the formation of the Wahianoa moraines pre-Little Ice Age. Although no definitive ages could be derived from this comparison due to differences in lithology between the two studies, it provided an idea as to where the formation of these moraines could belong.

This is the first time that the Boulder roundness method has been used in New Zealand, having only been developed by Kirkbride (2005). This method was used to determine which of the ridges in the Wahianoa Valley were older. It was found that the Wahianoa 'A' moraines were the oldest in the valley followed by Wahianoa 'B' and 'C' respectively.

A climate reconstruction was also conducted for the Wahianoa Valley to see what conditions may have been in existence during the formation of the Wahianoa moraines. The paleo-ELA for the Wahianoa Glacier was estimated using the Accumulation-Area Ratio (AAR), Terminus to Headwall Ratio (THAR), Maximum Elevation of the Lateral

Moraines (MELM) and Extrapolation methods. The current ELA was estimated using the AAR, THAR and Extrapolation methods. The difference between these estimates was used to determine what temperature decrease would have caused the formation of the Wahianoa moraines. The average paleo-ELA was found to be c. 1715m, while the current ELA was found to be 2475m which lead to a 4.5°C decrease. This temperature decrease correlates well with that of the Last Glacial Maximum.

This study found significant differences in relative age of the Wahianoa moraines. There are a number of factors that can affect the growth of lichens such as micro-environmental conditions and the fact that a growth curve was constructed off site. Factors such as petrography can affect the Schmidt hammer results and the Boulder roundness measurements. In addition, precipitation can affect the ELA values which can then cause the wrong placement within a glacial event. Further research lies in the use of the Schmidt hammer on a known age surface such as the Mangatepopo moraines which will aide in a better correlation of relative age. Also, further research using climate reconstructions on Mt Ruapehu and the effect of precipitation will also aide in a better correlation with a glacial event.

Acknowledgements

The completion of this project would not have been possible without the help and encouragement from a large number of people whom I would like to acknowledge:

- I am grateful for Dr Martin Brook's support and feedback both in the office and in the field.
- Special thanks to Victoria University for the loan of their Schmidt hammer.
- Special thanks to Dr Stefan Winkler's advice and help for this project
- Thanks to Dr Andrew Mackintosh for providing ELA values for the Mangatepopo moraine
- Winstone Pulp International for their use of the forestry tracks so I could gain access to the Wahianoa Valley
- Scott and Dara Graham, Alpine Motel Backpackers, for allowing me to arrange accommodation around Mt Ruapehu's temperamental weather
- Huge thanks to Alastair Clement, John Appleby and Clare Robertson for their assistance with the table of contents, list of figures and tables and for checking my references.
- Huge thanks to John Appleby and Clare Robertson for their assistance in the field and helping me complete my fieldwork
- Support and feedback from number of colleagues in the Geography department, in particular Dr Ian Fuller and Olive Harris
- Special thanks to Stephanie Mandolla for making the summer months fun as we scrambled around Mt Ruapehu trying to complete our field work.
- Finally to my family for their support and encouragement, could not have finished it without you. An extra special thanks to my Dad for using his spare time to proof read this thesis.

Table of Contents

Chapter 1: Introduction

Chapter 2: Literature Review

Chapter 3: Methodology

Chapter 4: Results - Lichenometry

Chapter 5: Results - Schmidt Hammer method

Chapter 6: Results - Boulder Roundness

Chapter 7: Results - Climate Reconstruction

Chapter 8: Discussion

Chapter 9: Conclusions

List of Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

List of Tables

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Chapter 1: Introduction

1.1 Introduction

Glaciers cover about 10% of the Earth's surface and contain over 33 million km^3 of the world's fresh water (Benn and Evans, 1998). Glaciers are extremely useful barometers for climate change as they are sensitive to changes in precipitation and temperature (Benn and Evans, 1998). In recent times, with the ever increasing awareness of climate change, research into how the world's glaciers are responding to this change has intensified.

A key to understanding a glacier's current processes is determining what has happened in the past. Relative age dating methods are becoming extremely useful in glacial research when attempting to determine approximate dates of glacial deposits and placing them within a glacial event. Paleo-equilibrium line altitude (ELA) reconstructions are also becoming useful when trying to determine the location of the ELA at various points in time and ultimately what environmental conditions existed at the time of its maximum extent. Understanding the past behaviour of a glacier provides an insight into its current and future behaviour and is extremely important to study in order to reach some understanding of the effects of climate change.

1.2 Mt Ruapehu

The Taupo Volcanic Zone (TVZ) extends 250km southwest from White Island to Mt Ruapehu and contains a series of volcanic centres either andesitic or rhyolitic in composition (Figure 1.1). The Tongariro Volcanic Centre (TgVC) is situated at the southern end of the TVZ and comprises five andesitic peaks (Mt Ruapehu, Mt Ngauruhoe, Mt Tongariro, Mt Pihanga and Kakaramea-Tihia) (Figure 1.1) (Cronin *et al.*, 1996; Donoghue and Neall, 1996). Mt Ruapehu is an active andesitic composite volcano and at 2797m is the highest point in the North Island. Mt Ruapehu has a volume of $110km^3$ and carries a permanent snow cap which was once down to a maximum elevation of 1100-1200m (Williams, 1984; McArthur and Shepherd, 1990; Donoghue, 1991; Cronin *et al.*, 1996; Cronin and Neall, 1997).

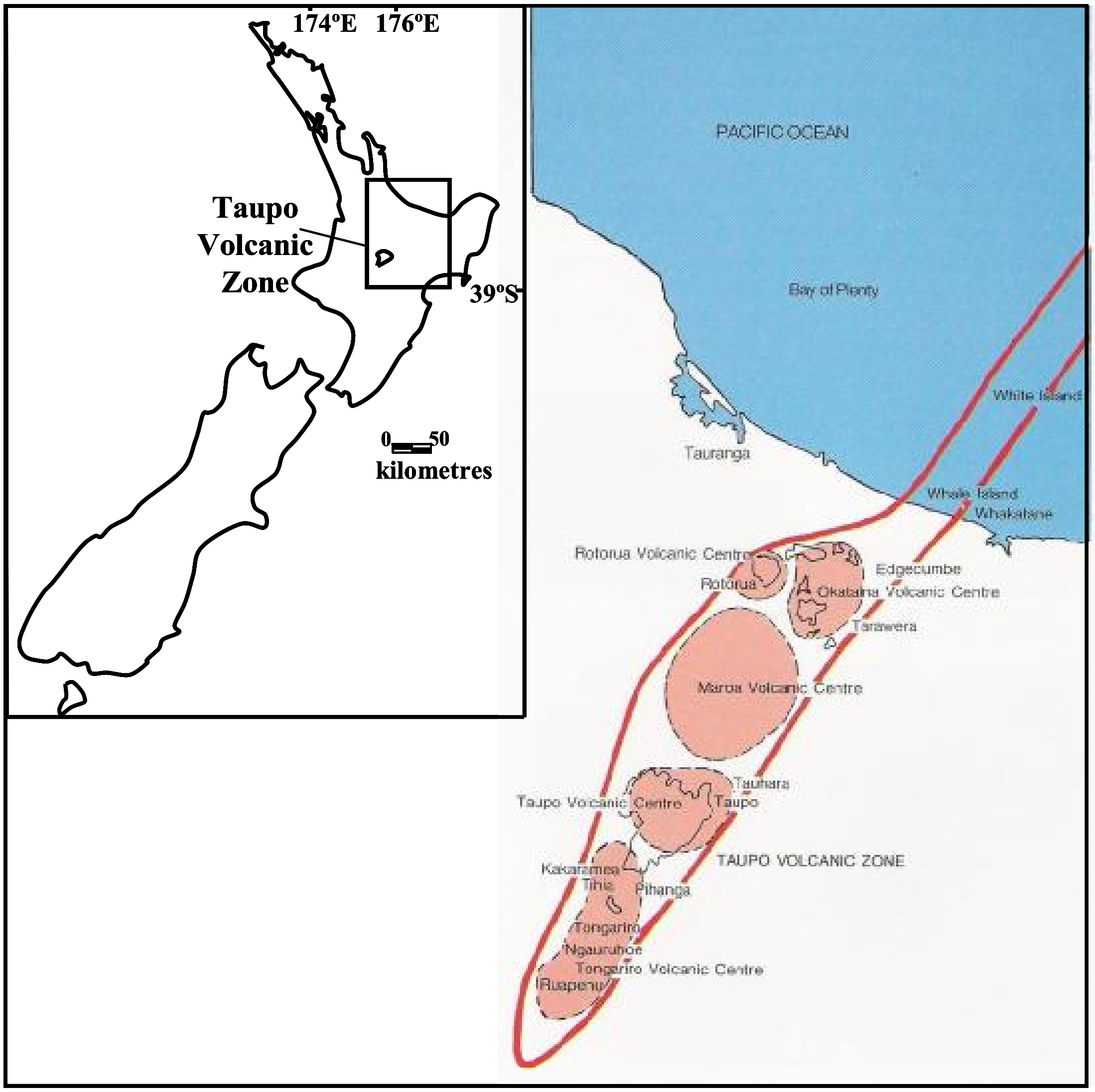

Figure 1.1. Location of the Taupo Volcanic Zone, North Island, New Zealand (Williams, 1984).

1.2.1 Mt Ruapehu's glaciers

There are currently nine named glaciers on Mt Ruapehu, (Donoghue, 1991): Crater Basin, Mangaehuehu (Figure 1.2), Mangatoetoenui, Mangaturuturu (Figure 1.2), Tuwharetoa, Whakapapa, Whakapapanui, Whangaehu, Wahianoa (Figure 1.9). Over the past century these glaciers have been observed to be undergoing significant retreat and decrease in volume.

The earliest photos taken of Mt Ruapehu's glaciers were the Crater Basin and Mangaehuehu Glaciers in the early 1900s (Figures 1.3 and 1.6). These photos when compared to later photos taken of the same glaciers in the 1970s and 2006/2007 provide an indication of just how much these glaciers have retreated (Figures 1.4, 1.5, 1.7, 1.8).

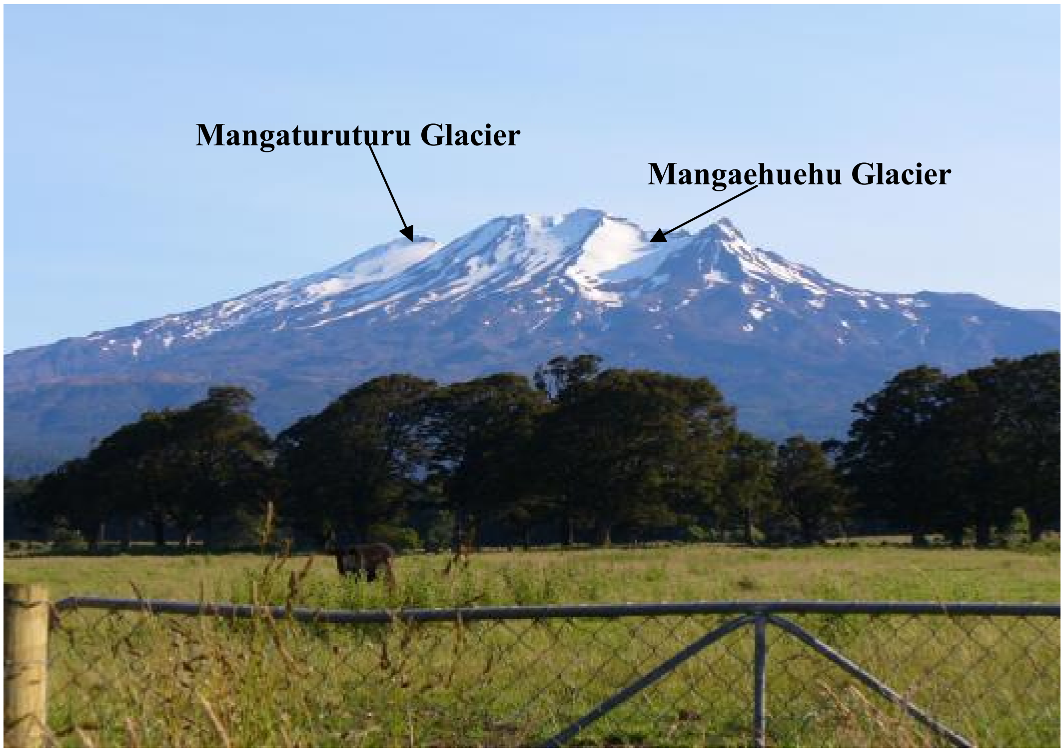

Figure 1.2. Looking northward onto Mangaehuehu and Mangaturuturu glaciers, Mt Ruapehu.

Figures 1.3, 1.4 and 1.5 illustrate the retreat of the Crater Basin Glacier over a period of 98 years. This glacier is viewed by Williams (1984) to be one of Mt Ruapehu's most active glaciers and in 1984 was 1200m in length (Williams, 1984). In Figure 1.3, there is an ice cliff which according to Williams (1984) is more than 60m high and which in Figure 1.4 (taken in 1973) has completely disappeared. Figure 1.5 is a photo taken of the Crater Basin Glacier in February 2007 and it can be seen that the glacier has retreated substantially since 1973 (Figure 1.4).

In 1909, the Mangaehuehu Glacier (Figure 1.6) extended 2km down the Mangaehuehu Valley, before it terminated in a 15m ice face (Williams, 1984) and the surface was significantly crevassed. In Figure 1.7, taken in the 1970s, it can be seen that the Mangaehuehu Glacier has undergone significant retreat and a riegel has begun to appear. In addition, the ice surface of the Mangaehuehu Glacier is smooth and lacking in crevasses which is indicative of surface lowering and mass loss. As can be seen in Figure 1.8 the Mangaehuehu Glacier has begun to retreat past this riegel.

Figure 1.3. Looking south onto Crater Basin Glacier, taken in April 1909 (Williams, 1984).

Figure 1.4. Looking south onto Crater Basin Glacier taken in January, 1973 (Williams, 1984).

Figure 1.5. Looking south onto Crater Basin Glacier taken in February, 2007.

Figure 1.6. Former extent of Mangaehuehu Glacier taken early 1900s, crevassing is highly evident on the surface. Girdlestone Peak can be seen to the right of the glacier (Williams, 1984).

Figure 1.7. Former extent of Mangaehuehu Glacier taken during the 1970s, note the smoother surface of the glacier, indicative of surface lowering, mass loss and few, if any crevasses (Williams, 1984).

Figure 1.8. Current extent of the Mangaehuehu Glacier taken in March 2006. Note that glacier has retreated past the riegel (rock ledge) and a new ridge is beginning to emerge in the top left corner.

There is no photographic evidence for the previous extent of the Wahianoa Glacier taken in the early 1900s like Figures 1.3 and 1.6. However, the Wahianoa moraines (Figure 1.10) provide the evidence required to piece together the previous extent of the Wahianoa Glacier.

1.2.2 Wahianoa Glacier

The Wahianoa Glacier is located on the southeastern slopes of Mt Ruapehu and is situated to the right of Girdlestone Peak (Figure 1.9). The current terminus of the Wahianoa Glacier is at approximately 2200m and the glacier is about 500m in length. However, the Wahianoa Glacier used to be approximately 1.5km extending down to approximately 1200m.

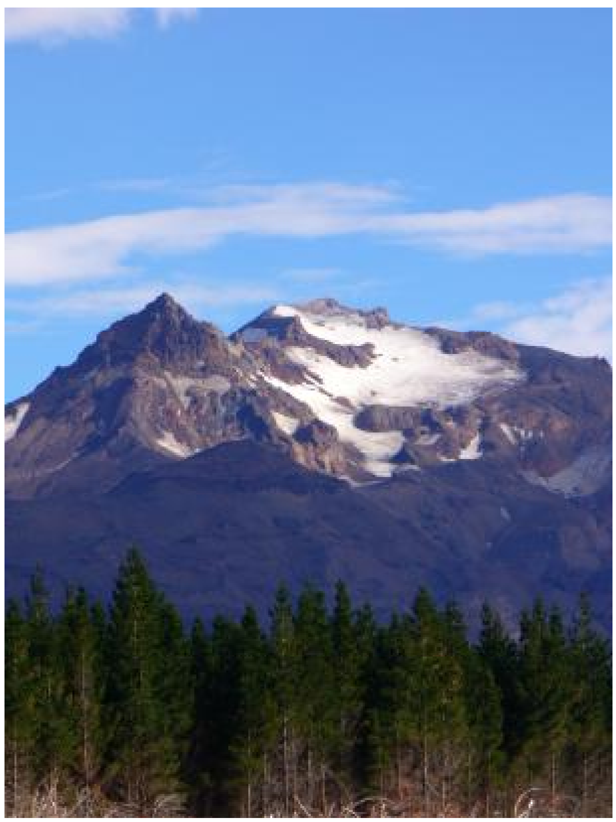

Figure 1.9. Looking westward onto Mt Ruapehu with Wahianoa Glacier situated to the right of Girdlestone peak.

1.2.2.1 Study Site

The Wahianoa moraines are an impressive site on the southeastern slopes and are easily detectable by air. The moraines are approximately 2km in length and at their maximum are between 140m and 150m in height. In Figure 1.10, there are significant ridges on the true left side of the Wahianoa Valley which make it difficult to discern what is actually morainic material or not. The study area for this thesis was located between these ridges on the true left and the base of the moraines (Figure 1.10) as well as two other sets of ridges in the valley.

Figure 1.10. Wahianoa Valley situated on the southeastern slopes of Mt Ruapehu, Wahianoa Glacier is at the head of the valley, and is little more than a small niche glacier today.

1.3 Relative Age Dating

Relative age dating methods are frequently used in glacial environments where there tends to be a lack of datable materials. Lichenometry is one of the most commonly used relative age dating methods in glacial research. This method is generally used to date previous extents of a glacier and on some occasions is used to refine results from other dating methods such as radiocarbon dating and weathering rinds.

Another common relative age dating method is Schmidt hammer rebound. This method is generally used to distinguish between different advance events of a glacier rather than between advances in the same event. The Schmidt hammer method is also sometimes used in conjunction with lichenometry to help identify separate advance events. The third relative age dating method used for this thesis is the Boulder roundness which has only been used previously in Scotland by Kirkbride (2005). This method uses the radius of curvature of a boulder to try and determine a relative age for the surfaces in question.

These three relative age dating methods will be used in a 'multi-proxy' approach to endeavour to determine the relative age of the Wahianoa moraines thereby determining which glacial event formed them.

1.4 Reconstructions of paleo-Equilibrium Line Altitudes (ELA)

The equilibrium line altitude of a glacier is one of the most important components in glacial research as it indicates where the annual accumulation equals the annual ablation (melting) thereby marking the boundary between the accumulation zone and ablation zone (Benn and Evans, 1998) (Figure 1.11).

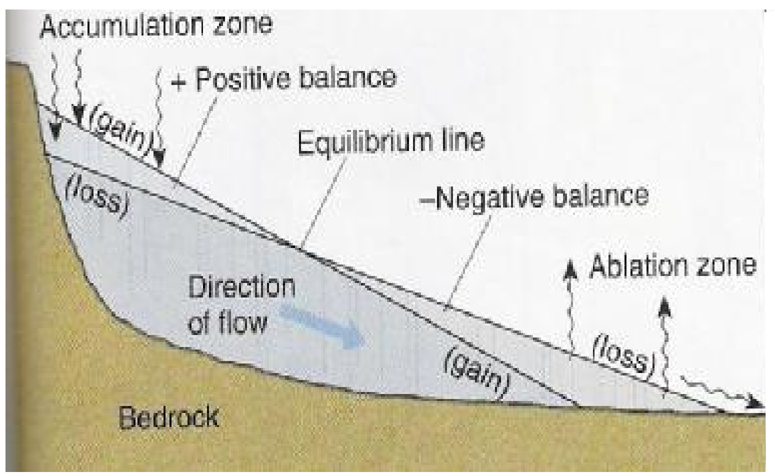

Figure 1.11. Annual mass balance of a glacier system, showing how the relation between accumulation and ablation controls the location of the equilibrium line altitude (ELA) (Christopherson, 2000).

The ELA is extremely sensitive to any change in both temperature and precipitation as these factors affect the mass balance of a glacier which in turn affects the ELA. It is because of this that researchers such as Benn and Evans (1998) and Nesje and Dahl (2000) regard the ELA as being an extremely good indicator of a glaciers response to climate change. There are various methods that can be used to reconstruct the paleo-ELA of a glacier, the most commonly used being the Accumulation-Area Ratio (AAR), Maximum Elevation of Lateral Moraines (MELM), Terminus to Headwall Altitude Ratio (THAR) and Extrapolation. Once the paleo-ELA is reconstructed it can be possible to reconstruct the paleoclimate that would have existed at that time.

For this thesis the paleo-ELA for the Wahianoa Glacier will be reconstructed using the AAR, MELM, THAR and Extrapolation methods. In addition, the difference between the current ELA and paleo-ELA will be determined thereby allowing for the paleoclimate to be reconstructed.

1.5 Thesis Structure

This thesis is divided into nine chapters. The next chapter (Chapter two) provides background information on Mt Ruapehu and the relative age dating methods used in this thesis. Chapter three outlines the methodology used to obtain a relative age of the Wahianoa moraines. There are four results chapters in total: Chapters four to seven are results chapters for the Lichenometric, Schmidt hammer, Boulder roundness and paleo-ELA methods respectively. Chapter eight is a discussion of these results and provides some ideas for further research. Finally, Chapter nine is a summary of the key findings of this thesis.

Chapter 2: Literature Review

2.1 New Zealand Climate during the Quaternary

The Quaternary was originally considered to have commenced 1.8-2.0 million years ago (Figure 2.1).

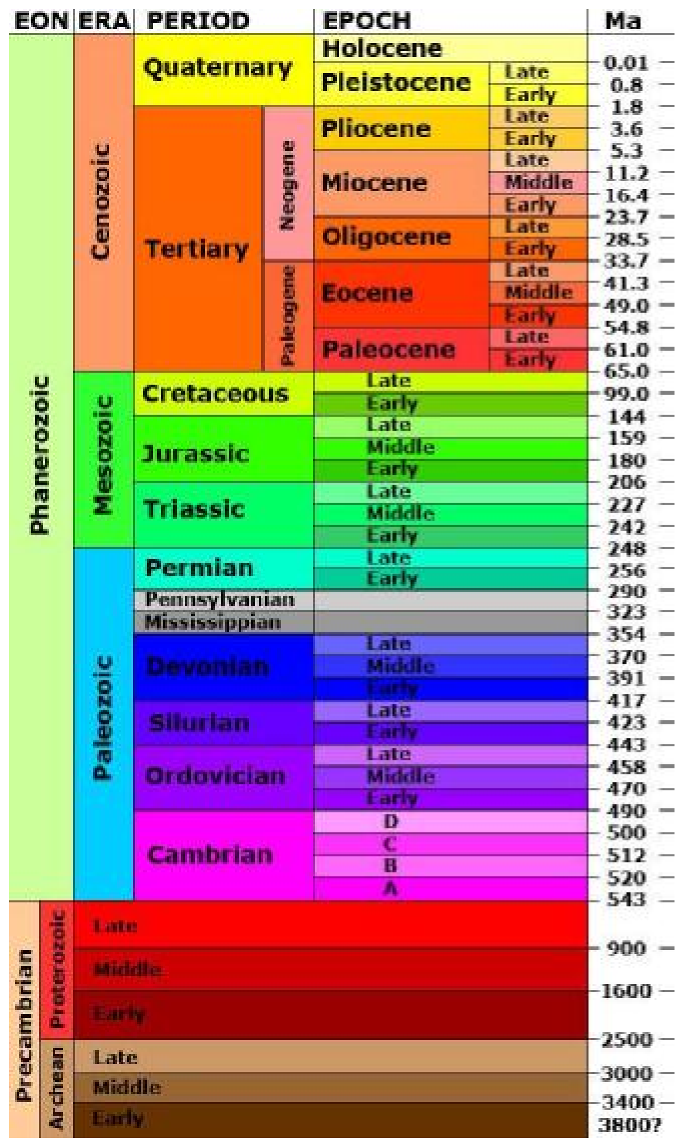

Figure 2.1. Geological Timescale (United States Geological Survey).

However, in recent years there has been fierce debate over the use of the term Quaternary and when the period was supposed to have commenced. Some researchers such as Gradstein *et al.* (2004) believe that the Neogene subperiod should be extended to a full period and encompass the Holocene, Pleistocene and Pliocene (Table 2.1) instead of the Quaternary.

Erathem/Era	System/Period	Series/Epoch	Italian Stages	Age (base)
Cenozoic	Neogene	Holocene		11.6ka
		Pleistocene	Calabrian	1.8 Ma
		Pliocene	Gelasian	2.6 Ma
			Piacenzian	3.6 Ma

Table 2.1. Preferred classification of the International Commission of Stratigraphy (2004). Source: Bowen and Gibbard, (2007).

Other researchers such as Pillans and Naish (2004) and Bowen and Gibbard (2007) believe that the term Quaternary should be kept in the geological time scale and be extended to a commencement date of 2.6 million years (Table 2.2). These researchers suggest that this extension will allow for the encompassment of the Gelasian Stage of the Pliocene which is considered to be an important period in terms of Northern Hemisphere glaciation.

Erathem/Era	System/Period	Series/Epoch	Age (base)
Cenozoic	Quaternary	Holocene	11.6 ka
		Pleistocene	~130 ka (Late)
			0.78 Ma (Middle)
			2.6 Ma (Early)

Table 2.2. Preferred classification: the base of the Pleistocene (Early Pleistocene subseries) coincides with the Gauss-Matuyama polarity reversal; that of the Middle Pleistocene coincides with the Matuyama- Brunhes polarity reversal; and the base of the Late Pleistocene coincides with that of the Eemian stage. Source: Bowen and Gibbard, (2007).

The Quaternary in New Zealand, as with the rest of the world, saw a drastic change in climate which allowed for the formation of glaciers in both the North and South Islands. The next section will review the research conducted on the Pleistocene in New Zealand.

2.1.1 The Pleistocene excluding the Otira Glaciation (2.6my-70ka BP)

The Pleistocene epoch saw a number of glaciations and interglacial periods in New Zealand. The South Island, in particular the Southern Alps, has been viewed as the major focal point for investigations of New Zealand's Quaternary as the Southern Alps were one of the major Southern Hemisphere centres of Quaternary glaciations (Newnham *et al.*, 1999). According to Soons (1992) and Suggate and Waight (1999) the Westland region (Figure 2.2) contains the best glacial/interglacial sequence as it was more extensively glaciated than any other area in New Zealand. Suggate (1990), Almond (1996) and Suggate and Waight (1999) have determined a sequence of at least five major glaciations and five major interglacial interval periods that are correlated with Marine Oxygen Isotope (MOI) records back to Stage 12 (Table 2.3). This sequence forms the basis of New Zealand climate stages (Newnham *et al.*, 1999).

Exploring the Pleistocene in New Zealand would not be complete without looking at the Wanganui Basin (Figure 2.2) as Pillans (1994) suggests that the Wanganui Basin contains one of the most complete Quaternary stratigraphic records in the world. In the Wanganui Basin there is a series of uplifted marine terraces, which have been correlated using rhyolitic tephras and loess layers in their coverbed stratigraphies with MOI Stages back to Stage 17 (Table 2.3). This, in turn, allows them to be correlated with the climatic stages (i.e.: interglacials and interstadials) in which they formed (Pillans, 1994).

Another series of landforms to consider when examining the Pleistocene are the river terraces in the Rangitikei Valley (Figure 2.2). Just like the marine terraces, it is the stratigraphy of loess layers within the coverbed stratigraphies, which have allowed them to be correlated with MOI stages back to Stage 10 (Table 2.3). In addition they have been able to be correlated with the stadial and glacial periods in which they formed (Pillans, 1994).

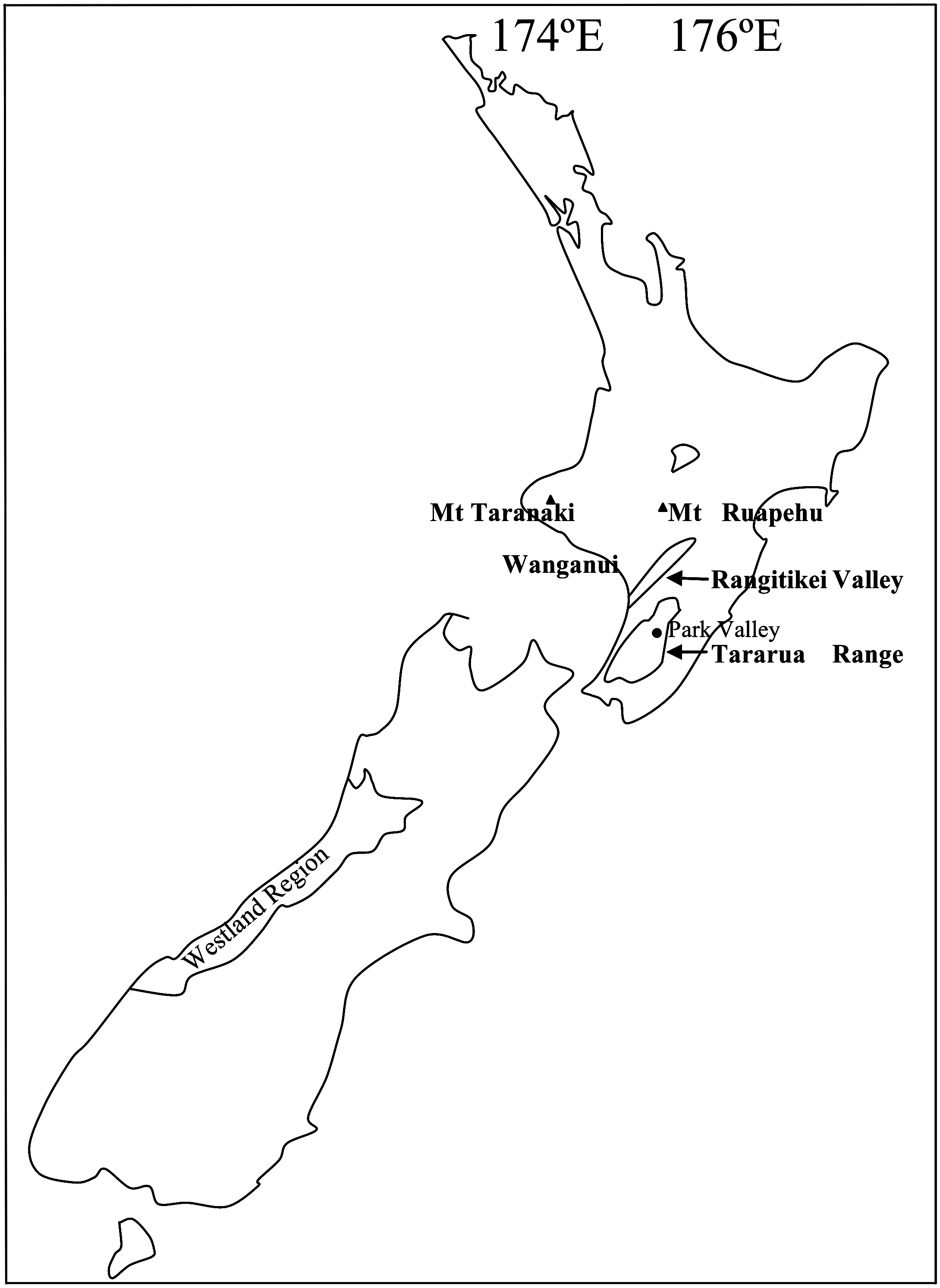

Figure 2.2. Significant locations of Quaternary glacial and interglacial evidence.

Table 2.3 Correlation of New Zealand Pleistocene glacial advances and interglacials (Pillans, 1994; Palmer and Pillans, 1996; Newnham *et al.,* 1999; Suggate and Waight, 1999 and Salinger, 2001).

Oxygen Isotope Stage	Glacial Stage	Westland Glacial Advances	Rangitikei River Terraces	Age (ka)	Interglacial Stage	South Taranaki Wanganui Marine Terraces	Age (ka)
1					Aranui		
2	Otira		Ohakea I Ohakea II	10 12			
		Kumara-3		13			
		Kumara-2_2	Ohakea III				
				22			
3			Rata	30-50		Rakaupiko	60
4		Kumara-2_1	Porewa	70-80			
5a					Oturi	Hauriri	80
5b			Cliff	90-100			
5c						Inaha	100
5d			Greatford	110-120			
5e						Rapanui	120
6	Waimea	Kumara-1	Marton	140-170			
7					Terangi	Ngarino	210
8	Waimaunga	Hohonu	Burnand	240-280			
9					Waiwhero	Brunswick Braemore	310 340
10	Nemona	Cockeye	Aldworth	340-350			
11					(unnamed)	Ararata Rangatatau	400 450
12	Kawhaka	Mudgie Ridge					
13						Ball	520
14							
15						Piri	600
16							
17						Marorau	680

The last major interglacial was the Oturi interglacial (120,000-80,000 yrs ago) which spanned MOI stage 5 (Figure 2.3). There is evidence for two stadials (5b and 5d) and for three interstadials (5a, 5c and 5e) within this climatic period (Table 2.3).

The earliest oxygen isotope stage within the Oturi Interglacial (5e) is regarded by Marra (2003) as being the thermal maximum of this climatic period (Figure 2.3). Temperatures during this period were in the range of 1.6-3.2ºC warmer than present day levels based on beetle fauna that existed during this climatic event (Marra, 2003). In addition, Marra (2003) suggests that present day temperatures were attained later in Oxygen Isotope Stage 5. Salinger (2001) further suggests that temperatures at the end of the Oturi Interglacial were approximately 1-2°C below present day levels based on vegetational evidence (Salinger, 2001).

A common phenomenon found in glaciated areas is the destruction of older advances by later advances and retreats, thereby making the most recent advance and retreat of a glacier the most examined. This has been observed in New Zealand by Newnham *et al* (1999) who suggest that out of all the glaciations, the best preserved evidence belongs to that of the Last Glacial Maximum.

2.1.2 Otira Glaciation excluding the Last Glacial Maximum (70ka-25ka)

The Otira Glaciation is the last major glaciation of New Zealand's Quaternary Period. This glaciation spanned three oxygen isotope stages (2-4) (Table 2.3). Just like the Oturi Interglacial, the Otira Glaciation also had stadials and interstadials (Figure 2.3).

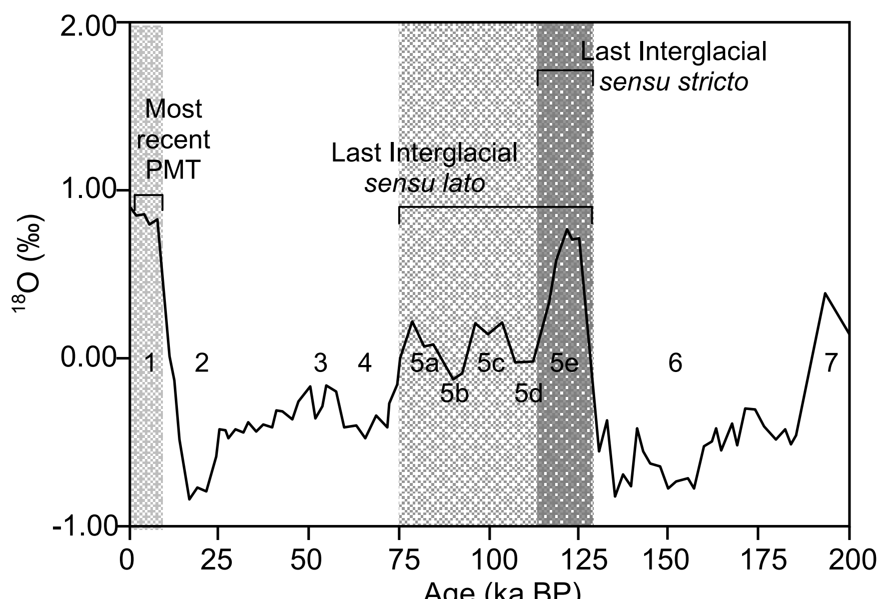

Figure 2.3 Marine oxygen isotope record over the last 200,000 years (Sloss, 2005).

2.1.2.1 Early Otiran Glacial Advances (MIS 4)

It can be seen in Figure 2.3 that cooling began prior to the commencement of the Otira Glaciation (MIS 4). The first advances of the Otira Glaciation are represented by the Tui Creek formations in the Rakaia Valley and the Kumara 2_1 advance in Westland. Other evidence for commencement of the Otira glaciation is shown in the Porewa river terrace, which is preserved in the Rangitikei River Valley (Table 2.3) and the Aurora-6 Fiordland glacial advance (Williams, 1996b).

Not only is there speleothem and geomorphic evidence for the beginning of the Otira Glaciation but also evidence of changes in vegetation. Evidence of cooling at approximately 70,000 years is seen these vegetation changes such as those observed by McGlone and Topping (1983) whereby Central North Island vegetational evidence shows a change from coniferous hardwood forest to sparse grassland/shrubland (McGlone and Salinger, 1990).

2.1.2.2 Mid Otiran Glacial Advances (MIS 3)

As can be seen in Figure 2.3 there appears to be some fluctuations in ^{18}O, therefore indicating changes in temperature. The MIS 3 stage was originally thought to be a full interglacial period which is why it has been given an odd number. However, it was found to be a glacial period. The Moerangi interstadial has been suggested by Shulmeister *et al*. (2001) to have occurred near the start of MIS 3 and prior to 50ka when temperatures were approximately 3ºC cooler than present day levels. Other evidence of this interstadial is found in the form of speleothems in Fiordland by Williams (1996b) and an increase of *Cyathea* (tree ferns) and *Coprosma* spp pollens (Shulmeister *et al*. 2001).

2.1.2.3 MIS 3/2 transition

The MIS 3/2 transition is defined by Woodward and Shulmeister (2007) as having occurred between c. 26,600 and 24,500 cal yr BP. Woodward and Shulmeister (2007) used a chironomid based reconstruction together with previous studies conducted by Soons and Burrows (1978) and Marra *et al*. (2006) on macrophyte remains and fossil beetle assemblages to estimate a temperature decrease during this time. The temperatures determined from these analyses indicated that there may have been a mild cooling during (<4ºC) thereby indicating an interstadial (Woodward and Shulmeister, 2007).

2.1.3 Last Glacial Maximum (LGM) (MIS 2)

It was found by Barrows and Juggins (2005) that sea-surface temperatures around New Zealand during the Last Glacial Maximum were 3-5ºC below present day levels. Vegetation during the LGM was mainly grass-shrubland (Figure 2.4) with the exception of regions north of Auckland which still had some patches of forest (McGlone *et al*., 1993).

The Last Glacial Maximum is thought by Salinger (2001) to have occurred between 26,000and 18,000 yrs BP based on vegetative evidence. While McGlone *et al*, (1993) suggest that the Last Glacial Maximum occurred c. 20,000 to 18,000 yrs BP with the Kumara 2_2 advance (Table 2.3). Furthermore, Hellstrom *et al*. (1998) found evidence for extreme glacial conditions centred on c. 19,000 cal yr BP based on speleothem data. Even though the dates vary for the Last Glacial Maximum due to differences in proxy measures, there is no denying that a significant cooling occurred and it not only affected the South Island but the North Island as well.

2.1.3.1 The South Island

During the LGM, an almost continuous glacial complex stretched nearly 700km along the Southern Alps (Figure 2.5). The West Coast glaciers during the LGM were extended beyond the present coastline (Figure 2.5) with Franz Josef Glacier extending approximately 14km beyond its present position (Mercer, 1988; McGlone *et al*. 1993; Purdie, 2005). At the same time equilibrium line altitudes (ELAs) were as low as c. 600-800m below present levels, which currently sit c.1600m (Porter, 1975; Hellstrom *et al.*, 1998; Newnham *et al.*, 1999 and Lamont *et al*, 1999).

There have been various proxy measures used to piece together the climate during the LGM. Hellstrom *et al*. (1998) suggested a moderate cooling for the Last Glacial Maximum based on speleothem data in northwest Nelson. While Marra *et al*. (2006) proposed temperatures of the Last Glacial Maximum to be possibly 2 to 3ºC lower than present day levels based on fossil beetle assemblages from Lyndon Stream in the South Island. Paleo-

ELA depressions have also been used as an indicator of temperature decrease by Porter 1975) and Bacon *et al*. (2001) who suggest a cooling of c. 4.5-5ºC based on evidence from the Southern Alps and Inland Kaikoura Range. Soons (1979) estimated a temperature decrease of approximately 4.5ºC based on pollen evidence in the central South Island.

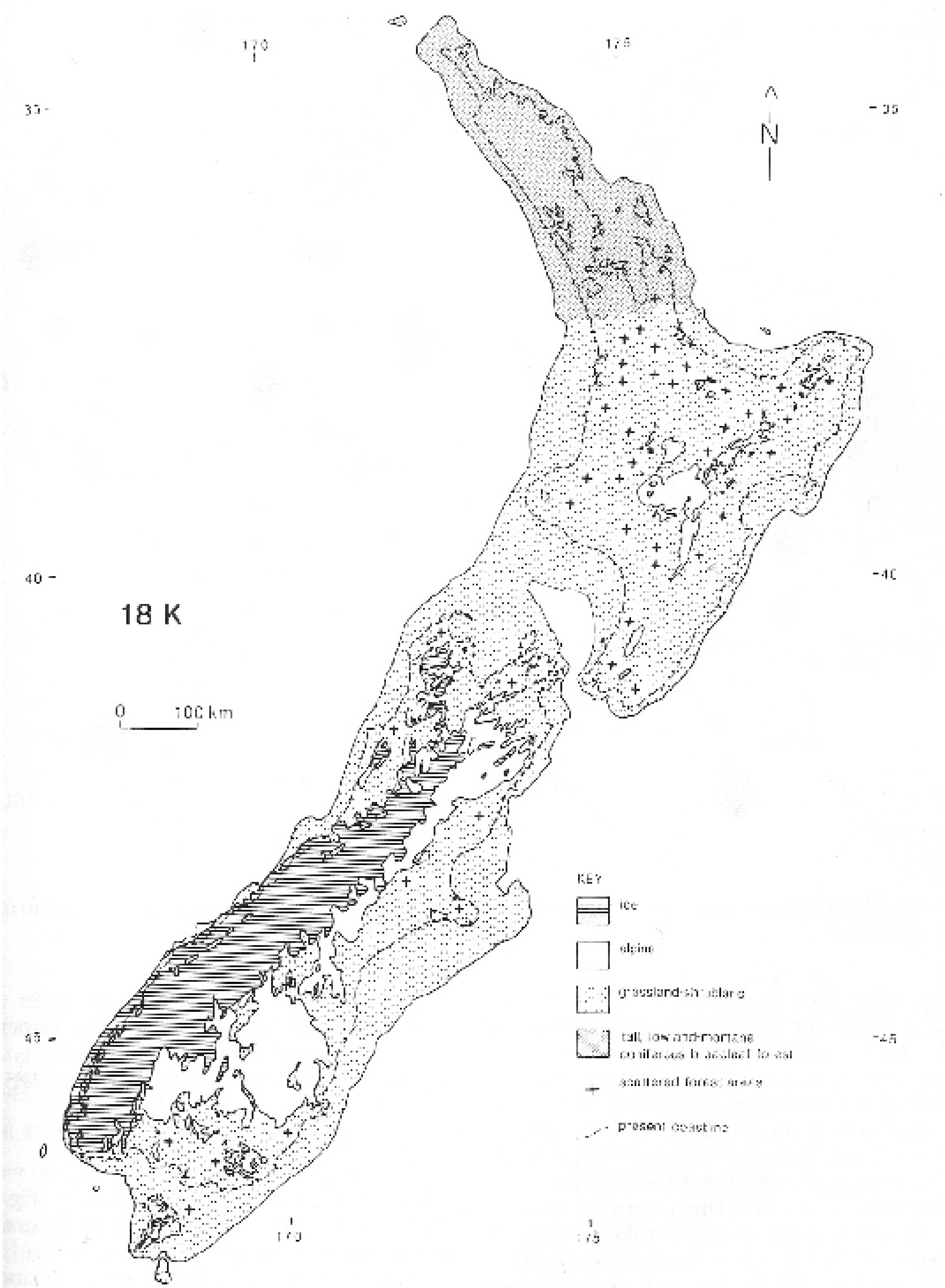

Figure 2.4. New Zealand vegetation at LGM. (McGlone *et al.*, 1993)

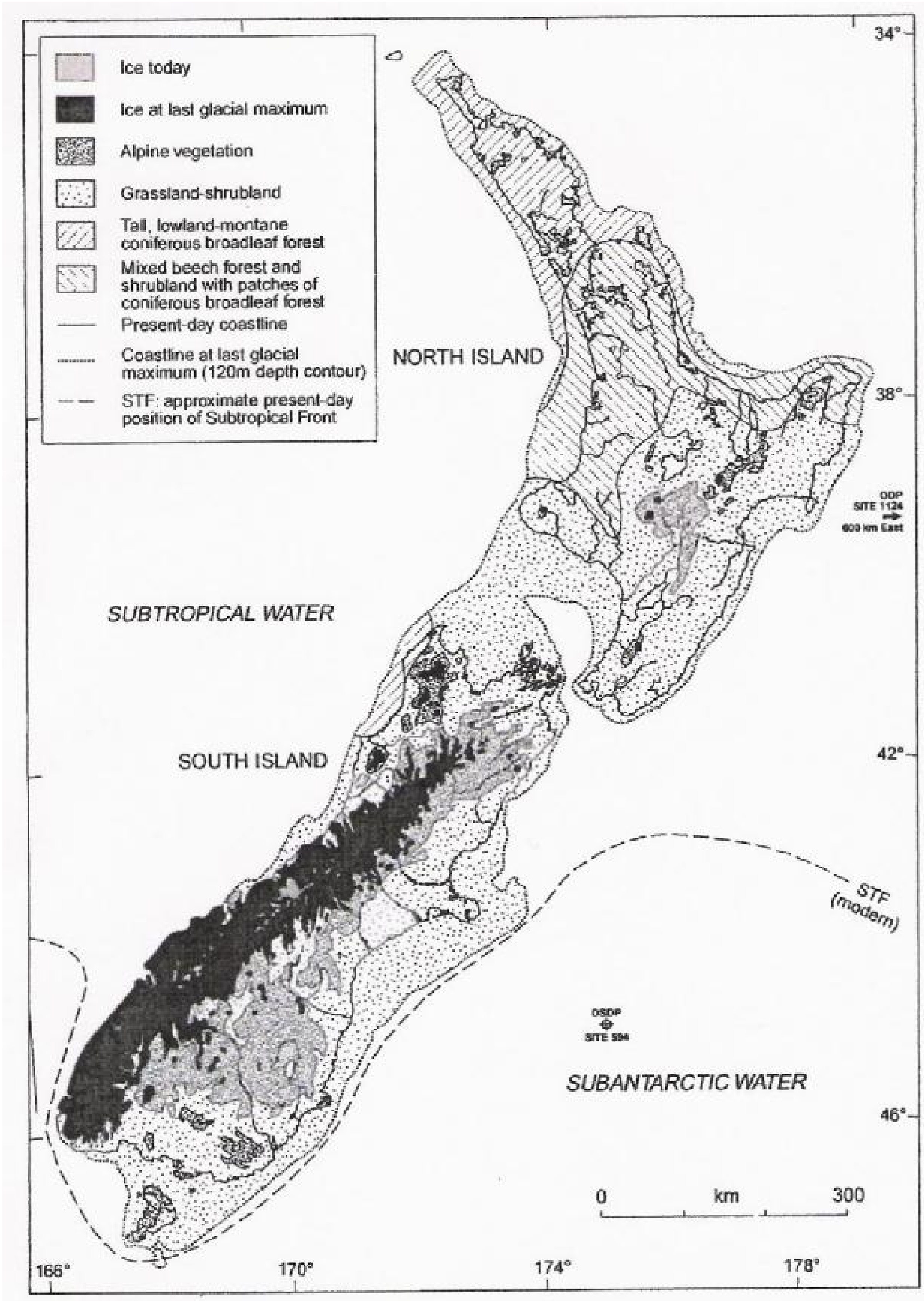

Figure 2.5. New Zealand at the Last Glacial Maximum (LGM), Newnham *et al*. (1999).

However, researchers such as Williams *et al*. (2005) suggest that the LGM was not uniformly cold and there was an interstadial c. 20.39-19.66ka which is supported by a similar cooling in the Byrd ice core. It is further supported by the separation of Aurora 3 and Aurora 2 glacial advances separated by a short glacial retreat (Williams, 1996).

2.1.3.2 The North Island

Glaciation in the North Island during the Last Glacial Maximum was minor in comparison to the South Island (Figure 2.5). It is thought that valley glaciation during the Last Glacial Maximum was only limited to Tararua Range and Tongariro National Park (in particular Mt Ruapehu) (Pillans *et al*. 1993, Brook and Brock, 2005). Adkin (1911) was the first researcher to suggest that the head of the Park Valley and five other valleys to be of u-shape in cross-profile which indicated the previous existence of valley glaciers. It has been suggested by Pillans and Moffat (1991) (as cited in Pillans *et al.* 1993) that the ELA lowering for the Tararua Range during this period was approximately 800 ± 100m.

