Stratigraphy, facies architecture and emplacement history of the c. 3.6 ka B.P. Ngatoro Formation on the eastern flanks of Egmont Volcano, western North Island, New Zealand.

By

Benjamin John Dixon

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"All inferences from experience suppose ... that the future will resemble the past" – David Hume (1777)

I would like to dedicate this thesis to my mother, Penny Dixon. You are a constant inspiration to me in all that you do. Without your encouragement to pursue excellence, both in science and in life, this thesis would not have been possible.

Love, Your “Baby Boy”

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Abstract

The Ngatoro Formation is an extensive volcanoclastic deposit distributed on the eastern lower flanks of Egmont Volcano, central North Island, New Zealand. Formally identified by Neall (1979) this deposit was initially attributed to an Egmont sourced water-supported mass flow event c. 3,600 ^{14}C years B.P. The Ngatoro Formation was subsequently described by Alloway (1989) as a single debris flow deposit closely associated with the deposition of the underlying Inglewood Tephra (c. 3,600 ^{14}C yrs B.P) that had laterally transformed into a hyperconcentrated- to- flood flow deposit. Such water-supported mass flows have been well documented on volcanoes both within New Zealand (i.e. Mt Ruapehu) and elsewhere around the world (i.e. Mt Merapi, Central Java and Mt St Helens, Washington). This thesis comprises field mapping, stratigraphic descriptions, field and laboratory grain size and shape analysis, tephrochronology and palaeomagnetic analysis with the aim of refining the stratigraphy, facies architecture and emplacement history of the c. 3,600 ^{14}C yrs B.P. Ngatoro Formation.

This study has found that the Ngatoro Formation has a highly variable and complex emplacement history as evidenced by the rapid textural changes with increasing distance from the modern day Egmont summit. The Ngatoro Formation comprises two closely spaced mass flow events whose flow and emplacement characteristics have undergone both proximal to distal and axial to marginal transformations. On surfaces adjacent to the Manganui Valley on the deeply incised flanks of Egmont Volcano, the Ngatoro Formation is identified as overbank surge deposits whereas at the boundary of Egmont National Park it occurs as massive, pebble- to boulder-rich debris flow deposits. At intermediate to distal distances (17-23 km from the modern Egmont summit) the Ngatoro Formation occurs as a sequence of multiple coalescing dominantly sandy textured hyperconcentrated flow deposits. The lateral and longitudinal textural variability in the Ngatoro Formation reflects downstream transformation from gas-supported block-and-ash flows to water-supported debris flows, then subsequently to turbulent pebbly-sand dominated hyperconcentrated flows.

Palaeomagnetic temperature estimates for the Ngatoro Formation at two sites (Vickers and Surrey Road Quarries, c. 10 km from the present day Egmont summit) indicate clast

incorporation temperatures of c. 300⁰C and emplacement temperatures of c. 200⁰C. The elevated emplacement temperatures supported by the Ngatoro Formation's coarse textured, monolithologic componentry suggest non-cohesive emplacement of block-and-ash flow debris generated by the sequential gravitational collapse of an effusive lava dome after the paroxysmal Inglewood eruptive event (c. 3,600 ¹⁴C yrs B.P.). The occurrence of a prominent intervening paleosol between these two events suggest that they are not part of the same eruptive phase but rather, the latter is a product of a previously unrecognised extended phase of the Inglewood eruptive event. This study recognises the potential for gravitational dome collapse, the generation of block-and-ash flows and their lateral transformation to water-support mass flows (debris, hyperconcentrated and stream flows) occurring in years to decades following from the main eruptive phase. This insight has implications with respect to the evaluation of post-eruptive hazards and risk.

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Chapter One: Introduction

1. Introduction

1.1. Field Area

Taranaki Region located in western North Island, New Zealand, is situated on the eastern edge of the Indo-Australian Plate and is strongly influenced by the oblique-compressional tectonic boundary associated with the subduction of the Pacific Plate occurring immediately eastward of the North Island. Within this tectonic regime, Taranaki Region occurs in the transitional zone between tectonic contraction, strike-slip motion and tectonic rotation that characterises eastern North Island to normal faulting that pervades in western portions of the North Island (Townsend et al., 2008). The geomorphology of the Taranaki Peninsula is dominated by Egmont Volcano (also known as Mount Egmont or Mount Taranaki) set in a complex landscape of eroded extinct andesitic volcanoes (i.e. Pouakai & Kaitake Volcanoes),

Figure 1: Map of the Taranaki Peninsula with key geomorphological features. These include Egmont National Park (green), the Egmont ring plain and the dissected hill country (orange). Base map 1:250,000 from Land Information New Zealand.

uplifted and fault-cut marine terrace and weathered volcanoclastic surfaces and a dissected inland hill country dominated by Tertiary-aged mudstones, siltstones and sandstones (Figure 1).

Egmont Volcano is a 2158m high andesitic stratovolcano which sits at the southern end of the NNW-SSE Taranaki Volcanic Lineament; comprising the Sugar Loaf Islands (1.75 Ma); Kaitake (c. 0.50 Ma); Pouakai (c. 0.25 Ma); and Egmont Volcano at the southern-most end (Neall, 1986). Composed of dominantly pyroxene-plagioclase-hornblende-phyric andesite and basaltic andesite (Price et al., 1992), the edifice comprises a prominent high-angle lava flow mantled upper cone and a ring plain of extensive coalesced laharic, pyroclastic and alluvial volcanoclastic fans (Alloway et al., 1995). Volcanoclastic deposits of the Egmont ring plain record a highly active and intermittent eruptive history stretching over the last 130,000 years with the last definitive eruption occurring c. 1755 A.D (Druce 1966; Alloway et al., 1995). Egmont Volcano has undergone multiple collapse and reconstruction phases over this time represented by multiple debris avalanche deposits – for example, the c. 23 ka Ngaere and the c. 105 ka Okawa Formation (Alloway et al., 2005). The modern volcanic edifice represents <8% by volume of the total erupted material over its history and was likely constructed in the last 10,000 years (Downey et al., 1994).

The geographical location of Egmont Volcano presents several volcanic hazards for the Taranaki region given its significant industrial, agricultural and urban development. Unlike the prominent central North Island andesite volcanoes (Mount Ruapehu, Tongariro and Ngauruhoe) Egmont Volcano has not erupted since European colonisation to the region – though there is archeological evidence that pre-European Maori did perhaps witness volcanic activity centred at Egmont Volcano (Alloway et al. 1990). Taranaki has a population of 104,127 people or 2.6% of the national population (Statistics New Zealand, 2006) with the majority of the population occupying the volcanic ring plain. Taranaki has a highly productive agriculture sector - 60% of the region's total 723,610 Ha comprising dairy farmland (Taranaki Regional Council, 2012). The Ministry of Economic Development New Zealand state the income from energy resource levies and royalties on petroleum resources was NZ\$360,612,600 in the 2011-12 financial year, with the majority coming from Taranaki's commercially producing condensate and natural gas fields.

1.2. Previous Work

The first documented evidence for activity on Egmont volcano was recorded by A. W. Burrell who found pumiceous clasts lodged in the forks of living Matai (*Podocarpus spicatus*) and Rimu (*Dacrydium cupressinum*) in 1888, later published in Oliver (1931). The first detailed study of ash and lapilli layers was published by Druce (1966) who identified nine eruptives since 1600 A.D. This included the Korito and Inglewood Tephra which underlie the Ngatoro Formation. The first compiled record of Egmont Volcanoes tephrostratigraphy, by Neall (1972), focused on western Taranaki, and included 10 previously unknown tephra formations and constituent members (Figure 2).