The only other site in the North Island showing evidence of glaciation, during the Last Glacial Maximum, are the volcanoes of the Central North Island. Although, it is thought that Mt Tongariro is too small to have been glaciated, there are moraines which exist on Mt Ngauruhoe (Mangatepopo moraines). Mt Ruapehu is the only location in the North Island to still be glaciated and there is evidence that these glaciers were much more extensive during the Otiran Glaciation (McArthur and Shepherd, 1990). The Mt Ruapehu ice cap was small and was centred in the summit crater with an estimated ELA depression of similar magnitude to that of the Tararua Range.

It has been suggested by Morgan and Gibson (1927); Willett (1950) and Flint (1957) that Mt Taranaki (Figure 2.2) was also glaciated during the Last Glacial Maximum or at least during the Pleistocene. Willett (1950) proposes that a depression of the snowline by c. 1060m would have led to a treeline depression and large permanent snowfields of approximately $13km^2$ on Mt Taranaki. In addition, Morgan and Gibson (1927) suggest that striated boulders at the head and partway down the Manganui Valley provide evidence for glaciers on Mt Taranaki, however no u-shaped valleys were found which are indicative of glaciation.

Temperature decreases for the North Island during the Last Glacial Maximum were found to be similar to that of the South Island. McGlone and Topping (1983) suggested that the temperature decrease during the Last Glacial Maximum in the Tongariro region was no more than 5ºC below present due to the presence of grassland-subalpine shrubland pollens.

2.1.4 Last Glacial Interglacial Transition (LGIT) (20 to 10ka)

The Last Glacial Interglacial Transition has been suggested by Shulmeister *et al*. (2005) to have occurred 20 to 10ka with the onset of the last deglaciation commencing no earlier than 18-19ka based on cosmogenic nuclide (^{10}Be and ^{26}Al) chronology in the Cobb Valley, northwest Nelson. Furthermore there is evidence for some minor readvances over the following 3-4kyr. However, probably the biggest debate associated with the LGIT is whether the Younger Dryas cooling event reached New Zealand or not.

2.1.4.1 Younger Dryas (YD)

The Younger Dryas cooling event has been described by Denton and Hendy (1994), McGlone (1995) and Singer *et al*. (1998) as having occurred 11,000-10,000 radiocarbon yrs BP. Denton and Hendy (1994) propose that the Waiho Loop terminal moraine formed during an advance of the Franz Josef Glacier in the Younger Dryas cooling event, based on a corrected radiocarbon age of 11,050 ± 14 yrs BP. Ivy-Ochs *et al*. (1999) dated the Lake Misery moraines in Arthur's Pass using ^{10}Be and determined a mean age of these moraines to be 11,720 years, therefore implying that they also formed during the Younger Dryas. However, Rother and Shulmeister (2006) suggest that these re-advances are not universally detected in the Southern Alps. But also state that the broader paleoecological data such as that found by McGlone (1995, *et al*. 2004) does point to a cooling in the same period around 12.7-11.5ka.

Singer *et al*. (1998) suggest that there was no Younger Dryas event in New Zealand through the lack of evidence in pollen records from northwest Nelson. However, even though there is no evidence for a readvancement in the Cobb Valley during the deglaciation, it is suggested by Shulmeister *et al*. (2006) that the Waiho Loop terminal moraine does provide evidence for readvance of the Franz Josef Glacier. But it is unclear with the Waiho Loop whether it formed during the Younger Dryas or before it (Shulmeister *et al*, 2006). If it does preceed the Younger Dryas then it is possible that the Waiho Loop formed during the Antarctic Cold Reversal (ACR).

2.1.4.2 Antarctic Cold Reversal (ACR)

The Antarctic Cold Reversal is thought to have occurred 14,000-12,500 cal yr BP (Jouzel *et al.,* 2001 as cited in McGlone *et al*. (2004)). McGlone *et al*. (2004) found evidence in pollen records for a retreat of forests around 14,600 to 13,600 cal yr BP which coincides, at least in part, with the ACR. Furthermore, McGlone *et al*., (2004) found podocarp pollen present in records between 12,800 and 11,300 cal yr BP therefore indicating that there was a sustained warming during the Younger Dryas chronozone. Turney *et al*. (2003) also provide support for the Antarctic Cold Reversal having occurred in New Zealand. It is suggested by Turney *et al*. (2003) that expansion of *Dacrydium* forests stopped c. 14,700 cal yr BP indicating the commencement of a cooling event and lasted approximately 1000 years with a reestablishment of a warming trend c. 12,900 cal yr BP.

2.1.5 The Holocene

The Holocene commenced approximately 10,000 radiocarbon years ago and is assigned to MIS 1 (Figure 2.3). As can be seen in Figure 2.3, there are some excursions in the ^{18}O isotope therefore indicating fluctuations in temperature.

McGlone *et al*., (2004) suggest from pollen evidence in the Cass Basin that climate deterioration began around 10,350 cal yr BP. This was demonstrated through the increase of frost-tolerant taxa such as *Phyllocladus*. Between 8200 and 7400 cal yr BP there was a rise of *N. cliffortioides* which further indicates a cooling in temperature. It was during this time that McGlone *et al*. (2004) suggest that *Nothofagus* began dominating the forests over the central and northern South Island. After approximately 7ka BP there was a decline of drought and frost sensitive species which indicates that temperatures were cooler than present day levels (Williams *et al*., 2004).

Temperatures were approximately 1-2 °C below present day at about 4000 yrs BP, which allowed for small glacial advances in the Southern Alps. From 2500 yrs BP, the forests began to become dominated by *Nothofagus fusca* indicating cooler conditions (McGlone *et al.*, 1993). Natural fires in central and southeastern regions of the South Island indicate a drier climate, with an establishment of the modern pattern of westerly and southerly winds over New Zealand (Salinger, 2001). Climatic change since 2500 yr BP has been relatively minor in comparison with previous periods of climatic change. However, there are some important changes to note over the last 1000 years the most notable being the Little Ice Age.

2.1.5.1 The Little Ice Age

The Little Ice Age is thought to have commenced as early as the 14th century and continued into the 19th and 20th centuries (Grove 1988, 2001, 2004; McKinzey *et al*. 2004a). Although the Little Ice Age is well documented overseas, in particular Europe, there is a lack of research focussing on the occurrence of this cooling event in New Zealand.

It has been suggested by researchers such as McKinzey *et al*. (2004a) that the Little Ice Age climate was extremely variable and therefore the termini of glaciers tended to fluctuate around advanced positions for several centuries. This is demonstrated in the South Island where there are three Little Ice Age advances identified for the Franz Josef Glacier. These three advances have been dated by McKinzey *et al*. (2004a) as having occurred before 1600 AD (LIA maximum for the Franz Josef Glacier); c. 1600AD and 1800AD. Winkler (2000, 2004) also identified a series of Little Ice Age advances for the Eugenie Hooker, Mueller and Tasman Glaciers with the maximums for each occurring at 1760 AD, 1735-1740 AD, 1726AD and prior to 1800AD respectively. .

There is evidence of the Little Ice Age occurring in the North Island as well. Palmer and Xiong (2004) have identified about three cooler periods within the Little Ice Age by examining tree rings of the *Libocedrus bidwillii* Hook.f (New Zealand cedar). The coldest period as identified by the tree rings was centred around 1623-1647 AD. Williams *et al.* (1999, 2004) have also found evidence of the Little Ice Age occurring on the North Island.

Williams *et al.* (1999, 2004) measured speleothems in the Waitomo district and found low ^{18}O values at about 325 yrs BP (c. 1675AD).

Temperatures reconstructed from these the speleothems and the tree rings suggest a cooling of about 0.8°C for the North Island. This temperature is lower than that estimated by Anderson and Mackintosh (2006a) who estimate that the temperature decrease required to cause the formation of the Little Ice Age moraines of the Franz Josef Glacier was c.1.1 °C.

2.1.6 Driver of Late Quaternary glaciations

Recently there has been debate over whether temperature or precipitation is the driver of Late Quaternary Glaciation. Rother and Shulmeister (2006) propose that glacial advances during the Last Glacial Maximum (LGM) and Last Glacial Interglacial Transition (LGIT), in New Zealand, occurred under very moderate cooling with enhanced precipitation. Furthermore that synoptic climate variations, such as enhanced regional flow of moist westerly air masses, may provide a better explanation for LGIT climatic events rather than Northern Hemisphere climate forcing being the exclusive driver.

Anderson and Mackintosh (2006b) disagree with this proposal put forward by Rother and Shulmeister (2006). Anderson and Mackintosh (2006b) suggest that temperature is the main driver of Late Quaternary Glaciation rather than precipitation. It was proposed by Anderson and Mackintosh (2006b) that even with a 40% increase in precipitation a cooling of 2.5-3.0°C would still be required to cause the Franz Josef Glacier to advance to Canavan's Knob/Waiho Loop.

There will be always a debate over what is the main driver of the Late Quaternary Glaciations whether it is temperature, precipitation or a combination. However, there is no doubt that New Zealand has been glaciated on a number of occasions and that further research needs to be conducted in order to ascertain a better understanding of the current behaviour of New Zealand's glaciers.

2.2. Mt Ruapehu

2.2.1 Volcanic History

The volcanic history of Ruapehu is much briefer when compared with the volcanic history of the Taupo Volcanic Zone, which spans about one million years (McArthur and Shepherd, 1990). Volcanic activity at Ruapehu is thought to have commenced approximately 250,000 years ago. Hackett (1985) mapped four main formations on Ruapehu, which span this time frame (Figure 2.6).

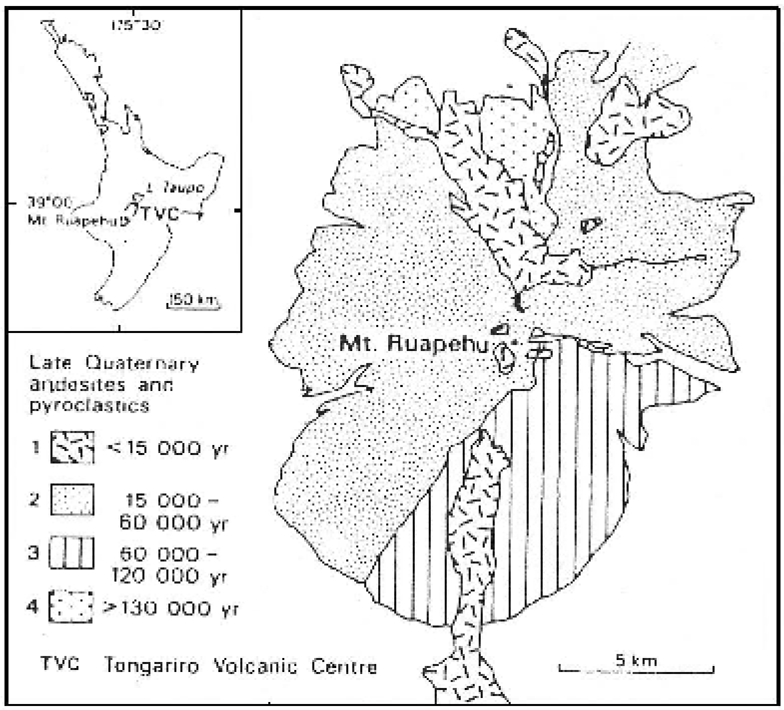

Figure 2.6. Location and geology of the four volcanic formations identified by Hackett (1985). 1= Whakapapa Formation; 2= Mangawhero Formation; 3= Wahianoa Formation; 4=Te Herenga Formation (McArthur and Shepherd, 1990)

Based on these formations, Hackett (1985) interpreted the history of Ruapehu as one of three cone-building episodes alternated with periods of cone dissection. He suggests that the Te Herenga Formation was formed in the first cone-building episode, which was then subsequently eroded in a period of cone dissection involving glaciers. The Wahianoa Formation also underwent a period of cone dissection involving glaciers. The Mangawhero Formation is unconformably deposited on the Wahianoa cone and is currently undergoing cone dissection. The final formation is the Whakapapa formation, which is unconformably deposited on top of the Mangawhero Formation (Hackett, 1985; McArthur and Shepherd, 1990). As can be seen from Figure 2.6 the highest peaks mainly consist of the Mangawhero formation, thereby built during the interval 60,000-15,000 yrs BP and are therefore of last glacial (Otira Glaciation) age.

2.2.2 Tephrochronology of eruptive sequences

2.2.2.1 Quaternary Eruptive Activity

The recent volcanic history of Ruapehu has been determined by dating Late Quaternary tephra deposits in the Ruapehu ring plain. Although the tephra deposits are preserved in various sites in the Ruapehu ring plain the most complete stratigraphy is best preserved in the southeastern sector, which has been the site of numerous studies (Donoghue, 1991; Donoghue *et al.*, 1995, 1997).

Fourteen rhyolitic tephras, (from Okataina and Taupo Volcanic Centres) are interbedded with seven andesitic formations (Table 2.4). The rhyolitic tephras are dated using ^{14}C dating, allowing the chronology of the andesitic formations to be determined (Table 2.4). Three main eruptive periods in the recent volcanic history of Ruapehu, which can be seen from this tephra. The most recent period saw the eruption of the Tufa Trig Formation, which has been dated using ^{14}C dates of the Taupo Pumice at its base and Tufa Trig Formation member Tf5, to be c. 1718 cal yr BP to present. There are in total at least 19 andesitic tephras in the Tufa Trig Formation, which indicate a series of frequent, small volume eruptions (Donoghue *et al.* 1995, 1997). The eruptive period 1718 cal – 10 000 years BP, found a significant amount of andesitic tephras (sourced from Mt Tongariro and Mt Ngauruhoe) and rhyolitic tephras (from the Okataina and Taupo Volcanic Centres) deposited on Mt Ruapehu (Table 2.4). This series of andesitic and rhyolitic tephras overlies the Bullot Formation, which signifies another important eruptive period in Mt Ruapehu's recent volcanic history. In comparison to the Tufa Trig Formation, the Bullot Formation demonstrates a period of high amounts of activity from Ruapehu (Donoghue *et al.*, 1995). Once again, the Bullot Formation contains important rhyolitic tephra marker beds, allowing it to be dated (Table 2.4).

Table 2.4. Tephrachronology of the southeastern sector of the Mt Ruapehu ring plain.

Formation	Source[§]	Age (yrs BP)
Tufa Trig Formation (Tf)	_Mt Ruapehu_	_ca. 1718 to present*_
Kaharoa	OVC	770 ± 20[†]
Ngauruhoe Formation	TgVC	ca. 1850 to present*
Taupo Pumice (Tp)	_TVC_	_ca. 1718 ± 30 cal_[¤]
Mapara (Mp)	_TVC_	_2160 ± 25_[†]
Mangatawai Tephra (Mg)	_Mt Ngauruhoe_	_2500 ± 200_[^]
Papakai Formation (Pp)	_TgVC_	_9700-2500*_
Waimihia (Wm)	_TVC_	_3280 ± 20_[†]
Hinemaiaia	TVC	4510 ± 80*
Whakatane	OVC	4830 ± 170*
Motutere	TVC	5430 ± 60[†]
Mangamate Formation	Mt Tongariro	9780-9700*
Poronui	TVC	9810 ± 50[†]
Karapiti	TVC	9820 ± 80[†]
Pahoka Tephra	Mt Tongariro	ca. 10 000*
Bullot Formation	Mt Ruapehu	22 500-10 000*
Waiohau	OVC	11 850 ± 60[†]
Rotorua	OVC	13 080 ± 50[†]
Rotoaira Lapilli	Mt Tongariro	13 800 ± 300
Rerewhakaaitu	OVC	14 700 ± 110[†]
Okareka	OVC	18 000[Ψ]
Kawakawa	TVC	22 590 ± 230

[§] TgVC= Tongariro Volcanic Centre; TVC = Taupo Volcanic Centre, OVC= Okataina Volcanic Centre, [^] Fergusson and Rafter (1959), [†] Froggatt and Lowe (1990), [Ψ] Nairn (1992), [*] Donoghue _et al._ (1995), [#] Donoghue _et al._ (1997), [¤] Alloway _et al._ (2007).

Donoghue (1991) has mapped the southeastern sector of Mt Ruapehu (the focus of the current study) and included two type sections from the Wahianoa Valley in the study sites. The tephra deposits found in the Wahianoa Valley are italicised in the table above and are shown in Figure 2.7.

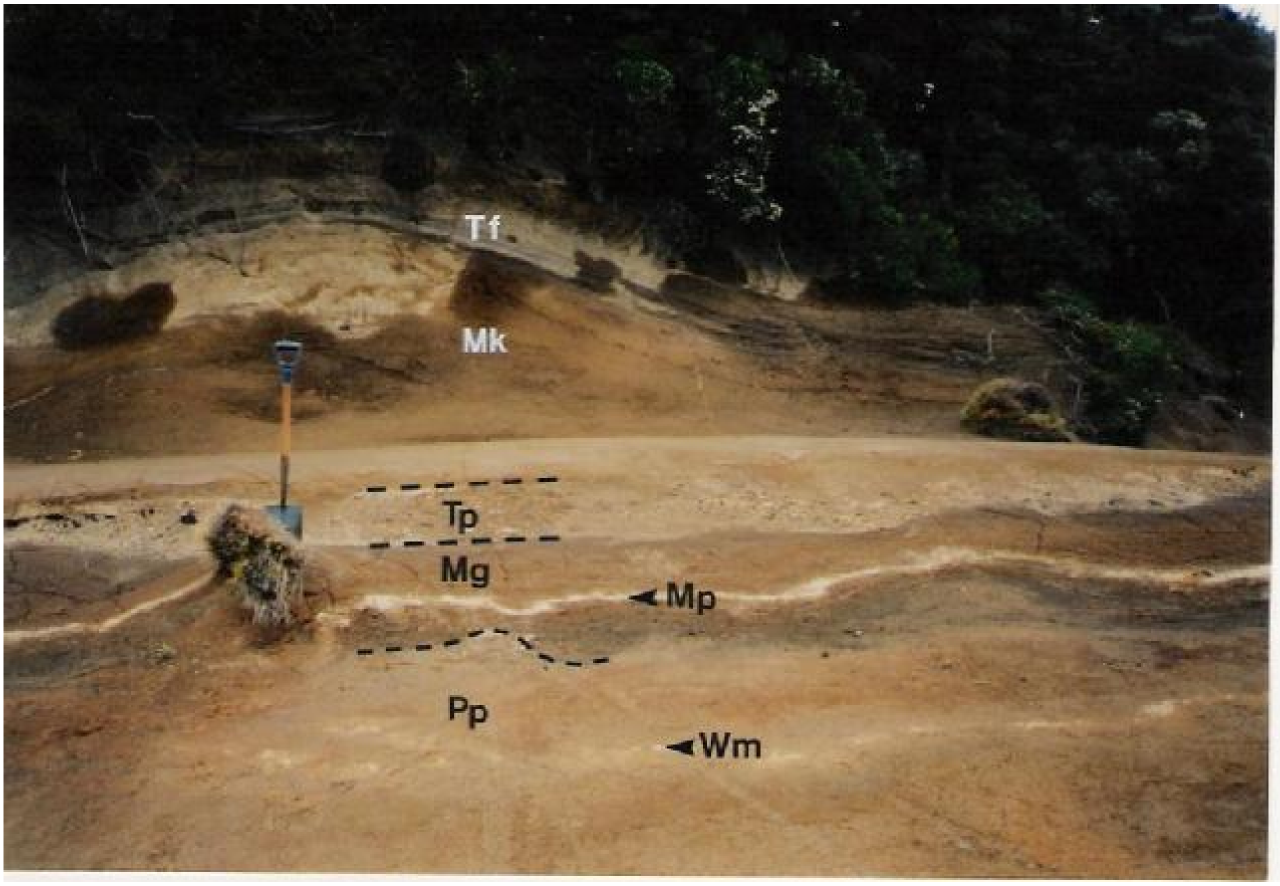

Figure 2.7. Stratigraphy of Tufa Trig type site (Donoghue, 1991), abbreviations described in Table 2.2, Mk stands for Makahikatoa sands.

2.2.2.2 Historical eruptive activity

Mt Ruapehu has remained active during historic time with the Crater Lake playing an important role as it is volcanically heated and surrounded by glaciers and snow. In periods of quiescence the Crater Lake may be observed to be completely covered in ice (Figure 2.8).

Figure 2.8. Climbers in the centre of the Crater Lake (Williams, 1996)

The first record eruption of Ruapehu was made in 1861 in the New Zealand Spectator and Cook's Strait Guardian (Williams, 1984). Since the first recording of this eruption in 1861, there have been numerous events of volcanic activity on Ruapehu. The most recent eruptive event of Ruapehu occurred in 1995-96 (Figure 2.9). This eruption was one of the biggest in the recorded history of Ruapehu and the volume of ash ejected was about 10^7-$10^8 m^3$ (Houghton *et al.* 1996).

2.2.2.3 Glacier-Volcanic interactions

Volcanic activity on Mt Ruapehu is a constant hazard as are lahars. Lahars usually originate on Ruapehu by eruptions through the Crater Lake causing water and mud to be blasted onto the surrounding glaciers (Williams, 1996). However, lahars have been known to flow down the Crater Lake's only outlet, the Whangaehu River, such as the 1953 lahar. There have been numerous lahars since the 1953 event, some of which are associated with eruptions (Figure 2.9).

Figure 2.9. 1995-96 eruption of Ruapehu, lahars in the foreground (Houghton *et al.* 1996)

2.2.3 Evidence for Glacial History of Mt Ruapehu

2.2.3.1 Introduction.

The glacial history of Ruapehu is limited to a few studies, with evidence for glaciation substantially shorter than evidence of the volcanic history. Indeed, all the remaining glaciers and their morainic deposits are located on volcanic formations that are less than 60,000 yrs BP. Therefore the moraines and glaciers are likely to have formed either during the Last Glacial Maximum, later stadials (McArthur and Shepherd, 1990) or later.

Some of the earliest research on glaciations of Ruapehu was carried out by Park (1910, 1916, 1926). In these papers he described what he believed to be glacial till in the Hautapu Valley, striated andesitic erratic blocks in the Rangitikei valley (Figure 2.4) and morainic mounds on the Waimarino Plain near Mt Ruapehu respectively. Park (1926) concluded that the boulders showed that a valley glacier extended south down the Hautapu Valley to the Rangitikei valley. Both the Rangitikei and Hautapu rivers run in deep rectangular troughs excavated in the floor of the old glacial valley. In addition, Park (1926) proposed the supposed morainic mounds at Waimarino were hummock moraines formed during glacial retreat.

These landforms described by Park in his 1910, 1916 and 1926 papers have since been found to be of volcanic (lahar) origin rather than glacial by Grange (1931) and Te Punga (1952). These authors suggest either (1) eruption from a crater lake, (2) collapse of a sector of a volcano or (3) the action of precipitation and volcanic ash on the sides of the volcano during/following an eruption could have led to the formation of the mounds.

2.2.3.2 Glacial retreat during 19th/20th century

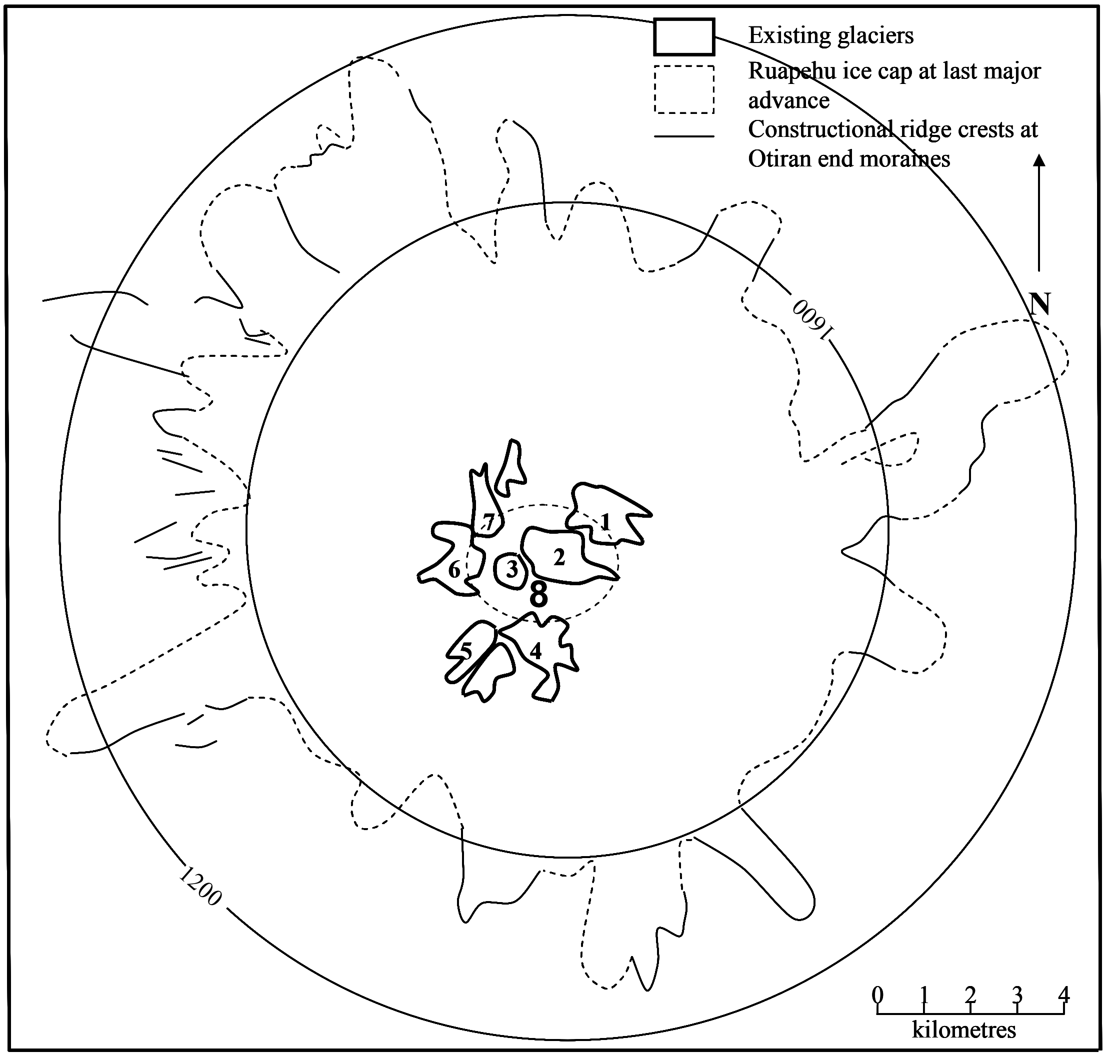

Figure 2.10. Moraine ridge crests and inferred ice limit of the Ruapehu ice cap and outlet glaciers at the maximum of the last major ice advance, which may have been the late Otiran glacial age (McArthur and Shepherd, 1990). 1= Mangatoetoenui Glacier, 2= Whangaehu Glacier, 3= Crater Lake which contains Crater Basin Glacier on southern side and Tuwharetoa Glacier on northern side, 4= Wahianoa Glacier, 5= Mangaehuehu Glacier, 6= Mangaturuturu Glacier, 7= Whakapapa Glacier, 8= Summit Ice Field.

At present there are nine named glaciers on Mt Ruapehu: Wahianoa, Whakapapa, Mangaehuehu, Whangaehu, Mangatoetoenui, Mangaturuturu, Crater Basin, Summit Ice field and Tuwharetoa. Currently, they are all less than 1km in length but during the Pleistocene glaciations, these glaciers were much more extensive (Figure 2.10). Also, it is likely that there was at least one advance during the Pleistocene of these glaciers as can be seen from the moraines preserved on Mt Ruapehu.

Glaciers of Mt Ruapehu have undergone substantial retreat recently. Between 1941 and 1954, the Whangaehu Glacier had retreated approximately 120 metres, and losing c.1.8ha in area (Krenek, 1959). The Mangatoetoenui Glacier was observed to have retreated the same distance but the northern section retreating only 20m, with a loss of c. 1.7 ha. Krenek (1959) also noted that the Wahianoa Glacier had also undergone a considerable shrinkage in area, with large areas of 'dead ice' present.

The most studied glacier on Ruapehu, Whakapapa Glacier, underwent substantial amounts of recession compared to the other glaciers. Whakapapa Glacier studied by Krenek (1959) between 1952 and 1955 was approximately 1.7km in length. Between 1952 and 1954, the glacier was relatively stationary, but, in 1955, it had receded by a 94m. In addition, a series of dirt cones began to appear on the surface of the Whakapapa Glacier, inferred by Krenek (1958) to have formed due to rapid melting, exposing an underlying ash layer of the 1945 eruption. Additionally, differential ablation caused by a protective debris cover is likely to have enhanced dirt cone development (Benn and Evans, 1998).

Heine (1962) observed the Whakapapa Glacier down-wasting and recession between 1957-1961 and noted that in 1958 bedrock began to appear separating the glacier in two, causing the glacial system to be renamed the Whakapapanui and Whakapapaiti Glaciers approximately 0.8km in length in 1960. In 1962, the snouts of the Whakapapanui and the Whakapapaiti Glaciers were estimated to be 2256m and 2377 m above sea level respectively (Heine, 1962).

Keys (1988) measured the elevation of the snouts of six of Ruapehu's glaciers and compared them with the elevations measured by Heine in 1961-1962 thereby estimating the recession of the glaciers (Table 2.5)

Table 2.5. Elevations and recession of glacier snouts between 1962 and 1988

Glacier	Elevation of snout in 1988 (m asl)	Elevation in 1961-1962 (m asl)	Recession of snout between 1962 and 1988 (m)
Mangaehuehu	2130±10	2070	250
Mangaturuturu	2260±20	2190	240
Whakapapanui	2420±20	2260	460
Whakapapaiti	2400±20	2380	100
Mangatoetoenui	2190±10	2100	320±70
Whangaehu	2090±20	2040	120±40
Wahianoa	2240±40	2170	160±70

As can be seen from the above table, the glaciers have receded between 100-460m during the period 1962-1988. The amount of recession can be attributed to the glaciers having a negative mass balance thereby losing more mass through ablation than they are gaining through accumulation.

It can be observed throughout this section that the Wahianoa Glacier has been largely ignored in terms of glacial research. The only measurements of its terminus were undertaken by Heine (1963) and Keys (1988).

2.3 Relative Age dating of glacier extents

2.3.1 Lichenometry

The basic premise of lichenometry is that lichens growing a rock surface or other suitable substrate can be used to obtain an approximation of the date of deposition of that surface. In order to estimate the age of the surface in question a lichen growth (dating) curve must be first established. Lichen growth (dating) curves are established using either direct or indirect methods. Direct methods involve the measurement of the growth of lichens over a given time period, which is usually done by using photography. Indirect methods involve the measurement of lichen diameters on surfaces of known ages and using these known ages as fixed points on the growth (dating) curves. However, in some cases the surfaces in question are of an unknown age, but this maybe overcome by measuring the diameters of lichen thalli on gravestones or other suitable anthropogenic surfaces (Innes, 1985; Winkler, 2003). Of particular use are in dating relative ages of glacial moraines, the premise being older moraines have larger (older) thalli on them.

2.3.1.1 Lichen parameter to be measured

Since Beschels (1950) initial development of the method there has been debate over what is the best parameter to use when measuring lichens. The main parameters measured are the longest axis, shortest axis and area. The longest axis is measured from edge to edge (Figure 2.11) along the greatest diameter (Noller and Locke, 2000). There have been numerous studies conducted using this parameter (for example: Bradwell, 2001; Winkler, 2003). However, some researchers suggest that the major disadvantage with measuring the longest axis is that coalesced individual thalli could be included and measured as single thalli, thereby affecting the overall results.

Some researchers (Birkeland, 1973; Locke *et al.*, 1979; Gellatly, 1983; Innes, 1985) suggest that the largest inscribed circle (shortest diameter) is a better parameter to measure rather than the greatest diameter as it reduces the chance of including coalesced thalli (Figure 2.11). However, Noller and Locke (2000) suggest that the use of the shortest diameter (largest inscribed circle) can be more subjective and therefore less reproducible than the longest axis. In some cases, researchers have measured both axes and have either averaged the longest and shortest axes or used both parameters to derive surface areas of the thalli (Innes, 1985).

Even though there is debate over which parameter to use, the measurement of the longest axis is the most widely used in the literature. Precautions must be taken when using this parameter to ensure that coalesced thalli are not included (Innes, 1985). Not only has there been debate over which parameter to measure but the biggest debated issue in lichenometry is how many thalli to measure and to use in the development of growth (dating) curves (Noller and Locke, 2000).

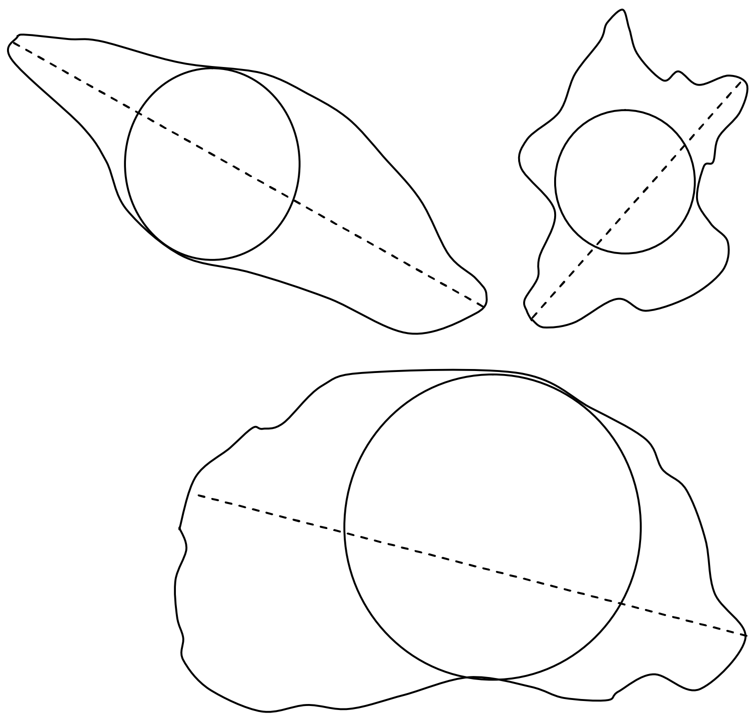

Figure 2.11. Alternative ways of measuring a lichen thallus. Inscribed circles and largest diameter (hatched lines) (Innes, 1985).

2.3.1.2 Largest lichen maximum diameters

This was the initial lichenometric technique developed by Beschel in 1950. This technique involves only the largest lichens being measured, thereby indicating the maximum age of the deposit in question. Beschel dated the moraines of the Vernagt and Guslar Glaciers in the European Alps and constructed lichenometric growth curves using the largest lichen found at each site (Figure 2.12).

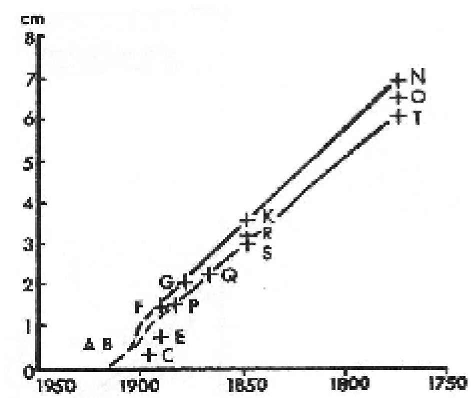

Figure 2.12. Growth curve of the *Rhizocarpon geographicum* from Vernagt Glacier foreland (Beschel, 1950). Letters indicate sample sites used.

Beschel's (1950) development of this technique has been adopted by Karlén (1979); sand Matthews (2005). Webber and Andrews (1973) suggest that this technique is essential for effective use in lichenometry as the lichen thallus with the maximum diameter is an indicator of surface age.

However, there are some disadvantages with this technique such as the possible inclusion of coalesced thalli, which have predated stabilization of the surface. Also, another major drawback is the dependence of the largest thallus on the size of the area searched as well as the lack of any statistical measure of uncertainty in estimation of the single largest thalli (Noller and Locke, 2000).

2.3.1.3 Maximum Diameters of all lichens

This technique was first proposed by Matthews (1974) in order to compensate for the disadvantages associated with the sampling of the single largest lichen. Matthews (1974) proposed that the mean of the largest lichens at five or ten sites be used instead, in order to provide a better approximation of the age of the surface in question (Noller and Locke, 2000). Since its initial proposal this technique is probably the most widely used in lichenometry. Winkler (2000, 2004) used this technique to produce a lichenometric growth (dating) curve (Figure 2.13) in order to date 'Little Ice Age' moraines in the South Island.

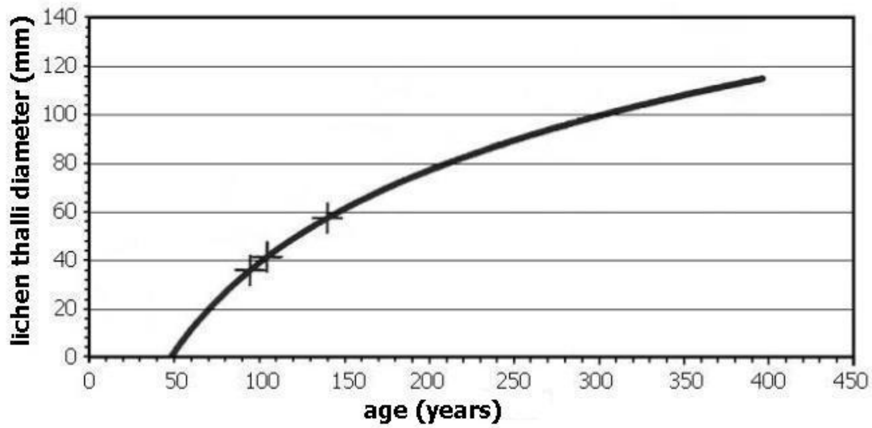

Figure 2.13. Lichenometric dating curve, South Island, New Zealand (Winkler, 2000).

Not only are the mean values of the largest lichens used as a standalone technique, some researchers (eg: Porter, 1981; Innes, 1984a, 1984b; Kirkbride and Dugmore, 2001; Matthews, 2005) e.g.use it in conjunction with the measurement of the single largest thalli.

2.3.1.4 Size Frequency

Benedict (1967) was the first to propose the size-frequency distributions of lichen populations as a potential tool in paleoenvironmental and geochronological work. This approach uses the frequency of the size of each lichen diameter measured as an indicator of relative age, i.e: the higher quantity of a larger lichen diameter indicates that that surface is older. Since this initial proposal there have been numerous size-frequency studies (Locke *et al.*, 1979; Gellatly 1982; Innes, 1983, 1986; Smirnova and Nikonov, 1990; Cook-Talbot, 1991; Bull and Brandon, 1998; Caseldine and Baker, 1998; Noller and Locke, 2000; Bradwell, 2004).

This method is viewed by all of these authors to have good potential in lichenometry. However, there is a debate among the proponents of this lichenometric method as to the nature of the size-frequency distribution in an undisturbed lichen population (Bradwell, 2004). Locke *et al.* (1979) suggested that the '1 in 1000' thallus diameter could be used to determine a relative age for the surface being studied. They proposed that a linear relationship may exist between the logarithm of the frequency and the lichen size (age). From this graph it is possible to extrapolate an estimate of the size of the largest thallus thereby determining an approximate age of the surface in question. This proposal has been met with criticism from other researchers (Benedict, 1985; Innes, 1986; Bradwell, 2004) who suggest that the method used by Locke *et al.* (1979) is strongly influenced by the class intervals chosen for the size-frequency histograms. Instead, these researchers suggest that the gradient of the size-frequency curve provides a better indication of the age of the surface (Figure 2.14). Bradwell's (2004) study focussed on using the size-frequency method in Iceland, which provided some promising results, differentiating moraines.

Indeed, Bradwell (2004) and other researchers (eg: Benedict, 1967; Innes, 1983) have found that a relationship exists between the gradient of the size-frequency curve and the age of the surface. These researchers propose that the shallower the gradient the older the surface (Figure 2.14) and the steeper the gradient the younger the surface.

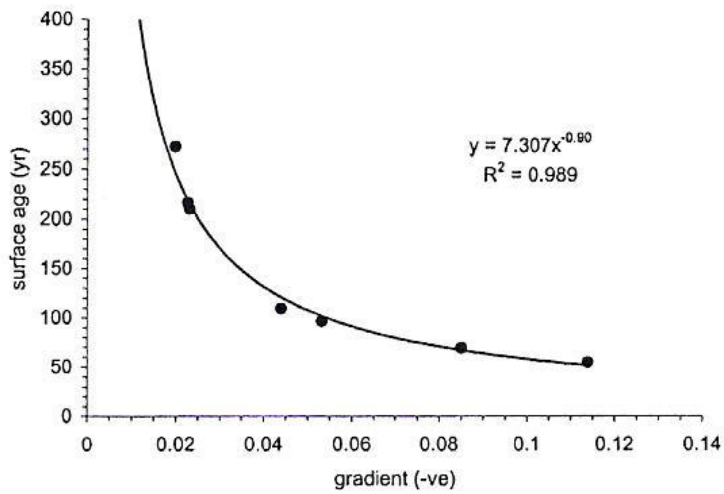

Figure 2.14. The relationship between the gradient of size-frequency distributions of *Rhizocarpon* and surface age on seven dated surfaces in southeast Iceland (Bradwell, 2004).

2.3.1.5 Percent Cover

Locke *et al.* (1979) first introduced the percent cover technique in 1979, and this involves the visual estimation of the ratio of the area of lichen-covered surface to the total exposed surface area. Although this technique has been used in the past, it is used very rarely as a method of lichenometry in recent studies. Included in the main reasons is that, since the percent cover is only an estimation, therefore it allows for operator bias. Also, this technique allows for the inclusion of coalesced thalli, which are avoided by other techniques, and Noller and Locke (2000) conclude that competition may skew the results. Furthermore, snowbanks may kill the lichen on the flanks of rocks but allow the upper surfaces of rocks to grow a cover of large thalli. Therefore, due to all the reasons outlined above, this technique finds little acceptance today, and is not discussed further in this study.

2.3.2 Schmidt Hammer

The Schmidt Hammer was originally developed for *in situ* testing of the surface hardness of concrete. Since the Schmidt Hammer's initial development it has been adopted by geomorphologists for a host of applications such as relative age dating. There are a few different versions of the Schmidt Hammer that can be used in geomorphological studies. These are described in Table 2.6.

Table 2.6. Properties and uses of the different versions of the Schmidt Hammer (Goudie, 2006).

Type of Hammer	Properties	Uses
N-type	Compressive strength values range from 20 to 250 MPa. Also has a digital version available.	It can be used on a wide range of rock types ranging from weak to strong.
L-type	Has an impact that is three times lower than the N-type hammer	Used on weak rocks and rocks that have thin weathering crusts.
P-type	Pendulum hammer that has compressive strengths less than 70kPa.	Used on rocks with very low hardness

The most commonly used Schmidt Hammer out of the three types described in Table 2.6, is the N-type hammer as it can be used on a wide range of rock types, which is appealing to geomorphologists (Goudie, 2006).

The instrument measures the distance of rebound of a controlled impact on a rock surface, which depends on the elastic recovery of the surface. This elastic recovery (the distance of repulsion of an elastic mass upon impact) itself depends on the hardness, which in turn is related to mechanical strength thereby the distance of rebound (*R*) gives a relative measure of surface hardness or strength (Day, 1980; McCarroll, 1989a, 1991; Winkler, 2005; Goudie, 2006).

Just like other techniques used in relative age dating there are factors which influence the accuracy of the *R* values results from the Schmidt Hammer. These factors have been described by McCarroll (1989a) and are summarised in the below figure (Figure 2.15).

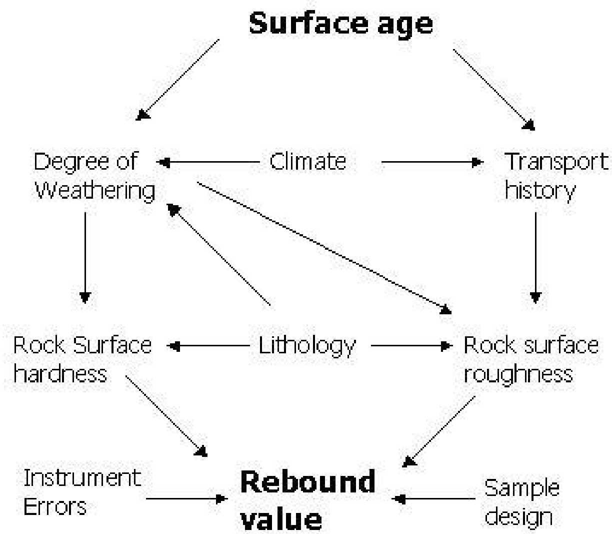

Figure 2.15. Some factors which influence *R*-values results, and their interrelationships (McCarroll, 1989a).

Day (1980) and McCarroll (1989a) proposed some practical points that need to observed when using the Schmidt Hammer in the field in order to minimize the impact of these sources of error by suggesting the following (Table 2.7).

Although there are limitations with the use of the Schmidt Hammer, it is still used in relative age dating. The Schmidt Hammer although may have a maximum time resolution of approximately 300 years (Winkler, 2005). However, the Schmidt hammer can be used to distinguish between single advance periods (i.e.: Little Ice Age and pre-Little Ice Age) but it cannot be used to distinguish between moraines formed within a single advance (ie: Little Ice Age (Evans *et al*, 1999; Winkler, 2005).

Table 2.7. Practical Points that need to be observed when using the Schmidt Hammer (Day, 1980; McCarroll, 1989a).

Instrument error and calibration	The instrument should be regularly calibrated to minimize instrument error.
Sample Site	Readings are not to be taken too close to voids or joints as this results in lower readings. Also impacts are not to be too close together otherwise higher values will result.
Orientation of Hammer	R values will vary if the Schmidt hammer is applied to horizontal or vertical surfaces. This is due the gravity acting on the mass inside of the hammer. There are corrections that can be made if the Schmidt Hammer is used on an inclination.
Lithology	Minimize the variation in lithology where possible as even the slightest variation has an effect on the R values.
Roughness	R values on a rough surface are lower than those read off a smooth surface.

2.3.3 Boulder Roundness

Kirkbride (2005) first proposed the utilisation of a boulders roundness as a relative age dating technique. The basic premise of the method is that the degree of curvature of a boulders edge may be quantified so that the degree of the edge roundness is a function of time.

Kirkbride (2005) proposes that there are four underlying assumptions associated with the Boulder roundness method, which are concerned with the origin of the bouldery tills in cirques and their post-depositional history:

1. The vast majority of boulders originated as rockfall debris from supraglacial sources, whereby clasts acquired initially sharp fractured edges.
2. Boulders have been passively transported in high-level pathways through glaciers, during which negligible edge-rounding occurred.
3. Following deposition at the ice margin, boulders have lain undisturbed except for surface weathering and edge rounding due to granular disintegration.

4. All boulders have experienced the same post-depositional weathering history, and similar rates of disintegration.

However, sample contamination can be expected which can be reduced by using careful sampling methods. In addition to the above assumptions, Kirkbride (2005) also suggested that there are five sampling criteria that must be met before any measurements can be taken at a sample site (Table 2.8).

Table 2.8. Sampling criteria for the selection of boulders. (Kirkbride, 2005).

Characteristic	**Criteria**
Boulder dimensions	Planar facets extending at least 0.5m in both directions from the edge.
Post-depositional change	Absence of post-depositional fracture of facets and edges at scales greater than granular disintegration.
Edges	Straight, uniform curvature, and long enough to avoid effects of increasing rounding towards the corners.
Exposure	Upstanding boulders reduce the effects of enhanced weathering due to late-lying snow. Edge must be high on the boulder and either a vertical corner or upward-facing edge, exposed to the wind and so reducing snow lie.
Boulder geometry	Angle between facets must be close to 90°. Angles between 70° and 110° were sampled to give strong correlations.

Kirkbride (2005) suggests that measurements can only be made when all the above criteria are met. Measurements are conducted using a simple instrument (Figure 2.16)

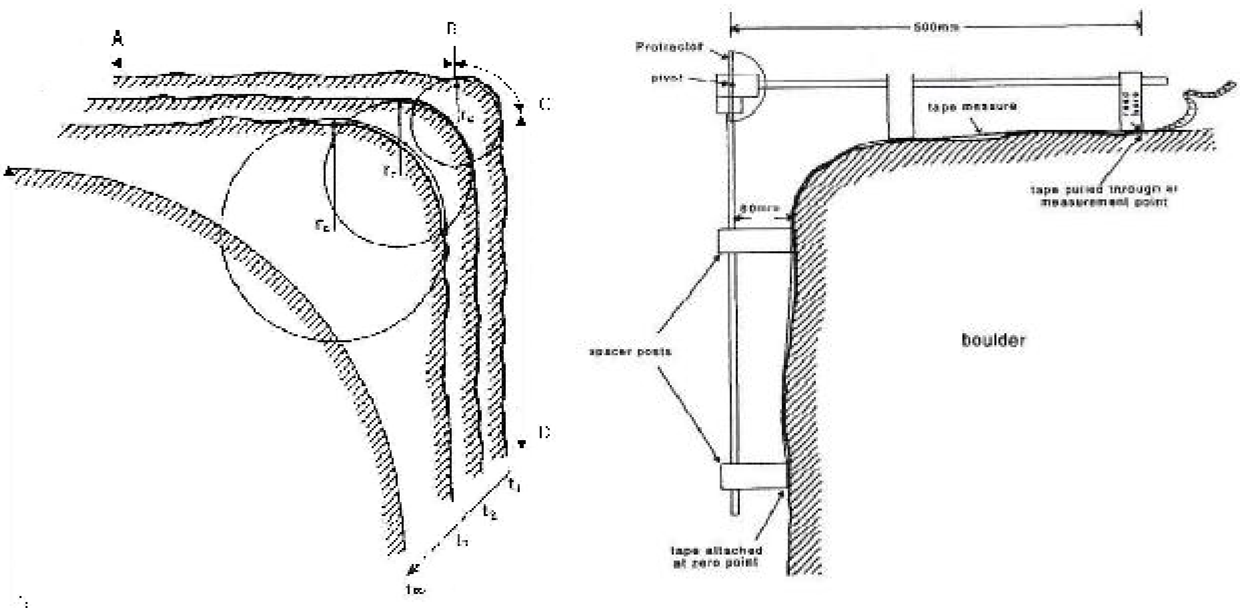

Figure 2.16. *Left*: Diagrammatic illustration of the use of radius of curvature to represent edge roundness. *Right*: Design of a simple instrument for measuring edge-roundness of large boulders (Kirkbride, 2005).