Figure 2: Tephrostratigraphic units described by Neall (1972). These include the Korito and Inglewood Tephra.

The Inglewood Tephra was formally named and described by Neall (1972). Named after the township located 15 km south-east of New Plymouth, the Inglewood Tephra was described as a single bed containing creamy pumiceous lapilli, blocks near source and an upper contact to topsoil formed on the modern day ground surface. No shower bedding or charcoal was observed and was considered to be less than 5,000 years old. The Inglewood Tephra was described at two locations (Table 1).

The Inglewood Tephra was subsequently redefined by Alloway et al. (1995) to include two closely spaced pumiceous lapilli beds exposed on the eastern Taranaki landscape. These beds were informally named Inglewood.a and Inglewood.b in order of decreasing age (Figure 3). On the lower flanks of Egmont Volcano, the lapilli beds are typically separated by <0.14m of medial-ashy material which thins with increasing distance from source to ultimately form a single composite tephra bed. On the upper flanks, both lapilli beds are separated by a variably thick pyroclastic density current deposit. An isopach map of

Inglewood Tephra (encapsulating both lapilli beds and its distal composite) was mapped by Alloway et al. (1995) extending broadly north-eastward in the direction of the settlements of Kaimata, Ratapiko as well as across to Onaero Beach on the north Taranaki coast (Figure 4).

The Inglewood Tephra has been dated at $3,690 \pm 80$ ^{14}C yrs B.P. using a peat sample directly beneath the Inglewood.a bed located at Onaero Beach (Alloway, 1989; Alloway et al., 1995), and at $3,610 \pm 80$ ^{14}C yrs B.P. from wood fragments directly underlying the Ngatoro Formation (Neall, 1979). The proximal Inglewood Tephra has been correlated with the distal Eg-2, medium to coarse ash bed sampled from Waikato Lake cores (Lowe, 1988). The Eg-2 ash has a radiocarbon age of $3,700$ ^{14}C yrs B.P. Based on these radiocarbon dates the Inglewood Tephra is considered to have an age of c. $3,600$ ^{14}C yrs B.P.

1.	0.2 km uphill along Maude Road, from the junction with Kent Road. Section exposed in sharp corner on western side of road. Grid Reference - N109/673752 (1965). <i>7.5YR/N7/ (light grey) dense andesite lapilli averaging 2.0cm across, with 5YR/6.6 (olive-yellow) pumiceous lapilli drying to creamy colours, averaging 3.0cm across, in 7.5YR/4.4 (dark brown) coarse ash matrix which is friable, weakly blocky, sandy clay loam. Black-grey colours towards the top where influence of organic topsoil. Sharp distinct boundary. [TYPE SECTION]</i>
2.	3.8 km due SW of junction of Korito and Kent Roads, last well exposed cutting at the top of Korito Road. Grid Reference – N109/650745 (1965). <i>7.5YR/N7/ (light grey) dense andesite lapilli averaging 2.0cm across, and 5YR/6.6 (olive-yellow) pumiceous lapilli, often drying to creamy colours, averaging 2.5cm across. Coarse ashy matrix 7.5YR/4.4 (dark brown) with blackish colours to topsoil, coarse sandy clay loam, friable, weakly blocky. Distinct boundary.</i>

Table 1: Inglewood Tephra sections at Maude Road and Korito Road described by Neall (1972).

Figure 3: Composite tephrostratigraphy from Egmont Volcano encompassing deposits from the Maketawa Tephra (c. 2,900yrs B.P.) to Mahoe Tephra (c. 11,000yrs B.P.) (Alloway et al., 1995). The tephra sequence described in this thesis is marked by the red line.

Figure 4: Isopach map (in centimetres) indicating the distribution of the Inglewood Tephra (Alloway et al., 1995).

Closely associated with Inglewood Tephra was a single lahar deposit formally named by Neall (1979) as Ngatoro Formation after the Ngatoro Stream where it was first recognized and is well exposed. The type section for the Ngatoro Formation is 0.4 km to the north and north east of Bedford Road and south of Norfolk Road Junction. The Ngatoro Formation was subsequently studied by Alloway (1989) in his PhD thesis who described the formation as a single debris flow deposit which transformed both laterally from its flow axes to its margins as well as downstream to a hyperconcentrated flow then subsequently to a flood flow deposit as it passed down Manganui and Waitara River tributaries. The lower boundary of the Ngatoro Formation is separated from Inglewood b tephra below by <0.10m of andic medial or hydrous material and its upper boundary from Manganui tephra above by <0.20m of andic medial or hydrous material. The Manganui Tephra manifests as multiple scoriaceous basaltic lapilli associated with an eruption from Fanthams Peak (Petrie, 1988).

Based on radiocarbon dates associated with Inglewood Tephra in Taranaki (Neall, 1972; Alloway, 1989; Alloway et al., 1995) and from distal sites in the Waikato (Lowe, 1988) the Ngatoro Formation is considered to have an age of c. 3,600 ^{14}C yrs B.P. (Alloway, 1989; Lowe, 1988).

To complement the two sections designated by Neall (1979), a new stratigraphic section was designated by Alloway (1989) (Figure 5). This is a prominent westward facing cut slope along State Highway 3 opposite the junction with Johns Road, Tariki (Figure 5a and b). The distribution of the Ngatoro Formation is divided into a north-eastern lobe (nt1) and an eastern lobe (nt2) (Figure 6):

- **nt1** – The north-eastern lobe is c. 1.0 km wide and preserved on the inter-fluves between the upper tributaries of the Ngatoro Stream. At c. 15.2 km from the modern Egmont summit the deposit becomes channelized within the Ngatoro and Ngatoroitia Streams, separated by the Kahui Formation exposed on the inter-fluve surface. The deposits are then combined where they enter the Manganui River c. 26.1 km north-east of the modern Egmont summit.
- **nt2** – The eastern lobe is preserved in the Maketawa and Mangatengehu Streams, with the southern extent buried beneath the overlying Te Popo Formation. At c. 14.6 km from the modern Egmont summit a northern and southern sub-lobe is formed separated by the Kahui Formation exposed on the inter-fluves. The northern sub-lobe deposits are distributed between the Maketawa Stream and a tributary of the Waitepuku Stream, becoming channelized at c. 16.6 km north-east of the modern Egmont summit, and the southern sub-lobe deposits are distributed between Waitepuku and Mangatengehu Streams.
- Both lobes nt1 and nt2 merge at the junction of the Manganui River and Ngatoro Stream, with the deposits extending c. 17.0 km northwards down the Manganui River valley. The distribution of the Ngatoro Formation was depicted in the Quaternary Geological Map of the Taranaki Region in Neall and Alloway (2004) (Figure 6).

A	Manganui tephra	
0.26m -----	Indistinct and wavy boundary -----	
0.13m	Brownish yellow (10YR 6/6), firmly friable, weakly developed, fine to medium blocky structured medial material. Distinct and wavy boundary.	
c.1.45m	Ngatoro Formation	
sub-layer	Moderately to poorly sorted, massive (upper portion) to stratified (lower portion), inversely graded sub-units of light greyish brown to greyish brown (10YR 6/2 to 5/2) angular to sub-rounded gravels supported in a very firm matrix of pebbly sand of similar lithology. Common pumice layers occur near base of unit which exhibits planar, as well as low angle X-stratification. Sharp and irregular boundary to <0.20m of firm, well sorted fine sand with flame dewatering structures evident. Sharp and irregular boundary.	
0.07m	Brownish yellow (10YR 6/6), firmly friable, massive structured medial material.	
1.91m -----	Distinct and wavy boundary -----	
Il.b of Inglewood Tephra		

Figure 5: (A) Stratigraphic description and (B) stratigraphic log (in meters) of the Ngatoro Formation, including the underlying Inglewood Tephra, located at the Johns Road junction with State Highway 3 near the Tariki rail overpass (Alloway, 1989). The Inglewood Tephra subunits are noted as II.a and II.b respectively.