Kirkbride (2005) proposes three equations that must be used when processing results from the boulder roundness method.

$$l_{adj} = l_m - b(\theta - 90) \qquad \text{(Equation 2.1)}$$

The first equation was suggested by Kirkbride (2005) to correct for the interfacet angle, l_{adj}. Since the instrument cannot lie flush with the surface due to the design of it (Figure 2.16). Also, very few boulders have right angles, thereby a wide range of angles need to be measured. Kirkbride (2005) suggests that the measurements taken (l_m) must have corrections applied to them (Equation 1), which he suggests will compensate for the problems that arise with the instrument and the angles of the boulders.

$$l_i = \frac{(l_m - l_{sp})}{(l_{cu} - l_{sp})} \qquad \text{(Equation 2.2)}$$

Kirkbride (2005) suggests that the measured length (l_m) and thereby the adjusted length (l_{adj}) are determined by the dimensions of the measuring instrument used. In the case of the instrument used by Kirkbride (2005) (Figure 2.16) measurement of a perfectly cubic corner would give a l_m and thereby l_{adj} of 1000mm. If a perfectly rounded boulder with a radius of 500mm would give a adjusted length of 786mm. The second equation, in the above list, was derived in order to provide a normalised index of the edge roundness, l_i. l_{cu} and l_{sp} are measured lengths across the surfaces of spherical and cubic boulders.

$$r_c = 2333 - 2.333 l_{adj} \qquad \text{(Equation 2.3)}$$

The final equation was derived from a graph (Figure 2.17) of measured length (l_m) versus radius of curvature (r_c)

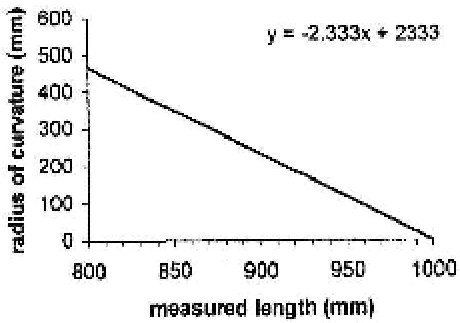

Figure 2.17. Graphed relationship between normalised length and radius of curvature (Kirkbride, 2005).

2.4 Climate reconstruction

The Equilibrium-Line Altitude (ELA) is an important component of a glacier as it marks the area or zone on a glacier where accumulation equals ablation. Any fluctuations in the ELA provide an indication of a glacier's response to climate change, which in turn may allow for a reconstruction of paleoclimate. There are a wide range of methods that may be adopted when reconstructing paleo-ELAs, however there are four which are more commonly used and these are described here (Benn and Evans, 1998).

2.4.1 Area-Accumulation Ratio (AAR)

The AAR is the ratio between a glacier's accumulation area and its total area (accumulation area and ablation area). This method is based on the assumption that under steady-state conditions, the accumulation area of the glacier occupies some fixed proportion of the glacier area (Meierding, 1982; Torsnes *et al.*, 1993; Benn *et al.*, 2005).

Steady-state AARs differ according to climate and elevation. Hawkins (1985) suggests that typical steady-state condition AARs for valley glaciers lie in the range of 0.5-0.8. However

Porter (1975, 1979) considers that an AAR of 0.6±0.05 provides a better indication of steady-state conditions for a valley glacier. In constrast, in the humid tropics tend to have higher steady-state AAR values (~0.8). Steady-state AARs are influenced by debris cover, which leads to lower values being calculated. In the Himalayas, steady-state AARs are around 0.2-0.4, which indicates that the extensive debris cover lowers the AAR value as a larger ablation area is required to balance the accumulation area (Kulkarni, 1992; Benn *et al.*, 2005).

When constructing a paleo-ELA the AAR is applied to a reconstructed glacier outline thereby producing an approximation of the location of the accumulation area. For example using Porter (2001)'s value of 0.65 ± 0.05 demonstrates that the accumulation area of the former glacier occupied approximately two-thirds of the total area (Figure 2.18).

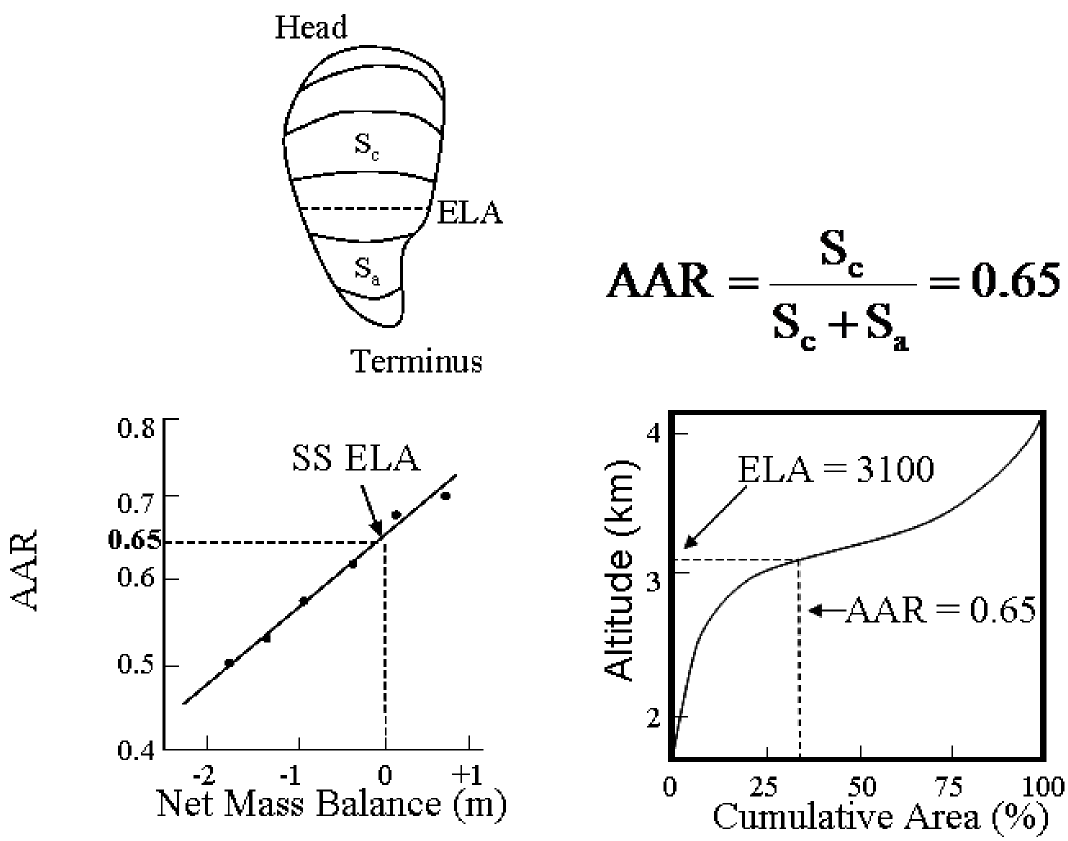

Figure 2.18. Accumulation Area Ratio (AAR). This method is based on the ratio of the accumulation area (S_c) to the total area of the glacier, (where S_a is the ablation area). A steady state (SS) AAR of 0.65 (when mass balance = 0) is regarded as the most appropriate for majority of temperate, debris-free glaciers (Porter, 2001).

One major disadvantage with this method is that it doesn't take into account glacier hypsometry (distribution of glacier area over its altitudinal range). This has lead to the development of the Area-altitude Balance Ratio method (Benn and Evans, 1998).

2.4.2 Area-Altitude Balance Ratios (AABR)

This method takes into account the mass balance gradients and glacier hypsometry. The AABR method was first proposed by Furbish and Andrews (1984) to try and overcome the disadvantages of the AAR method. This technique is based on the fact that for glaciers in equilibrium, the total annual accumulation above the ELA must balance the total annual ablation below the ELA. This can be expressed in terms of the areas above and below the ELA multiplied by the average accumulation and ablation, respectively (Benn and Evans, 1998).

2.4.3 Maximum Elevation of Lateral moraines (MELM)

Theoretically moraines are only deposited in the ablation zone below the ELA, thereby the maximum elevation of lateral moraines reflects a past position of an ELA (Figure 2.19). However, there are some limitations with this method such as underestimation and overestimation of the ELA. The former limitation can occur when ELA estimates are derived from eroded and/or non-deposited lateral moraines. The latter limitation could occur if the retreat of a glacier is slow thereby additional moraine material could be deposited (Torsnes *et al.*, 1993; Benn *et al.*, 2005).

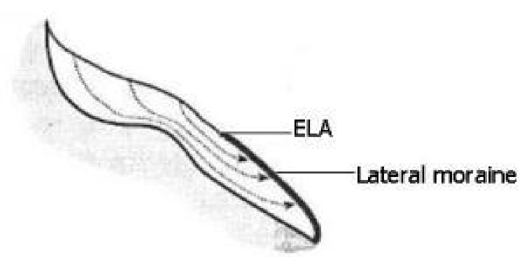

Figure 2.19. Maximum Elevation of Lateral Moraine (MELM) (Porter, 2001).

2.4.4 Terminus to Headwall Altitude Ratio (THAR)

The THAR is the ratio between the altitudinal range of a glaciers accumulation area and the glaciers total altitudinal range (Figure 2.20). Meierding (1982) found that ratios of between 0.35 and 0.4 gave the best results, especially on small cirque glaciers. On glaciers with large accumulation areas and narrow tongues, other researchers have used a THAR of 0.66. However, this approach for reconstructing ELAs has been viewed by Torsnes *et al.*, (1993) as not taking into account surface topography.

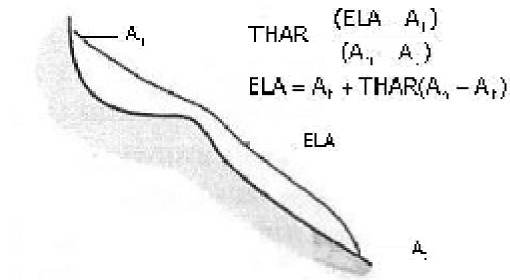

Figure 2.20. Terminus to Headwall Altitude Ratio. ELA lies midway between the headwall (A_h) and the terminus (A_t) (Porter, 2001).

2.5 Aims and objectives

There have been a number of important climatic change periods in New Zealand's history with the majority of climatic evidence preserved originating during the Otira Glaciation and the Holocene epoch, hence they have been most intensely studied by researchers. However there has not been a lot of research conducted on climate change on Mt Ruapehu when compared to other more key areas such as Westland and the Wanganui basin.

The glaciers on Ruapehu are situated at the extreme topographic and climatic limits therefore making them extremely sensitive to any climate change. Also they are situated in a volcanic environment thereby they are generally overlooked in terms of research. There are only a handful of papers, which have been outlined in this review, that have been focussed on glacial research on Ruapehu. The research that has been conducted has mainly focussed on the amount of ablation of the glaciers and thereby the rate at which they are retreating. There have been no definitive accounts on the actual age of the glacial deposits on Mt Ruapehu and therefore the glacial period within which they formed. In a few papers (eg: Hackett, 1985; McArthur and Shepherd, 1990) the Wahianoa moraines have been estimated to be less than 60,000 years in age as the morainic deposits are situated above the Wahianoa Formation which is approximately 60,000 years of age.

The majority of moraines can only be dated by using relative age methods. The methods outlined in this review have either only been carried out in the South Island (such as lichenometry and Schmidt hammer) or never before in New Zealand (Boulder roundness).

There are a few research questions, which arise from the lack of research outlined above:

- How old are the Wahianoa moraines?
- In which glacial period did the Wahianoa moraines form?
- What is the paleo-ELA of the Wahianoa Glacier?
- What conditions caused the Wahianoa Glacier to advance forming the moraines?

From the above research questions there are some objectives, which have been derived to try and answer them:

- To date the Wahianoa moraines using lichenometry, Schmidt hammer and boulder roundness.
- To determine in which glacial period the Wahianoa moraines have formed from the age derived from the above methods.
- To investigate the conditions that caused the formation of the Wahianoa moraines.

Chapter 3: Methodology

3.1 Introduction

This chapter will outline the methodology of the relative age dating and climate reconstruction techniques used in this study. There were three relative age dating techniques employed in this study: lichenometry, Schmidt hammer and Boulder roundness and the details of the application of these methods will be described in the first section of this chapter. The final section of this chapter will detail the application of the four climate reconstruction methods used to determine an estimate of the paleo-ELA of the Wahianoa Glacier.

3.2 Relative age dating techniques

There were three sampling areas used for the relative age dating techniques: Wahianoa 'A', Wahianoa 'B' and Wahianoa 'C' moraines and ridges. The Wahianoa 'A' moraines are the main set of ridges present in the Wahianoa Valley. The Wahianoa 'B' is a prominent ridge located on the true left side of the Wahianoa 'A' moraines. The final sampling area used was the Wahianoa 'C' ridges which are situated on the true right of the Wahianoa 'A' moraines.

3.2.1 Lichenometric measurements on Mt Ruapehu

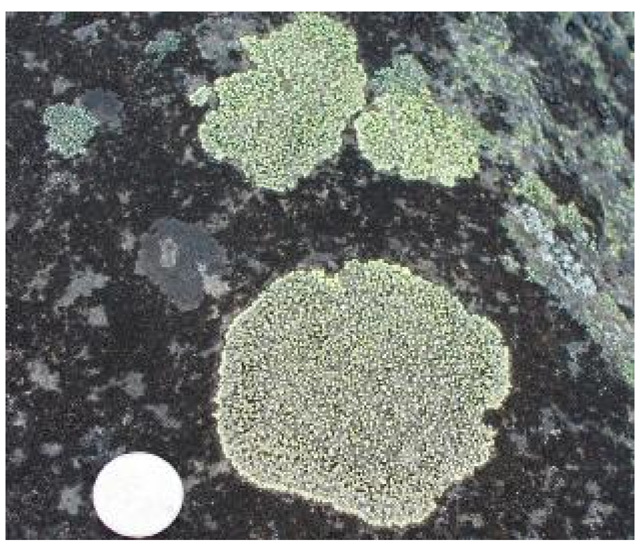

Figure 3.1. Yellow-green *Rhizocarpon* subgenus.

The lichens which were observed on Mt Ruapehu for this study were the yellow-green *Rhizocarpon* subgenus (Figure 3.1). This species is the most widely used in lichenometric studies and was used throughout this thesis.

As this is the first study of its kind on Mt Ruapehu, let alone on the North Island of New Zealand, an adequate number of sample sites were required in order to determine the best possible age approximation of the age of the Wahianoa moraines. In addition, as suggested by Winkler (2004), a number of sample sites were required so to include areas of lichens which have had optimal environmental growth conditions.

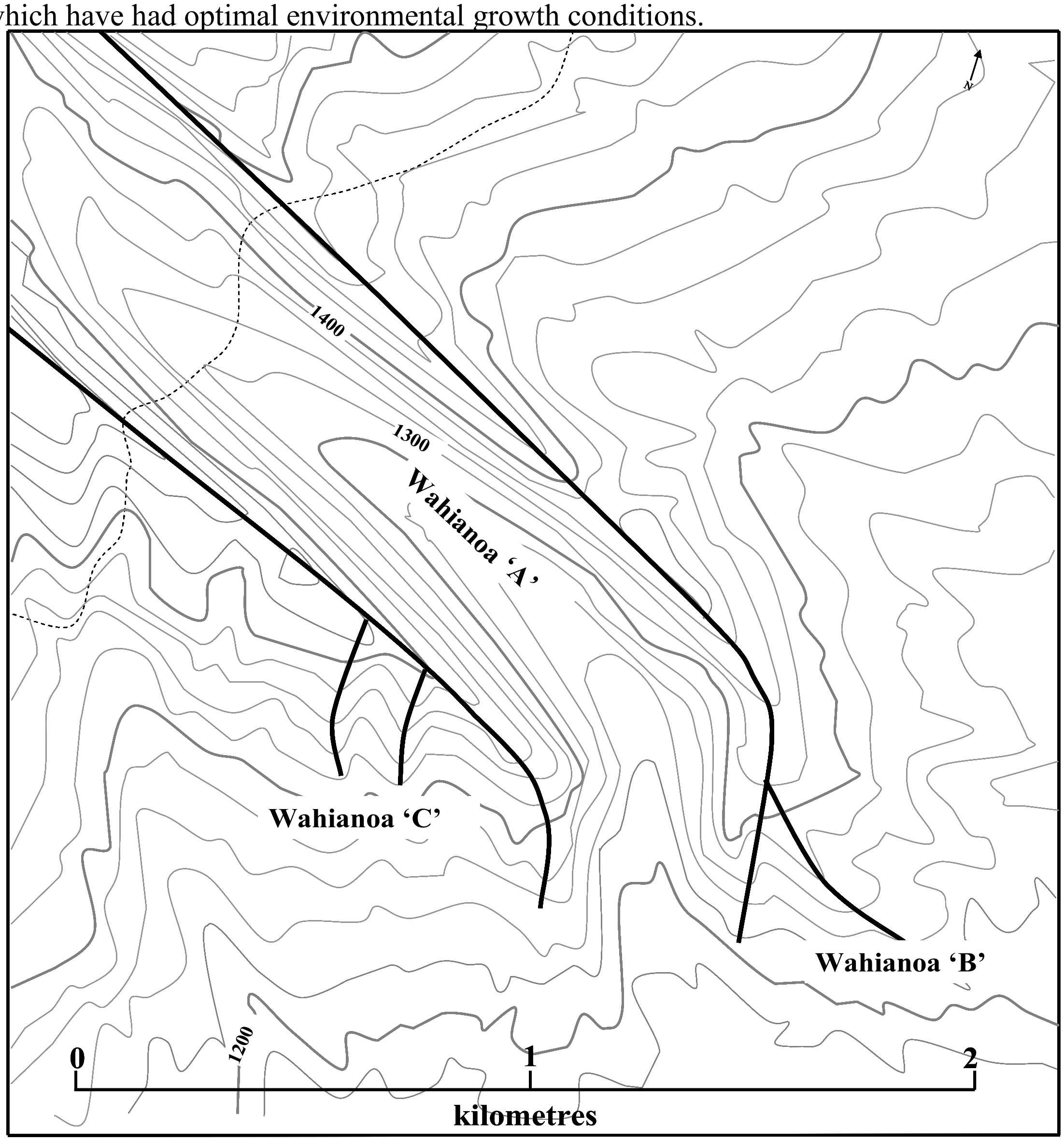

Figure 3.2. Sampling areas in the Wahianoa Valley. Dashed line is the round the mountain track and signifies the maximum extent of the study site for this thesis.

Sample sites for the lichenometric method were located near the proximal crests of the moraines at frequent intervals with some samples also being measured near the bases of the moraines. There were a total number of 38 sample sites for the Wahianoa 'A' moraines; 5 for the Wahianoa 'B' ridge and 10 sample sites for the Wahianoa 'C' ridges (Figure 3.2).

The most widely used parameter in lichenometric studies is the largest diameter, which was measured in this study using callipers. A total of 605 lichens were measured on the Wahianoa moraines (Figure 3.3). Also, as suggested by Innes (1985) precautions were taken not to include coalesced lichens when measuring the largest diameters.

Figure 3.3. Measurement of lichen using callipers.

Once the measurement of the lichens was completed, the two most common methods were used to determine an approximate age of the Wahianoa moraines: growth curve and size-frequency.

3.2.2 Growth curve

Since there are no known ages determined on the Wahianoa moraines that can be used to establish a lichenometric growth curve, lichens were measured on gravestones in the Ohakune cemetery (Figure 3.4) located on the south side of Ohakune which is approximately 26km southwest of the Wahianoa Valley.

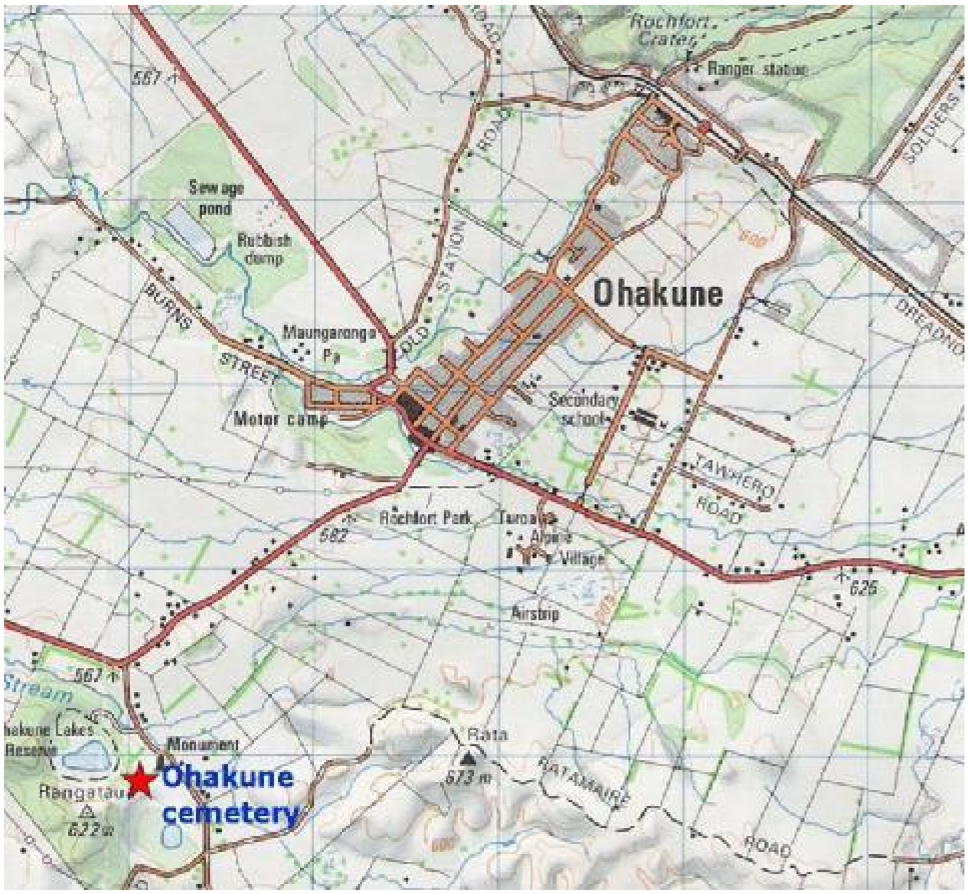

Figure 3.4. Location of Ohakune cemetery

The measurement of the lichens on the gravestones followed the same measurement procedure that was used on the Wahianoa moraines. The measurements taken off the headstones were plotted on a semi-logarithmic graph. The known ages were plotted on the *x* axis and the size measurements on the *y* axis with an equation in the form log y= mx + c derived from the semi-logarithmic line.

One of the biggest limitations that had to be taken into consideration when measuring lichens on Mt Ruapehu was that they were not the same species as found on the Wahianoa moraines. The difference in species can be mostly attributed to the differing environmental conditions and lithology of the rocks upon which the lichens have grown on Mt Ruapehu in contrast to the Ohakune cemetery. The growth rates may be different between the species thereby leading to a sparious result. Also, the headstones could have been constructed before their emplacement in the cemetery, thereby possibly allowing for the growth of lichens to commence prior to installation.

After a lichenometric growth curve was established using the measurements taken at the cemetery it was then applied to Mt Ruapehu. The largest lichen at each sample site was determined and the average of the five largest for each sample site was calculated (Winkler, 2004).

Once the average of the five largest lichens in the Wahianoa Valley was calculated, the largest of these values was substituted into the equation derived from the lichenometric growth curve which then provided an approximate age for the Wahianoa moraines.

3.2.3 Size-frequency measurements

There were 605 lichens measured in total on the Wahianoa moraines. In order to construct a size-frequency curve, the frequency (%) of each lichen diameter had to be first determined. The processing of the measurements for this method followed those previously established by Bradwell (2001, 2004). Once this was determined a $\log_{10}$ was taken of each frequency value, for example if it was found that a diameter of 20mm had a frequency of 3 then a $\log_{10}$ value was calculated for this frequency (Bradwell, 2001).

A size-frequency graph was then plotted with the frequency (%) values on the dependent x axis and the $\log_{10}$ of the frequency on the independent y axis. A line of best fit was applied to the data on the graph and an equation in the form $y = mx + c$ was derived. The gradient (m) was then used to provide an approximate age of the Wahianoa moraines.

3.3 Schmidt Hammer

3.3.1 Schmidt Hammer measurements on Mt Ruapehu

An L-type Schmidt hammer was used in the research on Mt Ruapehu. The majority of sample sites were located at the highest points of the Wahianoa moraines with some located in between these high points (Figure 3.2).

Sample sites consisted of 10 boulders per site with five blows being recorded off each boulder (Figure 3.5). Each blow was conducted a set distance apart, for maximum accuracy. Also, for maximum accuracy, measurements were taken on unweathered, unvegetated surfaces away from edges of a boulder and any joints present.

Figure 3.5. Measurements taken using L-type Schmidt hammer.

3.3.2 Power's Roundness

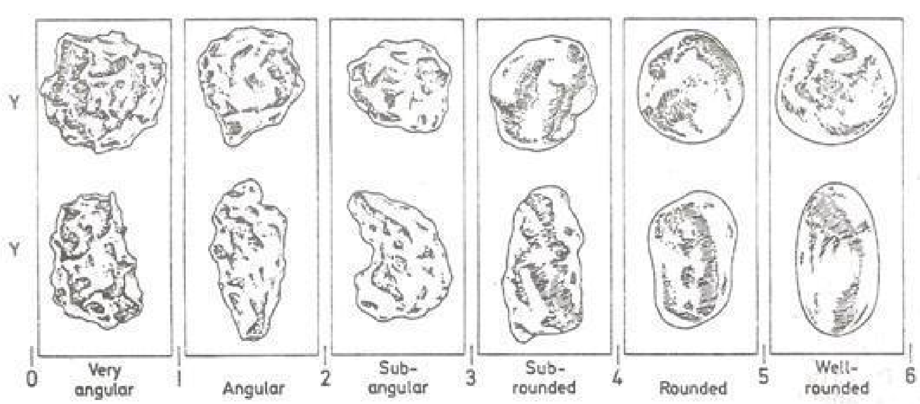

Figure 3.6. Roundness images and classes. Source: Powers (1953).

The roundness of each boulder was noted according to Power's chart (Figure 3.5). Matthews and Petch (1982) assigned a number to each roundness category (Table 3.1).

Table 3.1. Assigned values for each roundness category (Matthews and Petch, 1982)

Roundness Category	Very Angular (VA)	Angular (A)	Sub-angular (SA)	Sub-rounded (SR)	Rounded (R)	Very-rounded (VR)
Value assigned	1.0	2.0	3.0	4.0	5.0	6.0

This same method was adopted for the research on the Wahianoa moraines in order to see if there is a relationship existing between the R-values established by the Schmidt hammer method and the roundness of the clast measured. A graph was constructed plotting the mean R values (on *y* axis) against the mean roundness values (on *x* axis) arrived at by applying Power's roundness.

3.4 Boulder Roundness

3.4.1 Boulder Roundness measurements

Sample sites for the boulder roundness method were in the same location as the Schmidt hammer sample sites (Figure 3.2). As suggested by Kirkbride (2005) sample sites were located away from slope-foot areas and steep slopes.

Measurements were taken using the instrument devised by Kirkbride (2005). The instrument is placed on the rock facets with the spacer posts running parallel to these facets ensuring that all four spacer posts are resting on the surface of the boulder measured (Figure 3.7). A measuring tape was anchored to the end point of the instrument and fed past the opposite end post where it is pulled taut and a measurement is recorded.
A reading is also taken off the protractor which measures the angle between the arms of the instrument (Figure 3.7).

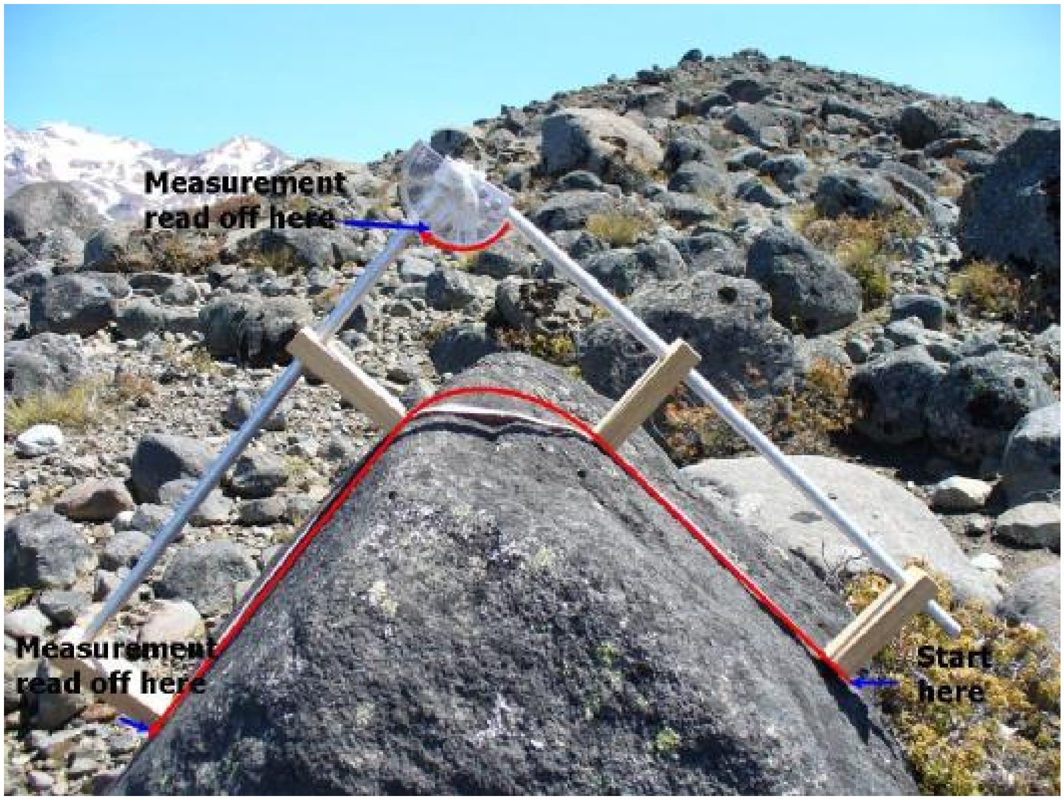

Figure 3.7. Measurement of a sample using boulder roundness instrument.

Once the measurements were completed they were processed using the equations formulated by Kirkbride (2005).

$$l_{adj} = l_m - b(\theta - 90) \qquad \text{(Equation 3.1)}$$

$$l_i = \frac{(l_m - l_{sp})}{(l_{cu} - l_{sp})} \qquad \text{(Equation 3.2)}$$

$$r_c = 2333 - 2.333 l_{adj} \qquad \text{(Equation 3.3)}$$

l_m is the measured length, l_{adj} is the calculated adjusted length, b is the regression coefficient, l_i is the index length and r_c is the radius of curvature.

3.5 Climate Reconstruction

3.5.1 Area-Accumulation Ratio (AAR)

Before an approximation of the location of the paleo and present accumulation area for the Wahianoa Glacier could be calculated, a reconstruction of the palaeo-glacier outline had to occur. The reconstruction was done following the methodology described by Lowe and Walker (1997). The proposed outline of the Wahianoa Glacier's former extent was traced and then ice-surface contour lines were drawn in. As suggested by Lowe and Walker (1997) the ice-surface contour lines were normal towards the valley walls and then became progressively more convex towards the terminus and more concave towards the headwall (Figure 7.1, pg 110). Before the paleo-ELA could be calculated using this method, a reconstruction of the former outline of the Wahianoa Glacier had to be completed (Figure 7.1, pg 110). This was done by tracing the current morphology of the Wahianoa moraines from a 1:50 000 NZMS 260 sheet T20. The glacial contour lines were drawn following Lowe and Walker's (1997) method.

Once the reconstruction was completed, the area between successive contour lines was calculated, by drawing a series of polygons from which the area of each could then be determined and totalled together (Porter, 2001). Once the area between each successive contour line was calculated the values were used to generate a cumulative curve which graphically displays the Wahianoa Glacier's former area/altitude distribution. As suggested by Porter (2001) a steady-state AAR of 0.65 was assumed from which the paleo-ELA could then be determined from the graph.

3.5.2 Maximum Elevation of Lateral Moraines (MELM)

This climate reconstruction method involves the approximation of the paleo-ELA using the maximum elevation of the Wahianoa moraines. Just like the previous method the extent of the Wahianoa moraines were traced. As shown in the above figure, the elevation of the paleo-ELA can be determined by looking at the topographic lines.

3.5.3 Terminus to Headwall Altitude Ratio (THAR)

Just as in the previous two methods, this method is also based on the tracing of the former extent of the Wahianoa Glacier. The altitude of the former terminus of the Wahianoa Glacier was approximated by looking at the contour lines (Figure 7.1, pg 110). This was a little difficult as it appears that there is no terminal moraine preserved in the Wahianoa valley. However, an approximation was determined by using the lower extent of the Wahianoa moraines.

Once the altitudes of the headwall and terminus were determined they were substituted into the equation below in order to calculate an approximation of the paleo-ELA. For the THAR values, Meierding (1982) found that ratios of between 0.35 and 0.4 gave the best results, especially on small cirque glaciers thus 0.35 and 0.4 were substituted into the equation for the THAR variable.

$$ELA = A_t + THAR(A_h - A_t)$$

(A_t = Terminus altitude, A_h = Headwall altitude, THAR = Terminus to headwall ratio)

3.5.4 Extrapolation method

Modern New Zealand ELAs display strong west-east and moderate north-south gradients (Shulmeister *et al*., 2005). The ELAs rise about 570m over a 400km (approximately 1.4m/km) distance from Caroline Peak in Fiordland to Mt Ella which is near the northernmost limit of the Southern Alps (Shulmeister *et al*., 2005). Shulmeister *et al*. (2005) used this northward ELA increase of 1.4m/km and applied it to distance between the Rakaia Valley and Cobb Valley, northwest Nelson to approximate the paleo-ELA. This climate reconstruction method employs this 1.4m/km northward ELA increase suggested by Shulmeister *et al*. (2005) and applies it to the Cobb Valley paleo-ELA, which is already established as being 1384m, in order to estimate the paleo-ELA of the Wahianoa Glacier. The northward distance between Cobb Valley and Mt Ruapehu was measured and multiplied by 1.4m to estimate the paleo-ELA of the Wahianoa Glacier (Figure 3.8).

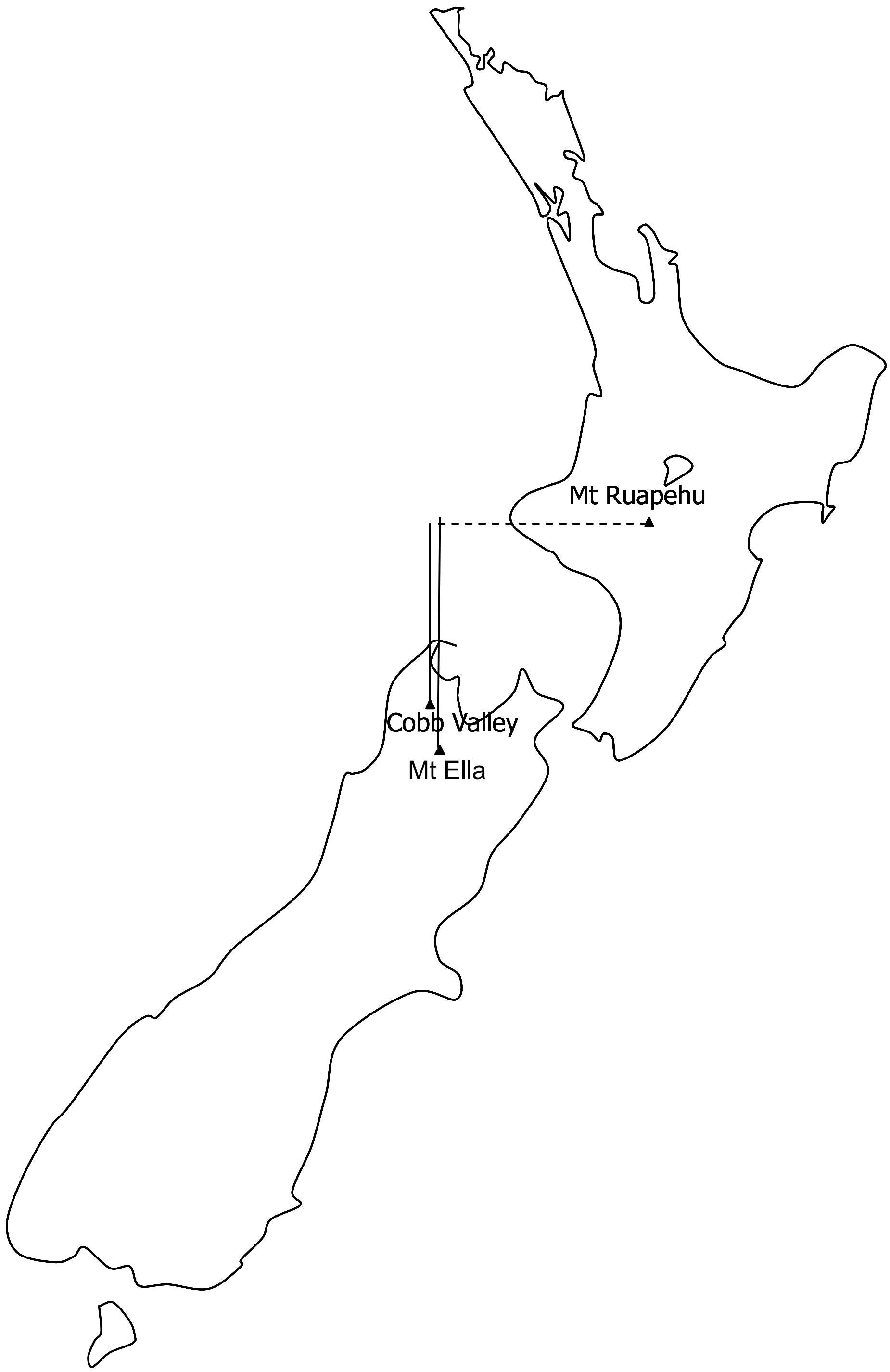

Figure 3.8. Map of New Zealand showing the northward vectors from Cobb Valley and Mt Ella to Mt Ruapehu.

Chapter 4: Results - Lichenometry

4.1 Introduction

This chapter presents results from the lichenometric method used on the Wahianoa moraines. The lichenometric results have been processed using the two main methods that exist in lichenometry today: growth curve and size-frequency. The first part of this chapter will look at the overall lichenometric results for the Wahianoa Valley before examining the results for each sampling area using both the growth curve and size-frequency methods in the second part of this chapter. The final part of this chapter will examine the factors which may affect the lichenometric results. An expected outcome of both lichenometric methods is that the lichens will demonstrate that the Wahianoa 'A', 'B' and 'C' moraines are of similar age, having formed in the same glacial event.

4.2 Lichenometric results for the Wahianoa Valley

The *Rhizocarpon geographicum* and *Rhizocarpon alpicola* species were measured in the Wahianoa Valley without any differentiation being made between the two species, as is the general practice by researchers such as Winkler (2000, 2004). A total of 605 lichens have been measured in the Wahianoa Valley using callipers, with the majority of them measured on the Wahianoa 'A' moraines. In Figure 4.1, the measurements (mm) show the average of the five largest lichen in each sample site.

4.2.1 General Trend

One expected trend would have been that a correlation existed between the sizing of the lichens and altitude whereby the smallest averages of the five largest lichens would be located at the highest altitudes. As can be seen from Figure 4.1, no such apparent trend is observed, which could be attributed to micro-environmental conditions that exist in the Wahianoa Valley (see Section 4.2.3.3).

Another expected trend would have been that, in general, the highest averages of the five largest lichens would be located on the furthest extents of the Wahianoa 'A', 'B' and 'C' moraines since these areas would have been the first to be deglaciated. However, as shown in Figure 4.1, this does not appear to be the case, which may also be attributed to micro-environmental conditions.

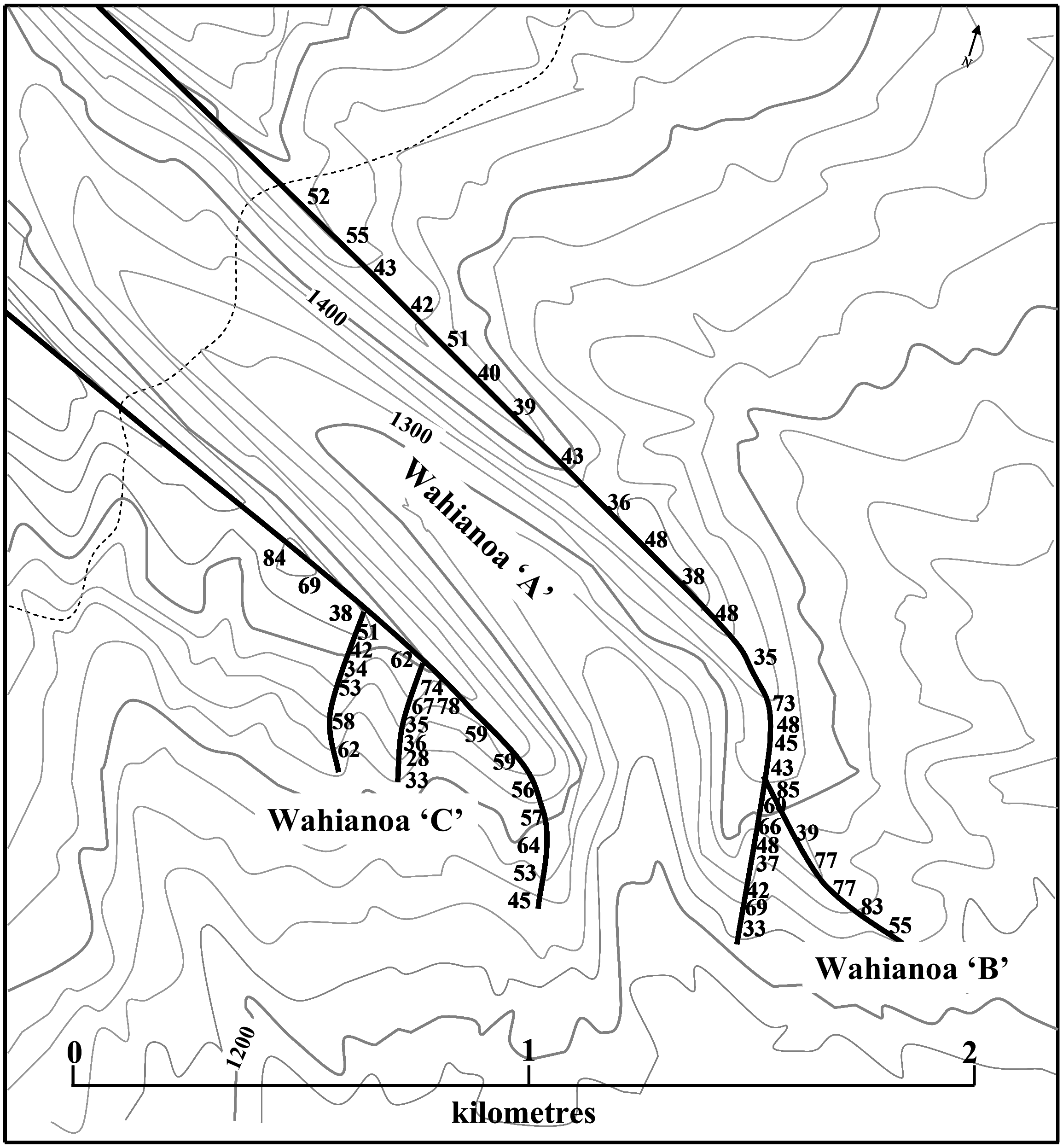

Figure 4.1. Lichenometric results for the Wahianoa Valley. Numbers indicate the average of the five largest lichens in each sample site.

4.2.2 Spatial Variability

An observation can be made from Table 4.1 and Figure 4.2 that the variation in the range of values displayed between the Wahianoa 'A', 'B' and 'C' moraines indicates that the Wahianoa 'B' moraine is potentially the oldest since it contains the majority of the highest averages of the five largest lichens. One implication of this is that the Wahianoa 'B' moraine may have formed during a different stage of the glacial event which caused the formation of the glacial landforms in the Wahianoa Valley.

Another observation to be made from Figure 4.2, is that the Wahianoa 'C' moraines contain the lowest averages of the five largest lichens. Therefore implying which they have formed in an earlier stage of the glacial event that caused the formation of the three sets of moraines.

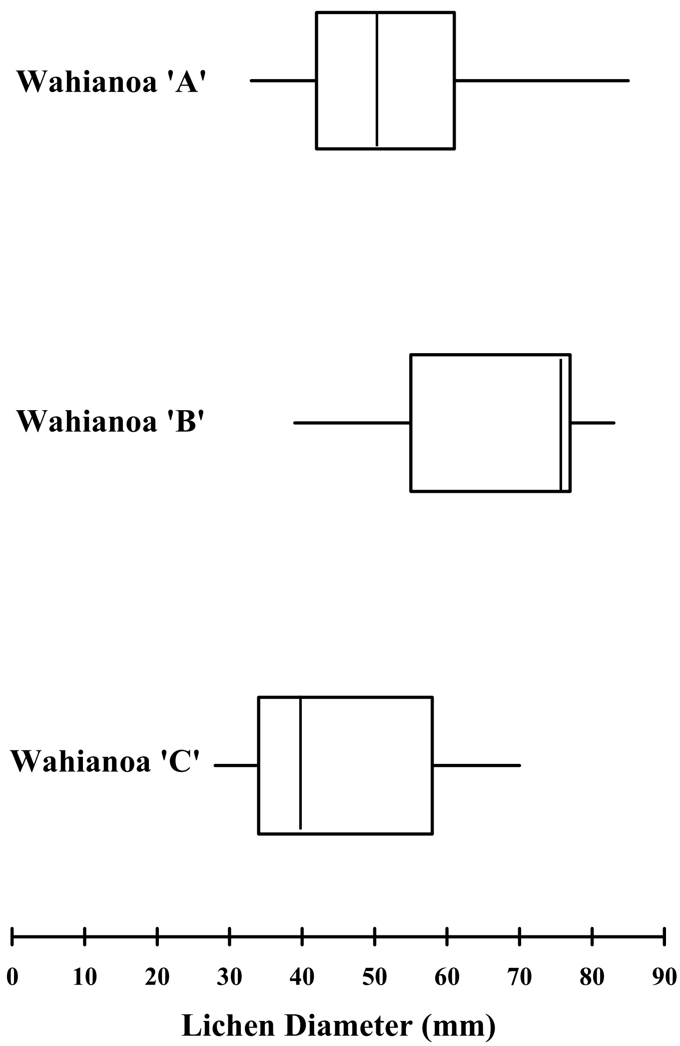

Figure 4.2. Box and Whisker plot for the average of the five largest lichens calculated for the Wahianoa Valley.

Table 4.1. Averages and range for lichenometric measurements in the Wahianoa Valley.

	Mean (mm)	Largest Lichen (mm)	Smallest Lichen (mm)
Wahianoa ‘A’	42	117	18
Wahianoa ‘B’	48	109	29
Wahianoa ‘C’	43	88	16

Similarly, it can observed from Figure 4.3, that not only is there a variation in the range of values within sample sites on each of the Wahianoa ‘A’, ‘B’ and ‘C’ moraines but also variations exist between each sample site.

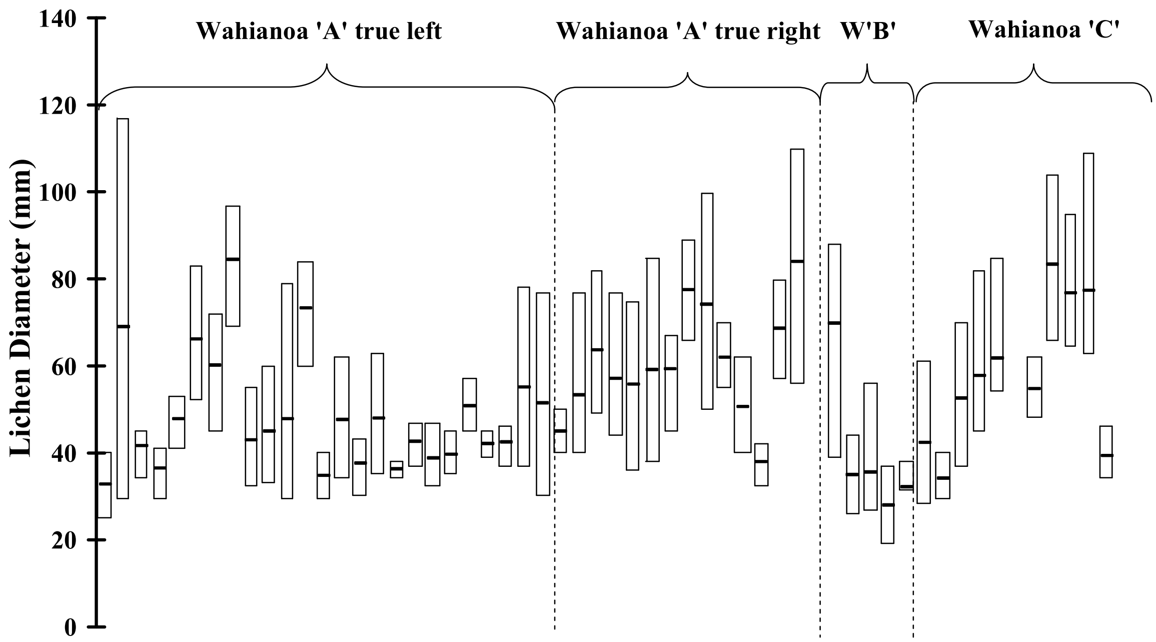

Figure 4.3. Range of the five largest lichens for each the sample sites in the Wahianoa Valley.