Figure 6: Mapped distribution of the Ngatoro Formation, including nt1 and nt2 lobes, and other Quaternary deposits on the Taranaki Peninsula (Neill and Alloway, 2004).

1.3. Importance of this Study

Detailed studies of past eruptive events expressed in the geological record are imperative to understanding likely impact scenarios during future eruptive events centred at Egmont Volcano. Such evidence suggests that water-supported mass flows (lahars), comparable in size and distribution to the Ngatoro Formation, are a common volcanic process associated with eruptive activity centred on Egmont Volcano (Neall, 1976; Alloway, 1989; Alloway et al., 1995; Neall and Alloway, 1995; Neall and Birks, 2004; Alloway et al. 2005). It can therefore be inferred that similar events can be expected to occur during future eruptive events.

Egmont Volcano is located in a populous and economically important region, so understanding the hazards posed by Egmont Volcano is vital for future regional planning, determining the location and design of infrastructure as well as, minimising loss of lives, property and livelihood. To understand the potential risk posed by future laharic events requires an insight into the mechanisms of emplacement, lateral variations and transformations of the flow, emplacement conditions (eg. temperature, sediment load, and flow regime), and timing.

Previous studies indicate that the Ngatoro Formation was immediately associated with the same eruptive phase that generated Inglewood Tephra. However, there is increasing evidence to suggest that the currently recognised Inglewood eruptive phases are temporally unrelated to the triggering and emplacement of Ngatoro Formation, and that Ngatoro Formation instead of forming a single deposit is indeed a series of closely-spaced events with broadly similar debris and hyperconcentrated flow characteristics.

This thesis aims to:

- Understand what the relationship is, if any, between the Ngatoro Formation and the Inglewood Tephra, and to determine the processes that generated Ngatoro Formation?
- How was the Ngatoro Formation emplaced and how does the internal architecture vary with increasing distance from source and from its axes to lateral margins?

- How are these changes influenced by the type of triggering event and its volume, grain-size characteristics and influencing factors such as catchment/stream containment (or lack thereof) and the potential for sediment bulking?

These aims are achieved through detailed descriptions, measured sections, geochemical characterisation of stratigraphically enveloping tephra, grain size/shape analysis and palaeomagnetic analysis at multiple locations. Ultimately, this information will provide insights into what processes can reasonably be expected to occur during and/or in the aftermath of a future eruption at Egmont Volcano.

1.4. Research Objectives

- Describe and measure the internal architecture and lateral transformations of the Ngatoro Formation using field observations and standard sedimentological analysis.
- Relate the internal architecture to the varying stages and phases of the lahar.
- Use palaeomagnetic analysis to understand the thermal history of the Ngatoro Formation and estimate its emplacement temperature.
- Relate emplacement temperatures, stratigraphy, internal architecture and sedimentology to understand the emplacement mechanisms of the Ngatoro Formation, and its spatial and temporal relationships to associated eruptive activity.
- Use the Ngatoro Formation as a prehistoric analogue for what could reasonably be expected to occur should Egmont Volcano reawaken in the future.

2. Volcanic Processes Review

2.1. Andesitic Volcanism

Andesitic volcanoes are dominant features in landscapes commonly associated with convergent plate boundaries. A large majority of the over 800 active volcanoes around the world are andesitic composite cones located along plate boundaries at the margins of oceanic basins; most notably along the circum-pacific belt known as the “Pacific Ring of Fire” (Tarbuck and Lutgens, 2009). Andesite, the second most common volcanic rock type, is an extrusive igneous rock containing mainly phenocrysts of zoned plagioclase, pyroxene or hornblende and a glassy or fine grained ground mass (Figure 7) (Sigurdsson et al., 2000). Andesite is considered to be a fine grained volcanic rock characteristically medium dark in colour and containing 54-62% silica (Scott, 1988).

Figure 7: Diagram showing the transitions between magma types, intrusive and extrusive volcanic rocks and their relative compositions (Sigurdsson et al., 2000).

2.1.1. Regional Processes

Andesite volcanoes are commonly associated with convergent plate boundaries where the older, colder and denser oceanic crust sinks beneath the relatively buoyant continental crust (Figure 8). As the oceanic crust sinks, the increased heat and pressure forces volatiles out of the crust and into the overlying mantle. These volatiles act to reduce the melting temperature of the mantle, resulting in basaltic magma production. After sufficient magma

has accumulated, it begins to rise to the Earth's surface (Tarbuck and Lutgens, 2009). This process forms island archipelagos, or more commonly known as island arcs. As an intermediate member between basaltic and rhyolitic magmas, andesite magma forms through fractional crystallisation of this basaltic magma (eg. Island arcs such as Mount Ngauruhoe, New Zealand) (Price et al., 2010), or through simple mixing of the magmatic end members (eg. The Ecuadorian Andes) (Schiano et al., 2010).

Figure 8: Diagram of regional tectonic processes associated with the formation of andesite volcanoes (Tarbuck and Lutgens, 2009).

2.1.2. Eruption Styles

The two dominant eruptive styles associated with andesite stratovolcanoes are plinian and vulcanian:

Plinian eruptions produce a steady and turbulent stream of fragmented magma and magmatic gas ejected from the vent at high velocities. This continuous eruptive style produces an eruption column containing pyroclasts, magmatic gas and entrained air that can commonly reach heights of 30km and remain for tens of hours (Wilson, 1958). These eruptive events can be characterised by specific parameters such as explosiveness ($VEI > 5$), eruptive volume (typically $> 10^9 \text{ m}^3/\text{s}$) and timing (Sigurdsson et al., 2000). Examples include; Mount Vesuvius, Italy (79 AD); Krakatoa Volcano, Indonesia (1883); and Mount Pinatubo, Philippines (1991).

Vulcanian eruptions are characterised by a series of short, discrete explosions with short repose time (Parfitt and Wilson, 2008). These eruptions are often described as the volcano clearing its throat (or vent) where a piece of cooled magma or material from a previous

eruption that has fallen into the vent forms a plug that prevents gas and other material escaping from the volcanoes interior (Sigurdsson et al., 2000; Parfitt and Wilson, 2008).

This explosive eruptive style produces ejection velocities of $200\text{--}400\text{ ms}^{-1}$ and can distribute blocks and bombs up to 5 km from the vent (Sigurdsson et al., 2000). Associated with vulcanian eruptions are eruption plumes, pyroclastic flows and surges, lahars and thick lava flows (Wohletz and Heiken, 1992). Vulcanian eruptions are generally associated with intermediate composition magma (andesite, dacite) and the material ejected is dominantly non-juvenile (Sparks et al., 1997). Examples include; Mount St Helens, United States of America (1980); Soufrière Hills Volcano, Montserrat (1997); and Island of Volcano (1888).

It should be noted however that any one volcano, including Egmont Volcano, is not limited solely to a specific eruptive style. The type of eruption can change both between and during an eruptive event.

2.2. Lahar

The term “lahar” is Indonesian in origin and was introduced by Scrivenor (1929) in a report of mudflows produced by the ejection of the crater lake at Kelut Volcano, East Java (Lavigne et al., 2000). The term was then used by Van Bremmelen (1949) to describe debris flows containing debris and angular blocks, chiefly of volcanic origin. This definition included both the lahar and its related deposits. Other definitions include flows involving a mixture of debris and water occurring in volcanic channels (Smith and Fritz, 1989); fluid mixtures of debris, mud and water descending from a volcano (Murcia et al., 2008); and a volcanic debris flow and its deposit (Scott, 1988).