Examining the results in Figure 4.3 the following observations can be made:

- There is a greater variation between the sample sites on the true left of the Wahianoa ‘A’ moraines and those on the true right which also display the greater ranges.
- The Wahianoa ‘B’ (W ‘B’) moraine appears to have little variation in the size of the lichens between each sample site with the exception of the first sample site which also displays the greatest range.

- The Wahianoa 'C' moraines also display variations in lichen sizes between each sample site as well as variations in the range of values.

The results displayed in Table 4.1, Figures 4.2 and 4.3 demonstrate that not only is there spatial variability between each of the Wahianoa 'A', 'B' and 'C' moraines but also within the moraines between each sample site. Thereby, demonstrating that the factors which affect lichen growth have had differing effects on each sample site and on each moraine (see Section 4.5).

These results will now be processed using the two most common lichenometric methods (growth curve and size-frequency) in an attempt to obtain a relative age for the Wahianoa moraines, thereby identifying which glacial event caused their development.

4.3 Growth Curve

4.3.1 Introduction

As this is the first time that this method has been applied to the glacial deposits of Mt Ruapehu, there was no regional lichenometric growth curve already established. Since there was no suitable known age points in the Wahianoa Valley which could be used to construct the growth curve, it was necessary to find known age points as close as possible to Mt Ruapehu. The location of these was found to be the Ohakune cemetery (see Section 3.3 for location).

4.3.2 Construction of the growth curve

Lichens were measured, using callipers, on twelve headstones at the Ohakune Cemetery and displayed in Table 4.2 and Figure 4.4. The trend that was expected to be observed, in Figure 4.4, was that the size of the lichens would increase with the age of the headstones. As can be seen, this trend did not appear, which could be explained by a number of factors (see Section 4.5.2). However, the most commonly used type of growth curve is semi-logarithmic as used by researchers such as Innes (1984b), Winkler (2000) and Winkler

(2003). The best fit points to establish this curve (Figure 4.5) are indicated by triangles in Figure 4.4 and bold numbers in Table 4.2.

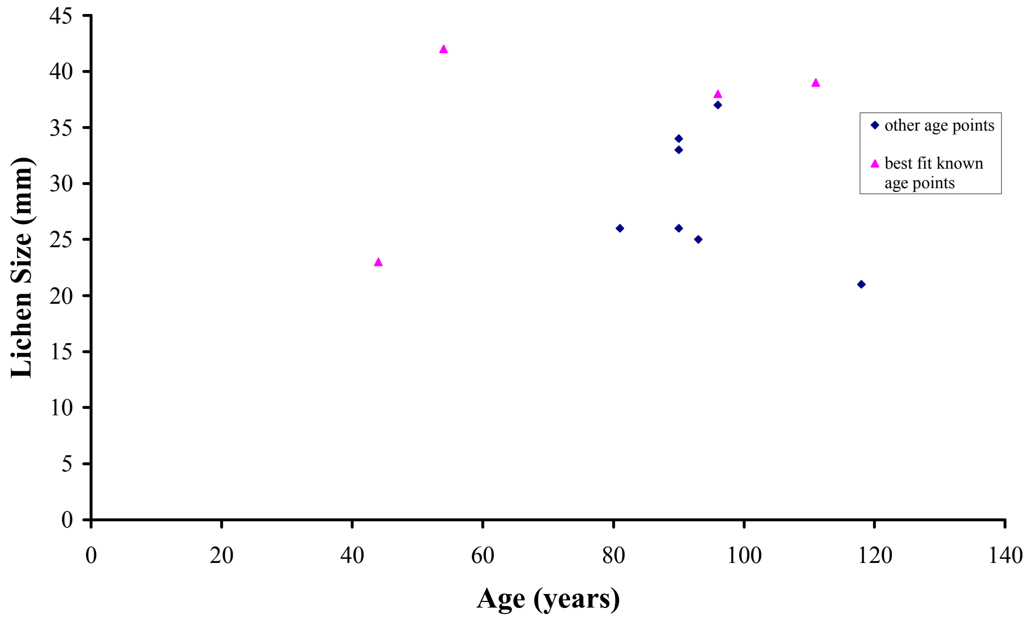

Figure 4.4. Graph of lichenometric results from Ohakune cemetery.

Table 4.2. Lichenometric results from Ohakune cemetery, bold values indicate those used in the growth curve (Figure 4.5).

Size (mm)	Date on gravestone
21	1888
39	**1895**
38	1910
37	1910
38	1910
25	1913
26	1916
33	**1916**
34	1916
26	1925
42	**1952**
23	**1962**

These points are then plotted in the lichenometric growth curve (Figure 4.5).

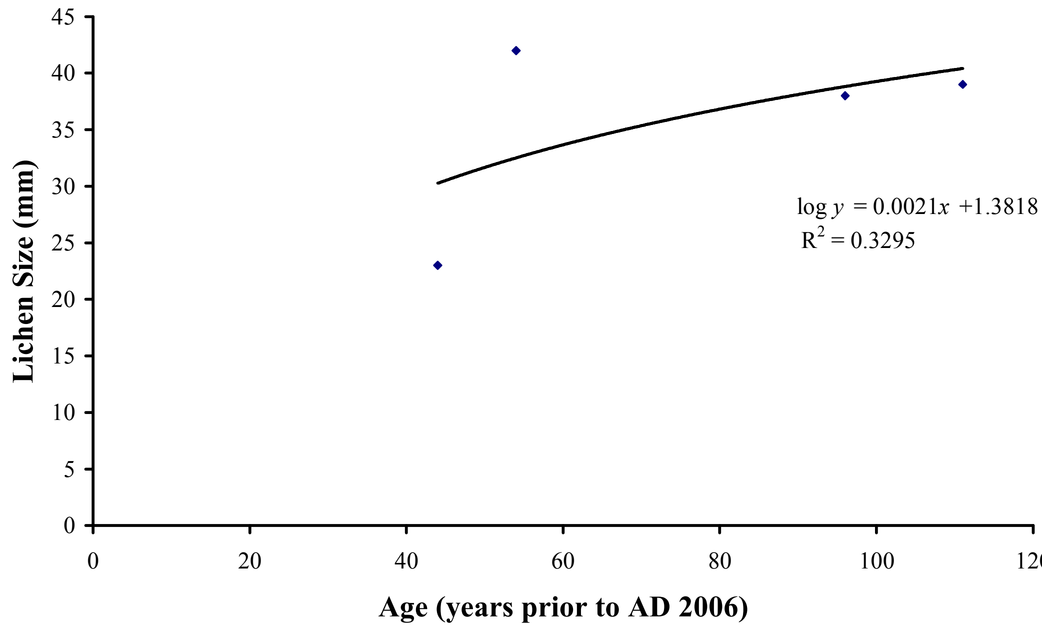

Figure 4.5. Lichenometric growth curve for Ohakune cemetery.

The equation derived from the lichen growth curve is: $\log y = 0.0021x + 1.3818$ (Equation 4.1). A regression analysis was conducted on the R^2 value shown on Figure 4.5 and this value was found to not be significant. The equation from Figure 4.5 can now be applied to the lichens found on the Wahianoa moraines in order to obtain an approximate age and thereby determine the glacial event in which they formed.

4.3.3. Application of growth curve to the Wahianoa moraines.

Table 4.3 displays the values from each of the three Wahianoa sample areas that will be substituted into Equation 4.1 derived from the growth curve, to attempt to date the moraines.

Table 4.3. Lichenometric results for the Wahianoa Valley

Moraine	Number of sample sites	Largest lichen (mm)[1]	Largest lichen (mean)[2]	Mean of five largest lichens (max)[3]	Mean of five largest lichens (mean)[4]
Wahianoa 'A'	39	117	66.2	84.0	52.9
Wahianoa 'B'	5	109	83.2	83.4	66.4
Wahianoa 'C'	10	88	60.1	69.8	45.0

[1]Single largest lichen for each moraine; [2]Mean of the largest lichen per sample site; [3]Highest average of the five largest lichens per moraine; [4]Mean of average of the five largest lichens per moraine

As can be seen in the second column, the largest lichen was found on the Wahianoa 'A' moraines followed by Wahianoa 'B' and 'C' respectively. One interpretation of this is that the Wahianoa 'A' moraines are slightly older than the Wahianoa 'B' and 'C' moraines. However, one of the biggest problems using the single largest lichen of each moraine to provide an approximation of the age of a surface is that this lichen may not be representative of the entire population.

The third column of Table 4.3 was determined by calculating the average of the largest lichens from each of the sample sites. It is observed in this column that the average largest lichen is found on the Wahianoa 'B' moraine. This could possibly indicate that the Wahianoa 'B' moraine is slightly older than the Wahianoa 'A' moraines. However, this calculation is solely dependent on lichens that have had optimum conditions for their growth and could possibly lead to sample areas appearing older than they in fact are.

The values in the fourth column in Table 4.3 are arrived at by first determining the average size of the five largest lichens per sample site for each moraine and secondly selecting the highest value per moraine. In contrast to the previous calculation the highest value in this column was found to be on the Wahianoa 'A' moraines followed very closely by the Wahianoa 'B' moraine.

In the final column in Table 4.3 the values were arrived at by calculating the mean of the average of the five largest lichens per moraine, instead of selecting the highest as in column four. As can be seen from Table 4.3, the largest value in this column is found on the Wahianoa 'B' moraine followed by Wahianoa 'A' and Wahianoa 'C' moraines respectively. From this it could be interpreted that the Wahianoa 'B' moraine is older than the other moraines as it has the largest value.

It is necessary to choose which of the above sets of values is the most appropriate to substitute into Equation 4.1. The values used by researchers, such as Winkler (2000, 2004), are the highest average of the five largest lichens (Column three in Table 4.3). It is viewed that these values are the most appropriate to use in determining age as it takes into account the less than optimal growing conditions for the lichens (Winkler, 2000).

The growth curve equation: $\log y = 0.0021x + 1.3818$ (Equation 4.1) is applied to the values in column four from Table 4.3, which can then allow for an approximate age to be determined for each of the moraines in the Wahianoa Valley. Table 4.4 displays the results from this calculation.

Table 4.4. Calculated ages of the moraines present in the Wahianoa Valley.

Site	Mean of five largest lichens (max)[3]	Approximate ages (yrs AD)
Wahianoa 'A'	84.0	1748
Wahianoa 'B'	83.4	1749
Wahianoa 'C'	69.8	1786

As can be seen from Table 4.4, the Wahianoa 'A' and Wahianoa 'B' sample areas are very close in age, while the Wahianoa 'C' moraines are slightly younger. A possible interpretation of this is that the Wahianoa Glacier advanced causing the formation of the Wahianoa 'A' moraines, then as it increased in volume it overtopped these moraines thereby causing the formation of the Wahianoa 'B' moraine. The Wahianoa 'C' moraines could have formed in a similar process but at a later stage in the event. In addition, the ages displayed in Table 4.4, place the formation of all three sample areas in the Wahianoa Valley as being between 1748 and 1786 AD which coincides with the Little Ice Age.

4.4 Size-Frequency

There are two steps to this lichenometric dating method, the first is the size-frequency histogram which is used to see if there is more than one age contained in the results. The second is a size-frequency curve from which the gradient indicates the age of the surface in question. First the main moraines (Wahianoa 'A') will be described followed by the Wahianoa 'B' and 'C' moraines.

4.4.1 Wahianoa 'A'

4.4.1.1 Size-frequency histogram

A total of 404 lichen diameters were measured on the Wahianoa 'A' moraines. Figure 4.6

is the size-frequency histogram plotting these values.

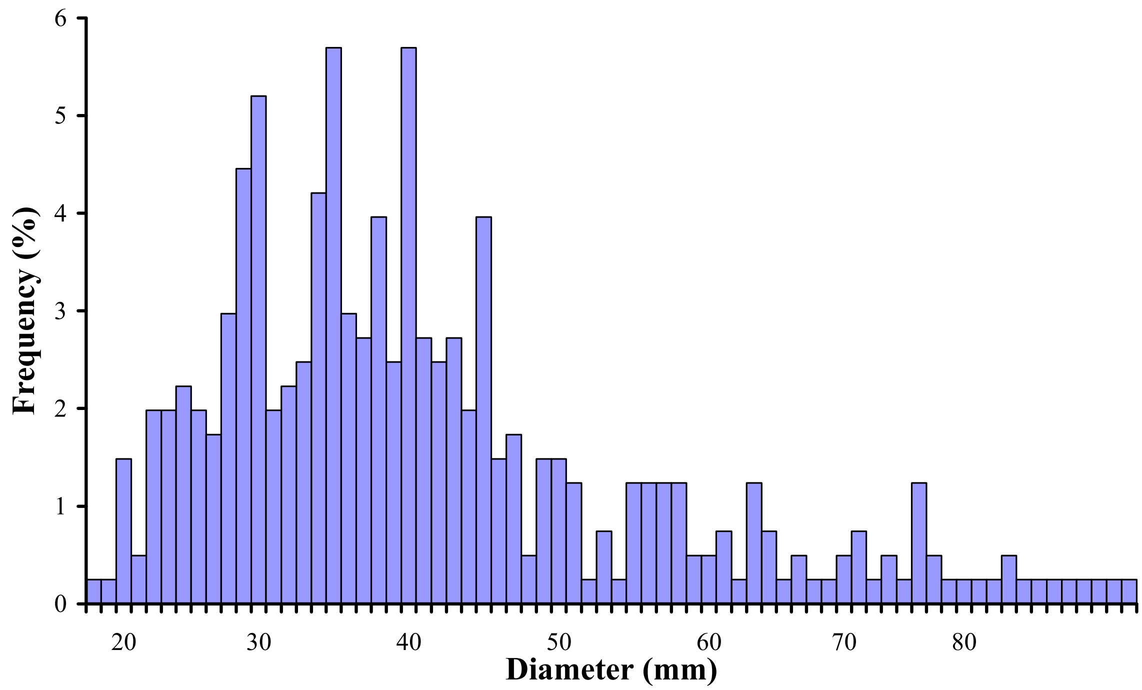

Figure 4.6. Size-frequency histogram for the Wahianoa ‘A’ moraines.

The majority of the lichens measured have a diameter between 20mm to 50 mm. Lichens with a diameter greater than 50mm tended to have a frequency of <10 and in most cases <5. The highest size-frequency was for lichens that have a diameter of 35mm and 40mm, both of had a frequency of 23. Another notable point of the graph is a frequency of 21 for lichens that have a diameter of 30mm.

It is also evident from this histogram that there is only one mode present thereby implying that the Wahianoa ‘A’ moraines are of a uniform age. The frequency distribution also appears to be positively-skewed and is leptokurtic, having a high degree of peakedness. All these observations are further demonstrated in Table 4.5 which displays the statistical values for the size-frequency method.

Table 4.5. Descriptive statistics of the lichenometric measurements

	N	Mean	Std Deviation	Skewness	Kurtosis
Wahianoa ‘A’	404	41.74	15.77	1.54	2.92
Wahianoa ‘B’	138	43.22	16.50	1.68	3.39
Wahianoa ‘C’	63	42.46	16.94	0.97	0.30

4.4.1.2 Size-frequency curve

A size-frequency curve (Figure 4.7) for the Wahianoa 'A' moraines was then constructed by taking the log of the frequency of the lichen sizes displayed in Figure 4.6. The gradient of this curve provides an indication of the age of the surface in question.

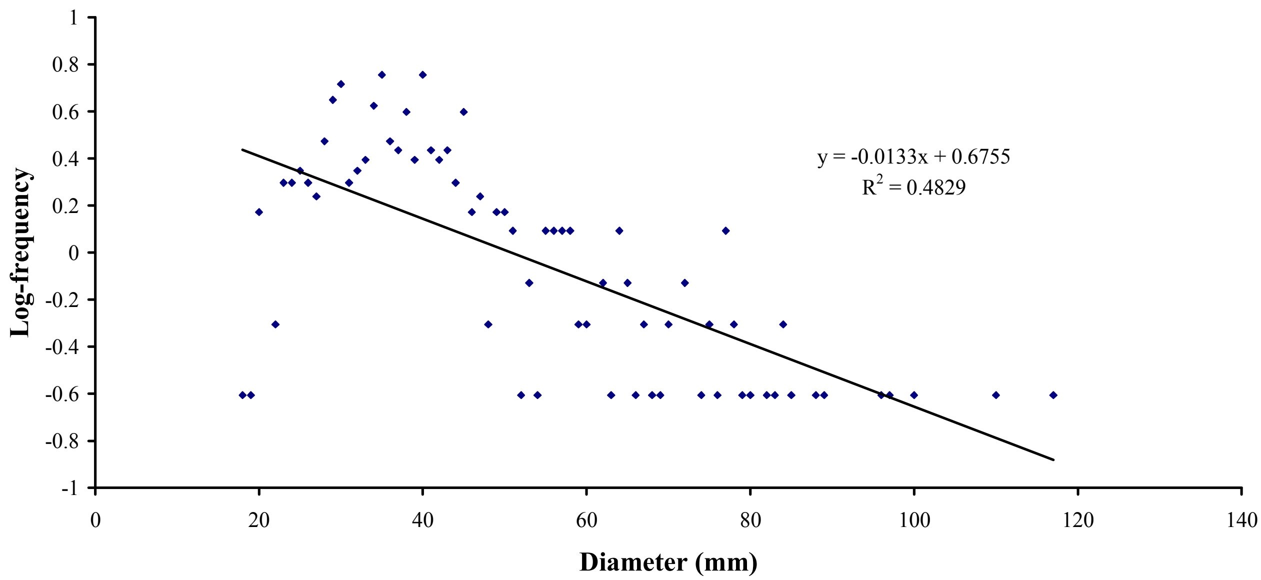

Figure 4.7. Lichenometric size-frequency curve for the Wahianoa 'A' moraines.

The R^2 value for Figure 4.7 is 0.4829 and this value is significant at the 99-100% interval ($p < 0.01$). The equation of the size-frequency curve (Figure 4.7) is $y = -0.0133x + 0.6755$, therefore the gradient is -0.0133. Bradwell (2004) suggests that size-frequency gradients equal to -0.0100 are approximately 400 years old and thereby the size-frequency gradient (-0.0133) for the Wahianoa 'A' moraines indicates that they are slightly younger than 400 years.

4.4.2 Wahianoa 'B' moraine

A total of 138 lichen diameters were measured on the Wahianoa 'B' moraine. Figure 4.8 is the size-frequency histogram plotting these values.

4.4.2.1 Size-frequency histogram

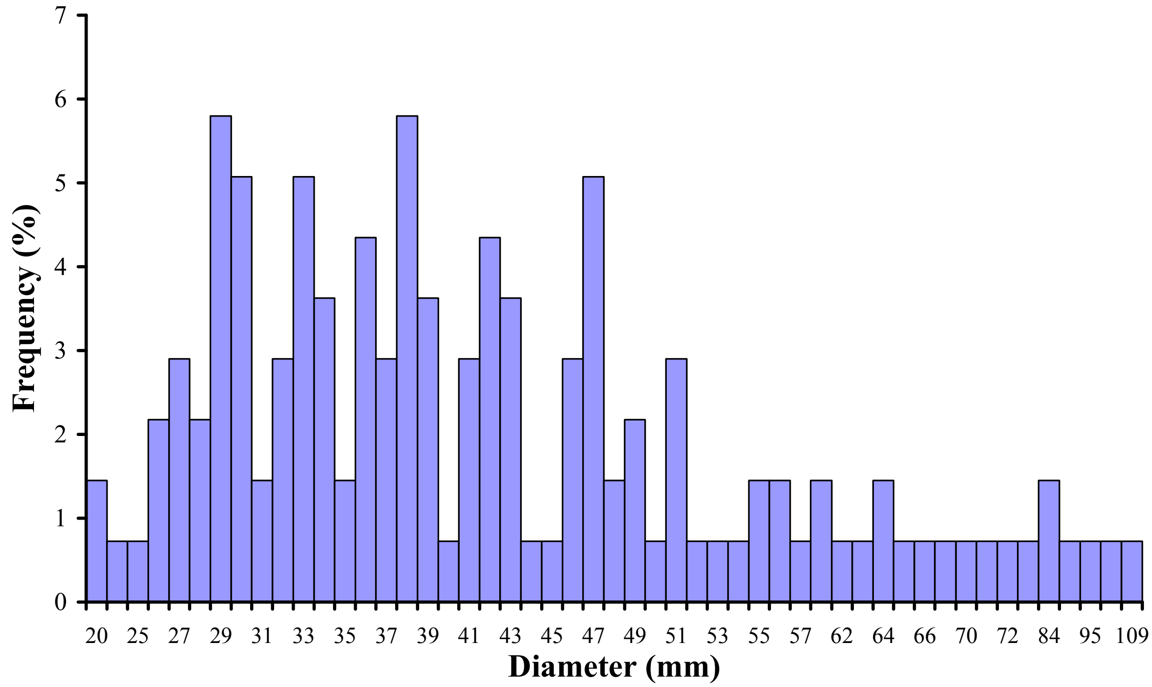

Figure 4.8 Histogram of the size-frequency for the Wahianoa 'B' moraine.

The majority of the lichens measured on the Wahianoa 'B' moraine had a diameter between 30mm and 50mm. The highest frequency belonged to lichens which had a diameter of 47mm.

It is also evident from this histogram that there is only one mode present thereby implying that the Wahianoa 'B' moraine is of a uniform age. The frequency distribution also appears to be positively-skewed with a skewness value is 1.68. It is also leptokurtic, having a high degree of peakedness as the kurtosis value is 3.39. All these observations are further demonstrated in Table 4.5 which displays the statistical values for the size-frequency method.

4.4.2.2 Size-frequency curve

A size-frequency curve (Figure 4.9) for the Wahianoa 'B' moraine was constructed by taking the $\log_{10}$ of the lichen diameters.

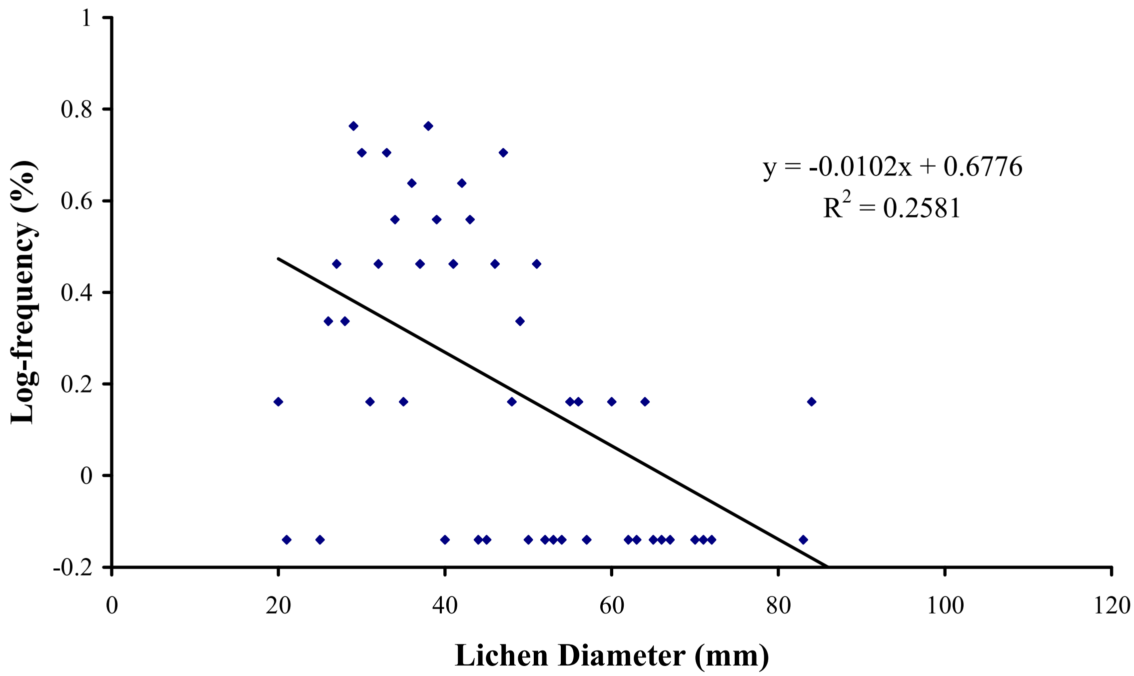

Figure 4.9. Size-frequency curve for the Wahianoa 'B' moraine.

The R^2 value for Figure 4.9 is 0.2581 and this value is significant at the 99-100% interval ($p < 0.01$). The equation from the size-frequency curve was found to be $y = -0.0102x + 0.8175$ therefore the gradient is -0.0102. A gradient of -0.0102 means that the Wahianoa 'B' moraine is approximately 400 years in age when compared to the size-gradients obtained by Bradwell (2004). Bradwell (2004) suggests that a size-frequency gradient equal to -0.0100 indicates that the area is approximately 400 years in age.

The gradient of this size-frequency curve is shallower than the gradient of the Wahianoa 'A' size-frequency curve (-0.0133) which could indicate that the Wahianoa 'B' is slightly older than the Wahianoa 'A' moraines.

4.4.3 Wahianoa 'C'

A total of 63 lichen diameters were measured on the Wahianoa 'C' moraines. Figure 4.10 is the size-frequency histogram plotting these values.

4.4.3.1 Size-frequency histogram

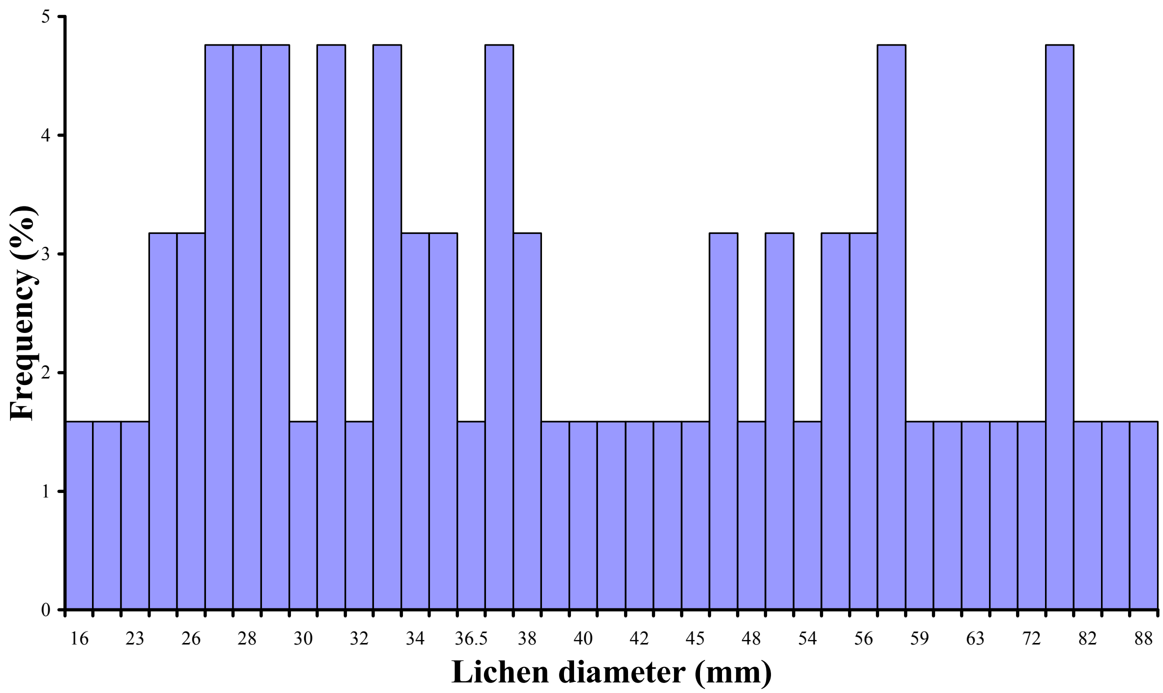

Figure 4.10. Histogram of the size-frequency for the Wahianoa 'C' moraines.

The majority of lichens measured had a diameter between 25mm and 38mm and a second smaller group with a diameter between 47mm and 80mm. As can be seen from Figure 4.10 the histogram appears to be bimodal, indicating that two ages could exist within the Wahianoa 'C' moraines. In addition, the size-frequency results for Figure 4.10 are not as positively skewed as the results for the other moraines in the Wahianoa Valley with a skewness value of 0.97 (Table 4.5). The kurtosis value for the histogram is 0.30 (Table 4.5) which indicates that the distribution is mesokurtic since the kurtosis value is close to zero.

4.4.3.2 Size-frequency curve

A size-frequency curve (Figure 4.11) for the Wahianoa 'C' moraines was constructed by taking the $\log_{10}$ of the lichen diameters. The R^2 value of 0.0604, was found to not be significant. The equation for the size frequency curve is $y = -0.0027x + 0.4886$ therefore the gradient for the curve in Figure 4.11 is -0.0027. This gradient when compared with

Bradwell's (2004) size-frequency gradients, indicates that the age is older than 400 years. In addition, it appears that the Wahianoa 'C' moraines are the oldest out of the three areas studied in the Wahianoa Valley.

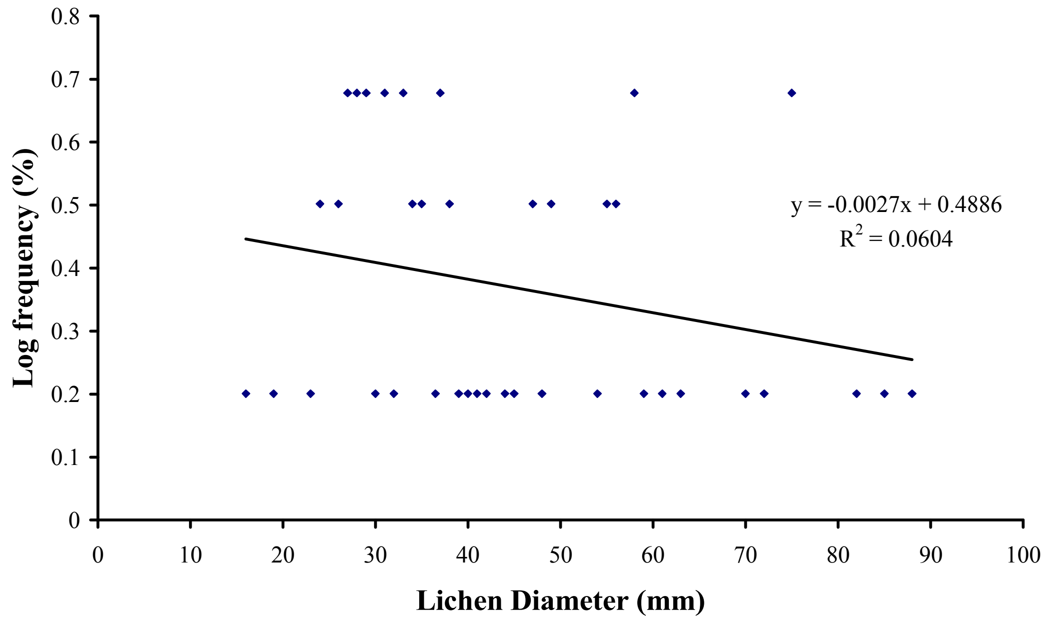

Figure 4.11. Size-frequency curve for the Wahianoa 'C' moraines.

4.5 Factors affecting lichenometric results.

4.5.1 Factors affecting lichen growth

The variation of the results and lack of general trend demonstrated in sections 4.2.1 and 4.2.2 could be influenced by a number of factors that affect the growth of lichens.

4.5.1.1 Surface Stability

Stability is one of the key factors affecting the growth of lichens as it governs when the lichens will commence colonization (Benedict, 1967). As Mt Ruapehu is an active volcano it is possible that, as a result of volcanic eruptions, existing surfaces of the Wahianoa moraines have become unstable at different times. In addition, instability can also be caused by periodic eruptions randomly depositing boulders onto the already existing surfaces of the Wahianoa moraines. The possible result of both these situations is the elimination of some existing lichen thereby causing recolonization of some surfaces and leading to smaller lichens being found in the vicinity of larger lichens.

A similar effect on surface stability may have been caused by one or more readvancements of the Wahianoa Glacier possibly during the Little Ice Age (see Section 4.5.1.4). Supraglacial deposits could have slid off the Wahianoa Glacier at random locations and become incorporated into the existing moraines.

4.5.1.2 Lithology

Another key factor that can affect the growth of lichens is lithology. In a stable surface environment, the degree of a boulders surface roughness dictates not only lichen colonization but also their growth rate. Benedict (1967) suggests that coarse-textured boulders are easier for lichens to colonize, are better at retaining moisture for lichen growth and providing shelter in the form of cracks and cavities which better protect young lichen. The benefits of the lithological features described by Benedict (1967) were observed in the Wahianoa Valley. The sizes of the lichens measured corresponded approximately with the degree of surface roughness of the boulder being colonized. Whereby, the larger lichens tended to be found on rougher surfaces, smaller lichens on finer and no lichen growth on polished surfaces.

It should be noted at this point that the spatial variation and lack of general trend observed in Sections 4.2.1 and 4.2.2 could have been due to an uneven placement of these boulders with differing degrees of surface roughness. However, while a quantitative study was not carried out, close observation of sample sites showed no major grouping of boulder surface types.

4.5.1.3 Micro-environmental conditions

Probably the most significant factor that can affect the growth of lichens is micro-environmental conditions. It has been suggested by researchers such as Benedict (1967), Burrows and Orwin (1971), Orwin (1972), Bull and Brandon (1998), Winkler (2004) and Lowell *et al.* (2005) that lichens prefer sheltered, humid conditions for growth.

In the Wahianoa Valley, the sheltered areas were found to be on the northern and eastern sides of the Wahianoa 'A', 'B' and 'C' moraines where the lichens were protected from the prevailing westerly winds. This was also observed by Benedict (1967). As expected the lichens in these areas tended to be larger and in some cases were up to 117 mm in diameter. In addition, it was generally observed that the largest lichens were found in areas where extra protection was also provided by other ridges (Figure 4.12).

In contrast, the lichens on the southern and western sides of the Wahianoa moraines are more exposed to prevailing westerly winds which can cause a lack of moisture and can also carry abrading sediments such as snow and ice. Researchers such as Benedict (1967), Burrows and Orwin (1971), and Orwin (1972) found the lichen growth rate in these areas to be slower and attributed it to these environmental conditions. In the Wahianoa Valley, the lichens were found to be generally smaller in these areas, with the smallest being 16mm in diameter and located on the southern aspect of the Wahianoa 'C' moraines (Table 4.1). A further consequence of these unfavourable micro-environmental conditions is that they can affect the characteristic circular shape of the lichens (Figure 4.13).

Figure 4.12. Lichen, approximately 80mm, located on the eastern slope of the true left Wahianoa 'A' moraine facing and near the junction with Wahianoa 'B' moraine.

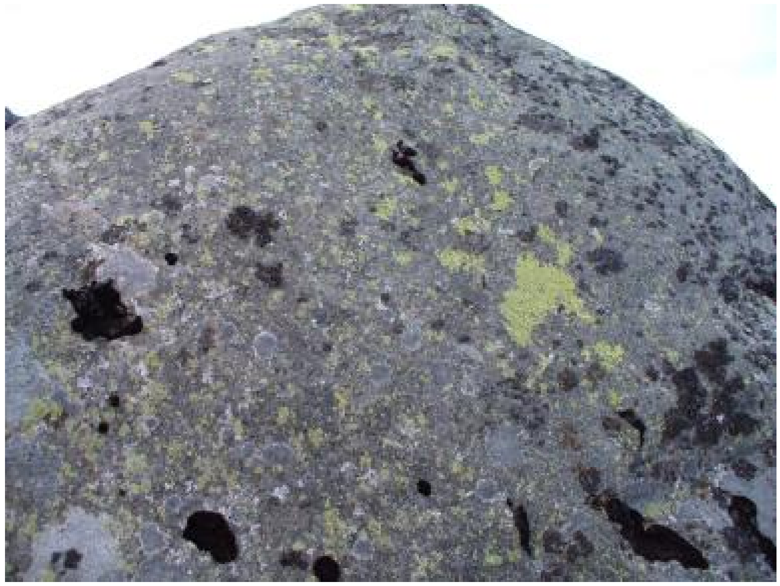

Figure 4.13. *Rhizocarpon* subgenus located on the southern face of the Wahianoa ‘A’ true left moraine. Note the lichen’s lack of circular shape.

An interesting point to note is that exposed to the unfavourable micro-environmental conditions on the top of the Wahianoa ‘A’ moraines there were some boulders which were found to have large lichens growing on their protected north facing facets while the lichens growing on the exposed facets were found to be considerably smaller in size and lacking circular shape.

4.5.1.4 Cooler temperatures

There is evidence of cooler periods occurring during the last 500 years in the North Island through tree rings in the Tongariro National Park measured by Palmer and Xiong (2004) and speleothems from the Waitomo Cave region measured by Williams *et al.* (2004). There is evidence from within this record coinciding with evidence of the Little Ice Age maximum (c. 1675 AD) in the South Island. During this time frame, temperatures were, at times, about 1°C lower than present day levels. It is possible that this temperature depression also occurred on Mt Ruapehu which, if this is the case, could have lead to a decrease in lichen growth rates thereby causing the moraines in the Wahianoa Valley to appear younger they are. Although this is difficult to prove or quantify, it is still needs to be considered as a factor affecting spatial variability of the lichen measurements.

4.5.1.5 Volcanic Eruptions

Volcanic activity could potentially slow the growth of lichens if there a sufficient volume of ash erupted into the atmosphere. There have been numerous eruptive events in recent times from Mt Ruapehu (see Section 2.21) with the last event occurring in 1995/96. It is possible that ash erupted during these events blocked sunlight thereby slowing the growth of the lichens. However, it is difficult to prove or disprove whether there is any influence on the growth of lichens by volcanic eruptions but due to Mt Ruapehu's volcanic history it is difficult to ignore.

4.5.2 Factors affecting the Growth Curve

Not only are there a number of factors that affect the growth of lichens, but also the growth curve used for age determination in the Wahianoa Valley as it was constructed from lichens in the Ohakune cemetery rather than Mt Ruapehu due to a lack of known age points in the Wahianoa Valley.

4.5.2.1 Environmental conditions

One of the most important factors that influenced the known age points used in the growth curve for the Wahianoa Valley is the environmental conditions that exist in Ohakune cemetery. It was observed in Ohakune cemetery that the environmental conditions did not appear to favour the growth of lichens as the gravestones are exposed to gusty winds loaded with abrading particles such as snow. Any gravestones which were sheltered also had other vegetation growing on their surface with which the lichens had to compete.

4.5.2.2 Differing lichen species

The Ohakune cemetery is not located in an alpine environment which has led to different lichen species growing on the headstones. These species may have different growth rates to the *Rhizocarpon* subgenus found in the Wahianoa Valley. If the lichen species in the Ohakune cemetery have a faster growth rate than the *Rhizocarpon* subgenus then when the growth curve is applied to the Wahianoa Valley it could cause an overestimation of the ages of the moraines. However, if the lichen species has a slower growth rate then the opposite situation will occur and the application of the growth curve will cause the moraines to appear older.

4.5.2.3 Lithology

Another factor which can affect the growth curve used on the Wahianoa Valley is the lithology of the gravestones in the Ohakune cemetery. The most common rock type used in the Ohakune cemetery is granite but this appears to only have been used since the 1930s. Prior to this another rock type resembling andesite had been used. These earlier headstones appear to have very little lichen growth due to a lack of surface roughness, while the granitic gravestones had larger lichens due to a higher degree of surface roughness. This observation was also made by Winkler (2003) in Norway where larvikite gravestones provided a rough surface for the lichens to grow on which seemed to be in their favour.

4.5.2.4 Anthropogenic influence

Another important factor to take into account when using the growth curve is the anthropogenic influence in the Ohakune cemetery. It is possible that there was a time delay with the emplacement of the headstones in the cemetery, thereby allowing for the commencement of the growth of lichens to occur prior to emplacement. In addition, there are signs of disturbance in the cemetery indicating that the oldest headstones may have been cleaned at some unknown point in time. If this is the case this may account for the lack of older lichen in the cemetery. The inclusion of possible older known age points would provide a different equation from the growth curve and ultimately a slightly older age of the Wahianoa moraines. A better growth curve may possibly be constructed using the tephras present in the Wahianoa moraines as these have been well documented and will probably provide a better idea on the age of the moraines in the Wahianoa Valley. However, some researchers such as Winkler (2000) consider tephras to be too old for accurate construction of a growth curve.

4.5.2.5 Coalesced lichens

Although obvious coalesced lichens were avoided there are some that could have still unknowingly been incorporated in the lichen measurements taken from the Wahianoa

Valley. Coalesced lichen can cause false readings of measurements thereby influencing the results.

4.6 Summary

As stated at the beginning of this chapter, an expected outcome of the two lichenometric dating methods (growth curve and size-frequency) is that the Wahianoa 'A', 'B' and 'C' moraines are of a similar age, having formed in the same glacial event.

From Table 4.6 it can be seen that both methods indicate that the Wahianoa 'A' and 'B' moraines formed at the same time. But the growth curve shows that the Wahianoa 'C' moraines formed at an earlier time, whereas the size-frequency method shows it to have formed at a later time. Also, the two methods produced two sets of dates differing by approximately 150 years. One possible cause for the difference in ages is that the size-frequency method uses the entire population of lichens, whereas the growth curve method uses a smaller proportion of the population.

Table 4.6. Summary of ages for the Wahianoa Valley.

Site	Growth Curve (date AD)	Size-frequency (date AD)
Wahianoa 'A'	1748	~1606
Wahianoa 'B'	1749	~1606
Wahianoa 'C'	1786	Pre-1606

To check the age differences between the three moraines (Table 4.6) a t-test was carried out in order to see if any differences in age do actually exist between the areas. The resulting *P* values (Table 4.7) were all greater than 0.05 which indicates that no difference exists between the Wahianoa 'A', 'B' and 'C' moraines thereby implying that they were formed in the same glacial event.

Table 4.7. Summary of T-test values for the Wahianoa Valley.

T-test between	Critical value of *t*	*t* statistic	*P* value
Wahianoa 'A' and 'B'[1]	1.65	-1.10	0.14
Wahianoa 'A' and 'C'[1]	1.65	-0.31	0.38
Wahianoa 'B' and 'C'[2]	1.97	0.42	0.68

[1] 1-tailed t-test; [2] 2-tailed t-test

Although, the lichenometric methods did not conclusively support the expected outcome that the Wahianoa 'A', 'B' and 'C' moraines formed in the same glacial event, the t-test carried out on the lichen measurements did provide support for this expected outcome. Hopefully the next two results chapters will help to obtain a better estimation of the relative ages of the Wahianoa 'A', 'B' and 'C' moraines.

Chapter 5: Results - Schmidt Hammer method

5.1 Introduction

The Schmidt Hammer was used in the Wahianoa Valley to try and determine a relative age of the ridges present. In addition, the roundness of each boulder, was noted according to Power's roundness to see if a relationship existed between the rebound (R values) and the roundness of the boulder. One expected outcome for this chapter would be to establish a relationship between these two variables specifically that as a boulder becomes rounder due to processes, such as subaerial weathering, the rebound (*R*) value would decrease indicating an increase in age. A second expected outcome is that the Schmidt Hammer (R) values will indicate that the Wahianoa 'A', 'B' and 'C' moraines formed during the same event. The first section of this chapter will present the overall results from using the Schmidt Hammer method in the Wahianoa Valley. The second section will examine the results arrived at from using Power's roundness on each of the boulders examined in section 5.1 and determine if the expected outcome does exist. The final section of this chapter will describe all the factors that can affect the results from the Schmidt Hammer method.

5.2 Schmidt Hammer measurements

An L-type Schmidt Hammer was used in the Wahianoa Valley on boulders, which appeared to be of a similar lithology (see Section 5.4.1). The total number of boulders measured in the Wahianoa Valley was 280, with 5 blows applied to each boulder. The median value was determined from each set of five values taken from each boulder and used in an attempt to determine relative ages of the three study areas in the Wahianoa Valley.

5.2.1 General trends

Figure 5.1 is an outline of the Wahianoa Valley with the median rebound values for each sample site determined from the medians of each boulder in each sample site. An expected trend upon examination of Figure 5.1 is that the lower R values would be found towards the base of the Wahianoa 'A' moraines since this would have been one of the first locations to be deglaciated. However, such a trend does not appear to exist as the lower R values are found randomly at various locations along the Wahianoa 'A' moraines. This lack of trend could be due to differences in petrography which lead to differences in weathering rates (see Section 5.4.1).

The first obvious trend that can be observed from Figure 5.1 is that the rebound values for the Wahianoa 'B' and 'C' moraines show little variance indicating that the ages of these moraines are close to uniform. Another obvious trend that can be observed from Figure 5.1 is that all the rebound (R) values on the true right side of the Wahianoa 'A' moraines show little variance which could indicate that the age of these deposits is nearly uniform. The highest rebound value for the true right side was 38 and the lowest was 33 (Figure 5.1). In contrast, there is a larger variance in the rebound values for the true left side of the Wahianoa 'A' moraines. The highest rebound value for this side was 48 and the lowest 21 (Figure 5.1), which again could be explained by differences in petrography (see Section 5.4.1). This substantial difference in rebound values indicates an approximate age difference of several thousand years when compared with rebound values recorded by Winkler (2005) in Mt Cook National Park. Another observation to be made from Figure 5.1 is that there is a cluster of values ranging from 46-48 near the bend on the true left side of the Wahianoa 'A' moraines. This again could be explained by differences in petrography. However, this could also indicate that there was an overtopping of this moraine by ice during an advance of the Wahianoa Glacier.

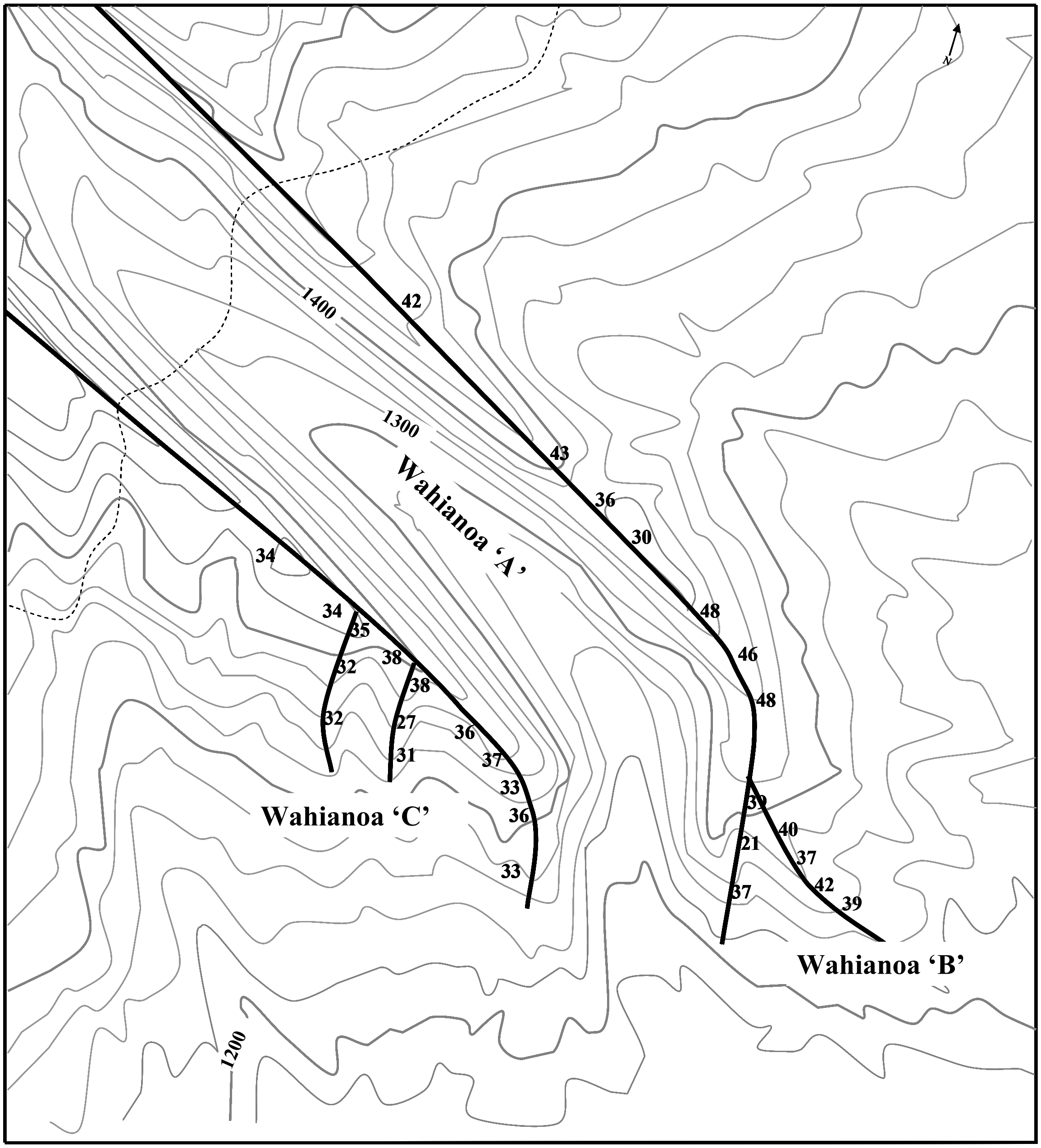

Figure 5.1. Schmidt hammer measurements for the Wahianoa Valley.