An issue that is apparent throughout relevant literature is the wide range of deposits and flows that are classified as “lahars” due to the vague and diverse definitions used. Smith (1986) outlines some of these variations:

- Restricted composition to pyroclastic material (Schmid, 1981).
- Must originate from the flanks of a volcano (Crandell, 1971).
- Debris flows not originating from volcanoes (Fairchild, 1984).
- Doesn't stipulate it being a debris flow (Hyde, 1975).

- Implies a hot pyroclastic flow (Fritz and Harrison, 1983).

The wide range of definitions leads to the conclusion that the term “lahar” is too general and does not describe the variability of the flow properties or the internal lateral variation in the deposits. The term lahar was deemed too general by Smith (1986) because the flow crosses rheological boundaries and encompasses a highly variable and wide range of grain sizes. In this thesis, the term lahar is used to describe a “rapidly flowing, gravity-driven, mixture of rock debris and water (other than normal stream flow) from a volcano” (Smith and Fritz, 1989).

Lahars are described by both their phase and stage. The phase describes the flow type at a specific time and place while the stage describes the height of the flow above the channel bottom. The stages of the lahar include the initial waxing, the peak flow and the final long-duration waning stage (Vallance, 2005). The phases of the lahar include the debris flow, hyperconcentrated flow and stream flow (Smith, 1986; Vallance, 2005). In this thesis the term “lahar” is avoided with preference given to the less ambiguous debris flow and hyperconcentrated flow. Deposit characteristics of the range of sediment rich mass flows are described in Table 2 (modified from Palmer et al. 1991; Alloway et al. 2005; Zenack et al. 2009).

2.2.1. Debris Flow

Debris flows are a water-supported mass flow with plastic properties that deposit sediment en masse when the shear stress decreases below the yield strength of the debris flow (Smith, 1986). The flow is constrained to a sediment concentration of >60% by volume (Lavigne et al., 2000; Lavigne and Suwa, 2004) or 80% by weight (Lavigne et al., 2000). Within the flow, clasts are supported by cohesive matrix strength, buoyancy and dispersive pressure (Smith, 1986).

Debris flows can be described as either cohesive or non-cohesive based on their clay content. Cohesive debris flows have >5% clay content and generally begin as water saturated debris avalanches that laterally transform, where as non-cohesive debris flows have <5% clay content and form through the entrainment of material and water as they flow downstream (Murcia et al., 2008).