5.2.2 Spatial variability

As can be seen from Figure 5.2, not only is there a wide range of rebound (*R*) values recorded within each sample site in the Wahianoa Valley but also between these sample sites. There a number of factors which may have influenced these R values (see section 5.4.1).

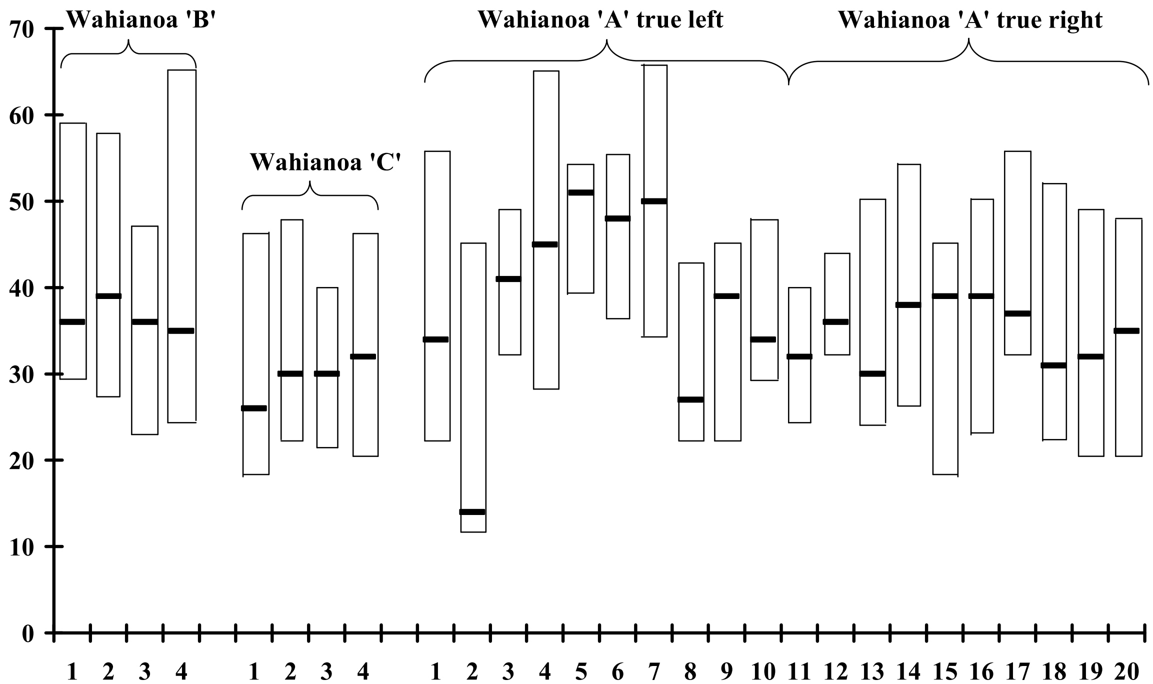

Figure 5.2. Box plots of the range of R values measured at each sample site on the Wahianoa ‘A’, ‘B’ and ‘C’ moraines.

There are two main observations to be made from examining Figure 5.2:

- There appears to be two groups of R values which exist on the Wahianoa ‘A’ moraines. Site numbers 3-7 seems to have a similar range of R values which could suggest that the boulders are of a similar age. Site numbers 1, 2 and 8-20 appear to be quite similar in their R value ranges again indicating that they are of a similar age. The preservation of these two groups of R values in the Wahianoa ‘A’ moraines indicate that there are two ages contained in these moraines. These two ages could indicate an advancement and readvancement of the Wahianoa Glacier. However, one major problem with this theory is that the sites with the highest R values are located towards the end of the true left of the Wahianoa ‘A’ moraines (Figure 5.2). If evidence existed for an advance and readvance it should be found on both sides of the Wahianoa ‘A’ moraines, which it is not. This may further support the theory that the Wahianoa Glacier overtopped the true left of the Wahianoa ‘A’ moraines or may simply have been caused by petrographical differences or possibly a combination of both influences.

- Also, it can be seen from Figure 5.2, that the rebound values for Wahianoa 'C' and Wahianoa 'B' appears close in age to sites 1, 2 and 8-20 for Wahianoa 'A' indicating that they are not too far apart in age.

Each of the sample locations will now be looked at in turn.

5.2.3 Individual Sampling sites

5.2.3.1 Wahianoa 'A'

As can be seen from Figure 5.1, the majority of measurements (200) for the Schmidt Hammer method were conducted on the Wahianoa 'A' moraines. Figure 5.3 is a histogram displaying the R values measured on the Wahianoa 'A' moraines.

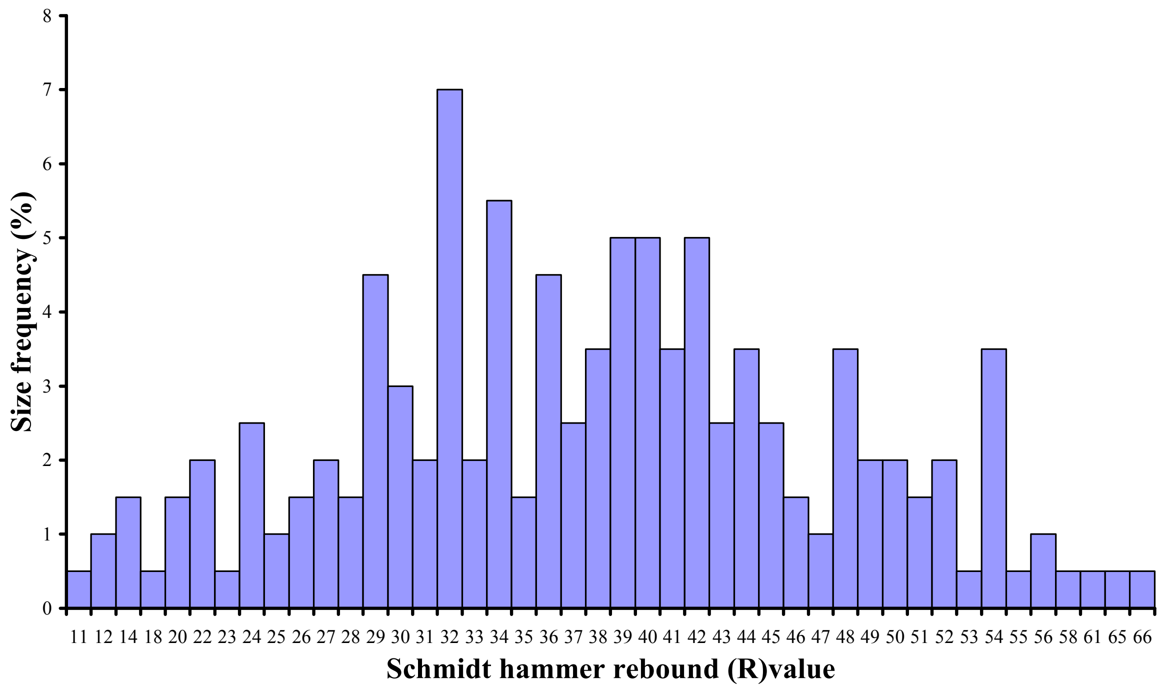

Figure 5.3. Size-frequency histogram of R values versus the size-frequency (%) for the Wahianoa 'A' moraines.

As can be seen from Figure 5.3, the histogram appears to be approaching normal distribution. However, it can also be interpreted that the distribution is bimodal and that these two modes are close in terms of R values, indicating that the two ages preserved in the Wahianoa 'A' moraines are close together. This could further support the theory that there was overtopping of the Wahianoa 'A' moraines by the Wahianoa Glacier, which was previously suggested by observations made from Figures 5.1 and 5.2.

The skewness value for this distribution (Table 5.1) indicates that the distribution is almost perfectly symmetrical when close to zero. The distribution displayed in Figure 5.3 is platykurtic as the kurtosis value is less than zero (Table 5.1) having a low degree of peakedness.

Table 5.1. Descriptive Statistics for the R values found in the Wahianoa Valley

Site	Sample Size	Median	Mean	Standard Deviation	Skewness	Kurtosis
Wahianoa 'A'	200	38	37	11.8	0.03	-0.47
Wahianoa 'B'	40	37	39.5	11.5	0.34	-0.08
Wahianoa 'C'	40	32	31.8	10.5	0.46	-0.48

5.2.3.2 Wahianoa 'B'

As can be seen from Figure 5.4 the distribution of the Wahianoa 'B' rebound (R) values, of the 40 boulders measured, is slightly positively skewed and mesokurtic with a low degree of peakedness (Table 5.1).

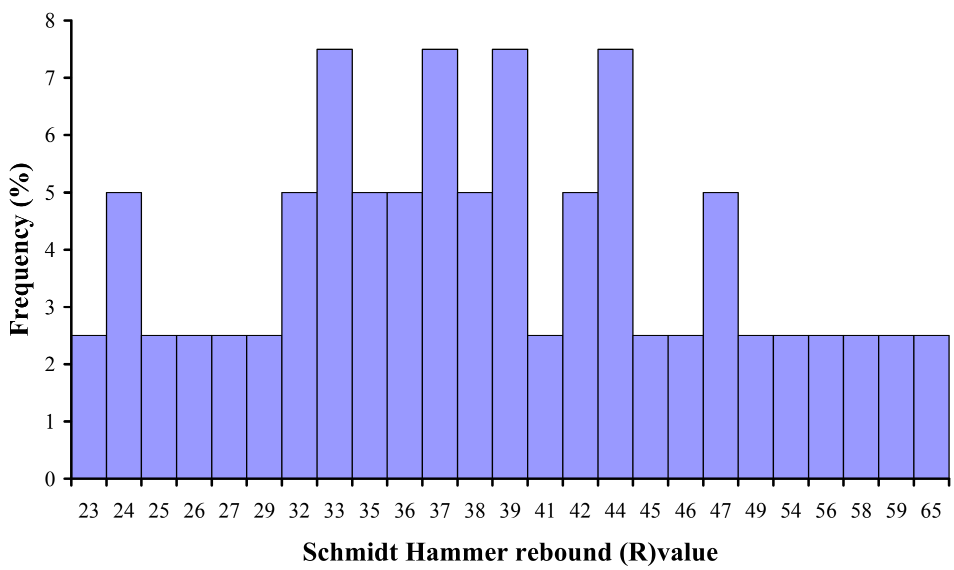

Figure 5.4. Size frequency histogram for R values of the Wahianoa 'B' moraine.

In addition, the distribution of the data in Figure 5.4 appears to contain one mode. This suggests that the Wahianoa 'B' moraine probably formed in a single glacial advance of the

Wahianoa Glacier. Also, it possibly suggests that there has not been a re-advancement of the Wahianoa Glacier since the moraines formation. The mode of the distribution further supports the observation made from Figure 5.2, where there was only slight variation between the sample sites of the Wahianoa 'B' moraine.

5.2.3.3 Wahianoa 'C'

The distribution of the data in Figure 5.5 is slightly positively skewed, while the kurtosis value indicates that it is leptokurtic with a low degree of peakedness (Table 5.1).

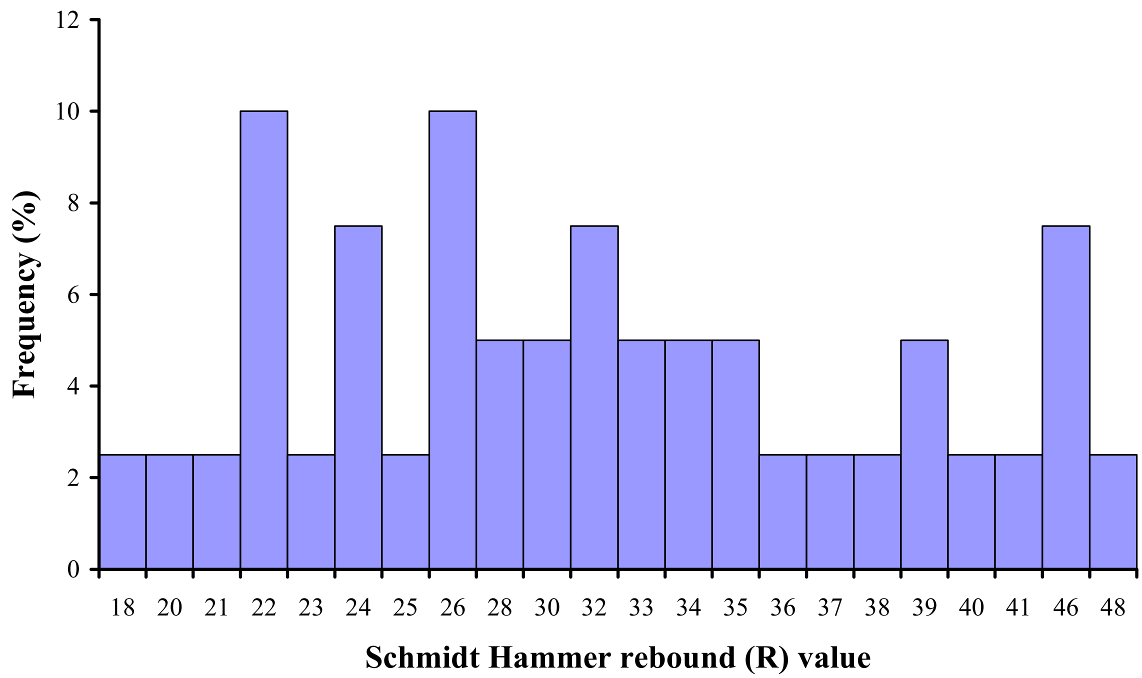

Figure 5.5. Histogram of the Wahianoa 'C' rebound (R) values.

As can be seen from Figure 5.5, it is difficult to distinguish whether the distribution is bimodal or multimodal. If the distribution is bimodal, then there are two ages contained within the Wahianoa 'C' moraines. However, if the distribution is multimodal then it becomes difficult to identify how many ages may be preserved in the Wahianoa 'C' moraines. One influencing factor may be that, deposits of differing ages from the true right of the Wahianoa 'A' moraines have become incorporated in the Wahianoa 'C' moraines due to their proximity.

5.2.3.4 Approximate age of the Wahianoa moraines

Based on the mean values in Table 5.1, a comparison can be drawn with results measured in the South Island of New Zealand by Winkler (2005). Some similarities can be observed with the mean R values for the Birch Hill moraines (Table 5.2). The mean R values for these moraines range between 36.78 and 40.56 while those for the Wahianoa 'A' and 'B' moraines have mean R values of 37.05 and 39.48, indicating that they could have formed in at approximately the same time. The Wahianoa 'C' moraines, which have a mean R value 31.79, may have formed at an earlier stage. While the boulders measured on the Birch Hill moraines are of a different lithology to those measured in this study, the Birch Hill study is the only other Schmidt hammer study conducted in a glacial environment in New Zealand and therefore to that degree has relevance.

Table 5.2. Comparison between selected R values for the Mueller Glacier catchment and the Wahianoa Valley.

Study	Location	Mean R value and S.E.	Approximate age (yrs BP)
Winkler (2005)	Birch Hill	40.56 ± 2.26	c. 10,000
	Birch Hill	36.78 ± 2.53	
	Birch Hill	37.06 ± 2.94	
This study	Wahianoa 'A'	37.05 ± 1.63	c. 10,000
	Wahianoa 'B'	39.48 ± 3.56	
	Wahianoa 'C'	31.79 ± 3.25	Prior to c.10,000

A T-test was carried out on the Schmidt hammer rebound (R) values for the Wahianoa Valley in order to deteremine if in fact any differences do exist between the different study areas. As can be seen from Table 5.3, there does not appear to be a difference in age between the Wahianoa 'A' and 'B' moraines. However, there does appear to be a difference in age between both the Wahianoa 'A' and 'C' and Wahianoa 'B' and 'C'.

Table 5.3. Ttest values for the Wahianoa Valley.

Ttest between	Critical value of *t*	*t* statistic	*P* value
Wahianoa 'A' and 'B'[1]	1.65	-0.93	0.18
Wahianoa 'A' and 'C'[1]	1.65	3.82	<0.05
Wahianoa 'B' and 'C'[2]	1.99	4.01	<0.05

[1] 1-tailed t-test
[2] 2-tailed t-test

5.3 Roundness

The roundness of each of the boulders measured using the Schmidt hammer method was evaluated according to Power's Roundness, with a value being assigned to each roundness category (1= very angular, 2= angular, 3=sub angular, 4=sub rounded, 5=rounded, 6= very rounded).

5.3.1 Roundness frequency

Figure 5.6 is a histogram displaying the frequency of the roundness categories for the Wahianoa 'A', 'B' and 'C' moraines.

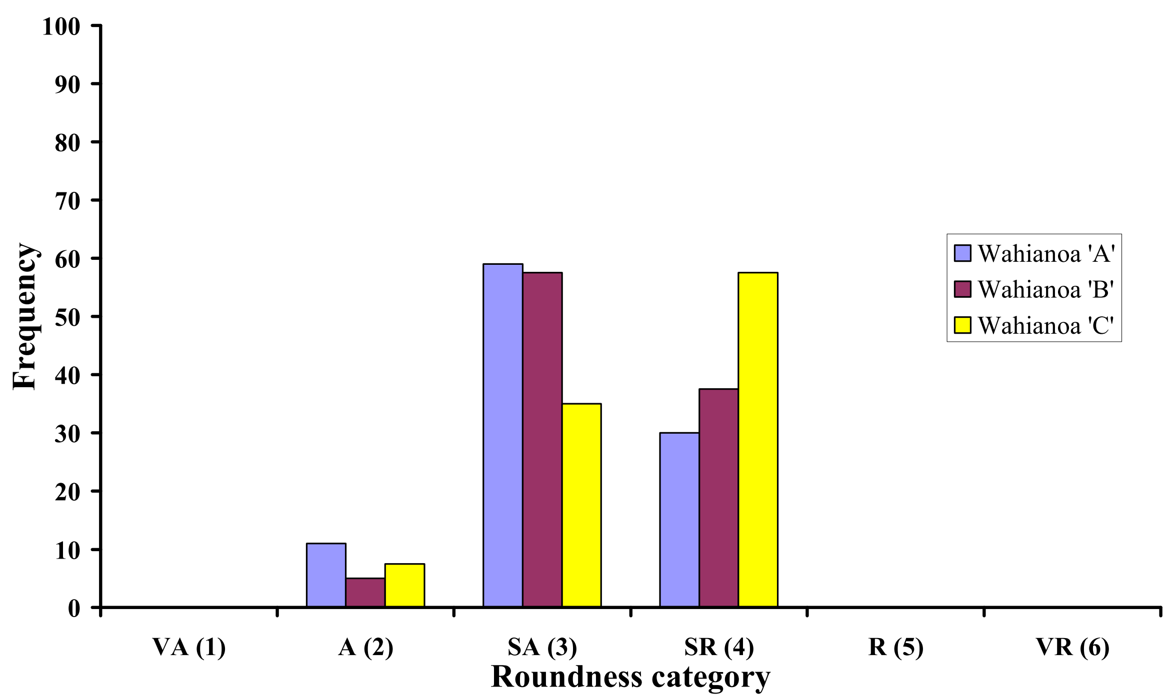

Figure 5.6. Histogram of the frequency of the roundness categories

As can be seen from Figure 5.6 there were only three roundness categories were found in the Wahianoa Valley. There are three key observations to made from Figure 5.6:

- The majority of the boulders examined were subangular (SA), indicating that they have undergone some form of weathering either during transportation or during post deposition onto the moraines or a combination of the two processes (Table 5.4 and Figure 5.6).
- There were also a number of subrounded boulders measured in the Wahianoa Valley (Table 5.4 and Figure 5.6). The presence of these boulders indicates that some boulders have been exposed longer thereby undergoing more subaerial weathering. Also, it indicates that some boulders have travelled further from their source thereby undergoing a greater amount of mechanical weathering during transportation before being incorporated into the moraines.
- The presence of the smaller number of angular boulders indicates that some may have been erupted directly in more recent times onto the surfaces of the Wahianoa moraines thereby undergoing a lesser amount of weathering. It is also possible that due to petrographical differences these boulders may have been less affected by mechanical weathering during transportation (see Section 5.4.2).

Table 5.4. Frequency (%) values for the roundness measurements for the Wahianoa Valley.

Site	Power's Roundness category					
	Angular (A)		Subangular (SA)		Subrounded (SR)	
	Number	%	Number	%	Number	%
Wahianoa 'A'	22	11	118	59	60	30
Wahianoa 'B'	2	5	23	57.5	15	37.5
Wahianoa 'C'	3	7.5	14	35	23	57.5

These results from the Power's roundness evaluation were then plotted against their respective R values in order to see if a relationship exists between the roundness of a boulder and its rebound value (Figure 5.7).

5.3.2 Roundness versus Schmidt hammer rebound (R) values

A negative trend would be expected to be observed with Figure 5.7 indicating that the R value decreases with an increase in boulder roundness. Therefore, indicating that as the boulder increases in age its roundness increases due to a longer exposure to subaerial weathering. It can be seen from Figure 5.7, that the Wahianoa ‘A’ moraines are the only location to display a slight negative trend between these two variables. In contrast, the Wahianoa ‘B’ and ‘C’ moraines both display positive trends which could be explained by influencing factors (Section 5.4).

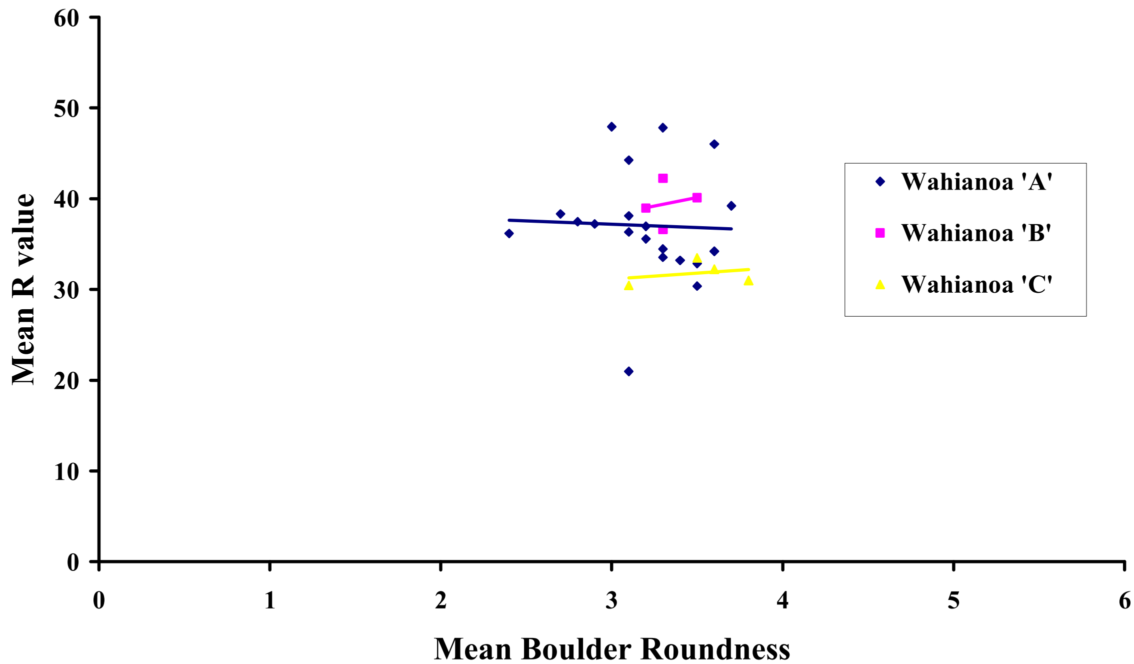

Figure 5.7. Mean Roundness versus Mean R value of each site.

As can be seen from Figure 5.7, the expected trend of establishing a relationship between the roundness of the boulders measured and their Schmidt hammer R values does not appear to have eventuated to any great degree for the Wahianoa ‘A’ and not at all for the Wahianoa ‘B’ and ‘C’ moraines.

5.4 Factors affecting Schmidt hammer rebound (R) values and boulder roundness

The rebound values measured in the Wahianoa Valley were highly variable with the average R values ranging from 21 to 48 (Figure 5.1). Not only did the differences in R values exist between the Wahianoa ‘A’, ‘B’ and ‘C’ moraines but also between each sample site (Figure 5.2). There are various factors which may help to explain these differences.

5.4.1 Lithology

One of the major factors that can affect the R values and boulder roundness is lithology. Even though the boulders measured in this study using the Schmidt hammer were all andesitic in composition, there are petrographical variations that exist between them. These petrographical variations can lead to differences in surface roughness (McCarroll, 1991; Goudie, 2006), weathering rates (Goudie, 2006) and surface hardness of a boulder which can affect the R values measured (Winkler, 2005).

The majority of the boulders measured had similar surface textures in that they were not completely smooth. Although in some cases they had some minor surface irregularities, it was still possible to avoid these irregularities when obtaining the measurements. These minor surface irregularities can result in the head of the Schmidt hammer not being able to make full contact with the surface, therefore resulting in inaccurate lower R values (Williams and Robinson, 1983).

Petrographical differences can also lead to differences in weathering rates (Goudie, 2006). Some of the boulders measured in the Wahianoa Valley have probably been sourced from the lava flows that are preserved at the head of the valley. These lava flows have been found by Hackett (1985) to contain plagioclase feldspar and pyroxenes. Plagioclase feldspar is more resistant to weathering than pyroxene (Boggs, 2001), and the proportionate content of these two minerals would have differing effects on both the weathering rates and the surface hardness of the boulders and therefore on both their roundness and R values. It is difficult to identify the composition of the boulders visually and therefore difficult to quantify the effect on both these variables.

5.4.2 Transport history

It is likely that other deposits have been incorporated into the Wahianoa moraines after their emplacement. Volcanic eruptive deposits younger than the moraines emplacement could have been deposited directly onto their surfaces at random times and locations along the moraines thereby leading to higher R values and lower Power's roundness values. Also, these younger eruptives could have been deposited directly onto the surface of the Wahianoa Glacier itself, then transported supraglacially and undergoing rounding in the process before their incorporation into the moraines.

Some of the deposits are likely to have originated from lava flows of differing ages, at the head of the Wahianoa Valley. These lava flows would have already been exposed to different degrees of weathering, thereby creating a differing range of lower R values before incorporation into the moraines.

5.4.3 Micro-environmental conditions

Although this factor probably only plays a minor role in the variation in the R values observed in the Figures 5.1 and 5.2, it is still worth noting. It is possible that the variation in R values could be attributed in part to micro-environmental conditions existing in the Wahianoa Valley. The boulders that were measured on the windward side of the Wahianoa moraines could have been exposed to higher amounts of abrading winds which could cause an increase in the amount of weathering thereby yielding lower R values and affecting rounding. In contrast, the boulders that were located in more sheltered locations could be exposed to lesser amounts of abrading winds thereby yielding higher R values. However, the extent to which these micro-environmental conditions affect the R values and rounding is mainly governed by the boulder's petrography.

5.4.4 Instrument and operator error

Incorrect measurements can be recorded if the Schmidt hammer is not calibrated, therefore, regular calibration must be carried out to try and reduce this error (McCarroll, 1989). In addition, it has been suggested by McCarroll (1987) that the R values recorded can decrease with an increase use of the Schmidt hammer. Although, these factors may not have a huge influence on the R values measured in the Wahianoa Valley they still need to be mentioned as a factor to consider when examining the results.

5.5 Summary

At the beginning of this chapter there were two expected outcomes. The first expected outcome was that a relationship would be established between rebound (R) values and Power's roundness values, which demonstrated that as a boulder became rounder due to weathering processes, the R value would decrease indicating an increase in age. As observed in section 5.2.2, no relationship was found to exist between these two variables. This lack of relationship can probably be attributed to factors that have been outlined in section 5.4 as affecting the R values and ultimately the rounding of the boulders.

The second expected outcome was that the Schmidt Hammer R values would indicate that the Wahianoa 'A', 'B' and 'C' moraines formed during the same event. It was observed in Figure 5.2 that the Wahianoa 'B' and 'C' moraines appeared to have formed at about the same time as the true right and some of the true left of the Wahianoa 'A' moraines. There was evidence found on the true left side of the Wahianoa 'A' moraines that could indicate a potential overtopping of this moraine by the Wahianoa Glacier at some stage of its advance. However, when comparing the mean R values to those obtained by Winkler (2005) in the South Island (Table 5.2) it appears that the Wahianoa 'A' and 'B' moraines may have formed at a similar time to the Birch Hill moraines, while the Wahianoa 'C' moraines may have formed at an earlier date. But taking into account the factors described in the previous section that can affect the R values measured in the Wahianoa Valley, the difference between the mean R value (31.79) for the Wahianoa 'C' moraines and the lowest mean R value (36.78) from Winkler (2005) is not sufficient to conclusively say that the Wahianoa 'A' and 'B' have formed in a separate event to Wahianoa 'C'.

Chapter 6: Results - Boulder Roundness

6.1 Introduction

This is the third relative age dating technique used in the Wahianoa Valley. The Boulder roundness method, utilising the technique of Kirkbride (2005), has never before been used in New Zealand. This method was used in the Wahianoa Valley in order to attempt an estimate of a relative age of the moraines present by comparing the radii of boulders. The radius of curvature will increase over time as a boulder becomes rounder due to subjection to processes associated with transportation and subaerial weathering. An expected outcome of this method is that the Wahianoa 'A', Wahianoa 'B' and 'C' moraines will contain boulders of similar radii of curvature, therefore showing that the moraines have formed in the same event. The first section of this chapter will describe the results from the Boulder roundness method used in the Wahianoa Valley. The final section will examine the factors that could affect the results from this method.

6.2 Boulder Roundness measurements

The roundness of 85 boulders were measured using the simple instrument devised by Kirkbride (2005). The distance and angle between the posts of the instrument were recorded and then processed using the following formulas (Kirkbride, 2005).

$$l_{adj} = l_m - b(\theta - 90) \qquad \text{(Equation 6.1)}$$

Where l_m is the measured length between the posts of the instrument, θ is the measured angle between the posts of the instrument, b is the gradient derived from the graph of this measured angle versus the measured length, l_{adj} is the calculated adjusted length.

$$l_i = \frac{(l_m - l_{sp})}{(l_{cu} - l_{sp})} \qquad \text{(Equation 6.2)}$$

Where l_i is the normalised index length, l_{sp} is the measured length of a perfectly spherical boulder which is 786mm; l_{cu} is the measured length of a perfectly sharp cubic corner.

$$r_c = 2333 - 2.333 l_{adj} \qquad \text{(Equation 6.3)}$$

Where r_c is the radius of curvature

The radius of curvature (Equation 6.3) is the value that was used by Kirkbride (2005) as an indicator of relative age. Figure 6.1 displays the average radius of curvature of the five boulders measured in each of the 17 sample sites in the Wahianoa Valley.

6.2.1 General Trend

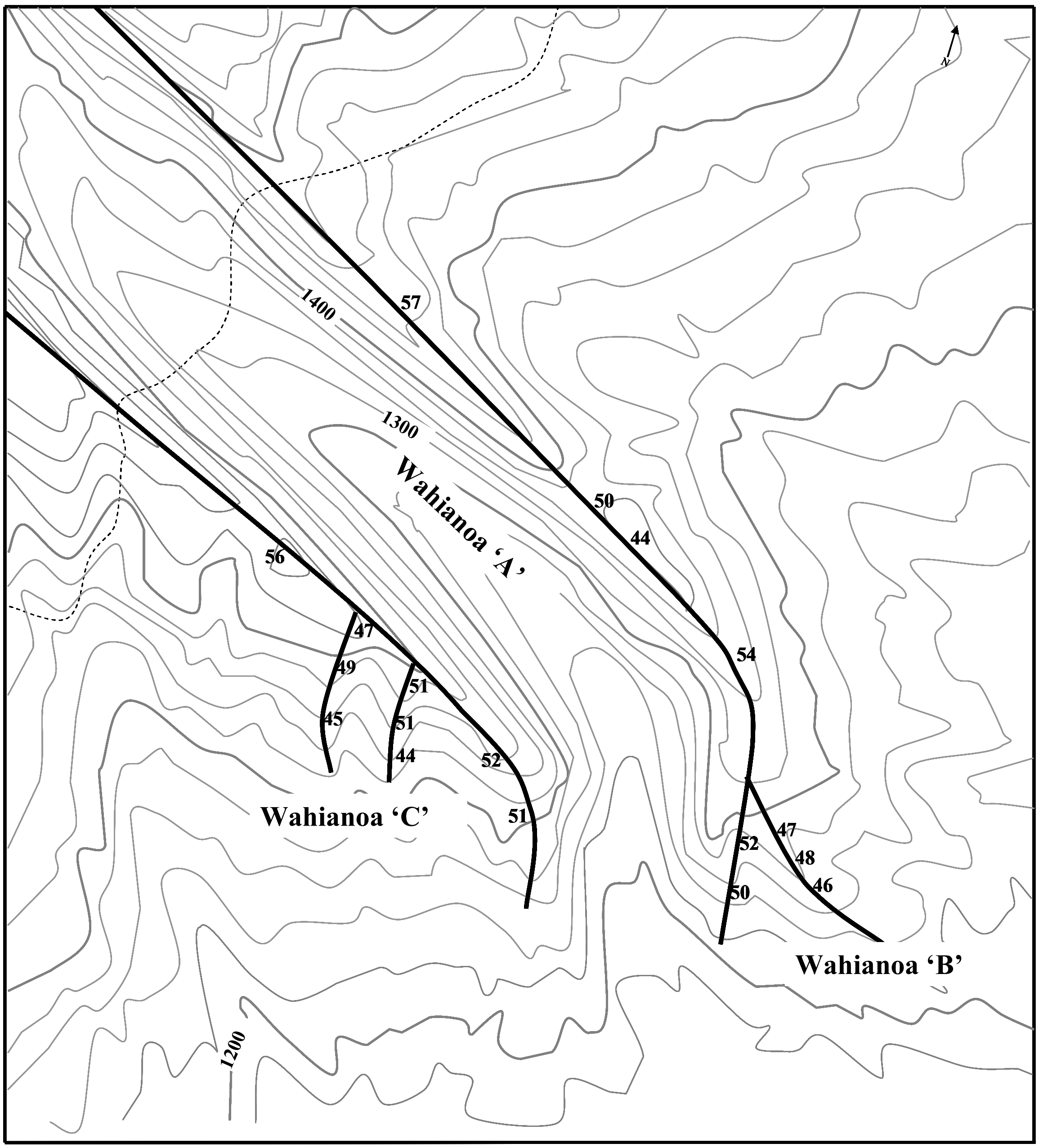

Figure 6.1. Boulder roundness measurements for the Wahianoa Valley. Numbers indicate the average radius of curvature for each sample site.

An observation can be made from Figure 6.1 that the larger averages of the radii of curvature are not located towards the base of the Wahianoa ‘A’ moraines which would have been expected if this was one of the sites to be deglaciated first. It is also observed from Figure 6.1 that the lower averages of the radii of curvature are found on the Wahianoa ‘B’ and ‘C’ moraines which would not be expected as these are likely to have been deglaciated at around the same time as the base of the Wahianoa ‘A’ moraines. However, this is based on the assumption that they formed in the same event.

6.2.2 Spatial Variation

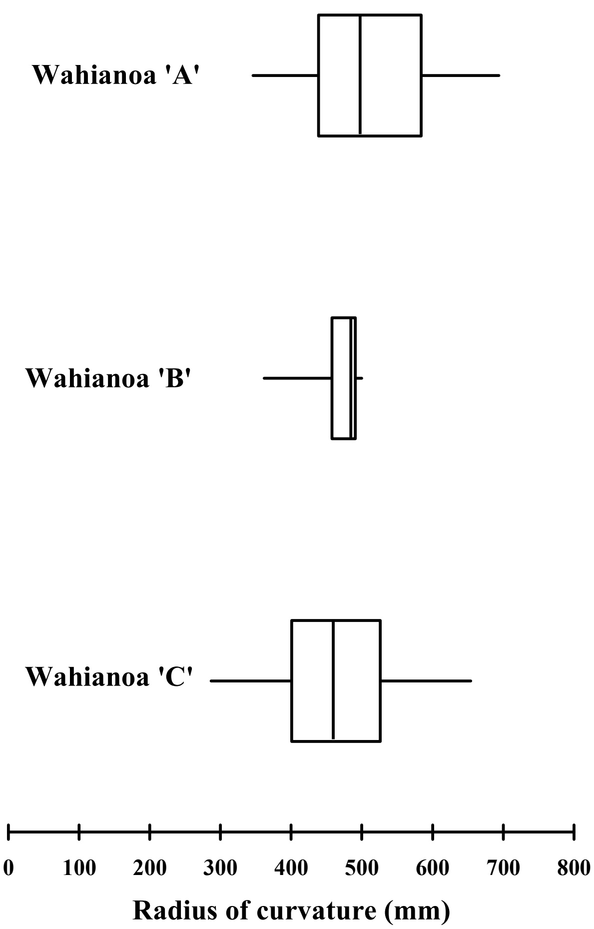

Figure 6.2. Box and Whisker plot of the Boulder roundness measurements of the Wahianoa Valley.

As can be seen from Figures 6.1 and 6.2, the Wahianoa ‘A’ moraines have the largest mean radii of curvature, indicating that they could be the oldest moraines out of those studied. The Wahianoa ‘C’ moraines have a wide range of results, but overall the average radius of curvature is smaller than that of the Wahianoa ‘A’ moraines thereby indicating that they could be slightly younger. The Wahianoa ‘B’ ridge also appears to be younger than the Wahianoa ‘A’ moraines as the average radii of curvature is generally smaller than the Wahianoa ‘A’ moraines. In addition, the average radii of curvature for the Wahianoa ‘B’ moraine is similar to that of the Wahianoa ‘C’ moraines which suggests that they could have formed in the same event.

However, not only do the radii of curvature differ between the Wahianoa ‘A’, ‘B’ and ‘C’ moraines but also within and between each sample site.

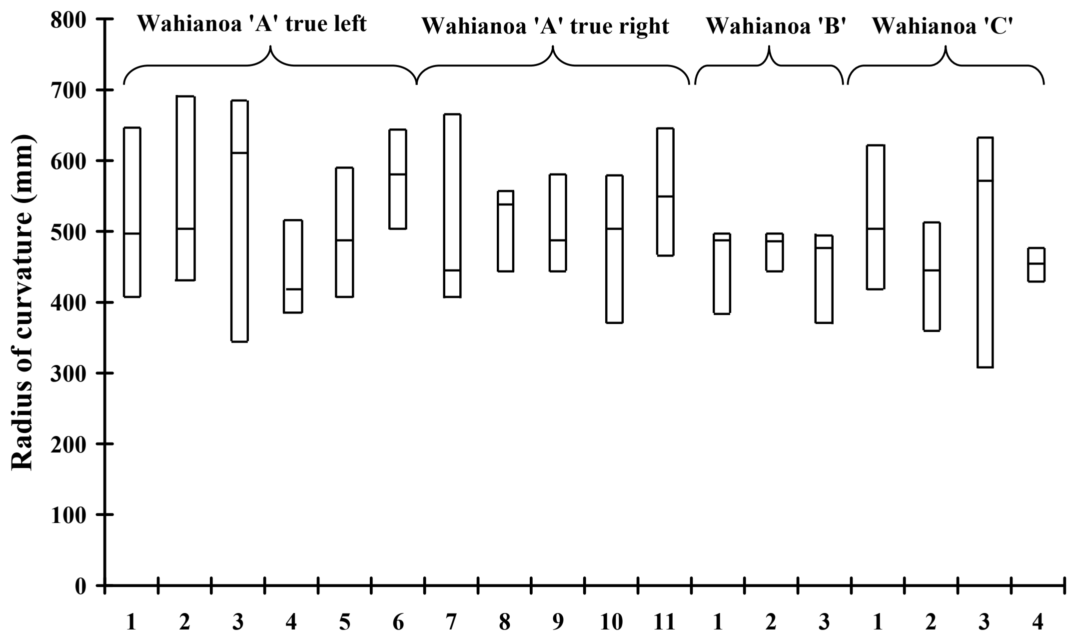

Figure 6.3. Box plots of the range of radii of curvature of each sample site in the Wahianoa Valley.

It can be observed from Figure 6.3 that there is a variation of radii of curvature at each sample site in the Wahianoa Valley. Although, this variation exists there is no departure large enough between any of the sample sites to suggest that more than one age is preserved on any of the Wahianoa ‘A’, ‘B’ and ‘C’ moraines or between these moraines.

The range of radii of curvature at each of the Wahianoa 'B' sample sites is consistently smaller than the remainder determined for the Wahianoa Valley. However, this still fits in with the overall range observed on the Wahianoa 'A' and 'C' moraines. In addition, there are some higher radii of curvature observed in sample sites 1 and 3 on the Wahianoa 'C' moraines which are not observed in sample sites 2 and 4. This could be explained by the proximity of the Wahianoa 'C' moraines to the true right Wahianoa 'A' moraine where sample sites 1 and 3 could have had boulders become incorporated in their deposits after they slid off the true right Wahianoa 'A' moraine.

As can be seen from Figure 6.3, there was a wide range of Boulder roundness measurements recorded in the Wahianoa Valley which indicates that there are boulders of different ages present. These differences could be attributed to factors such as supraglacial debris, eruptive deposits and frost shattering.

6.2.3 Individual Sampling areas

6.2.3.1 Wahianoa 'A'

A total of 55 Boulder roundness measurements were recorded on the Wahianoa 'A' moraines. Figure 6.4 is a histogram of the Boulder roundness measurements for this sample area. As can be seen from Figure 6.4, the distribution is negatively skewed (Table 6.1), while there is only one mode present which could indicate that the Wahianoa 'A' moraines are uniform in age. In addition, the distribution is platykurtic with a low degree of peakedness (Table 6.1).

Table 6.1. Descriptive statistics of the Boulder roundness measurements from the Wahianoa Valley.

Site	Standard deviation	Skewness	Kurtosis
Wahianoa 'A'	38.89	-0.20	-0.90
Wahianoa 'B'	18.23	1.64	1.78
Wahianoa 'C'	38.53	-0.22	-0.46

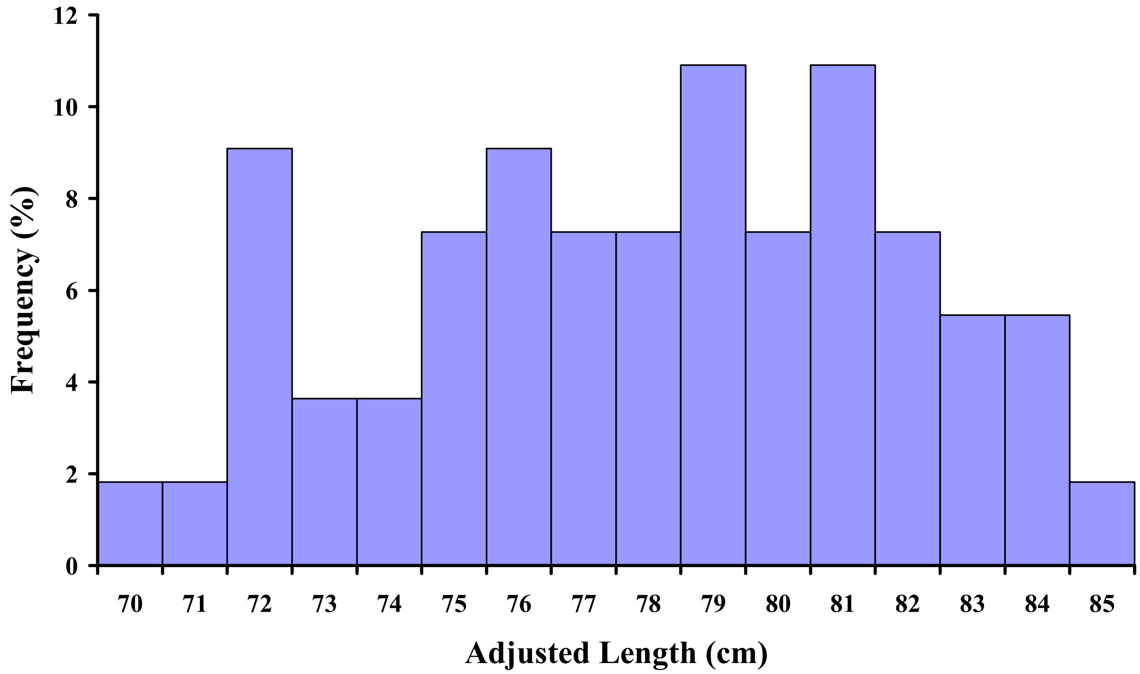

Figure 6.4. Histogram of adjusted length versus frequency of the Wahianoa 'A' boulder roundness measurements.

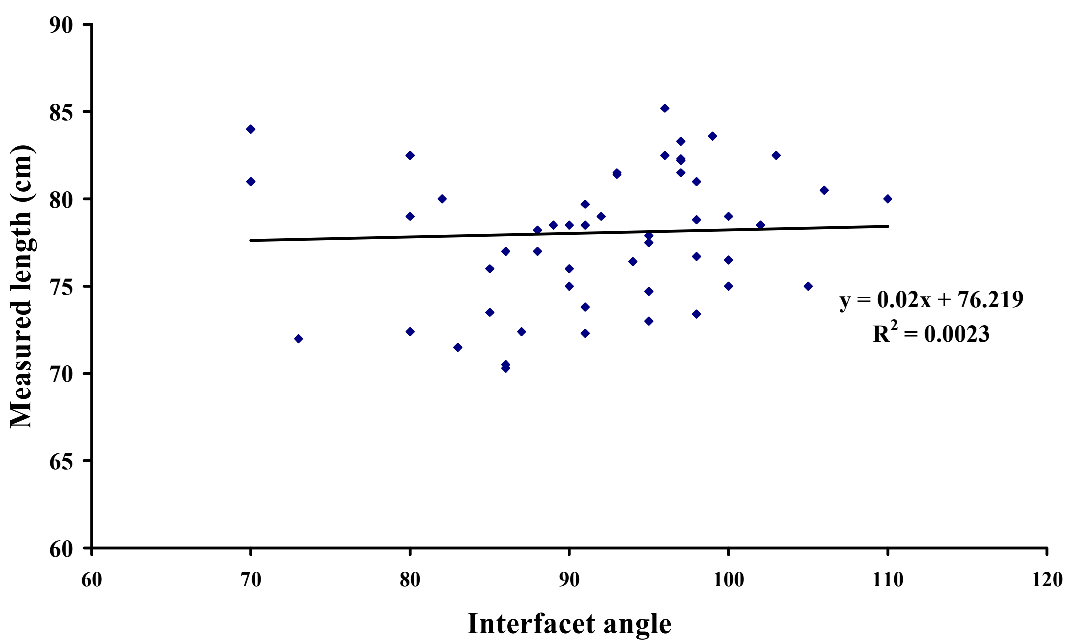

Figure 6.5. Interfacet angle versus measured length for the Wahianoa 'A' moraines.

A regression analysis was conducted on Figure 6.5 and the R^2 value was found to be insignificant. The gradient (0.02) from Figure 6.5 is used in Equation 6.1 in order to evaluate the adjusted length (l_{adj}) which is displayed in Table 6.2. As can be seen from Table 6.2, there is little variance between the measured length and the adjusted length.

Once the adjusted length was calculated it was substituted into Equation 6.3 in order to evaluate the radius of curvature for the Wahianoa 'A' moraines. As can be seen from Table 6.2, the Wahianoa 'A' moraines have the largest radii of curvature which indicates that these are potentially the oldest surfaces in the Wahianoa Valley.

Table 6.2. Boulder roundness measurements from the Wahianoa Valley

Sample Site	n	θ^o	l_m (mm)	l_{adj} (mm)	Median l_{adj} (mm)	l_i	R_c(mm)
Wahianoa 'A'	50	92.1	785.4	784.3	783.6	-0.03	501.4
Wahianoa 'B'	15	95.5	800.8	799.0	791.1	0.07	468.9
Wahianoa 'C'	20	95.3	799.3	796.4	800.0	0.06	469.0

6.2.3.2. Wahianoa 'B'

A total number of 15 boulders were measured on the Wahianoa 'B' moraine. As can be seen in Figure 6.6, the distribution is positively skewed (Table 6.1). In addition there appears to be only one mode in the distribution and it is leptokurtic with a high degree of peakedness (Table 6.1).

The observations made from Figure 6.6, is further supported by Figure 6.3. In Figure 6.3, it can be seen that the box plots for the Wahianoa 'B' boulder roundness measurements appear to be almost uniform. This together with the observations made from Figure 6.6 indicate that the Wahianoa 'B' ridge formed in one event.

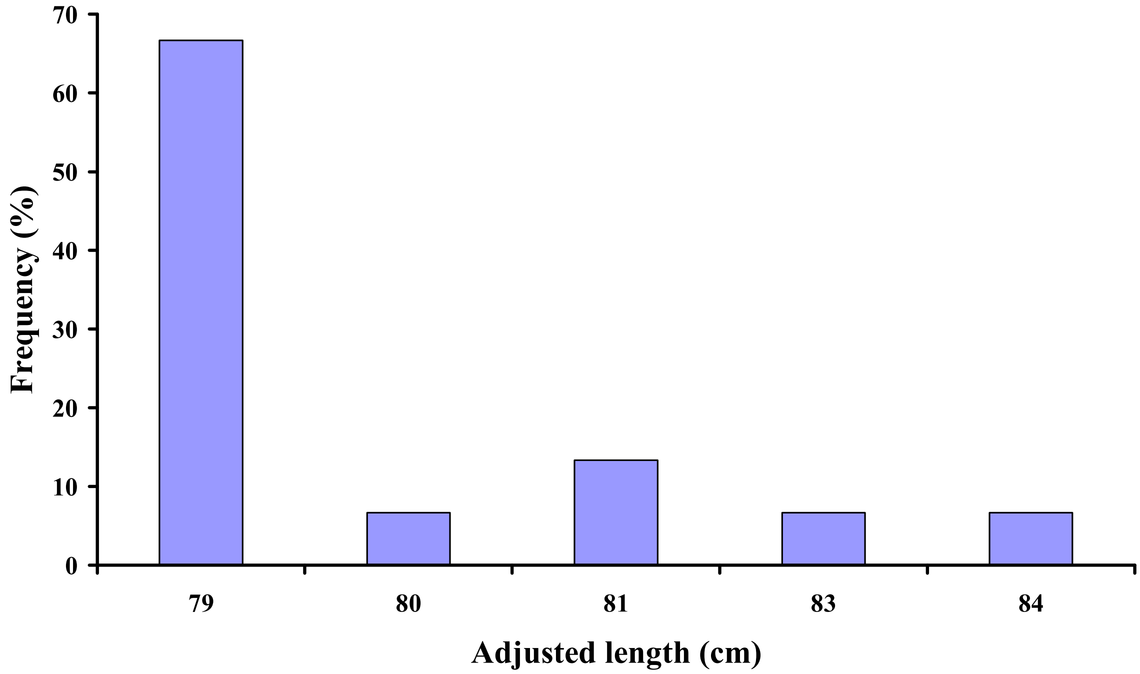

Figure 6.6. Histogram of the Boulder roundness measurements for the Wahianoa 'B' moraine.

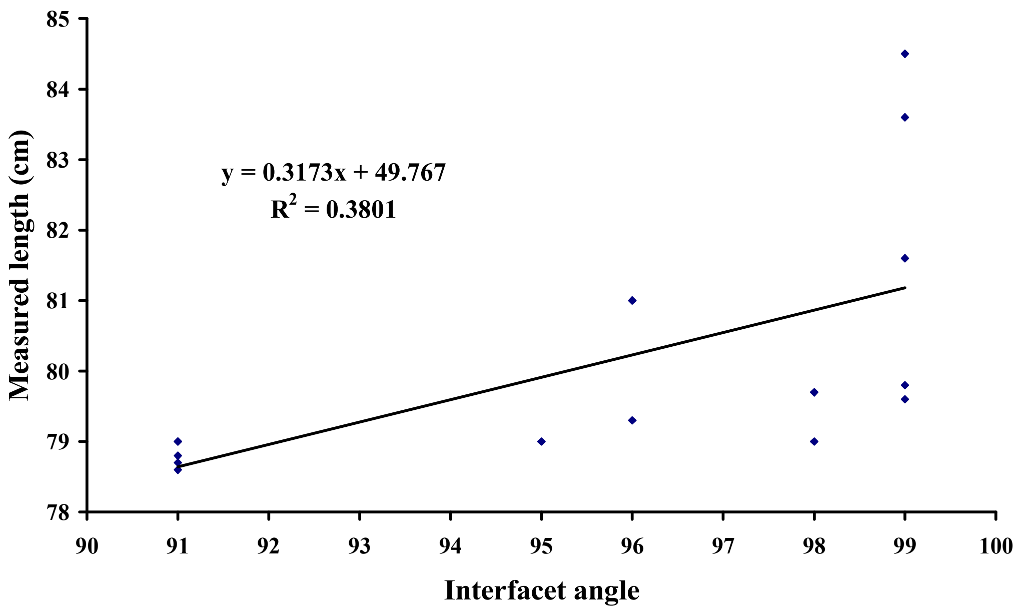

Figure 6.7. Interfacet angle versus measured length of the Wahianoa 'B' Boulder roundness measurements.

A regression analysis was conducted on Figure 6.7 and it was found that the R^2 value is significant at the 99% interval (p= 0.01). As can be seen from Figure 6.7 the gradient is 0.3173, which is substituted into equation 6.1 in order to calculate the adjusted length (Table 6.2).

After this calculation the adjusted length can be substituted into equation 6.3 from which the radius of curvature (468.9mm) can be determined (Table 6.2). The radius of curvature for the Wahianoa 'B' moraine is smaller than that of the Wahianoa 'A' moraines (501.4mm) which indicates that it is younger. Also, the Wahianoa 'B' moraine appears to be of a similar age to the Wahianoa 'C' moraines (469.0mm) (Table 6.2).

6.2.3.3 Wahianoa 'C'

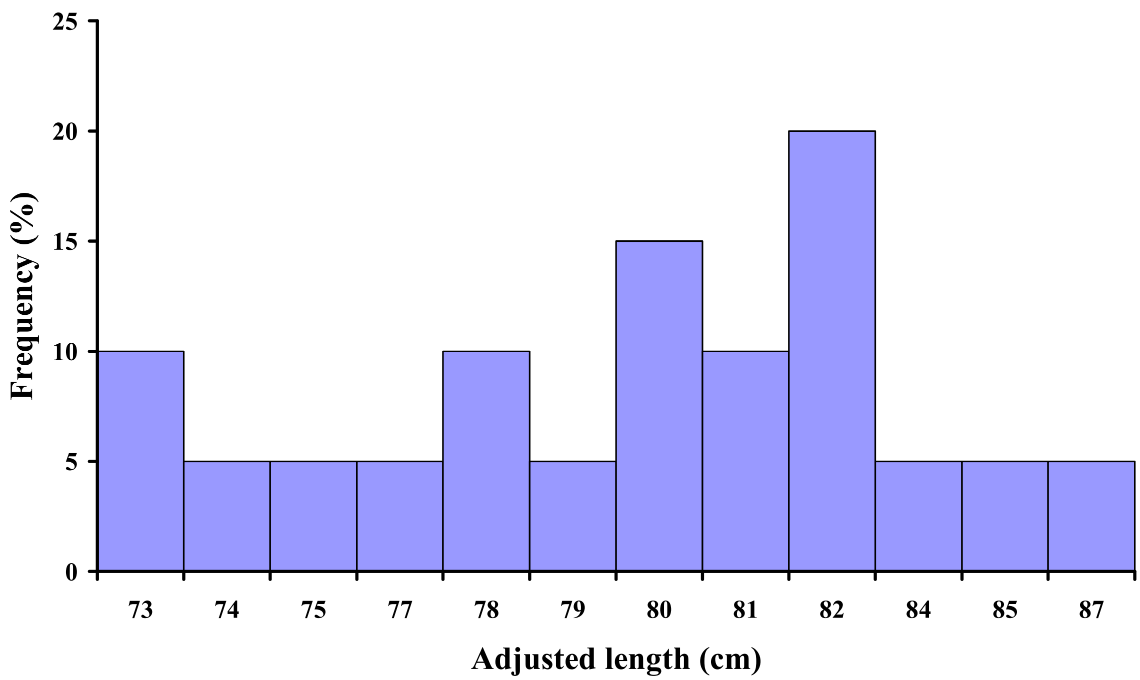

Figure 6.8. Histogram of the Wahianoa 'C' Boulder roundness measurements.

The distribution of the 15 Wahianoa 'C' boulders measured for roundness (Figure 6.8) is negatively skewed and leptokurtic with a low degree of peakedness (Table 6.1). In addition there is one mode present in the distribution, indicating that the Wahianoa 'C' moraines are close to uniform in age. This is further demonstrated in Figure 6.4 where the Boulder roundness measurements for each sample site are very similar.

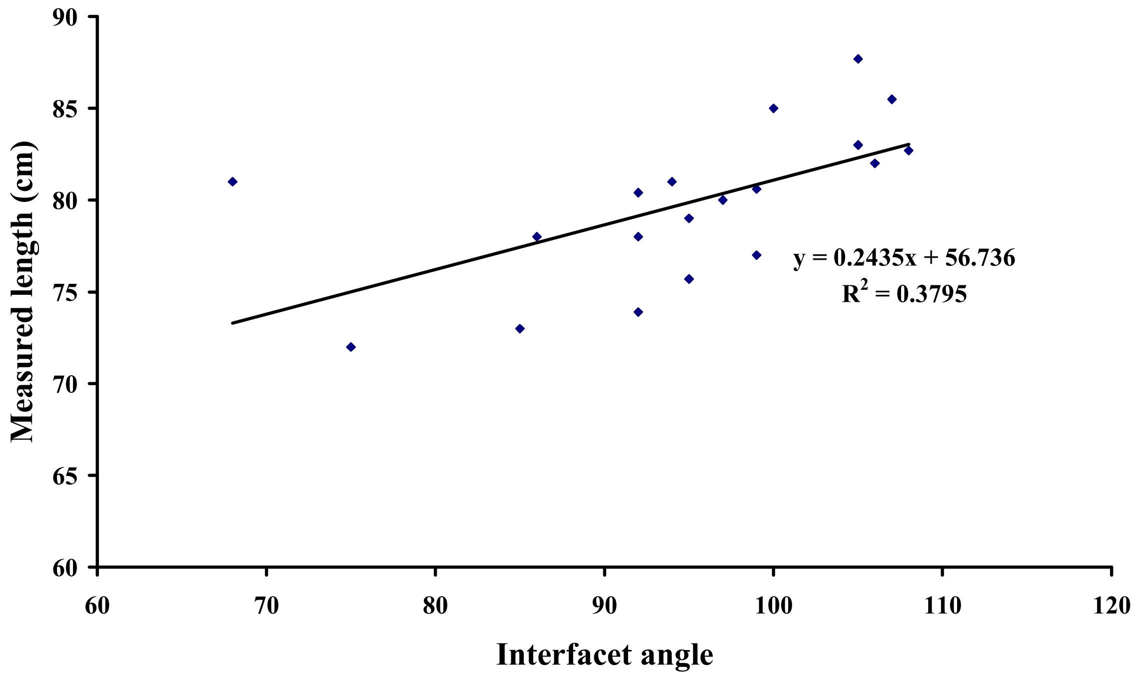

Figure 6.9. Interfacet angle versus measured length of the Wahianoa 'C' Boulder roundness measurements.

A regression analysis was conducted on Figure 6.9 and the R^2 value of 0.3795 was found to be significant at the 99% interval (*p*=<0.01). The gradient for Figure 6.9 is 0.2435 which is substituted into equation 6.1 and the result from this equation into equation 6.3. The resultant radius of curvature for the Wahianoa 'C' moraines is 469mm which is almost identical to the Wahianoa 'B' moraine (468.9 mm) (Table 6.2). It is evident from this that the Wahianoa 'C' moraines is of the same or similar age to the Wahianoa 'B' moraine and younger than the Wahianoa 'A' moraines. This observation is further supported by Figure 6.4 where the box plots for the Wahianoa 'C' moraines are very similar to those determined for the Wahianoa 'B' moraine, in particular sample sites 2 and 4.

6.2.3.4 Statistical Analysis

A T-test was carried out on the Boulder roundness measurements in order to see if there is any difference between the relative ages of the Wahianoa 'A', 'B' and 'C' moraines. Table

6.3 displays the findings from this T-test. As can be seen from Table 6.3, a difference exists between the Wahianoa 'A' and 'B' moraines which supports the observations made from Figures 6.2 and 6.4. Also, there is a difference that exists between Wahianoa 'A' and 'C' which also supports the observations made from Figures 6.2 and 6.4. The *p* value for the Wahianoa 'B' and 'C' indicates that no difference exists between these two moraines.

Table 6.3. T-test values for the Boulder roundness measurements

T-test between	Critical value of *t*	*t* statistic	*P* value
Wahianoa 'A' and 'B'[1]	1.67	1.83	0.04
Wahianoa 'A' and 'C'[1]	1.67	1.82	0.04
Wahianoa 'B' and 'C'[2]	2.03	-0.008	0.99

[1]one-tailed test
[2]two-tailed test

6.3 Factors affecting Boulder Roundness values

The radii of curvature calculated for the Wahianoa Valley were variable with the largest calculated being 57cm and the smallest 44cm (Figure 6.1). There are differences that exist between the sample sites on each of the Wahianoa 'A', 'B' and 'C' moraines. Also, there are differences in these values between the Wahianoa 'A', 'B' and 'C' moraines themselves. These differences can be attributed to various factors which will be discussed in this section.

6.3.1 Lithology

Lithology is probably one of the most important factors that can influence the radius of curvature of a boulder. Although the boulders in the Wahianoa Valley are all andesitic in composition there are petrographical differences that exist between them which can affect the boulders resistance to weathering. As previously mentioned in section 5.3.1 there are likely to be boulders that contain more resistant minerals such as plagioclase feldspar and boulders that contain less resistant minerals such as pyroxene. These differences in the petrography can lead to differences in the weathering of the boulders. In terms of Boulder roundness the boulders that contain more resistant minerals will have lower radii of curvature as the weathering rate of these boulders will be slower than those with less resistant minerals. In contrast, those with less resistant minerals will have a higher radius of curvature as the weathering rate would be faster.

6.3.2 Transport history

There is an underlying assumption by Kirkbride (2005) that the boulders used in this method have undergone negligible edge-rounding during their passive transportation in high-level pathways on a glacier. However, rounding during transportation on the surface of the Wahianoa Glacier can not be totally discounted. Some of the varying radii of curvatures values may be attributed to this process occurring prior to their incorporation into the Wahianoa moraines. If this is the case then it could account for some of the higher radii of curvatures calculated for the Wahianoa Valley.

However, some of the boulders on the Wahianoa 'A', 'B' and 'C' moraines are likely to have been sourced directly from eruptions of Mt Ruapehu. Some of the boulders could have been erupted directly onto the surface of the Wahianoa Glacier whereby they became rounded during their passive transportation resulting in higher radii of curvatures. However, some of the boulders could have been erupted directly onto the surfaces of the Wahianoa 'A', 'B' and 'C' moraines whereby they have had some rounding during their emplacement and subsequently subaerial weathering post-deposition. Some of the lower radii of curvatures could be as a result of this scenario as the boulders have been exposed to a shorter period of subaerial weathering.

6.3.3 Micro-environmental conditions

A minor factor that could also affect the radii of curvature of the boulders is micro-environmental conditions. It is possible that boulders in slightly more exposed conditions may have a faster rate of weathering due to abrading winds whereas those in slightly more sheltered conditions have a slower rate of weathering. The effects of this factor is largely governed by the petrography of the boulder thereby highlighting petrography as one of the most important factor in the results for the Boulder roundness method.

6.3.4 Frost-shattering

The last factor that can influence the radius of curvature of the boulders in the Wahianoa Valley is frost-shattering. Frost-shattering generally causes the formation of large angular boulders due to the repeated freezing and thawing of water within a boulder (Boggs, 2001). This could account for some of the lower radii of curvature measured in the Wahianoa Valley.

6.4 Summary

This method is still relatively new having been developed in 2005 and this study uses it for the first time in New Zealand. The results from this method indicate that the Wahianoa 'A' moraines are possibly the oldest with the Wahianoa 'B' and 'C' moraines being younger and of similar age. Unlike other methods this theory was supported by the T-test used. A possible scenario that can be ascertained from these results is that the Wahianoa Glacier extended down the valley and as the ice increased in volume it overtopped the Wahianoa 'A' moraines causing the formation of the Wahianoa 'B' and 'C' moraines. This is consistent with the observations made from Figure 6.3. and Table 6.2.where there is little or no difference between the Wahianoa 'B' and 'C' moraines indicating that they likely formed in the same event. However, for this to be the case these moraines should contain the highest radii of curvature, which they do not. But this may be explained by a higher degree of rounding caused by the Wahianoa Glacier on the Wahianoa 'A' moraines during this advance as it increased in volume. This scenario also fits with the Schmidt hammer results from the true left of the Wahianoa 'A' moraine where there is potential evidence for overtopping by ice on this moraine, but more research would be required in order to test this scenario.

The expected outcome of this method was that the Wahianoa 'A', Wahianoa 'B' and 'C' moraines would contain boulders of similar radii of curvature, therefore showing that they formed in the same event.

Chapter 7: Results - Climate Reconstruction

7.1 Introduction

In order to achieve an understanding of a glacier's past behaviour, reconstructions of paleo-equilibrium line altitudes (ELAs) are commonly used. The determination of paleo-ELAs can then lead to evaluation of environmental conditions that would have been in existence at that ELA depression.

The expected outcome for this chapter is to determine the difference between the paleo and current ELA for the Wahianoa Glacier, thereby evaluating the temperature decrease required to cause this ELA depression and if possible identify with which glacial event it is associated. The first section of this chapter will use four methods to reconstruct the paleo-ELA for the Wahianoa Glacier. The second section of this chapter will use three methods to try and determine the current ELA of the Wahianoa Glacier. The third section will approximate the basal shear stress acting upon the Wahianoa Glacier when it was at its full extent. The fourth section will estimate the ablation rate for the Wahianoa Glacier based on previous documentation. The final section of this chapter will use the differences between the estimated current and paleo ELAs for the Wahianoa Glacier in order to attempt an approximation of the temperature change required to cause the ELA depression.

7.2 Paleo-ELA reconstruction

7.2.1 Accumulation Area Ratio (AAR) method

7.2.1.1. Introduction

This method is one of the most commonly used in paleo-ELA reconstructions and has been used by researchers such as McArthur and Shepherd (1990); Torsnes *et al*. (1993) and Porter (2001). The underlying assumption with this method is that in steady-state conditions the accumulation area of a glacier occupies approximately two-thirds of its total area (AAR=0.65) (Porter, 2001).

An approximation of the paleo-ELA for the Wahianoa Glacier was conducted following the techniques of Lowe and Walker (1997) and Porter (2001), by first reconstructing the former outline of the Wahianoa Glacier using the morphology of the Wahianoa Valley (Figure 7.1) and then calculating the area between each successive contour line (see Section 3.41 Chapter 3). The results from this method are presented in the following section.

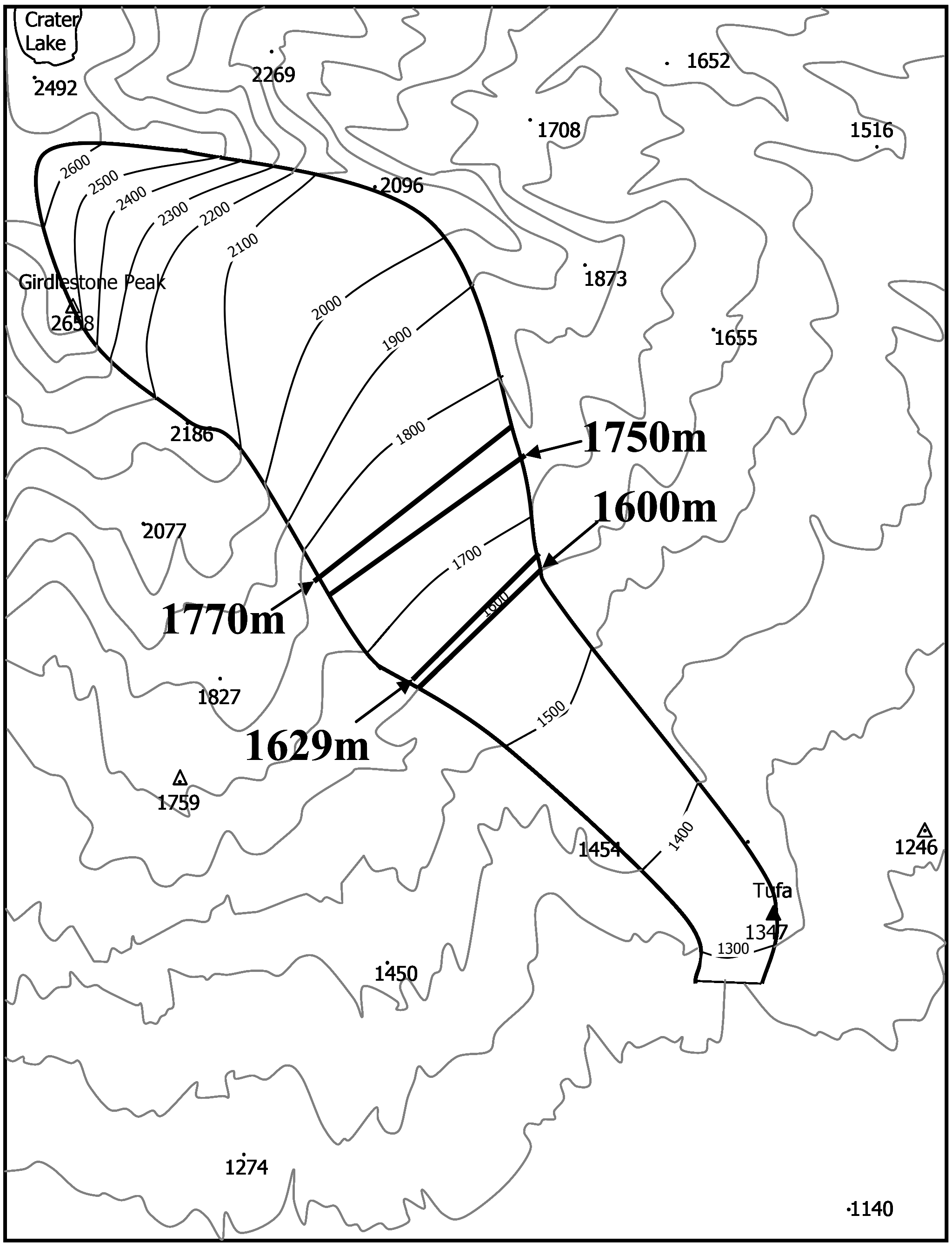

Figure 7.1. Reconstructed Wahianoa Glacier outline with estimated paleo-ELA values labelled.

7.2.1.2 Determination of the paleo-ELA

Once the reconstructed outline for the previous extent of the Wahianoa Glacier was determined, the area between each successive contour lines was evaluated. This was done by overlaying a grid over the outline and counting the squares between each successive pair of contour lines. The results from this calculation are displayed in Table 7.1.

Table 7.1. Area calculations for each region between successive contour lines on the reconstructed glacial outline for Wahianoa Glacier

Elevation (m)	Area (m^2)
>2600	1,100
2500-2600	4,350
2400-2500	5,450
2300-2400	6,150
2200-2300	7,700
2100-2200	12,200
2000-2100	16,700
1900-2000	24,950
1800-1900	14,050
1700-1800	28,200
1600-1700	7,900
1500-1600	11,200
1400-1500	15,100
1300-1400	8,200
<1300	1,300
TOTAL	**164,550**

As can be seen from Table 7.1, the total area for the reconstructed Wahianoa Glacier outline, shown in Figure 7.1, was found to be 164,550 m^2. These values in Table 7.1 are now used to construct the cumulative area-altitude graph (Figure 7.2), which is the basis for the AAR method.

As an ELA is found at the base of an accumulation area, the paleo-ELA value is extrapolated by using the graph where the cumulative area is equal to 35%. The error limits in Figure 7.2 were determined by using an AAR range of 0.65±0.05. The results from Figure 7.2 indicate the estimated paleo-ELA for the Wahianoa Glacier to be 1750m ± 25m. This value is higher than the estimated paleo-ELA range of 1500-1600m which was estimated by McArthur and Shepherd (1990) using a different method (MELM) for the whole of Mt Ruapehu. However, there are factors, such as glacier hypsometry, associated with the use of this method which can affect the results.

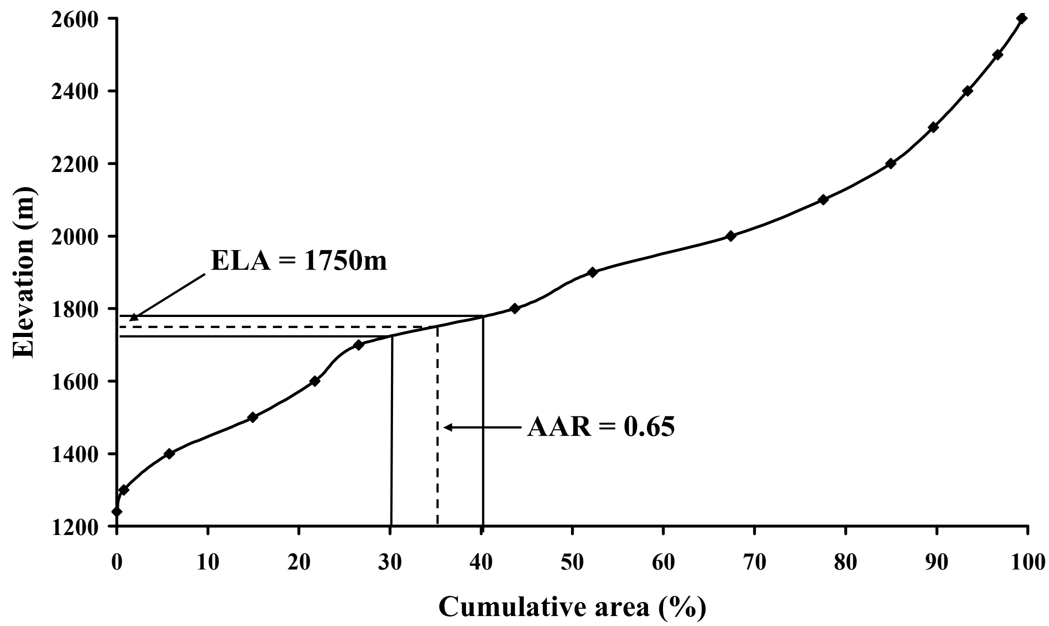

Figure 7.2. Cumulative area-altitude graph for the reconstructed outline of the Wahianoa Glacier. An AAR of 0.65 yields a paleo-ELA of 1750m (dashed line). Error lines ± 0.05 (solid lines) are also shown.

7.2.2 Terminus to Headwall Altitude Ratio (THAR) method

7.2.2.1 Introduction

This method has been used previously by Meierding (1982); Torsnes *et al.* (1993) and Porter (2001). It employs the difference in elevation between the terminus of a glacier and the headwall so as to approximate the location of the paleo-ELA. The paleo-ELA is calculated from these values using Equation 7.1.

$$ELA = A_t + THAR(A_h - A_t) \quad \text{(Equation 7.1)}$$

A_t is the altitude of the terminus
A_h is the altitude of the headwall
THAR is the terminus to headwall ratio.

There are a range of values that can be used to substitute for the THAR variable, however the most commonly used is 0.35-0.40 as it is viewed by researchers, such as Meierding (1982) and Nesje and Dahl (2000), to provide the best estimates for the paleo-ELA. These values were also used in this study.

7.2.2.2 Determination of the paleo-ELA

The headwall of the Wahianoa Glacier is estimated to be at 2720m, while the former terminus was estimated to be approximately 1200m as shown in Figure 7.1. These values were then substituted into Equation 7.1 and the results from which are displayed in Table 7.2.

Table 7.2. Results from the THAR method used on the Wahianoa Glacier reconstruction.

THAR value	Paleo-ELA (m)
0.35	1732
0.40	1808

As can be seen in Table 7.2, the paleo-ELA for the THAR values 0.35-0.40 were 1732m and 1808m respectively. The median ELA estimated from this method is 1770 ± 38m, as shown in Figure 7.1. This paleo-ELA reconstruction method has never been used before on Mt Ruapehu or even in the North Island. The result is higher than the paleo-ELA range of 1500-1600m for Mt Ruapehu, estimated by McArthur and Shepherd (1990).

This method is generally used for a quick estimation of the paleo-ELA as it is sometimes difficult to discern the elevation of the headwall (Nesje and Dahl, 2000). Nevertheless it still provides a good approximation of the paleo-ELA for the Wahianoa Glacier.

7.2.3 Maximum Elevation of Lateral Moraines (MELM)

7.2.3.1 Introduction

This method of estimating the paleo-ELA is based on the assumption that, under steady-state conditions, the maximum elevation of the lateral moraines lies approximately at the ELA (Porter, 2001). Therefore, if the lateral moraines are well preserved, it should be relatively easy to identify the maximum elevation and provide an estimation of the paleo-ELA. The moraines in the Wahianoa Valley are well preserved, which makes this a good method to use in the approximation of the paleo-ELA (Figure 7.3).

Figure 7.3. Approximate location of the maximum elevation of the Wahianoa moraines.

7.2.3.2 Determination of the paleo-ELA

The Maximum Elevation of the Wahianoa moraines was extrapolated from NZ 1:50 000 NZMS 260 Sheet T20, and was found to be approximately 1600m (Figure 7.1). This value correlates well with McArthur and Shepherd's (1990) approximation of the paleo-ELAs for Mt Ruapehu as being between 1500-1600m which was estimated using this method. However, this method has met with mixed success overseas and is generally used as a lower limit estimate for the paleo-ELA (Nesje and Dahl, 2000). In Figure 7.1, it can be seen that this method has resulted in the lowest paleo-ELA value.

7.2.4 Extrapolation method

7.2.4.1 Introduction

This method is based on the north-south gradient of the ELAs in the South Island. It is suggested by Shulmeister *et al.* (2005) that the modern ELAs in the South Island rise 570m over a distance of about 400km (1.4m/km). This was derived from the difference in height of Lamont *et al*.'s (1999) ELA values for Caroline Peak in Fiordland which has an estimated modern ELA of 1570m and Mt Ella (ELA is 2140m) which is almost the northernmost point of the Southern Alps. Shulmeister *et al*. (2005) used this northward increase of 1.4m/km to extrapolate a paleo-ELA for the Cobb Valley in north-west Nelson based on the distance of 250km from the Rakaia Valley (see section 3.4.4, Chapter 3).

7.2.4.2 Determination of the paleo-ELA

The distance between Mt Ruapehu and Cobb Valley was found to be 175km (see Section 3.4.4, Chapter 3), which was then applied to Shulmeister *et al*.'s (2005) northward ELA increase. The resultant value was 245m, which was added to Shulmeister *et al.*'s (2005) paleo-ELA value of 1384m thereby providing a paleo-ELA value of 1629m. This value compares well with that calculated by Brook and Crow (pers comm), of 1419m for Park Valley in the Tararua Range which lies 150km south of Mt Ruapehu.

There is a limitation with this method in that the extrapolation rate is based on ELA depressions in a different climatic regime to that of the North Island. However, it is still a useful method for estimating paleo and current ELAs.

7.3 Current ELA

As can be seen in Figure 7.4, the current Wahianoa Glacier is substantially smaller than the paleo-Wahianoa Glacier outline (Figure 7.1). Figure 7.4 displays all of the current ELA values estimated by using three methods: AAR, THAR and extrapolation.

7.3.1 Accumulation Area Ratio (AAR) method

7.3.1.1 Introduction

The current ELA of the Wahianoa Glacier was estimated by tracing the current glacial outline on a 1:50 000 NZMS 260 Sheet T20. The method for calculating the area of the current Wahianoa Glacier followed that described briefly in section 7.2.1.1 and in more detail in Chapter 3.

7.3.1.2 Determination of the current ELA

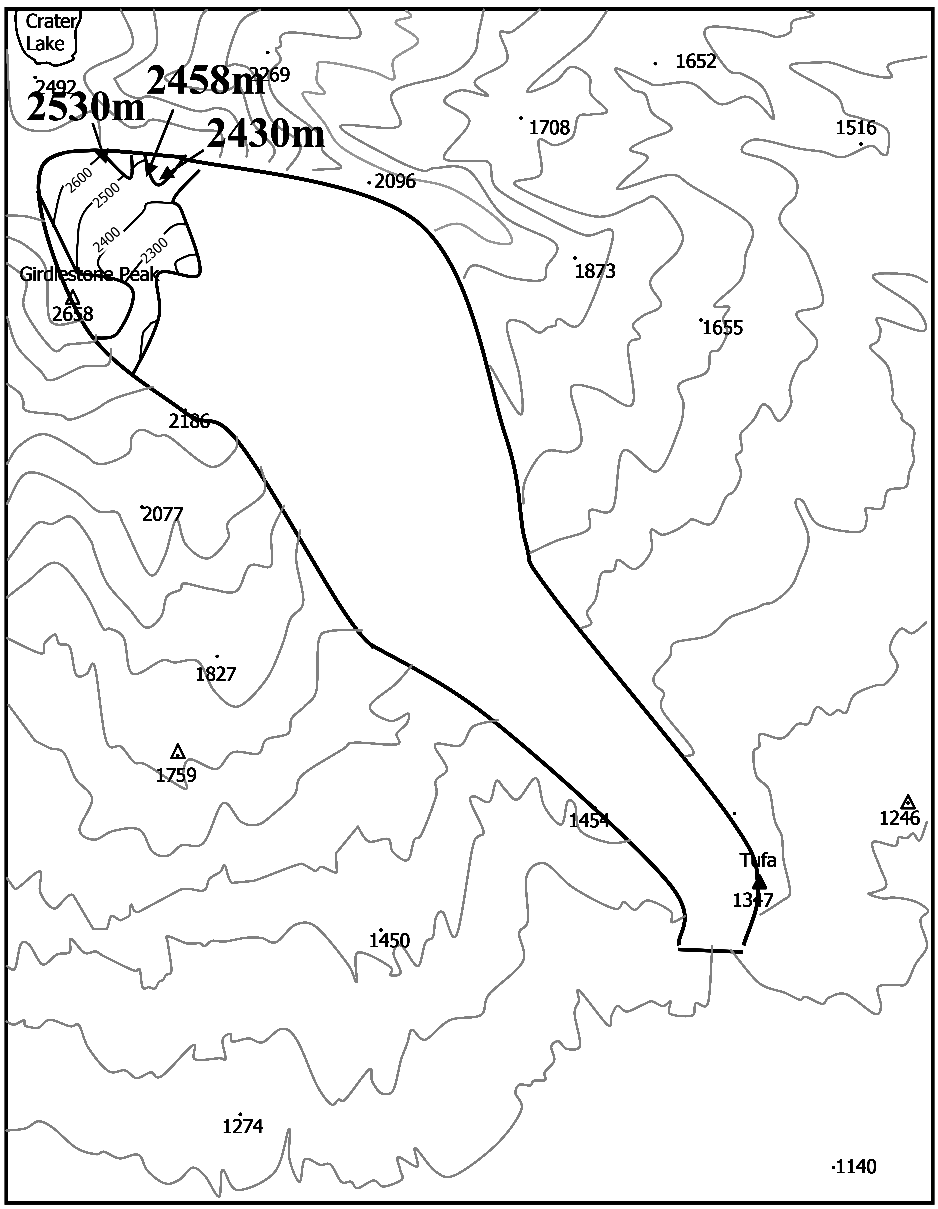

Figure 7.4. Current outline of the Wahianoa Glacier with estimated current ELAs labelled.

Table 7.3 is the resultant values from calculating the area between the successive contour lines in Figure 7.4. As can be seen in Table 7.3, the estimated area of the current Wahianoa Glacier is 11,550m^2 and this is substantially lower than the area reported in Table 7.1 for the reconstructed paleo-Wahianoa Glacier outline.

Table 7.3. Resultant values (m^2) for areas between successive contour lines for current Wahianoa Glacier in Figure 7.4.

Elevation (m)	Area (m^2)
>2600	1425
2600-2500	2750
2500-2400	4675
2400-2300	2700
Total	**11,550**

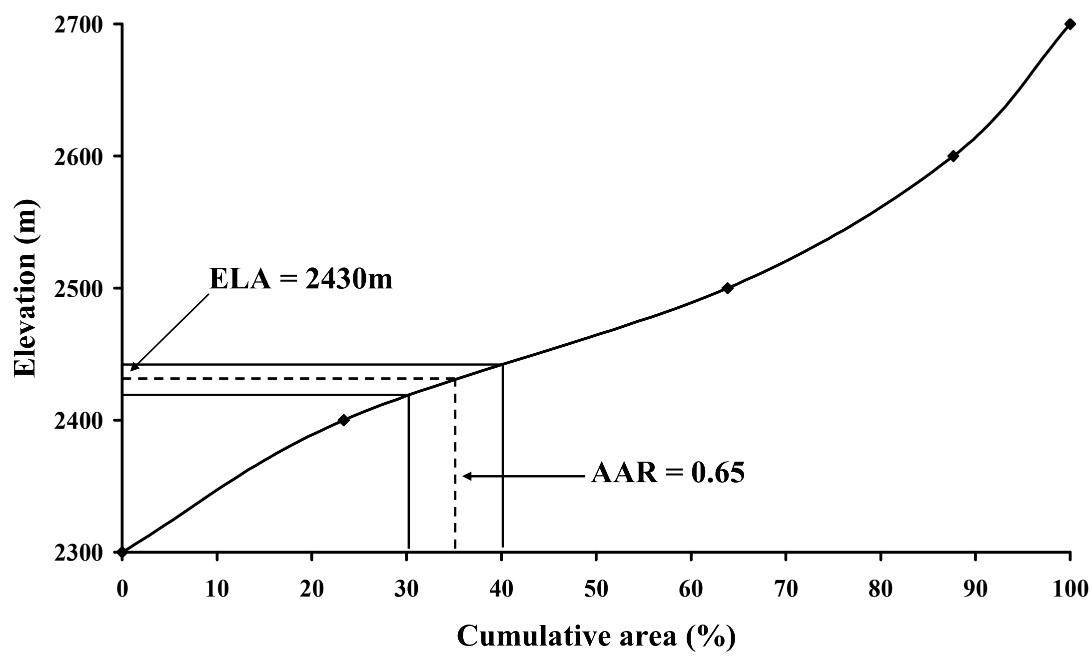

Figure 7.5. Cumulative area-altitude graph for the reconstructed outline of the Wahianoa Glacier. An AAR of 0.65 yields an ELA of 2430m (dashed line). Error lines ±0.05 (solid lines) are also shown.

As can be seen from Figure 7.5, the estimated ELA for the current Wahianoa Glacier is 2430m ± 10m. This value is in the same order of magnitude as that reported by McArthur and Shepherd (1990) and Mackintosh (pers.comm) who suggests that the current ELA range of Mt Ruapehu is between 2300-2400m and c.2500m respectively.

7.3.2 Terminus to Headwall Altitude Ratio (THAR) method

7.3.2.1 Introduction

The method used in this section was the same as the one adopted in section 7.2.2. The equation used was also the same:

$$ELA = A_t + THAR(A_h - A_t) \qquad \text{(Equation 7.1)}$$

A_t is the altitude of the terminus
A_h is the altitude of the headwall
THAR is the terminus to headwall ratio.

7.3.2.2 Determination of the current ELA

The terminus of the current Wahianoa Glacier was estimated to be 2300m while the headwall was approximated at 2720m. Therefore, when these values are substituted into Equation (7.1) above, the paleo-ELAs were calculated to be 2447m and 2468m based on THAR values 0.35 and 0.40 respectively (Figure 7.4). Therefore the estimated median current ELA value was evaluated to be c. 2458 ± 10m.

Table 7.4. Results from the THAR method.

THAR value	ELA (m)
0.35	2447
0.40	2468

The current ELA for the Wahianoa Glacier estimated from this method also does not differ greatly from Mackintosh's (pers comm.) estimation of c. 2500m and McArthur and Shepherd's (1990) range of 2300-2400.

7.3.3 Extrapolation Method

7.3.3.1 Introduction

This is the final method used to estimate the current ELA for the Wahianoa Glacier. The process used to derive this estimation is the same as previously used in section 7.2.4.

However, instead of using the Cobb Valley as the basis for determining the ELA, Mt Ella was used. Mt Ella has a modern ELA of approximately 2140m and is located near the northern limit of the Southern Alps (Lamont *et al.* 1999; Shulmeister *et al*. 2005).

7.3.3.2 Determination of the current ELA

The distance between Mt Ella and Mt Ruapehu was estimated to be 280km (see Section 3.4.4, Chapter 3). Therefore, applying the northward ELA increase of 1.4/km resulted in an approximate current ELA of c. 2530m. This estimation of the current ELA of the Wahianoa Glacier is in the same order of magnitude as that approximated by Mackintosh (pers comm). However, it is higher than the approximation of 2300-2400 made by McArthur and Shepherd (1990). The reason for this is most probably the amount that the Wahianoa Glacier has melted since McArthur and Shepherd's (1990) study, which will be estimated in the following section.

7.4 Basal Shear Stress

7.4.1 Introduction

An approximation of the maximum basal shear stress helps provide an idea of the stresses acting upon a glacier at its full extent. The shear stress found at the base of a glacier is due to the weight of the overlying ice and the slope of the ice surface and can be calculated using Equation 7.2 (Benn and Evans, 1998).

$$\tau = \rho_i g h \sin a \qquad \text{Equation (7.2)}$$

where τ is shear stress, a is the surface slope (assumed to be 6º), ρ_i is the density of the ice (900 kgm^{-3}), h is the ice thickness, and g is the gravitational acceleration (9.81 ms^{-2}).

7.4.2 Determination of the maximum Basal Shear Stress

As it was difficult to determine the trimline on the Wahianoa moraines, the maximum ice thickness of the Wahianoa Glacier was estimated to be 130m based on the present morphology of the Wahianoa moraines. Therefore based on this ice thickness the maximum basal shear stress was calculated to be 119kPa. This basal shear stress value fits into the range of values for normal glaciers proposed by Paterson (1994) which is 40-120kPa. Although this value is only approximate it still provides an indication of the basal shear stress acting upon the Wahianoa Glacier when it was at its full extent.

7.5 Ablation Rate

7.5.1 Introduction

The glaciers on Mt Ruapehu, have retreated rapidly over the last century, for example the Mangaehuehu Glacier has retreated ~1.5km over the last 98 years. There is little documentation on the previous termini of some of Mt Ruapehu's glaciers, in particular the Wahianoa Glacier, from which to determine an approximate ablation rate. However, Heine (1963) mapped the termini of various glaciers on Mt Ruapehu, including the Wahianoa Glacier, which will form the basis of the ablation rate calculation in this section.

7.5.2 Determination of the ablation rate

Heine (1963) approximated the terminus of the Wahianoa Glacier to be 2170m. The current terminus of the Wahianoa Glacier is estimated at being c. 2300m. Thereby, the difference between these two values is 130m leading to an ablation rate of approximately 3m/yr. This value correlates well with Williams (2001) ablation rate of 3-5m/yr for the Crater Basin Glacier on Mt Ruapehu.

7.6 Lapse Rate

7.6.1 Introduction

The lapse rate model is commonly used in order to approximate the temperature decrease required to cause an ELA depression. Mackintosh (pers comm.) suggests that the lapse rate can vary as much as 4-8ºC/1000m. However, the standard lapse rate value utilised by researchers such as Shulmeister *et al*. (2005) is a decrease of 6ºC/1000m and is the value that will be used in this study.

7.6.2 Determination of lapse rate

As has been demonstrated throughout this chapter, there have been three ELA reconstruction methods used to estimate both the paleo and current ELA of the Wahianoa Glacier. The ELA depression was calculated between the results from each of these methods and the lapse rate applied to the differences. Table 7.5 displays the results from these calculations.

Table 7.5. Lapse rate calculations for the Wahianoa Glacier ELA depressions

Climate Reconstruction Method	Modern ELA (m)	Paleo-ELA (m)	Difference (m)	Temperature (°C)
AAR	2430 ± 10	1750 ± 25	680 ± 15	c. 4.08
THAR	2458 ± 10	1770 ± 38	688 ± 28	c. 4.13
Extrapolation	2530	1629	901	5.41
Range	c. 2430-2530m	c.1629-1770	c.755	c.4.08-5.41

As can be seen from Table 7.5 the ELA depression ranges from 902m to c. 680m. This leads to a temperature decrease of 4-5ºC which correlates with the accepted Last Glacial Maximum (LGM) temperature depressions of 4-5ºC. The variability in these values can be partially explained by the factors described in each of the respective results sections. But the factor that requires special mention is the effect of precipitation on ELAs.

7.7 ELAs and precipitation

There is an ongoing debate as to whether temperature or precipitation is the main driver behind New Zealand glaciation. Although, the temperature decrease that may have caused the ELA depression in the Wahianoa Valley has been highlighted in the previous section, the effect of precipitation on this depression can not be ignored.

Soons (1979) suggests that glaciation in New Zealand can be as much a response to increased precipitation as it to depressed temperatures. Soons (1979) also postulates that a moderate cooling with the correct amount of precipitation can have the same effect as a lesser amount of precipitation with a larger decrease in temperature. This is also supported by Rother and Shulmeister (2006) who suggest that a moderate cooling of 2-4ºC combined with a sustained 5000-8000mm precipitation regime in the Southern Alps can create the same effect as the temperature decrease of 4-5ºC that caused glacial advances of the Last Glacial Maximum. Furthermore, it has been viewed by Keys (1988) that the glaciers on the western side of Mt Ruapehu such as the Whakapapa Glacier are more susceptible to changes in precipitation than temperature. In contrast, Keys (1988) suggests the glaciers on the leeward side of Mt Ruapehu such as the Wahianoa Glacier are susceptible to temperature rather than precipitation change.

7.8 Summary

As can be seen throughout this chapter, there has been a significant change in the elevation of the ELAs for the Wahianoa Glacier. All four climate reconstruction methods used yield four different elevations for the paleo-ELA ranging from 1600-1770m. Likewise, the three climate reconstruction methods used to determine an approximation of the modern ELAs provide three different elevations ranging from 2430-2530m but the difference is smaller than that for the paleo-ELAs.

The average ELA depression determined for the Wahianoa Glacier was c. 755m which equated to an average temperature decrease of c. 4.5ºC based on a lapse rate of 6ºC/1000m (Table 7.5). Furthermore, this temperature decrease appears to indicate that the Wahianoa moraines could have been formed during the Last Glacial Maximum. This seems to satisfy the expected outcome of this chapter which was to evaluate the temperature decrease required to cause the average ELA depression and if possible identify with which glacial event it is associated.

Chapter 8: Discussion

8.1 Introduction

This chapter will be divided into two major sections. The first section will compare the findings from the three relative age dating methods used in the Wahianoa Valley in order to determine if a relationship exists between these results. An expected outcome is that the sample sites with the oldest ages, as indicated by the number on the outside of each box in Figure 8.1, would tend to have the largest averages of the five largest lichens, the lowest Schmidt hammer rebound values (R) and the highest radii of curvature. The second section will examine the overall results from the climate reconstruction methods used for the Wahianoa Glacier and compare them with regional, national and international studies to see where these results fit in the wider scale of glaciation.

8.2 Comparison of the relative age dating methods

8.2.1 General trends

Ideally, the results from the comparison of these methods would show that a relationship exists between them. This relationship would demonstrate that the highest average of the five largest lichens per sample site is associated with the lowest Schmidt hammer rebound value and the highest radius of curvature. The relative age dating results will now be compared against each other to see if such a relationship exists (Figure 8.1).

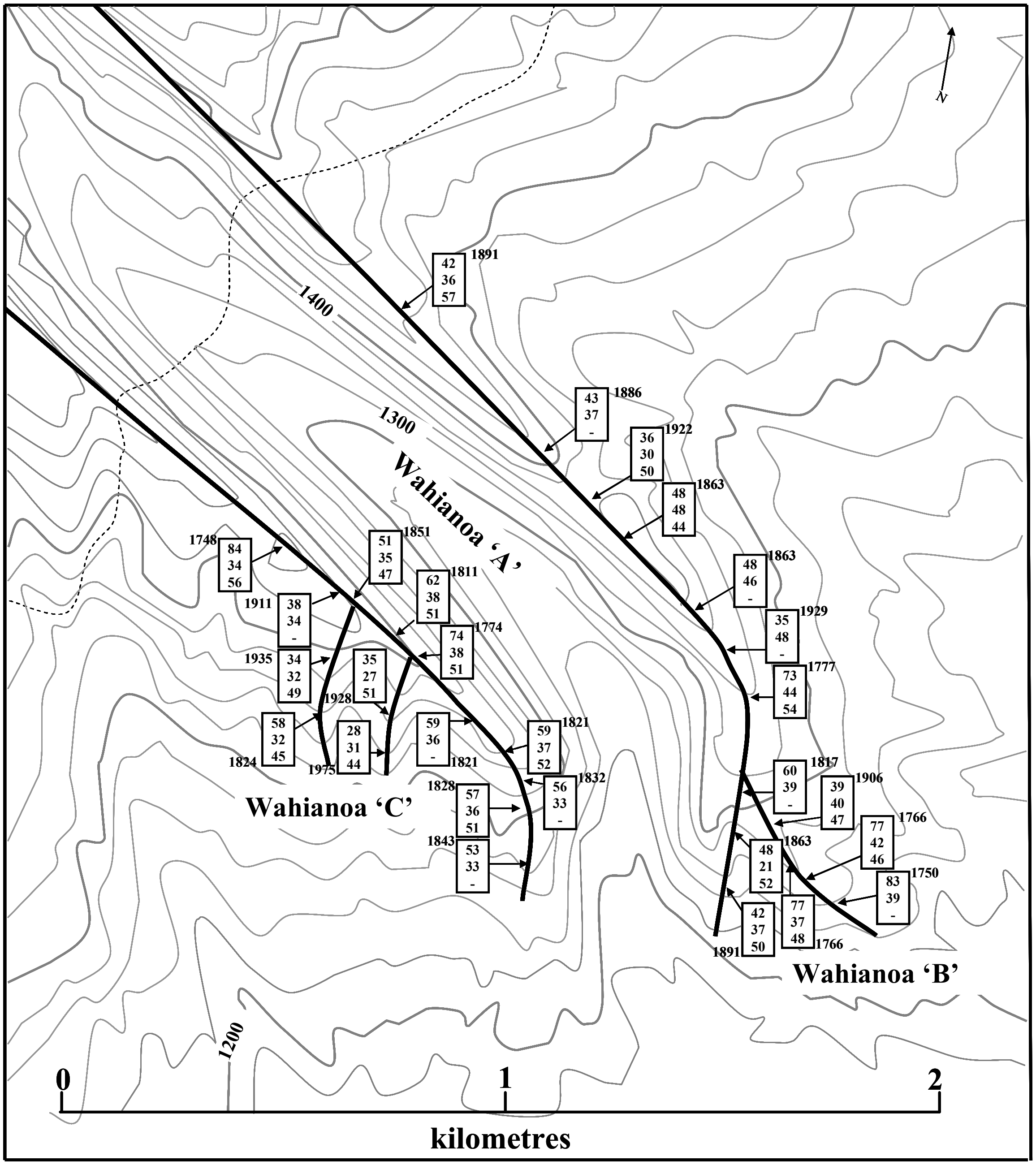

Figure 8.1. Comparison of results from the relative age dating methods. Top numbers in each box indicate the average of the five largest lichen. Middle numbers indicate Schmidt hammer rebound values and the bottom numbers indicate average radius of curvature.

As can be seen from Figure 8.1, the ages derived from the lichen growth curve indicate that the moraines in the Wahianoa Valley formed during the Little Ice Age (LIA). However, the fact that these dates are based on a lichen growth curve that was constructed using lichens from a site outside the Wahianoa Valley, with the associated problems outlined in Section 4.5 questions the validity of these results. If the lichen measurements were indeed suitable data for a relative age dating method in the Wahianoa Valley then it would be expected that there would a relationship between them and the Schmidt hammer R values whereby an increase in lichen size should correspond with a decrease in R values. The results from the lichenometric methods will now be compared with the Schmidt hammer results in order to see this relationship does exist between these two sets of values.

8.2.2 Comparing lichen results and Schmidt hammer rebound values

An expected result from the comparison of these methods would be a negative relationship demonstrating that the highest average of the five largest lichens would be found at the same location as the lowest average rebound value. However, due to possible operator and equipment errors this is probably too high an expectation to achieve. Instead, a general trend should be observed in that the larger averages of the five largest lichens should be associated with the lower average Schmidt hammer rebound values.

The top values in the boxes in Figure 8.1 are the average of the five largest lichens per sample site and the middle values are the average rebound values. It is very difficult to try and discern a relationship between these two sets of values. There are some sample sites which have higher averages of the five largest lichens associated with lower Schmidt hammer rebound values. However, there are also sites which have lower averages of the five largest lichens associated with lower Schmidt hammer rebound values such as sample site 2 on the true left of the Wahianoa ‘A’ moraines. This disparity of results is also observed on the Wahianoa ‘B’ and ‘C’ moraines where it is difficult to discern any consistent relationship between the average of the five largest lichens and Schmidt hammer rebound values to support the expected outcome.

The observations made from Figure 8.1 are further supported by Figure 8.2 which is a graph comparing the results from these two methods for the Wahianoa Valley. If the expected relationship existed this graph should show a negative trend between these two sets of values, namely that as the lichen size increased the average Schmidt hammer rebound value should decrease. There is no such apparent trend in Figure 8.2 which could be explained by the factors outlined in sections 4.5 and 5.4 and together with associated subsections. This lack of negative trend is further supported by the low R^2 value of 0.0446.

It is possible that the boulders used in the Schmidt hammer method were already subjected to subaerial weathering thereby lowering R values prior to lichen colonization. An implication of this is that the Wahianoa moraines were formed earlier than the lichen results suggest.

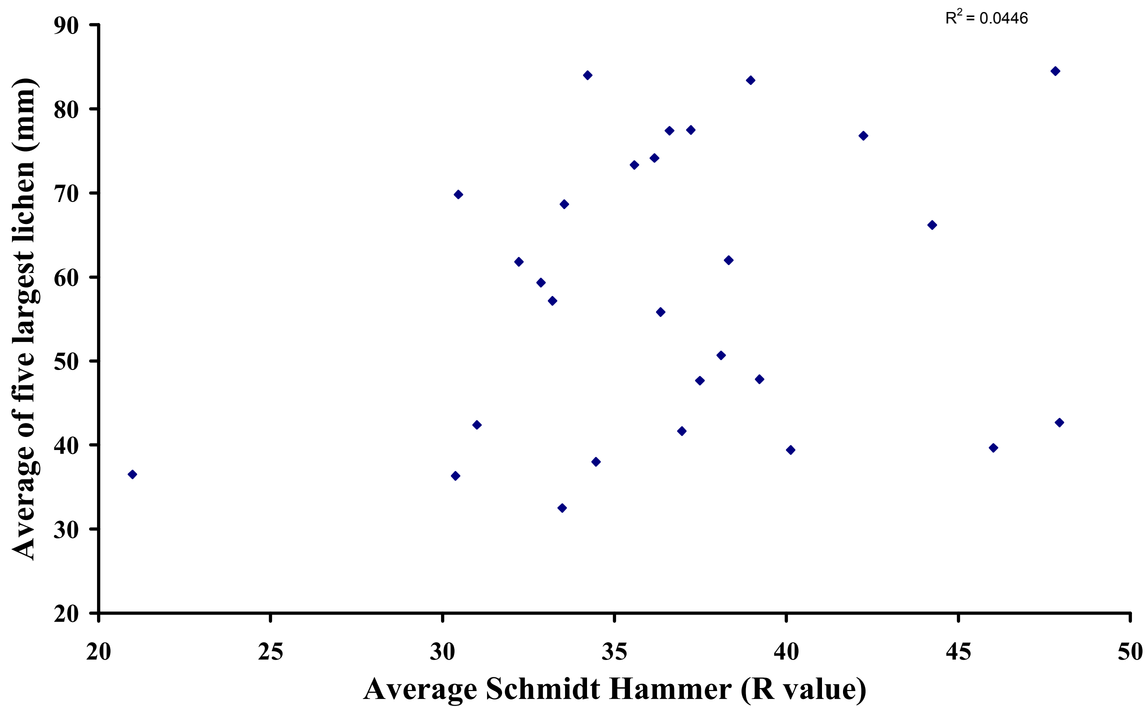

Figure 8.2. Comparison between average five largest lichens and respective average rebound values of the Wahianoa Valley.

8.2.3 Comparing lichen results and Boulder roundness values

This section will compare the top numbers and bottom values in each of the boxes in Figure 8.1. An expected outcome from the comparison of these two methods is that as the average of the five largest lichens increases, so too should the radius of curvature. It would be ideal to find these results at the same sample site, however factors such as lithology can affect the relationship between these results.

It can be seen in Figure 8.1 that there is a slight relationship between the averages of the five largest lichens and the radii of curvature, where it appears that the higher radii of curvature is associated with the larger averages of the five largest lichens. However, this relationship is only slight which could indicate that the boulders have undergone either mechanical or subaerial weathering (or a combination of both) prior to colonization by lichens.

This is further demonstrated in Figure 8.3 which is a graph comparing these two sets of values for the Wahianoa Valley. Even though there is a slight positive trend (R^2 = 0.0161), a stronger correlation is needed in order to determine whether this is random chance or a statistically significant association. Also, there are a number of factors which have been described in sections 4.5 of the Lichenometry results chapter and 6.3 of the Boulder roundness results chapter which need to be taken into consideration in terms of their potential influence on the relationship between these two results.

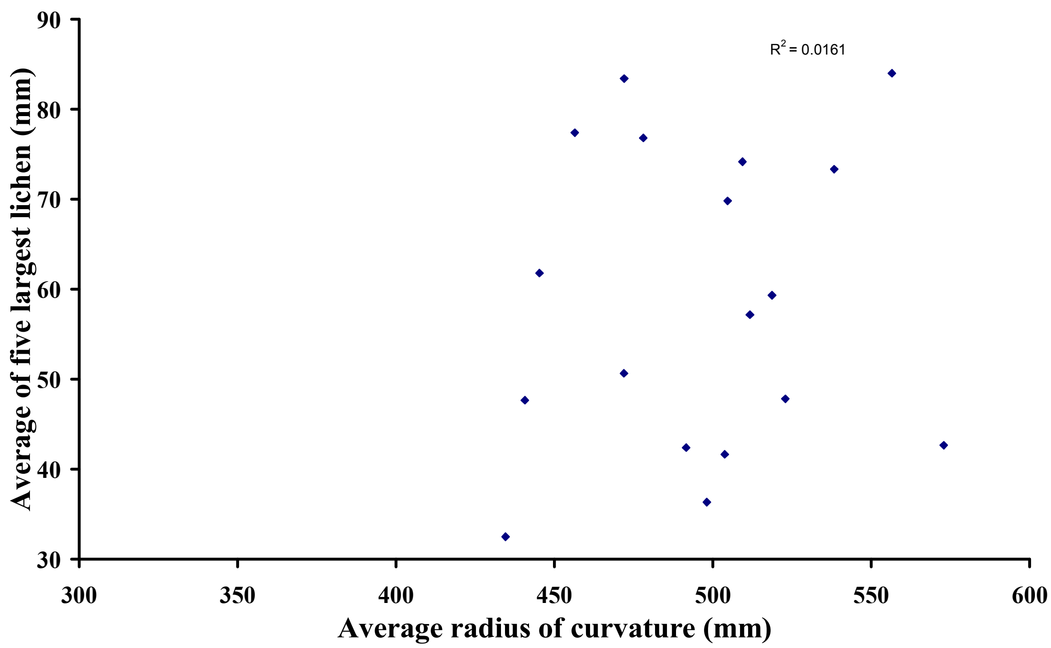

Figure 8.3. Comparison between the average of the five largest lichen and radius of curvature for the Wahianoa Valley.

8.2.4 Comparing Schmidt hammer and Boulder roundness values

This section will compare the middle value and bottom values in the boxes in Figure 8.1. It is expected that the Schmidt hammer rebound values will decrease with an increase in the radii of curvature. Figure 8.1 shows a slight negative trend between these two sets of results in that the lower rebound values are generally associated with the higher radius of curvature. This is further demonstrated in Figure 8.4 where a slight negative trend is also observed. The implication of this is that as the radius of curvature increases over time the Schmidt rebound (R value) of the boulder decreases. However, the trend is only slight ($R^2 = 0.047$) and there are factors which have been outlined previously in the respective results chapters for these methods and (sections 5.4 and 6.3) that may have affected the results individually and thereby the relationships between them.

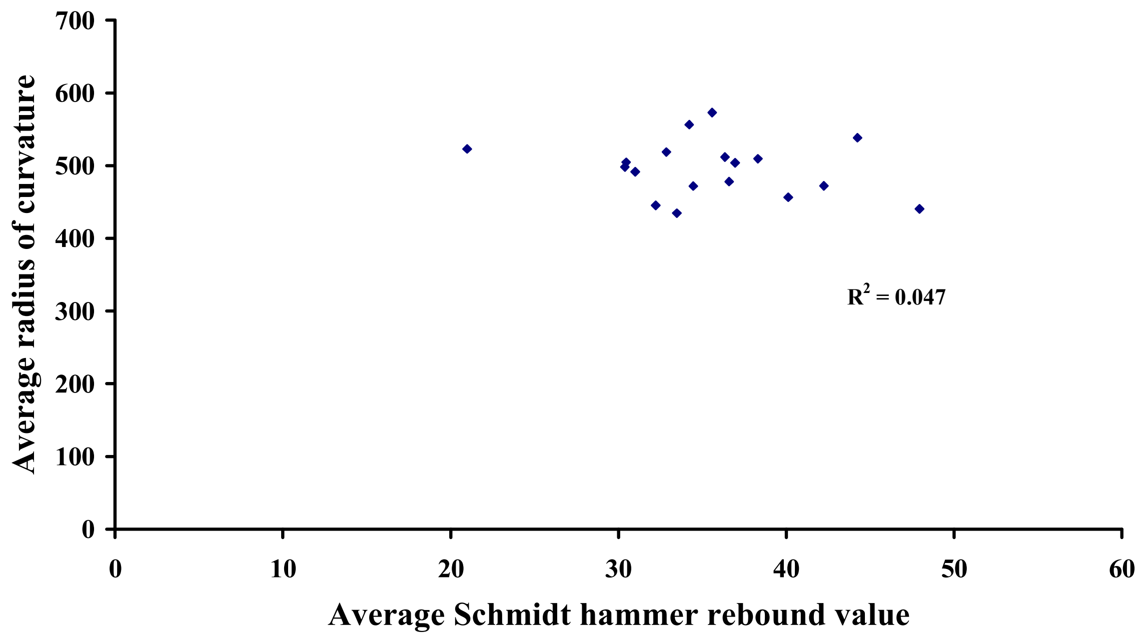

Figure 8.4. Comparison between Boulder roundness and Schmidt hammer results.

8.2.5 Summary

Overall, there does not appear to be a relationship between the results of the Lichenometric and Schmidt hammer methods. However, there appears to be tentative relationships between both Lichenometric results and Boulder roundness as well as between Boulder roundness and Schmidt hammer. But the relationships between these two sets of values are only very slight and the various factors outlined in sections 4.5, 5.4 and 6.3 may make these relationships inconclusive.

8.3 Comparison with other lichenometric research

The two lichenometric methods used in the Wahianoa Valley provided slightly different ages for the Wahianoa Valley. This section will examine the ages evaluated from these methods and put the ages of the Wahianoa Valley in a New Zealand and an overseas context.

8.3.1 Growth curve

Based upon the ages determined using this lichenometric method the current surface of the moraines of the Wahianoa Valley were formed by an advancement of the Wahianoa Glacier during the Little Ice Age. In Figure 8.1, the age of the furthest extent of the Wahianoa 'B' moraine is 1750AD and ~1824AD for the Wahianoa 'C' moraines, with the Wahianoa 'A' moraines being between the mid to late 1800s.

8.3.1.1 Comparison on a regional scale

Regionally, if the Wahianoa moraines were to have formed during the Little Ice Age then these are the youngest ages reported for the glaciers on Mt Ruapehu. Previous research conducted by Williams (1984) suggests that the moraines on Mt Ruapehu are all at least 14,000 years old as this is an approximate age of the oldest volcanic tephra layer not disturbed by glacial erosion. McArthur and Shepherd (1990) propose that the moraines on Mt Ruapehu formed during the Last Glacial Maximum and are either a result of the final retreat of the glaciers or a readvance during the final stadials.

However, there is evidence for the occurrence of the Little Ice Age in the North Island. $\delta^{18}O$ values in speleothems measured in Waitomo Caves demonstrate a cooling at approximately 1675AD thereby coinciding with the Little Ice Age (LIA) (Williams *et al.*, 2004). In addition, there is evidence for alternate warm and cold periods preserved in tree rings of *Libocedrus bidwillii* Hook. F. (New Zealand cedar) in Tongariro National Park (Palmer and Xiong, 2004). There are cooler periods that occurred around 1630-1680AD (which appears to correspond with Williams *et al.* (2004)'s LIA data), 1790-1810AD and 1880-1910AD with warm periods around 1730-1780AD, 1820-1840AD, 1870s. If the Wahianoa moraines were to have formed during the Little Ice Age then ages for the Wahianoa 'B' and 'C' moraines place them within the first and second warm periods identified by Palmer and Xiong (2004) respectively. However, there is a wider range of ages for the maximum extent of the Wahianoa 'A' moraines making it difficult to discern exactly during which stage within the Little Ice Age that the Wahianoa Glacier was at its full extent. If indeed it formed during this glacial event at all.

8.3.1.2 Comparison on a national scale

On a national scale, this is the youngest age for glacial deposits on the North Island. The only other known location to display evidence of glaciation are the Park Valley moraines in the Tararua Ranges which are thought to have formed during the Last Glacial Maximum (Adkin, 1911; Pillans *et al*., 1993; Brook *et al*., 2005).

Table 8.1. Comparison between lichenometric results from the Wahianoa Valley and selected Little Ice Age dates in New Zealand.

Study	Region	Dating Method	Glacial moraines	Little Ice Age Dates (AD)
McKinzey *et al*, (2004)	Westland	Diameter breast height measurements and tree ring counting of rata and kamahi	Franz Josef	Max: <1600 LIA '2': c.1600 LIA '3': c.1800
Winkler (2004)	Mt.Cook National Park	Lichenometry	Eugenie	Max: 1760
			Hooker	Max: 1735-1740 Readvance: 1860
			Mueller	Max: 1725-1730 Readvance: 1860
This study	Mt Ruapehu	Lichenometry	Wahianoa 'A'	Mid to late 1800s
			Wahianoa 'B'	c. 1750
			Wahianoa 'C'	c. 1824

The ages calculated for the Wahianoa 'A', 'B' and 'C' moraines are younger than the Little Ice Age maximum and the second Little Ice Age advance (LIA '2') of the Franz Josef Glacier which is thought to have occurred before 1600AD and c. 1600 AD respectively (McKinzey *et al*., 2004a) (Table 8.1). Also, the Wahianoa 'A', 'B' and 'C' moraines are younger than the Little Ice Age maximums of the Hooker and Mueller Glaciers as seen in Table 8.1.

In addition, the ages of the Wahianoa 'A' and 'C' moraines (Table 8.1) appear to be younger than the Little Ice Age maximum of the Eugenie Glacier. The age range for the Wahianoa 'A' moraines place their formation at about the same time as the readvance of the Hooker and Mueller Glaciers (~1860 AD) (Winkler, 2004). The age of the Wahianoa 'B' moraine (Figure 8.1) appears to nearly coincide with the LIA maximum for the Eugenie Glacier which is dated by Winkler (2004) as having occurred by approximately 1760AD. However, the age of the Wahianoa 'C' moraines suggests that it could coincide with the third Little Ice Age (LIA '3') advance of the Franz Josef Glacier which was dated by McKinzey *et al.* (2004a) as having occurred by c.1800AD (Table 8.1).

The ages of the Wahianoa moraines appear to correlate with Little Ice Age advances in the South Island. However, there appears to be a contradiction in terms of geomorphology. The height of the Wahianoa moraines (130-140m) appearing to be similar to the pre-Little Ice Age outer ridges (LM "a"-"d") of the Hooker Glacier which are suggested by Winkler (2005) to be up to 150m in height. In addition, the Park Valley moraines in the Tararua Ranges are approximately 130m in height which is in a similar order of magnitude to that of the Wahianoa moraines (130-140m). However, the Park Valley moraines are thought to have formed during the Last Glacial Maximum (Adkin, 1911; Pillans *et al.*, 1993; Brook *et al.*, 2005) rather than during the Little Ice Age.

8.3.1.3 Comparison on an international scale

On an international scale, one of the most studied regions using the growth curve method is Norway, which will be the focus of comparison for the Wahianoa Valley. The ages of the Little Ice Age maximum of the Wahianoa 'A' and 'C' moraines are younger than those determined for the maritime plateau Jostedalsbreen Glacier in Norway which have been dated to the mid-1700s (Bogen *et al.*, 1989 as cited in Winkler *et al.*, 2005; Bickerton and Matthews, 1993; Chinn *et al.*, 2005). Also the Wahianoa 'A' and 'C' moraines appear to coincide with further LIA advances of the Øvre Beiarbre Glacier in the Svartisen area which occurred c. 1858-1882AD and c. 1831AD respectively (Winkler, 2003).

Table 8.2. Comparison between lichenometric results from the Wahianoa Valley and selected Norwegian Little Ice Age results

Study	Region	Dating Method	Glacial moraines	Little Ice Age dates (AD)
Bogen *et al.* as cited in Winkler *et al.*, (2005); Bickerton and Matthews, (1994) and Chinn *et al.*, (2005).	Jostedalsbreen	Lichenometry	Jostedalsbreen region	Max: c.1750
Winkler (2003)	Svartisen	Lichenometry	Øvre Beiarbre	Max: c. 1750 Adv*: c. 1831 Adv*: c. 1831-1882
	Okstindan	Lichenometry	Mørkbrekkbreen	Max: c. 1750 Adv*: 1806
Matthews (2005)	Jotunheimen	Lichenometry	Jotunheimen region	Max: c. 1750 Adv*: 1818 Adv*: 1838-1898.
This Study	Mt Ruapehu	Lichenometry	Wahianoa 'A'	Mid to late 1800s
			Wahianoa 'B'	c. 1750
			Wahianoa 'C'	c. 1824

There are no ages similar to that of the Wahianoa 'A' moraines preserved in the Mørkbekkbreen Glacier (Table 8.2). But the ages of the Wahianoa 'A' moraines appear to coincide with the third advance preserved in the Jotunheimen region (Table 8.2).

The age of the Wahianoa 'B' moraine also appears to be almost synchronous with ages calculated for the Svartisen and Okstindan areas in northern Norway which are found by Winkler (2003) to have occurred c. 1750 AD. In addition, the age of the Wahianoa 'B' moraine appears to coincide with the ages of the Little Ice Age maximums of the Jostedalsbreen Glacier and the Jotunheimen region (Table 8.2).

The age of the Wahianoa 'C' moraines is very similar to that determined for the Mørkbekkbreen Glacier in Okstindan which appeared to have had an advance c. 1806AD (Winkler, 2003). In addition, the age calculated for the Wahianoa 'C' moraines places it between the 5th and 6th regional Little Ice Age advances for this area.

Since the climatic regimes for these glaciers are different to the Wahianoa Glacier it is difficult to be certain of the relevance of this international comparison.

8.3.2 Size-frequency

The average date for the Wahianoa Valley determined from this lichenometric method was about 1606AD. This is an older age than that calculated using the growth curve method in the previous section. Regionally, this age is younger than the age hypothesised by Williams (1984) and McArthur and Shepherd (1990) (see Section 8.3.1.1) and is older than the Little Ice Age date of ~1675 AD obtained from the speleothems in Waitomo Caves by Williams *et al* (2004). In addition, this date predates the oldest cooler period determined from New Zealand cedar tree rings by Palmer and Xiong (2004) which was 1630-1680AD. This lichenometric method uses all the lichens that are measured in the Wahianoa Valley thereby including all those that are affected by the factors outlined in Section 4.5.1, in particular micro-environmental conditions which could account for the older age.

On a national scale the date of about 1606 AD is younger than the age approximated by Adkin (1911), Pillans *et al.* (1993) and Brook *et al.* (2005) for Park Valley in the Tararua Ranges. In addition this age predates all of the Little Ice Age maximum dates calculated by Winkler (2004) for the Eugenie, Hooker and Mueller Glaciers (Table 8.2). However, this age appears to coincide with the second Little Ice Age (LIA '2') advance of the Franz Josef Glacier (Table 8.1) which occurred c.1600 AD (McKinzey *et al.*, 2004a).

Internationally this lichenometric method has been most frequently used in Iceland which will be the focus of comparison for the Wahianoa Valley results. The ages of the Wahianoa 'A', 'B' and 'C' moraines predates all the dates for glaciers in Iceland determined by Bradwell (2004); McKinzey *et al.* (2004b) and Bradwell *et al.* (2006) (Table 8.3). For the Skálafellsjökull and Heingabergsjökull the Little Ice Age maximum is thought to have occurred in the late 18th to mid-19th century, the size frequency curves of which had negative gradients of 0.0285-0.0457 and 0.0336-0.0592 respectively (McKinzey *et al*, 2004). The negative gradients of the size-frequency curves for the Wahianoa 'A', 'B' and 'C' ridges were found to be 0.0133, 0.0102 and 0.0027 respectively. When these gradients are compared to those from McKinzey *et al.* (2004b)'s study they indicate that the

Wahianoa 'A', 'B' and 'C' moraines formed prior to the late 18th century (c. 1780AD). The upper limit for the gradients from the Wahianoa 'A' and 'B' size-frequency curves is ~400 years based on the gradient of -0.01 which was suggested by Bradwell (2004) to be equivalent to an age of about 400 years. Bradwell *et al* (2006)'s work on the Lambatungnajökull Glacier in the southeast of Iceland determined a date for the Little Ice Age maximum as having occurred in the late 18th century (~1780-1800AD). In addition, an age gradient curve for the nearby glacial valley of Hoffellsdalur yielded a Little Ice Age maximum ages of ~1796 which corresponded to a negative age gradient of 0.0253 (Table 8.3).

Table 8.3. Comparison of the dates derived from the size-frequency method and the corresponding negative gradients from the Wahianoa Valley and Iceland.

Study	Location	Glacial moraines	Negative gradient	Little Ice Age date (AD)
McKinzey *et al* (2004)	Iceland	Skálafellsjökull	0.0285-0.0457	Late 18th to mid 19th century
		Heingabergsjökull	0.0336-0.0592	Late 18th to mid 19th century
Bradwell *et al* (2006)	Southeast Iceland	Lambatungnajökull		~1780-1800
		Hoffellsdalur	0.0253	~1796
This study	Mt Ruapehu	Wahianoa 'A'	0.0133	>1606
		Wahianoa 'B'	0.0102	<1606
		Wahianoa 'C'	0.0027	Prior to 1606

8.3.3 Summary

It appears that the ages of the Wahianoa moraines derived from the lichenometric results of both methods find some correlation with other Little Ice Age advances both nationally and internationally. However, the geomorphology of the Wahianoa moraines does not appear to bear any similiarity to those formed in the South Island during the Little Ice Age. But they are of a similar order of magnitude in height (130-140m) when compared to the pre-Little Ice Age outer ridges of the Hooker Glacier (up to 150m) and the Park Valley moraines in the Tararua Ranges (c. 130m) which are thought to have formed during the LGM. In addition, the Wahianoa moraines are of a similar height to the Mangatepopo moraines on Mt Ngauruhoe, which are known to be older than 14.7ka BP (Williams 2001;

Mackintosh pers. comm.). These discrepancies together with the lack of support from the Schmidt hammer R values and the obvious problems affecting the application of the lichenometric methods used in this study suggest that lichenometry may not be a suitable method for dating the Wahianoa moraines.

8.4 Schmidt Hammer

8.4.1 Comparison of results on a national scale

The Schmidt hammer results from this study indicate that the Wahianoa moraines may have formed in the same glacial event. The Schmidt hammer method has never been used before in a glacial environment on the North Island. Prior to this there has been only two other Schmidt hammer studies conducted in a New Zealand glacial environment, both in the South Island (Winkler 2000, 2005). The results from the Wahianoa Valley are compared with those from this research to provide an approximate age represented by the R values of the Wahianoa moraines. Due to the inaccuracy of the Schmidt hammer it is not generally used to provide any absolute dates, but since it was used in the South Island on previously dated materials it allows an opportunity for a tentative correlation to be established with the R values obtained from the Wahianoa moraines.

Table 8.4. Comparison between selected R values for the Birch Hill moraines and the Wahianoa Valley.

Study	Location	R value	Approximate age (yrs BP)
Winkler (2005)	Birch Hill	40.56 ± 2.26	c. 10,000
	Birch Hill	36.78 ± 2.53	
	Birch Hill	37.06 ± 2.94	
This study	Wahianoa ‘A’	37.05 ± 1.63	c. 10,000
	Wahianoa ‘B’	39.48 ± 3.56	
	Wahianoa ‘C’	31.79 ± 3.25	Prior to c.10,000

The mean R value for the Wahianoa ‘A’ moraines was 37.05 ± 1.63, which, when compared to the South Island results from Winkler (2005), indicate that the moraines possibly formed at approximately the same time as the Birch Hill moraines (c. 10,000 years BP) (Table 8.4). The Wahianoa ‘B’ moraine also appears to have formed in the same glacial event as the Birch Hill moraines since it has an average R value of 39.48 ± 3.56 (Table 8.4). The average R value for the Wahianoa 'C' moraines was 31.79 ± 3.25, which indicates that it possibly formed in an event prior to the oldest of the Birch Hill moraines and therefore could potentially have an age greater than c. 10,000 yrs BP (Table 8.4). However, the difference between R value from the Wahianoa 'C' moraines and that of the Birch Hill moraines is not substantial enough to conclusively say that they formed at an earlier date.

A factor influencing the comparison between the Schmidt hammer R values of both sets of moraines is that the lithology existing in each study was different. In addition, the Birch Hill moraines exist in a different climatic regime to that of the Wahianoa moraines thereby potentially leading to differences in weathering rates. Another factor that could have some influence on the comparison of these two sets of R values is that Winkler (2000, 2005) used an N type Schmidt hammer which has a different compressive strength to the L type Schmidt hammer used in this study. So it needs to be noted that there are differing variables between the two studies which may render comparison inaccurate. Therefore, the ages approximated may only be used as a guideline for determining where the Wahianoa moraines fit into New Zealand's glacial timescale. However, the Birch Hill research has relevance because it provides the closest comparable R values currently in existence. Given these limitations, the comparison between these two sets of results appears to indicate that the Wahianoa moraines formed prior to the Little Ice Age.

8.4.2 Comparison on an international scale

On an international scale, the R values for the Wahianoa moraines are lower than those measured on the moraine crests of Kvíárjökull, Skalafellsjökull and Heinabergsjökull by Evans *et al.* (1999). This indicates that the moraines in the Wahianoa Valley are potentially older than those found in these glacial regions in Iceland. In addition the ages established in the Icelandic sample sites indicate that these moraines formed during the Little Ice Age thereby suggesting that the Wahianoa moraines are pre-Little Ice Age. The R values for the Wahianoa moraines are also lower than those measured by Winkler *et al.* (2003) in the Breheimen region in southern Norway, where the moraines are thought to have formed during the Little Ice Age. Likewise, the mean R values for the Wahianoa Valley are lower than those found in the glacial sequence at the front of the Boyabreen in Norway by Aa and Sjåstad (2000). The M1 moraine in this study had an approximate age of 8560 yrs BP and had a mean R value of 44.59. Also there is a pre-Little Ice Age maximum at Greinbreen (38.22 ± 2.73) (Winkler *et al.*, 2003) which displays similar R values to the Wahianoa Valley (31.79 - 39.48). However, it is even more difficult to compare the R values between the Wahianoa Valley and these international locations, than was previously done in Section 8.4.1, as the lithology and climatic regimes are so different.

8.4.3 Summary

In summary, comparison with other Schmidt hammer studies, both nationally and internationally, has provided indications that the Wahianoa moraines predate the Little Ice Age. However there are differences in lithology and climatic regimes that must be taken into consideration when comparing the Wahianoa Valley R values to those of other locations. Therefore, the R values for the Wahianoa Valley may only be used to attempt a very approximate relative age for these moraines.

8.5 Paleo-glacier Reconstruction

8.5.1 Summary of results

There were four methods (see Chapter 7) used to reconstruct the paleo-equilibrium line altitude (ELA) for the Wahianoa Glacier. The results from these four methods were varied, which could be due to some of the factors described in Chapter 7. The average paleo-ELA for the Wahianoa Glacier was estimated to be 1715m, based on ELA calculations using the Accumulation-Area Ratio (AAR), Terminus to Headwall Altitude Ratio (THAR), Maximum Elevation of Lateral Moraine (MELM) and Extrapolation methods.

The average modern ELA was approximated to be c. 2475m based on results from the AAR, THAR and Extrapolation methods. The difference between the average estimated paleo- and modern ELAs was evaluated at 760m which indicates a temperature decrease of c. 4.5ºC (based on the standard environmental lapse rate of 6ºC/1000m, Shulmeister *et al.*, 2005). The basal shear stress of the Wahianoa Glacier was also calculated using an approximate ice thickness of c. 130m (based on approximate height of the Wahianoa moraines) and found to be 119kPa.

8.5.2 Comparison with other research

This section will compare the findings from the climate reconstruction for the Wahianoa Glacier with other results on a regional, national and international scale in order to attempt a correlation of these changes with a past New Zealand glacial event.

8.5.2.1 Regional Climatic Implications

Prior to this study there has been very little research conducted on the reconstruction of the ELAs and climate for Mt Ruapehu and the greater Tongariro National Park. The estimation of the ELA values from this study are very close to those approximated by McArthur and Shepherd (1990) and Mackintosh (pers. comm.) for Mt Ruapehu and Mangatepopo Valley, respectively (Table 8.5).

McArthur and Shepherd (1990) estimated the paleo-ELAs for Mt Ruapehu to range between 1500-1600m based on morainic evidence on Mt Ruapehu. Mackintosh (pers. comm.) has estimated the paleo-ELA for the Mangatepopo moraines (Mt Ngauruhoe) to be 1550 ± 50m based on both the median value from numerous studies and on the upper limit of these moraines. The current ELA for Mt Ruapehu was estimated by Mackintosh (pers. comm.) to be ~2500m which is in accordance with the estimation of the average modern ELA in the current study. McArthur and Shepherd (1990) estimated the ELAs of the glaciers at the time of their study to be 2300-2400m, which is lower than estimated for this study. However, this difference can be attributed to the retreat of Mt Ruapehu's glaciers since McArthur and Shepherd's (1990) study. The Wahianoa Glacier has melted at approximately 3m/yr in the period 1963-present based on the current snout having retreated 130m between Heine's (1963) measurement and the current estimation. Therefore this has led to a 60-110m retreat of the ELA between McArthur and Shepherd's (1990) and the current study.

The decrease in temperature required to cause the ELA depression for the Wahianoa Glacier appears to compare well with other values for Mt Ruapehu and Mt Ngauruhoe (Table 8.5). It appears from Table 8.6 that a c. 4.5-5ºC temperature decrease would cause an advance in Mt Ruapehu's glaciers based on the ELA depressions calculated for this study and also for McArthur and Shepherd's (1990) results. In addition, based on the ELA depression for the Mangatepopo moraines, Mt Ngauruhoe, it appears that a c. 6ºC temperature decrease would cause an advance of the glacier that resulted in their formation (Table 8.5).

Table 8.5. Comparison between estimated current and paleo ELAs for Mt Ruapehu and Mt Ngauruhoe.

Study	Location	Estimated paleo-ELA (m)	Estimated current ELA (m)	ELA depression (m)	Temperature depression (ºC)
McArthur and Shepherd (1990)	Mt Ruapehu	1500-1600	2300-2400	800 ± 100	4.8 ±0.6
Mackintosh (pers. comm.)	Mangatepopo Valley	1550 ± 50	c.2500	950 ± 50	5.7 ± 0.3
This study	Wahianoa Valley	c. 1715	c.2475	c. 760	4.5

On a broader regional scale, this decrease in temperature required to cause the depression of the ELAs is substantially larger than the temperatures obtained for the Little Ice Age in the North Island.

From speleothems in Max's Cave located within the Waitomo Caves, Williams *et al.* (1999) suggest that the Little Ice Age temperatures recorded in this region were up to 0.8ºC cooler than the present day. In addition, tree rings of the New Zealand cedar, measured by Palmer and Xiong (2004) indicate a cooling of at least 0.2ºC, based on the difference in temperature during the Little Ice Age period and the running mean temperature for the period 1459-1986AD. If the temperatures in the Little Ice Age were about 1°C lower than present day levels this could indicate an ELA depression of approximately 167m based on the standard lapse rate of 6°C/1000m. However, as mentioned in Chapter 7, there are factors such as precipitation that need to be taken into account which would tend to cause the ELA depression of the Wahianoa Glacier to be greater than the one calculated based on

Williams *et al.*'s (1999) speleothem values but still unlikely to equate to the large ELA depression observed in Table 8.5. Therefore, it can be deduced that the Little Ice Age is unlikely to have caused the formation of the Wahianoa moraines.

Also, further evidence from speleothems in the Waitomo district indicate that there was a cooling around 3ka BP with temperatures decreasing about 1.5ºC below present day levels (Williams *et al.*, 1999; 2004) which is lower than the temperature decrease estimated in this study (Table 8.5). The ELA depression based on this decrease in temperature is approximately 250m, which does not correlate with the ELA depression estimated for the Wahianoa Glacier (Table 8.5). It can likewise be deducted that this cooling event did not cause the formation of the Wahianoa moraines, even with taking precipitation into account.

However, the temperatures from this study (Table 8.5) do compare well with McGlone and Topping (1983)'s temperature decrease of ~5ºC for the Last Glacial Maximum based on pollen evidence in the Tongariro region and this temperature decrease equates to a very similar ELA depression estimated for the Wahianoa Glacier.

8.5.2.2 New Zealand Climatic Implications

Prior to this study there has been no basal shear stress value estimated for the Wahianoa Glacier or any glacier on Mt Ruapehu for when they were in their full extent. The estimated paleo-maximum basal shear stress value for the Wahianoa Glacier of 119 kPa compares well with Brook *et al.*'s (2005) value of 99kPa for Park Valley in the Tararua Ranges. Both of these values fit within the range of 50-150 kPa which is suggested by Benn and Evans (1998) as being indicative of modern glaciers.

The average paleo-ELA value of c. 1715m estimated for the Wahianoa Valley (Table 8.6) correlates well with previous research carried out by Brook and Crow (unpub. data) and Shulmeister *et al.* (2005). Brook and Crow (unpub. data) reported an estimated paleo-ELA for the Park Valley of 1419m based on a northwards ELA increase of 1.4/km from Cobb Valley, northwest Nelson. The paleo-ELA for the Cobb Valley was estimated by Shulmeister *et al.* (2005) to be 1384m based on 4ºC of cooling.

The modern ELAs for the glaciers in the South Island are lower than that estimated for Mt Ruapehu (Table 8.6), which is to be expected because of differing climatic conditions between the two islands causing a difference in the behaviour of the glaciers. The glaciers located on the west of the main divide of the South Island were estimated to have ELAs of at least 1500m while the glaciers on the east of the main divide at least 2300m (Lamont *et al*, (1999); Shulmeister *et al*, (2005)). In addition, Lamont *et al.* (1999) and Shulmeister *et al*. (2005) estimate that the modern ELAs range from c. 1570m in the south (Caroline Peak) to 2140m in the north (Mt Ella) (Table 8.6).

Table 8.6. Comparison of the estimated paleo and current ELA values for the Wahianoa Valley with other estimated ELA values in New Zealand.

Study	Location	Paleo-ELA (m)	Current ELA (m)
This study	Wahianoa Valley	1715	2475
Shulmeister *et al* (2005)	Cobb Valley	1384	
Brook and Crow (unpub. data)	Park Valley	1419	
Lamont *et al* (1999) and Shulmeister *et al* (2005)	West of main divide, South Island		~1500
	East of main divide, South Island		>2300
	Mt Ella		2140
	Caroline Peak		~1570

The decrease in temperature required for the depression of ELAs calculated in Table 8.6 is higher than the estimation for the Little Ice Age in the South Island. Anderson and Mackintosh (2006) propose that temperatures for the Little Ice Age were between 0.8ºC and 1.4ºC below present day levels, based on the three Little Ice Age advances (LIA '1', '2' and '3') of the Franz Josef Glacier. Burrows (1977) reported a temperature of 1.2ºC for the Rakaia Glacier at the time of the Little Ice Age which could correlate with the Franz Josef Glacier. Bacon *et al.* (2001) report a 150m ELA depression in the Inland Kaikoura Range which equates to a temperature decrease of c. 1ºC.

Taking into account the different climatic regimes between the glaciers in the South Island it is possible that there were ELA depressions greater than 150m associated with the above mentioned temperatures. However, the 760m ELA depression in the Wahianoa Valley is of too great a magnitude to have been caused by this range of temperatures. Therefore it again indicates that the Wahianoa moraines are unlikely to have been formed during the Little Ice Age.

In contrast, the temperature change based on the ELA depression for the Wahianoa Glacier does correlate well with Last Glacial Maximum temperatures estimated by Porter (1975), Soons (1979) and Bacon *et al*. (2001) (Table 8.7). Soons (1979) estimated a cooling of temperatures by c. 5 ºC inferred from an approximate ELA decrease of 830-850m across the central South Island. A similar value was estimated by Porter (1975) for glaciers in the Mt Cook National Park. Bacon *et al*. (2001) report an ELA depression of between 750-850m in the Inland Kaikoura Range during the LGM, from which it was inferred that the associated temperature decrease was in the vicinity of 4.5 to 5ºC (Table 8.7).

Table 8.7 Comparison between estimated ELA depression and associated decrease in temperature with national LGM estimates.

Study	Location	ELA depression (m)	Temperature decrease (ºC)
Porter (1975)	Mt Cook National Park	[redacted]	c. 5
Soons (1979)	Central South Island	830-850	c. 5
Bacon *et al* (2001)	Inland Kaikoura Range	750-850	4.5-5
This study	Wahianoa Valley	760	4.5

However, a slightly wider range of Last Glacial Maximum temperatures are being reported based on speleothems (Williams *et al.*, 1996; Hellstrom *et al.*, 1998), fossil beetle assemblages (Marra *et al.*, 2006) and pollen evidence (Shulmeister *et al.*, 2001) with values from these studies reporting a decrease of about <4-5 ºC, 2 to 3ºC, and 7ºC respectively. Based on these decreases, Rother and Shulmeister (2006) suggest that the LGM temperatures were probably no more than 5-7ºC below present day levels which still correlates with the temperature decrease estimated for the ELA depression of the Wahianoa Glacier (Table 8.7).

However, considering temperature alone is simplifying climate too much. A combination of precipitation and temperature could have caused the Wahianoa Glacier to advance during a later glacial event such as ACR. Even though the estimated temperatures for the Wahianoa Glacier correlate well with those from the LGM, it cannot be overlooked that these temperatures are also similar to those reported by Anderson and Mackintosh (2006a). Anderson and Mackintosh (2006a) suggest that the temperature decrease required to cause the late glacial advance of the Franz Josef Glacier to the Waiho Loop in South Westland would be in the range of 4.1-4.7°C which fits well with ACR values from the Vostok Ice Core. Thereby, it is possible that the Wahianoa Glacier could have advanced during this climatic event.

8.5.2.3 International Climatic Implications

On a global scale, New Zealand's glaciers are commonly compared with their counterparts in the European Alps and Norway. Prior to this study, South Island glaciers have been compared with glaciers in Norway as they have similarities in climatic conditions in terms of precipitation (Chinn *et al.*, 2005) and also with the European Alps due to their locality as a mid-latitude mountain belt (Rother and Shulmeister, 2006).

The Little Ice Age ELA depression for the Jostedalsbreen ice cap in Norway was estimated by Nesje *et al.* (1991) to be 150m which corresponds to an approximate temperature decrease of c. 1.5°C (Dahl and Nesje, 1992). However, Torsnes *et al.* (1993) estimated an ELA depression of about 80m for the same ice cap. These estimated ELA depressions and associated temperature decrease during the LIA are less than that calculated for the Wahianoa Glacier in this study.

Younger Dryas (11,000-10,000 yrs BP) temperatures in the Central European Alps have been reported by Nesje and Dahl (2000) as being 4-6°C lower than the present day levels. This temperature decrease correlates well with that estimated for the Wahianoa Glacier in this study. However, the temperature decrease for the Gran Sasso Massif in the central Apennines during the Last Glacial Maximum was in the vicinity of 7-8°C (Nesje and Dahl, 2000), which is slightly larger than the decrease estimated for the Wahianoa Glacier in this study.

Even though it appears from these comparisons that the temperature decrease associated with the ELA depression of the Wahianoa Glacier is approximately the same as that of the Younger Dryas in the central European Alps, there are differences in climatic regimes. Rother and Shulmeister (2006) suggest that even though the European Alps are on average higher than the Southern Alps they receive substantially smaller amounts of precipitation. This in turn causes the ELAs for the Southern Alps to be of a magnitude of 1000m lower than their counterparts in the European Alps. However, this comparison appears so far to be restricted only to the Southern Alps and has never before been used as a comparison with Mt Ruapehu. Because of the different climatic regimes that exist between Norway, the European Alps and Mt Ruapehu it is very difficult to draw any conclusive parallels, but the indications are very strong that the Little Ice Age did not cause the formation of the Wahianoa moraines.

8.5.2.4 Summary

It has been observed throughout this section that the temperature decrease associated with the Little Ice Age was not sufficient to result in the advance of the Wahianoa Glacier which caused the formation of the Wahianoa moraines. Even though not conclusive, it appears that the climatic conditions required to cause the formation of the Wahianoa moraines closely mirror that of the Last Glacial Maximum.

8.6 Future Research opportunities

8.6.1 Relative Age dating

From this research project two main areas of future research have arisen using relative age dating methods, both focussing on obtaining a better approximation of the age of the Wahianoa moraines. Firstly, the tephras are well documented in the Wahianoa Valley by researchers such as Donoghue (1991). However, these tephras are not as well documented on the moraines themselves and their use could provide a bracket age for the moraines and therefore an opportunity to more accurately correlate their formation with a past glacial event. There are some very important points that must be taken into consideration when conducting this study, such as the tephras depositional environment, exactly how the tephra was emplaced, and to ensure that it hasn't been re-transported to its current location. Taking these points into account as well as basic geological principles will help ensure that accurate dates can be determined.

Secondly, it was also seen throughout this study that the Schmidt hammer has seldom been used in glacial environments in New Zealand and never before in glacial environments on the North Island. In order to attempt better relative age dating of the Wahianoa moraines using this method, it needs to be used firstly in a known age environment in the Tongariro National Park. A perfect candidate for this would be the Mangatepopo Valley, which at present is known to be at least 14.7ka in age (Williams, 2001; Mackintosh pers. comm.). If the Schmidt hammer method was carried out on the Mangatepopo moraines it would provide more accurate comparative data for the Wahianoa moraines than that from the South Island. Thereby allowing for an opportunity to better associate the formation of the Wahianoa moraines with a glacial event.

8.6.2 Climate Reconstruction

Although the advances and retreats of the South Island glaciers since the Last Glacial Maximum have been well documented (Porter, 1975; Burrows, 1977; Soons, 1979; Bacon *et al.*, 2001; McKinzey *et al.*, 2004; Anderson and Mackintosh, 2006; Rother and Shulmeister, 2006), there is a lack of research in the same order of magnitude for Mt Ruapehu. This is mostly due to the research on Mt Ruapehu being focussed on volcanic activity, lahars and their associated hazards. However, these glaciers have played an important role in the formation of the current landscape on Mt Ruapehu and deserve further research.

There have only been two other studies prior to this one which have employed some climatic reconstruction methods to estimate the paleo-ELAs for Mt Ruapehu and the Mangatepopo Valley (McArthur and Shepherd, 1990 and Mackintosh, pers. comm.). The results from the climate reconstruction methods used in this study for the Wahianoa Glacier have highlighted the importance of future research in this area. Future research opportunities exist in the determination of the current and paleo ELAs for the other glacial moraines on Mt Ruapehu, thereby estimating the decrease in temperatures that would have been required to cause the ELA depressions for these areas. The correlation of these ELA depressions and associated temperature decreases could aide in a better understanding of which glacial event/s caused the formation of the glaciers of Mt Ruapehu.

Future research lies in using studies carried out by Heine (1962, 1963); Kells (1970) and Keys (1988) to establish the contemporary retreat of Mt Ruapehu's glaciers. Ablation rates and past ELAs could be determined by the differences of the snout measurements between these past studies and present day. This will aide in the understanding of not only past glacial behaviour due to climate change but also due to volcanic activity.

Chapter 9: Conclusions

9.1 Objectives Revisited

This research project attempted to determine a relative age for the formation of the Wahianoa moraines by using the Lichenometry, Schmidt hammer and Boulder roundness methods and to correlate their formation with a New Zealand glacial event. In addition, the results from these methods were compared with each other in order to identify and examine any relationships existing between them and ultimately establish whether they arrived at a similar age for the formation of the Wahianoa moraines. A climate reconstruction was also conducted on the Wahianoa Valley to determine the climatic conditions which would have caused the Wahianoa Glacier to form the Wahianoa moraines.

The resulting questions being addressed by this thesis were:

- How old are the Wahianoa moraines?
- In which glacial period did the Wahianoa moraines form?
- What is the paleo-ELA of the Wahianoa Glacier?
- What conditions caused the Wahianoa Glacier to advance forming the moraines?

The following sections will provide a summary of the objectives achieved by this thesis (see Section 2.7):

9.2 Lichenometry

There were two lichenometric methods used to attempt to establish a relative age of the Wahianoa moraines and therefore the climatic event which caused their formation.

9.2.1 Growth Curve

- The equation derived from this growth curve was: $\log y = 0.0021x + 1.3818$.
- When this equation was applied to the highest average of the five largest lichens for each sample area (Wahianoa 'A', 'B' and 'C' moraines) the ages determined were 1748AD, 1749AD and 1786AD respectively.

- These ages for the Wahianoa 'A', 'B' and 'C' moraines placed their formation during the Little Ice Age.

9.2.2 Size-frequency

- There were three size-frequency curves constructed for the Wahianoa 'A', 'B' and 'C' moraines from which the following size-frequency gradients were derived: -0.0133, -0.0102 and -0.0027 respectively.
- The resulting ages approximated were: Wahianoa 'A' – c. 400 years old; Wahianoa 'B' – c. 400 years old and Wahianoa 'C' – less than 400 years old.
- These ages also placed the formation of the Wahianoa moraines during the Little Ice Age.

9.3 Schmidt Hammer

- The R values measured in the Wahianoa Valley were variable which may be attributed to the factors outlined in Section 5.4.
- The mean R values determined for the three sampling areas were:
    - Wahianoa 'A': 37.05 ± 1.63
    - Wahianoa 'B': 39.48 ± 3.56
    - Wahianoa 'C': 31.79 ± 3.25
- There was a lack of relationship between this set of results and the results from the lichenometric methods. A potential implication of this is that the Wahianoa moraines had been formed prior to lichen colonization which was further supported by the tentative correlation between the Wahianoa Valley and Birch Hill moraine R values.
- Although no conclusive age can be determined due both to the lack of comparable results and also differences in lithology, the correlation indicated that the Wahianoa moraines could have formed in a pre-Little Ice Age advance.

9.4 Boulder Roundness

- This is the first time that this newly developed method (Kirkbride, 2005) has been used in New Zealand.
- It established that the Wahianoa 'A' moraines had the highest average radii of curvature (501.4mm), while the Wahianoa 'B' and 'C' moraines had the lowest average radii of curvature (468.0mm) and (469.0mm) respectively.
- A potential implication of this was that the Wahianoa 'B' and 'C' moraines are younger than the Wahianoa 'A' moraines. However, the Wahianoa 'B' and 'C' are distal moraines so they would have been deglaciated first followed by the 'A' moraines which would have steadily deglaciated in an up-valley direction.
- The results obtained were limited to comparing the relative ages between the Wahianoa 'A', 'B' and 'C' moraines and not to correlating their formation with a glacial event.

9.5 Climatic Reconstruction

- The average estimated paleo-ELA for the Wahianoa Glacier was 1715m, while the average current ELA was found to be 2475m.
- The temperature decrease that could have caused this ELA depression was evaluated at approximately 4.5 ºC.
- This temperature decrease appears to correlate well with the temperature decreases associated with the Last Glacial Maximum. This seems to imply that the Wahianoa moraines may have formed in the Last Glacial Maximum or associated stadials, but probably not during the Little Ice Age.

9.6 Summary

- The ages determined from both lichenometric methods suggest that Wahianoa moraines appear to have formed during the Little Ice Age.
- A tentative correlation between the Schmidt hammer R values from the Wahianoa Valley and those from the Birch Hill moraines in the South Island suggests that the Wahianoa moraines are pre-Little Ice Age.

- The temperature decrease required to cause the formation of the Wahianoa moraines appears to correlate well with the Last Glacial Maximum temperature decreases.

This thesis has demonstrated how difficult it is to assign the formation of the Wahianoa moraines to a glacial event. The wide range of factors outlined in each of the results chapters have had considerable effect on their respective methods leading to the contradictory results described above.

However, this study has identified future research opportunities in both fields of relative age dating and climate reconstructions which are recommended in Chapter 8. The measures outlined in these recommendations should achieve more accurate results in determining the past glacial event/s forming the Wahianoa moraines and a better understanding of Mt Ruapehu's past and present glacial behaviour. The one conclusion to be drawn from this study is that it is unlikely that the Wahianoa moraines formed during the Little Ice Age but are instead likely to have formed pre-Little Ice Age and possibly during the Last Glacial Maximum or associated stadials.

References

Aa, A.R. and Sjåstad, J.A. (2000). Schmidt hammer age evaluation of the moraine sequence in front of Bøyabreen, western Norway. *Norsk Geologisk Tidsskrift*, **80**: 27-32.

Adkin, G.L. (1911). The discovery and extent of former glaciation in the Tararua Ranges, North Island, New Zealand. *Transactions of the New Zealand Institute*, **44**: 308-317.

Alloway, B.V.; Lowe, D.J.; Barrell, D.J.A.; Newnham, R.M; Almond, P.C; Augustinus, P.C.; Bertler, N.A.N; Carter, L; Litchfield, N.J.; McGlone, M.S.; Shulmeister, J; Vandergoes, M.J.; Williams, P.W. and NZ-INTIMATE members (2007). Towards a climate even stratigraphy for New Zealand over the past 30,000 years (NZ-INTIMATE project). *Journal of Quaternary Science*, **22(1)**: 9-35.

Almond, P.C. (1996). Loess, soil stratigraphy and Aokautere ash on late Pleistocene surfaces in south Westland, New Zealand: interpretation and correlation with the glacial stratigraphy. *Quaternary International*, **34-36**: 163-76.

Anderson B. and Mackintosh, A (2006a). Temperature change is the major driver of late-glacial and Holocene glacier fluctuations in New Zealand. *Geology*, **34(2)**: 121-124.

Anderson, B. and Mackintosh, A. (2006b). Interactive comment on "Synoptic climate change as a driver of late Quaternary glaciations in the mid-latitudes of the Southern Hemisphere" by Rother, H. and Shulmeister, J. *Climate of the past discussions*, **1**: S161-S167.

Bacon, S.N.; Chinn, T.J.; Van Dissen, R.J.; Tillinghast, S.F.; Goldstein, H.L. and Burke, R.M. (2001). Paleo-equilibrium line altitude estimates from late Quaternary glacial features in the Inland Kaikoura Range, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, **44**: 55-67.

Barrows, T.T. and Juggins, S. (2005). Sea-surface temperatures around the Australian margin and Indian Ocean during the Last Glacial Maximum. *Quaternary Science Reviews*, **24**: 1017-1047.

Benedict, J.B. (1967). Recent glacial history of an alpine area in the Colorado Front Range, USA. I. Establishing a lichen growth curve. *Journal of Glaciology*, **6**: 817-832.

Benn, D.I. and Evans, D.J.A. (1998). *Glaciers and Glaciation*. Arnold, London.

Benn, D.I.; Owen, L.A.; Osmaston, H.A.; Seltzer, G.O.; Porter, S.C.; Mark, B (2005). Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glaciers. *Quaternary International*, **138-139**: 8-21.

Beschel, R.E. (1973). Lichens as a measure of the age of recent moraines. *Arctic and Alpine Research*, **5(4)**: 303-309. *Translated from*: Beschel, R.E. (1950). Flechton als Altersmasstab rezenter Moränen. *Zeitschrift für Gletscherkunde und Glazialgeologie*, **1**: 152-161.

Bickerton, R.W. and Matthews, J.A. (1993). 'Little Ice Age' variations of outlet glaciers from the Jostedalsbreen ice-cap, southern Norway: a regional lichenometric-dating study of ice-marginal moraine sequences and their climatic significance. *Journal of Quaternary Science*, **8(1)**: 45-66.

Birkeland, P.W. (1973). Use of relative age dating methods in a stratigraphic study of rock glacier deposits, Mt Sopris, Colorado. *Arctic and Alpine Research*, **5**; 401-416.

Boggs, S., Jr (2001). *Principles of Sedimentology and Stratigraphy: Third Edition*. Prentice Hall, New Jersey.

Bowen, D.Q. and Gibbard, P.L. (2007). The Quaternary is here to stay. *Journal of Quaternary Science*, **22(1)**: 3-8.

Bradwell, T. (2001). A new lichenometric dating curve for southeast Iceland. *Geografiska Annaler*, **83A**: 91-101.

Bradwell, T (2004). Lichenometric dating in Southeast Iceland: the size-frequency approach. *Geografiska Annaler*, **86A(1)**: 31-41.

Bradwell, T; Dugmore, A.J. and Sugden, D.E. (2006). The Little Ice Age glacier maximum in Iceland and the North Atlantic Oscillation: evidence from Lambatungnajökull, southeast Iceland. *Boreas*, **35**: 61-80.

Brook, M.S. and Brock, B.W. (2005). Valley morphology and glaciation in the Tararua Range, southern North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, **48**: 717-724.

Brook, M.S., Purdie, H.L, and Crow, T.V.H (2005). Valley cross-profile morphologhy and glaciation in Park Valley, Tararua Range, New Zealand. *Journal of the Royal Society of New Zealand*, **35(4)**; 399-407.

Bull, W.B. and Brandon, M.T. (1998). Lichen dating of earthquake-generated regional rockfall events, Southern Alps, New Zealand. *Geological Society of America Bulletin*, **110(1)**: 60-84.

Burrows, C.J. (1977). Late-Pleistocene and Holocene glacial episodes in the South Island, New Zealand and some climatic implications. *New Zealand Geographer*, **33**: 34-39.

Burrows, C.J. and Orwin, J (1971). Studies on some glacial moraines in New Zealand I – the establishment of lichen-growth in the Mount Cook area. *New Zealand Journal of Science* **14**: 327-35.

Caseldine, C.J. and Baker, A. (1998). Frequency distribution of *Rhizocarpon geographicum*, s.l., modelling and climate variation in Tröllaskagi, northern Iceland. *Arctic and Alpine Research*, **30(2)**: 175-183.

Chinn, T.; Winkler, S.; Salinger, M.J. and Haakensen, N (2005). Recent glacier advances in Norway and New Zealand: a comparison of their glaciological and meteorological causes. *Geografiska Annaler*, **87A (1)**: 141-157.

Christopherson, R.W. (2000). *Geosystems: Fourth edition*. Prentice Hall, New Jersey.

Cook-Talbot, J.D. (1991). Sorted circles, relative-age dating and palaeo-environmental reconstruction in an alpine periglacial environment, eastern Jotunheim, Norway: Lichenometric and weathering-based approaches. *The Holocene*, **1**:128-141.

Cronin, S.J.; Neall, V.E. and Palmer, A.S.(1996). Geological history of the north-eastern ring plain of Ruapehu volcano, New Zealand. *Quaternary International*, **34-36**: 21-28.

Cronin, S.J. and Neall, V.E. (1997). A late Quaternary stratigraphic framework for the northeastern Ruapehu and eastern Tongariro ring plains, New Zealand. *New Zealand Journal of Geology and Geophysics*, **40**: 185-197.

Dahl, S.O. and Nesje, A. (1992). Paleoclimatic implications based on equilibrium-line altitude depressions of reconstructed Younger Dryas and Holocene cirque glaciers in inner Nordfjord, western Norway. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **94**: 87-97.

Day, M.J. (1980). Rock Hardness: field assessment and geomorphic importance. *Professional Geographer*, **32(1)**: 72-81.

Denton, G.H. and Hendy, C.H. (1994). Younger Dryas Age advance of Franz Josef Glacier in the Southern Alps of New Zealand. *Science*, **264**: 1434-1436.

Donoghue, S.L. (1991). *Late Quaternary Volcanic Stratigraphy of the southeastern sector of the Mount Ruapehu ring plain, New Zealand*. Unpublished PhD thesis, Massey University of Palmerston North.

Donoghue, S.L.; Neall, V.E.; Palmer, A.S. (1995). Stratigraphy and chronology of late Quaternary andesitic tephra deposits, Tongariro Volcanic Centre, New Zealand. *Journal of the Royal Society of New Zealand*, **25(2)**: 115-206.

Donoghue, S.L. and Neall, V.E. (1996). Tephrostratigraphic studies at Tongariro volcanic centre, New Zealand: an overview. *Quaternary International*, **34-36**: 13-20.

Donoghue, S.L.; Neall, V.E.; Palmer, A.S.; Stewart, R.B. (1997). The volcanic history of Ruapehu during the past 2 millennia based on the record of Tufa Trig tephras. *Bulletin of Volcanology*, **59**: 136-146.

Evans, D.J.A; Archer, S and Wilson, D.J.H. (1999). A comparison of the lichenometric and Schmidt hammer dating techniques based on data from the proglacial areas of some Icelandic glaciers. *Quaternary Science Reviews*, **18**: 13-41.

Fergusson, G.J. and Rafter, T.A. (1959). New Zealand ^{14}C measurements – 4. *New Zealand Journal of Geology and Geophysics* **2**: 208-241.

Flint, R.R. (1957). *Glacial and Pleistocene Geology*. John Wiley, New York.

Froggatt, P.C. and Lowe, D.J. (1990). A review of late Quaternary silicic and some other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume and age. *New Zealand Journal of Geology and Geophysics*, **33(1)**: 89-109.

Furbish, D.J. and Andrews, J.T. (1984). The use of hypsometry to indicate long-term stability and response of valley glaciers to changes in mass transfer. *Journal of Glaciology*, **30(105)**: 199-211.

Gellatly, A.F. (1982). Lichenometry as a relative-age dating method in Mount Cook National Park, New Zealand. *New Zealand Journal of Botany*, **20**: 343-353.

Gellatly, A.F. (1983). Revised dates for two recent moraines of the Mueller Glacier, Mt Cook National Park. *New Zealand Journal of Geology and Geophysics*, **26**: 311-315.

Goudie, A.S. (2006). The Schmidt Hammer in geomorphological research. *Progress in Physical Geography*, **30(6)**: 703-718.

Gradstein, F.; Smith.; and Ogg, J.G. (2004). *A geologic time scale 2004.* Cambridge University Press, Cambridge.

Grange, L. I. (1931). Conical Hills on Egmont and Ruapehu volcanoes. *New Zealand Journal of Science and Technology*, **12**: 376-384.

Grove, J.M. (1988). *The Little Ice Age*. Methuen, London

Grove, J.M. (2001). The initiation of the "Little Ice Age" in regions round the North Atlantic. *Climatic Change*, **48**: 53-82.

Grove, J.M. (2004). L*ittle Ice Ages: Ancient and Modern, Second edition, Volume I.* Routledge, London.

Hackett, W.R. (1985). *Geology and Petrology of Ruapehu volcano and related vents*. Unpublished PhD Dissertation, Victoria University of Wellington.

Hawkins, F.F. (1985). Equilibrium-line altitudes and palaeoenvironments in the Merchants Bay area, Baffin Island, NWT, Canada. *Journal of Glaciology*, **31**: 205-213.

Heine, A.J. (1962). Glacier changes on Mount Ruapehu, New Zealand – 1957-1961. *Proceedings of the Symposium on the variations of the Regime of Existing glaciers,* Obergurgl, 10-18 Sept (1962), pp 173-78.

Heine, A.J. (1963). Mount Ruapehu Ice and Snow photo survey. *New Zealand Journal of Geology and Geophysics*, **6**: 261-267.

Hellstrom, J.; McCulloch, M. and Stone, J (1998). A detailed 31,000-year record of climate and vegetation change from the isotope geochemistry of two New Zealand speleothems. *Quaternary Research*, **50**: 167-78.

Houghton, B; Neall, V. and Johnston, D (1996). *Eruption!*. Viking, Auckland

Innes, J.L. (1983). Size-frequency distributions as a lichenometric technique: an assessment. *Arctic and Alpine Research*, **15**:285-294.

Innes, J.L. (1984a). The optimal sample size in lichenometric studies. *Arctic and Alpine Research*, **16**: 233-244.

Innes, J.L. (1984b). Lichenometric dating of moraine ridges in Northern Norway: Some problems of application. *Geografiska Annaler,* **66A(4)**: 341-352.

Innes, J.L. (1985). Lichenometry. *Progress in Physical Geography*, **9(2)**:187-254.

Innes, J.L. (1986). The size-frequency distributions of the lichens *Sporastatia testudinea* and *Rhizocarpon alpicola* through time at Storbeen, southwest Norway. *Journal of Biogeography*, **13**: 283-291.

Ivy-Ochs, S; Schlüchter, C.; Kubik, P.W. and Denton, G.H. (1999). Moraine exposure dates imply synchronous Younger Dryas glacier advances in the European Alps and in the Southern Alps of New Zealand. *Geografiska Annaler*, **81A(2)**: 313-323.

Karlén, W (1979). Glacier Variations in the Svartisen area, Northern Norway. *Geografiska Annaler*, **61A(1/2)**: 11-28.

Keys, H (1988). 1988 survey of the glaciers on Mt Ruapehu, Tongariro National Park: a baseline for detecting effects of climatic change. *Science and Research Internal Report No. 24.*

Kirkbride, M.P. (2005). Boulder Edge-roundness as an indicator of Relative Age: a Lochnagar Case Study. *Scottish Geographical Journal*, **121(2)**: 215-232.

Kirkbride, M.P. and Dugmore, A.J. (2001). Can Lichenometry be used to date the "Little Ice Age" glacial maximum in Iceland?. *Climatic Change* **48**: 151-167.

Krenek, L.O. (1958). The formation of dirt cones on Mount Ruapehu, New Zealand. *Journal of Glaciology*, **3(24)**: 312-314.

Krenek, L.O. (1959). Changes in the glaciers of Mt Ruapehu in 1955. *New Zealand Journal of Geology and Geophysics*, **2(4)**: 643-653.

Kulkarni, A.V. (1992). Mass balance of Himalayan glaciers using AAR and ELA methods. *Journal of Glaciology*, **38**: 101-104.

Lamont, G.N.; Chinn, T.J. and Fitzharris, B.B. (1999). Slopes of glacier ELAs in the Southern Alps of New Zealand in relation to atmospheric circulation patterns. *Global and Planetary Change*, **22**: 209-219.

Locke, W.W.; Andrews, J.T. and Webber, P.J. (1979). A manual for lichenometry. *British Geomorphological Research Group Technical Bulletin* **26**:1-47.

Lowe, J.J. and Walker, M.J.C. (1997). *Reconstructing Quaternary Environments: Second Edition*. Addison Wesley Longman Limited, London.

Lowell, T.V.; Schoenenberger, K.; Deddens, J.A.; Denton, G.H.; Smith, C.; Black, J and Hendy, C.H. (2005). *Rhizocarpon* calibration curve for the Aoraki/Mount Cook area of New Zealand. *Journal of Quaternary Science* **20(4)**: 313-325.

Marra, M.J. (2003). Last interglacial beetle fauna from New Zealand. *Quaternary Research*, **59**: 122-131.

Marra, M.J.; Shulmeister, J. and Smith, E.G.C. (2006). Reconstructing temperature during the Last Glacial Maximum from Lyndon Stream, South Island, New Zealand using beetle fossils and maximum likelihood envelopes. *Quaternary Science Reviews*, **25**; 1841-1849.

Matthews, J.A. (1974). Families of lichenometric dating curves from the Storbeen gletschervorfeld, Jotunheimen, Norway. *Norsk Geografisk Tidsskrift* **29**: 97-109.

Matthews, J.A. and Petch, J.R. (1982). Within-valley asymmetry and related problems of Neoglacial lateral moraine development at certain Jotunheimen glaciers, southern Norway, *Boreas*, **11**: 225-247.

Matthews, J.A. (2005). 'Little Ice Age' glacier variations in Jotunheimen, southern Norway: a study in regionally controlled lichenometric dating of recessional moraines with implications for climate and lichen growth rates. *The Holocene*, **15(1)**: 1-19.

McArthur, J.L. and Shepherd, M.J. (1990). Late Quaternary glaciation of Mt Ruapehu, North Island, New Zealand. *Journal of the Royal Society of New Zealand*, **20**: 287-96.

McCarroll, D (1987). The Schmidt Hammer in Geomorphology: five sources of instrument error. *British Geomorphological Research Group Technical Bulletin*, **36**: 16-27.

McCarroll, D (1989a). Potential and limitations of the Schmidt hammer for relative-age dating: field tests on neoglacial moraines, Jotunheimen, southern Norway. *Arctic and Alpine Research*, **21(3)**: 268-275.

McCarroll, D (1989b). Schmidt hammer relative-age evaluation of a possible pre-'Little Ice Age' Neoglacial moraine, Leirbreen, southern Norway. *Norsk Geologisk Tidsskrift*, **69**: 125-130.

McCarroll, D (1991). The Schmidt hammer, weathering and rock surface roughness. *Earth Surface Processes and Landforms*, **16**: 477-480.

McGlone, M.S. (1995). Lateglacial landscape and vegetation change and the Younger Dryas climatic oscillation in New Zealand. *Quaternary Science Reviews*, **14**: 867-881.

McGlone, M.S. and Salinger, M.J. (1990). New Zealand climate: The past 2 million years. *In*: *New Zealand Climate Report 1990*, pp 11-20. Royal Society of New Zealand.

McGlone, M.S.; Salinger, M.J. and Moar, N.T. (1993). Paleovegetation studies of New Zealand's climate since the Last Glacial Maximum. *In*: Wright, H.E.; Kutzbachm, J.E.; Webb III, T.; Ruddiman, W.F.; Street-Perrott, F.A. and Bartlein, P.J. (eds) *Global Climates Since the Last Glacial Maximum*, pp 294-317. University of Minnesota Press, Minneapolis.

McGlone, M.S. and Topping, W.W. (1983). Late Quaternary vegetation, Tongariro region, central North Island, New Zealand. *New Zealand Journal of Botany*, **21**: 53-76.

McGlone, M.S.; Turney, C.S.M. and Wilmshurst, J.M. (2004). Late-glacial and Holocene vegetation and climatic history of the Cass Basin, central South Island, New Zealand. *Quaternary Research*, **62**: 267-279.

McKinzey, K.M.; Lawson, W.; Kelly, D and Hubbard, A (2004a). A revised Little Ice Age chronology of the Franz Josef Glacier, Westland, New Zealand. *Journal of the Royal Society of New Zealand*, **34(4)**: 381-394.

McKinzey, K.M.; Orwin, J.F. and Bradwell, T (2004b). Re-dating the moraines at Skálafellsjökull and Heinabergsjökull using different lichenometric methods: implications for the timing of the Little Ice Age Maximum. *Geografiska Annaler*, **86A (4)**: 319-335.

Mercer, J.H. (1988). The age of the Waiho Loop terminal moraine, Franz Josef Glacier, Westland. *New Zealand Journal of Geology and Geophysics*, **31**: 95-99.

Meierding, T.C. (1982). Late Pleistocene glacial equilibrium-line altitudes in the Colorado Front Range: A comparison of methods. *Quaternary Research*, **18**: 289-310.

Morgan, P.G. and Gibson, W (1927). *The geology of the Egmont Subdivision, Taranaki*. Geological Survey Branch, Bulletin No. 29. Department of Scientific and Industrial Research, Wellington.

Nairn, I.A. (1992). The Te Rere and Okareka eruptive episodes – Okataina Volcanic Centre, Taupo Volcanic Zone, New Zealand. *New Zealand Journal of Geology and Geophysics*, **35**: 93-108.

Nesje, A.; Kvamme, M.; Rye, N.; and Løvlie, R. (1991). Holocene glacial and climate history of the Jostedalsbreen region, western Norway; evidence from lake sediments and terrestrial deposits. *Quaternary Science Reviews*, **10**: 87-114.

Nesje, A. and Dahl, S.O. (2000). *Glaciers and Environmental change*. Hodder Headline Group, London.

Newnham, R.M.; Lowe, D.J. and Williams, P.W. (1999). Quaternary environmental change in New Zealand: a review. *Progress in Physical Geography*, **23(4)**: 567-610.

Noller, J.S. and Locke, W.W. (2000). Lichenometry. *In*: Noller, J.S.; Sowers, J.M. and Lettis, W.R. (eds). *Quaternary Geochronology*: *Methods and Application*, pp 261-272. American Geophysical Union, Washington DC.

Orwin, J (1972). The effect of environment on assemblages of lichens growing on rock surfaces. *New Zealand Journal of Botany* **10**: 37-47.

Owen, L.A. and Benn, D.I. (2005). Equilibrium-line altitudes of the Last Glacial Maximum for the Himalaya and Tibet: an assessment and evaluation of results. *Quaternary International*, **138-139**: 55-78.

Palmer, A.S. and Pillans B.J. (1996). Record of climatic fluctuations from ca. 500ka loess deposits and paleosols near Wanganui, New Zealand. *Quaternary International*, **34-36**: 155-162.

Palmer, J.G. and Xiong, L (2004). New Zealand climate over the last 500 years reconstructed from *Libocedrus bidwillii* Hook. F. tree-ring chronologies. *The Holocene*, **14(2)**: 282-289.

Park, J. (1910). On the Glacial Till in Hautapu Valley, Rangitikei, Wellington. *Transactions of the New Zealand Institute*, **42**: 580-584.

Park, J. (1916). On the occurrence of a striated erratic block of andesite in the Rangitikei Valley, North Island. *Transactions of the New Zealand Institute*, **48**: 135-137.

Park, J. (1926). Morainic mounds on the Waimarino plain near Ruapehu. *Transactions of the New Zealand Institute*, **56**: 382-383

Pillans, B.J.; McGlone, M; Palmer, A; Mildenhall, D; Alloway, B and Gerger, G (1993). The Last Glacial maximum in central and southern North island, New Zealand: a paleoenvironmental reconstruction using the Kawakawa Tephra Formation as a chronostratigraphic marker. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **101**: 283-304.

Pillans, B.J. (1994). Direct marine-terrestrial correlations, Wanganui Basin, New Zealand: the last million years. *Quaternary Science Reviews*, **13**: 189-200.

Pillans, B. and Naish, T. (2004). Defining the Quaternary. *Quaternary Science Reviews*, **23**: 2271-2282.

Porter, S.C. (1975). Equilibrium line of late Quaternary glaciers in Southern Alps, New Zealand. *Quaternary Research*, **5**: 27-48.

Porter, S.C. (1979). Hawaiian glacial ages. *Quaternary Research*, **12**: 161-187.

Porter, S.C. (1981). Lichenometric studies in the Cascade Range of Washington: Establishment of Rhizocarpon geographicum growth curves at Mount Rainier. *Arctic and Alpine Research*, **13(1)**: 11-23.

Porter, S.C. (2001). Snowline depression in the tropics during the Last Glaciation. *Quaternary Science Reviews*, **20**:1067-1091.

Powers, M.C. (1953). A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology*, **23**: 117-119.

Purdie, H. (2005). *Intra-annual variations in ablation and surface velocity on the lower Fox Glacier, South Westland, New Zealand.* Unpublished MSc thesis, Massey University, Palmerston North.

Rother, H and Shulmeister, J (2006). Synoptic climate change as a driver of late Quaternary glaciations in the mid-latitudes of the Southern Hemisphere. *Climate of the Past*, **2**: 11-19.

Salinger, J (2001). Climate Variation in New Zealand and the Southwest Pacific. *In*: Sturman, A and Spronken-Smith, R (eds) *The Physical Environment: A New Zealand Perspective* pp 130-151. Oxford University Press, Melbourne.

Shulmeister, J.; Shane, P., Lian, O.B.; Okuda, M.; Carter, J.A.; Harper, M.; Dickinson, W.; Augustinus, P and Heijnis (2001). A long late-Quaternary record from lake Poukawa, Hawke's Bay, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **176**: 81-107.

Shulmeister, J.; Fink, D and Augustinus, P.C. (2005). A cosmogenic nuclide chronology of the last glacial transition in North-West Nelson, New Zealand – new insights in Southern Hemisphere climate forcing during the last deglaciation. *Earth and Planetary Science Letters*, **233**: 455-466.

Shulmeister, J.; Rodbell, D.T.; Gagan, M.K. and Seltzer, G.O. (2006). Inter-hemispheric linkages in climate change: paleo-perspectives for future climate change. *Climate of the Past*, **2**: 167-185.

Singer, C; Shulmeister, J. and McLea, B (1998). Evidence against a significant Younger Dryas cooling event in New Zealand. *Science*, **281**: 812-814.

Sloss, C.R. (2005). *Holocene sea-level change and the aminostratigraphy of wave-dominated barrier estuaries on the southeast coast of Australia.* Unpublished PhD thesis, University of Wollongong, Australia.

Smirnova, T. Y. and Nikonov, A.A. (1990). A revised lichenometric method and its application dating great past earthquakes. *Arctic and Alpine Research*, **22(4)**: 375-388.

Soons, J.M. (1979). Late Quaternary environments in the Central South Island of New Zealand. *New Zealand Geographer*, **35(1)**: 16-23.

Soons, J.M. (1992). The West Coast of the South Island. *In*: Soons, J.M. and Selby, M.J. (eds) *Landforms of New Zealand*, pp 439-456. 2nd edition, Longman Paul, Auckland.

Soons, J.M. and Burrows, C.J. (1978). Dates for Otiran deposits, including plant microfossils and macrofossils, from Rakaia Valley. *New Zealand Journal of Geology and Geophysics*, **21**: 607-615.

Suggate, R.P. (1990). Pliocene and Pleistocene glaciations of New Zealand. *Quaternary Science Reviews*, **9**: 175-98.

Suggate, R.P. and Waight, T.E. (1999). *Geology of the Kumara-Moana area (sheet J32 and part sheet K32) 1:50,000*. *Geological Map 24.* Lower Hutt: Institute of Geological and Nuclear Sciences.

Te Punga, M.T. (1952). The geology of the Rangitikei Valley. *New Zealand Geological Survey Memoir 8*.

Torsnes, I; Rye, N; and Nesje, A (1993). Modern and Little Ice Age equilibrium-line altitudes on outlet valley glaciers from Jostedalsbreen, Western Norway: an evaluation of different approaches for their calculation. *Arctic and Alpine Research*, **25(2)**: 106-116.

Turney, C.S.M.; McGlone, M.S. and Wilmshurst, J.M. (2003). Asynchronous climate change between New Zealand and the North Atlantic during the last deglaciation. *Geology*, **31(3)**: 223-226.

United States Geological Survey, www.usgs.gov.

Webber, P.J. and Andrews, J.T. (1973). Lichenometry: a commentary. *Arctic and Alpine Research*, **5(4)**: 295-302.

Willett, R.W. (1950). The New Zealand Pleistocene snowline, climatic conditions and suggested biological effects. *New Zealand Journal of Science and Technology*, **32 (1)**: 18-48.

Williams, K. (1984). *Volcanoes of the South Wind*. Tongariro Natural History Society, Wellington.

Williams, K. (1996a). *Ruapehu Erupts*. Godwit Publishing Ltd, Auckland.

Williams, K (2001). *Volcanoes of the South Wind.* Tongariro Natural History Society, Wellington.

Williams. P.W. (1996b). A 230ka record of glacial and interglacial events from Aurora Cave, Fiordland, New Zealand. *New Zealand Journal of Geology and Geophysics,* **39**: 225-241.

Williams, P.W.; Marshall, A; Ford, D.C. and Jenkinson, A.V. (1999). Palaeoclimatic interpretation of stable isotope data from Holocene speleothems of the Waitomo district, North Island, New Zealand. *The Holocene*, **9(6)**: 649-657.

Williams, P.W.; King, D.N.T.; Zhao, J.-X and Collerson, K.D. (2004). Speleothem master chronologies: combined Holocene ^{18}O and ^{13}C records from the North Island of New Zealand and their palaeoenvironmental interpretation. *The Holocene*, **14(2)**: 194-208.

Williams, P.W.; King, D.N.T.; Zhao, J.-X and Collerson, K.D. (2005). Late Pleistocene to Holocene composite speleothems ^{18}O and ^{13}C chronologies from South Island, New Zealand – did a global younger Dryas really exist? *Earth and Planetary Science Letters*, **230**: 301-317.

Williams, R.B.G. and Robinson, D.A. (1983). The effect of surface texture on the determination of the surface hardness of rock using the Schmidt Hammer. *Earth Surface Processes and Landforms*, **8**: 289-292.

Winkler, S. (2000). The 'Little Ice Age' maximum in the Southern Alps, New Zealand: preliminary results at Mueller Glacier. *The Holocene*, **10(5)**: 643-647.

Winkler, S. (2003). A new interpretation of the date of the 'Little Ice Age' glacier maximum at Svartisen and Okstindan, northern Norway. *The Holocene*, **13(1)**: 83-95.

Winkler, S.; Matthews, J.A.; Shakesby, R.A. and Dresser, P.Q. (2003). Glacier variations in Breheimen, southern Norway: dating Little Ice Age moraine sequences at seven low-altitude glaciers. *Journal of Quaternary Science*, **18(5)**: 395-413.

Winkler, S. (2004). Lichenometric dating of the 'Little Ice Age' maximum in Mt Cook National Park, Southern Alps, New Zealand. *The Holocene*, **14(6)**: 911-920.

Winkler, S. (2005). The Schmidt hammer as a relative-age dating technique: potential and limitations of its application on Holocene moraines in Mt Cook National Park, Southern Alps, New Zealand. *New Zealand Journal of Geology and Geophysics*, **48**: 105-116.

Woodward, C and Shulmeister, J. (2007). Chironomid-based reconstructions of summer air temperature from lake deposits in Lyndon Stream, New Zealand spanning the MIS 3/2 transition. *Quaternary Science Reviews*, **26**: 142-154.

Appendix

Schmidt hammer

Wahianoa 'A'							
True Left	Readings					Roundness	Roundness value
Site 1	28	30	40	46	49	SR	4
	21	22	22	23	27	SA	3
	51	53	56	59	63	SA	3
	34	36	36	44	45	SA	3
	19	27	29	30	42	SA	3
	24	26	32	33	34	SA	3
	23	26	27	30	40	SR	4
	24	26	31	33	34	SA	3
	48	49	54	54	58	SA	3
	35	36	37	48	54	SA	3
Site 2	11	12	20	20	20	SA	3
	12	13	14	15	17	SA	3
	10	10	12	12	13	SA	3
	10	11	11	12	14	SA	3
	12	12	14	16	18	SA	3
	10	12	14	17	18	SR	4
	11	12	12	12	13	SA	3
	20	22	30	36	48	SA	3
	33	37	45	45	51	SA	3
	32	41	42	44	51	SA	3
Site 3	28	29	33	34	36	SR	4
	32	38	44	44	51	SR	4
	23	42	46	46	50	SR	4
	28	30	34	34	36	SA	3
	42	45	46	50	55	SR	4
	39	40	41	41	44	SR	4
	28	30	42	42	43	SR	4
	34	40	41	42	49	SR	4

	24	26	32	34	38	SA	3
	37	48	49	50	51	SA	3
Site 4	46	58	65	66	67	SA	3
	22	26	28	30	36	SR	4
	25	34	38	40	44	SA	3
	30	41	49	50	54	SA	3
	35	38	54	56	61	SA	3
	23	33	40	42	61	SA	3
	42	44	48	48	50	A	2
	42	42	45	45	50	SR	4
	30	41	41	42	43	SR	4
	46	52	54	57	58	A	2
Site 5	46	48	52	54	57	SA	3
	44	47	48	53	57	SR	4
	34	46	48	48	50	SR	4
	42	52	54	54	56	SR	4
	42	50	51	51	61	SA	3
	26	40	43	45	54	SA	3
	31	38	39	47	53	A	2
	43	50	52	54	54	SR	4
	22	50	51	57	59	SA	3
	33	44	51	54	56	SA	3
Site 6	39	43	44	50	54	SA	3
	30	34	38	45	50	SA	3
	47	51	54	54	55	SR	4
	24	44	45	47	56	SR	4
	28	42	48	50	52	SR	4
	48	49	49	51	55	SR	4
	30	31	36	38	42	SA	3
	46	48	50	53	53	SR	4
	30	45	55	56	56	SR	4
	44	48	52	54	58	SA	3

Site 7	22	36	37	39	44	SA	3
	46	48	58	64	68	SA	3
	30	36	50	52	65	SA	3
	32	54	54	57	58	SA	3
	54	57	61	66	67	SA	3
	56	64	66	69	70	A	2
	32	53	53	54	56	SA	3
	32	37	38	42	46	SR	4
	29	33	34	37	42	SA	3
	25	40	42	46	46	SA	3
Site 8	14	21	22	24	28	SR	4
	22	28	40	55	56	SR	4
	32	34	36	37	48	SR	4
	32	34	43	50	54	SR	4
	18	19	26	31	35	SA	3
	21	28	29	30	31	SA	3
	24	24	27	30	32	SR	4
	22	27	30	32	36	SA	3
	22	23	24	31	32	SA	3
	19	23	25	28	30	SA	3
Site 9	13	20	22	26	32	A	2
	29	32	37	38	44	SA	3
	30	31	41	42	48	SA	3
	31	34	43	48	53	A	2
	26	28	32	40	40	SA	3
	14	29	32	42	48	SA	3
	37	38	40	40	41	SA	3
	35	38	39	41	44	SA	3
	43	44	45	52	54	SR	4
	40	42	42	43	51	A	2
Site 10	40	41	48	48	52	SA	3
	38	38	41	43	45	SA	3

	25	39	39	42	43	SA	3
	28	37	39	40	43	SA	3
	22	27	32	34	35	SR	4
	26	30	34	37	39	SA	3
	24	28	30	37	40	SA	3
	22	24	29	31	33	SA	3
	20	24	31	34	38	SR	4
	36	41	42	43	47	SA	3
True Right	30	31	32	36	38	SR	4
Site 1	14	22	24	26	48	SR	4
	21	32	34	35	46	SA	3
	23	36	40	46	46	SA	3
	24	24	40	41	46	SA	3
	28	29	32	35	41	SA	3
	24	25	34	39	53	SA	3
	28	29	30	35	35	SA	3
	22	30	35	38	54	SR	4
	26	28	31	32	32	SR	4
Site 2	22	28	34	37	38	SA	3
	20	24	36	44	48	A	2
	18	30	34	34	55	SA	3
	26	42	44	48	56	SA	3
	24	26	34	36	38	SR	4
	33	36	40	47	54	SR	4
	30	30	38	39	40	SA	3
	20	38	39	54	54	SA	3
	25	30	36	48	58	SA	3
	20	31	32	34	35	SA	3
Site 3	25	27	32	44	50	SA	3
	22	23	24	29	31	SR	4
	19	26	30	33	36	SA	3
	32	38	44	46	47	SR	4

	22	26	29	31	38	SR	4
	23	24	29	32	37	SR	4
	16	24	29	32	32	SR	4
	24	29	32	40	40	SA	3
	26	33	33	35	35	SA	3
	32	42	50	54	56	SA	3
Site 4	28	32	36	39	46	SA	3
	34	41	44	46	58	SR	4
	30	46	54	55	56	SA	3
	22	22	32	33	34	SR	4
	26	40	41	45	48	A	2
	22	31	38	39	48	SA	3
	26	37	39	40	56	A	2
	34	38	47	48	54	A	2
	18	21	26	31	34	A	2
	18	29	29	30	40	SR	4
Site 5	22	25	40	50	53	SA	3
	19	38	39	44	56	A	2
	24	35	39	44	56	SA	3
	28	30	34	38	52	SA	3
	16	30	43	44	59	A	2
	23	30	40	41	51	A	2
	24	28	34	44	46	SA	3
	12	15	18	33	34	A	2
	14	22	25	51	56	A	2
	29	31	45	49	55	A	2
Site 6	21	26	27	29	47	A	2
	26	28	28	32	40	SA	3
	28	36	39	41	51	SA	3
	21	22	23	34	37	SA	3
	46	48	50	52	58	SA	3
	28	30	35	36	42	A	2

	40	48	48	50	54	A	2
	25	31	42	42	44	SA	3
	38	40	44	46	48	A	2
	36	38	41	44	56	SR	4
Site 7	40	44	56	57	59	SA	3
	14	31	33	42	55	SA	3
	23	26	33	37	37	SA	3
	16	28	36	37	46	SA	3
	32	38	42	43	48	SA	3
	28	33	38	39	43	SA	3
	24	40	43	44	58	SA	3
	26	31	32	39	47	SR	4
	36	36	42	44	45	SA	3
	31	33	37	41	42	SA	3
Site 8	16	21	24	33	34	SR	4
	20	28	34	37	40	SA	3
	16	22	29	42	45	SA	3
	24	40	46	50	55	SR	4
	28	33	37	38	42	SA	3
	29	30	30	36	40	SA	3
	45	48	52	56	59	SR	4
	15	17	22	24	29	SA	3
	28	28	31	32	39	SA	3
	38	40	40	40	41	SA	3
Site 9	34	35	39	41	44	SA	3
	26	26	38	40	47	SR	4
	30	32	32	43	45	SA	3
	16	19	20	22	22	SR	4
	24	27	32	34	36	SA	3
	23	23	29	33	33	SA	3
	18	25	28	29	31	SA	3
	32	34	42	42	44	SR	4

	26	36	36	38	49	SA	3
	34	36	49	50	53	SA	3
Site 10	19	23	24	25	28	SR	4
	44	46	48	48	50	SR	4
	33	34	44	48	52	SR	4
	22	24	27	34	37	SA	3
	22	30	35	36	45	SA	3
	16	16	20	28	37	SA	3
	28	31	36	43	45	SR	4
	14	22	42	47	50	SR	4
	29	40	47	49	49	SR	4
	20	25	26	34	39	SA	3
Wahianoa 'B'							
	Reading s					Roundnes s	Roundness Value
Site 1	29	34	36	43	47	SA	3
	40	41	44	47	49	SA	3
	28	29	33	34	36	SA	3
	27	29	32	38	50	SR	4
	21	38	39	49	53	SA	3
	42	43	44	47	47	SA	3
	24	34	35	43	51	SR	4
	24	29	29	36	45	SA	3
	26	44	59	61	62	SA	3
	22	28	38	44	45	SA	3
Site 2	37	40	42	46	49	SA	3
	45	51	54	54	56	SA	3
	53	57	58	59	63	SR	4
	32	38	38	40	43	SR	4
	38	39	39	43	46	SA	3
	22	40	47	48	53	A	2
	32	34	37	45	47	SA	3

	20	24	37	38	41	SR	4
	25	27	27	38	45	SR	4
	39	44	46	47	49	SA	3
Site 3	20	32	42	49	51	SA	3
	19	20	23	28	38	SA	3
	26	32	32	36	39	SA	3
	34	35	36	38	40	SA	3
	30	31	33	48	54	SR	4
	41	43	45	46	57	SA	3
	18	33	41	41	43	SR	4
	30	39	39	47	50	SR	4
	28	37	47	48	53	SA	3
	21	22	24	35	36	SA	3
Site 4	22	22	26	29	38	SR	4
	33	36	37	38	39	SR	4
	31	38	49	50	56	SR	4
	22	29	33	44	51	SR	4
	27	28	35	46	53	SR	4
	60	62	65	74	74	SA	3
	29	36	44	46	61	A	2
	45	49	56	57	69	SA	3
	18	20	24	40	40	SR	4
	22	24	25	26	28	SA	3
Wahianoa 'C'							
	Reading s					Roundnes s	Roundness value
Ridge 1	16	22	24	28	36	SR	4
	16	19	22	23	52	SA	3
	13	14	18	26	33	SR	4
	28	32	35	36	42	SA	3
	18	21	22	25	28	A	2
	16	26	28	39	40	SR	4

	24	28	39	40	44	SA	3
	22	32	34	40	50	SA	3
	22	22	26	34	34	SA	3
	44	45	46	47	52	A	2
Ridge 2	32	34	48	53	56	SA	3
	24	28	30	35	36	SR	4
	18	19	23	25	26	SR	4
	21	23	32	46	50	A	2
	18	20	26	28	30	SR	4
	19	20	26	34	46	SR	4
	30	38	38	41	45	SA	3
	28	36	46	56	56	SA	3
	18	19	22	28	36	SR	4
	38	41	41	44	47	SR	4
Ridge 3	17	19	26	31	31	SR	4
	19	22	30	33	33	SR	4
	14	21	24	28	39	SA	3
	20	30	34	36	42	SR	4
	32	37	40	43	45	SR	4
	15	20	21	21	21	SR	4
	26	28	33	34	39	SR	4
	28	35	36	38	48	SA	3
	22	28	28	32	40	SR	4
	34	37	39	46	55	SR	4
Ridge 4	24	31	35	35	38	SR	4
	16	21	22	29	52	SR	4
	20	22	24	31	38	SA	3
	16	19	20	20	22	SA	3
	19	32	32	34	55	SA	3
	27	32	32	49	51	SR	4
	25	33	33	34	41	SR	4
	40	41	46	57	58	SR	4

	20	24	25	26	28	SR	4
	32	33	37	39	41	SA	3

Lichenometry

	Wahianoa 'A'										
True Left	Site 1	40	30	25	29	33	20					
	Site 2	27	49	29	64	117	38					
	Site 3	26	27	30	27	22	44	45	40	42	34	
	Site 4	39	29	33	41	36						
	Site 5	38	20	28	23	36	31	41	30	34	41	
		30	41	36	34	34	36	38	53	48	51	38
	Site 6	40	39	32	52	47	46	83	37	38	44	38
		65	57	29	57							
	Site 7	58	56	58	72	31	45	45	37	35	40	
	Site 8	76	43	48	45	50	49	40	97	69	96	56
		64	64	53	72							
	Site 9	35	25	55	23	20	32	19	35	46	27	
	Site 10	28	35	45	23	29	60	30	33	31	37	
	Site 11	38	28	29	79	29	20	32	30	26	23	
	Site 12	38	60	65	39	84	41	25	47	72	75	
	Site 13	35	40	20	27	30	26	26	24	35	29	
	Site 14	40	44	30	25	62	34	30	44	26	34	
	Site 15	43	28	24	29	24	35	40	30	30	35	
	Site 16	63	33	23	36	36	35	35	30	34	25	55
	Site 17	28	30	29	28	38	30	35	34	35	24	38
	Site 18	47	27	47	38	31	18	35	40	37	35	
	Site 19	28	33	47	23	30	20	34	40	32	25	
	Site 20	33	36	32	34	35	32	39	38	34	45	
	Site 21	49	45	39	33	47	50	43	36	34	57	
	Site 22	45	24	45	40	26	30	39	39	28	29	
	Site 23	44	39	43	28	35	37	46	26	25	28	
	Site 24	78	37	37	29	25	57	42	36	39	24	
	Site 25	30	50	29	41	24	23	77	34	24	30	
True Right	Site 1	29	40	34	31	41	29	49	25	40	50	

	Site 2	34	41	27	77	35	42	39	32	40	43	
	Site 3	51	34	28	43	49	45	54	64	43	82	
	Site 4	43	42	45	55	40	45	77	44	31	41	
	Site 5	45	29	75	58	36	31	46	30	30	22	
	Site 6	85	38	33	59	34	46	29	42	33	35	
	Site 7	67	64	51	45	36	37	62	40	43	38	
	Site 8	66	70	42	46	45	89	40	68	84	67	
	Site 9	43	100	88	56	44	50	38	40	36	51	
	Site 10	43	63	40	70	35	37	40	55	35	56	
		53	47	58	35							
	Site 11	55	37	43	62	38	42	42	40	29	40	
	Site 12	37	32	40	35	23	31	26	28	42	32	
	Site 13	51	78	80	45	57	30	50	33	58	59	
	Site 14	49	41	110	77	56	44	42	35	77	74	
	Wahianoa 'B'											
Site 1	29	30	46	42	38	36	43	43	39	62	31	38
	47	30	41	44	33	26	26	38	48	30	37	29
	33	51	21	57	39	56	36	25				
Site 2	71	47	33	37	49	36	56	55	51	42	47	65
	29	66	41	42	30	43	52	49	104	45	38	34
	92	84	35	51	38							
Site 3	41	34	26	28	72	30	29	32	83	42	38	28
	27	34	46	64	29	70	50	47	95	54	47	30
	43	47	60	48	40							
Site 4	60	49	67	33	32	32	38	36	37	84	39	55
	47	34	109	63	64	42	30	28	51	33	37	46
	27	29	41	36	42	53	38	39	36			
Site 5	43	31	27	29	33	20	33	32	27	34	39	20
	35	46	29									
	Wahianoa 'C'											
	Site 1	88	75	75	72	39						
	Site 2	41	37	27	26	44						

Ridge 1	Site 3	33	56	27	28	34		
	Site 4	37	29	27	28	19		
	Site 5	38	29	32	31			
	Site 6	24	31	54	61	28	23	38
	Site 7	16	24	37	30	29	35	40
	Site 8	45	63	36.5	33	26	48	70
Ridge 2	Site 9	48	56	45	42	82	58	35
	Site 10	34	59	47	54	55	49	56
		31	33	85				

Boulder roundness

Wahianoa 'A'						
Site 1	Angle	86	96	97	87	98
True left	Measured Length (l_m)	770	815	815	724	788
Site 2	Angle	89	93	94	93	86
	Measured Length (l_m)	785	815	764	814	703
Site 3	Angle	86	96	73	91	97
	Measured Length (l_m)	705	852	720	738	833
Site 4	Angle	91	97	99	95	97
	Measured Length (l_m)	797	823	836	779	822
Site 5	Angle	100	98	95	106	103
	Measured Length (l_m)	790	767	747	805	825
Site 6	Angle	100	88	98	91	102
	Measured Length (l_m)	750	782	734	723	785
Site 1	Angle	95	80	83	80	98
True right	Measured Length	730	825	715	825	810

	(l_m)					
Site 2	Angle	70	80	90	88	85
	Measured Length (l_m)	810	790	760	770	760
Site 3	Angle	90	70	90	92	82
	Measured Length (l_m)	760	810	750	790	800
Site 4	Angle	105	70	70	90	95
	Measured Length (l_m)	750	840	840	785	775
Site 5	Angle	85	80	100	110	91
	Measured Length (l_m)	735	724	765	800	785
Wahianoa 'B'						
Site 1	Angle	91	99	91	91	99
	Measured Length (l_m)	790	796	786	787	836
Site 2	Angle	96	99	95	99	91
	Measured Length (l_m)	793	798	790	816	788
Site 3	Angle	98	99	96	91	98
	Measured Length (l_m)	790	845	810	790	797
Wahianoa 'C'						
Site 1	Angle	68	86	85	105	99
	Measured Length (l_m)	810	780	730	830	770
Site 2	Angle	105	100	92	95	106
	Measured Length (l_m)	830	850	780	790	820
Site 3	Angle	75	92	95	107	105
	Measured Length (l_m)	720	739	757	855	877
Site 4	Angle	97	92	108	94	99

	Measured Length (l_m)	800	804	827	810	806