Deposit Type	Sedimentary Characteristics	Contacts & Geometry
Debris flow (df) deposits (Non-cohesive mass-flow deposits)	- Matrix-supported - Predominantly monolithologic angular to sub-angular gravel- to boulder-sized clasts in a sandy matrix - Very poorly to poorly sorted - Massive, unstratified - Ungraded or crudely reverse-to-normal grading - Typically 0.4–0.6 m but up to 1.8 m thick - Deposits often reflect transformation of debris to hyperconcentrated flow: they consist of an inversely graded, fine-grained layer with faint stratification and a coarse, massive, poorly sorted unit that grades into a finer-grained, bedded upper part	Typically tabular, non-erosive, some lenticular with scored basal contacts.
Channel facies	- Predominantly clast-supported with subordinate sandy matrix - Very coarse, gravel- to boulder-sized clasts - Very poorly to extremely poorly sorted - Massive, lack of internal stratification but often show a thin matrix-supported base Non-graded lateral transition to marginal overbank deposits - Up to 5 m thick - Often upward transition to bedded, sandy deposits with weak horizontal fabric (hyperconcentrated flow) - Intercalated lenses of cross-bedded and well well-sorted sands (fluvial) due to rapid post-depositional reworking	Erosive basal and marginal contacts Channel-confined, several tens of metres wide,
Marginal facies	- Fine gravelly sands but coarser near channel Poorly sorted near channel, becoming moderately to well-sorted with distance from channel margins - Faint internal stratification near channel, becoming progressively more distinct with thin horizontal and often very low-angle cross beds near the deposit margin - Ungraded - Up to 2 m thick but pinch out over 20 to 250 m from the channel margins	Non-erosive Wedge-shaped, extend up to 250 m from channel margins
Hyperconcentrated flow (hcf) deposits	- Gravelly sands, isolated gravel- to cobble-sized clasts, predominantly monolithologic - Poorly to moderately sorted ;Massive or bedded - Reverse-to-normal grading, normal grading or no grading - Typically 0.2–0.5 m thick, up to 2 m faintly bedded coarser units, up to 1.2 m well-bedded fine-grained units - Occurrence of pumice ‘trains’ and aligned clasts - Post-depositional deformation and dewatering structures (flame, dish and pillar structures) - Fine- to coarse-grained sands Moderately to well-sorted - Horizontal bedding to low-angle cross-bedding, lenses of cross-bedded fine sands and gravels - Ungraded - Few-cm to 0.5 m thick units	Typically non-erosive, though more dilute units lenticular with erosive basal contacts Sheets, up to 2.5 km wide
Transitional hcf/normal stream-flow deposits	- Fine- to coarse-grained sands Moderately to well-sorted - Horizontal bedding to low-angle cross-bedding, lenses of cross-bedded fine sands and gravels - Ungraded - Few-cm to 0.5 m thick units	Erosive, wavy basal contacts Lenticular, often steep and overlapping cut’n’fill channels
Normal Stream-flow deposits	- Clast-supported - Fine to coarse sands, sands and rounded gravels- to boulder-sized rounded clasts - Well to moderately sorted in individual beds, but overall apoorly sorted as an aggradational deposit - Horizontal lamination of sands, low-angle cross-stratification and prominent scour-fill cross-bedding - of alternating thin lenses (few mm to 1 cm thick) of well-sorted sands and beds (1 to 10 cm thick) of moderately to poorly sorted gravels and sands - Massive to faintly bedded aggradational sequences of silts and sands with intercalated crossbedded lenses of fine gravels and sand - Up to 4 m-thick sequences of alternating sandy and pebbly beds, >10 m thick	Erosive, lenticular Complex sequences of overlapping cut’n’fill channels up to 150 m wide

Table 2: Sedimentary characteristics and criteria for differentiating between types of volcanic, water-supported mass flows (modified from Palmer et al. 1991; Alloway et al. 2005; Zenack et al. 2009). These include debris flows, hyperconcentrated flows and normal stream flows.

Figure 9: Grain size versus cumulative percentage distribution comparing debris flows with lahar-runout flow and stream flow on Mt St Helens (Scott, 1988).

Deposits:

Poorly sorted, lack of internal stratification and support of larger clasts in a finer grained matrix; can show none, reverse, reverse-to-normal, and coarse tail normal grading.

Generally deposits are matrix supported (rarely clast supported) with variable clast orientation and imbrication (Smith, 1986). In general, debris flow material can be more poorly sorted than pyroclastic deposits (Lavigne et al., 2000) and can be differentiated from other phases based on grain size distributions (Figure 9).

2.2.2. Hyperconcentrated flow

Hyperconcentrated flow is considered the runout phase of the proximal lahar from which it was transformed (Scott, 1988; Murcia et al., 2008; Pierson, 2005). The flow is constrained to a sediment concentration 20-60% by volume (Lavigne et al., 2000; Lavigne and Suwa 2004) or 40-80% by weight (Lavigne et al., 2000). Smith (1986) uses the term to describe high-

discharge, visibly turbulent flows where inter-grain interaction is an important sediment support mechanism and where neither turbulence is the sole support mechanism or where deposition en masse occurs. Features suggest rapid sediment deposition from suspension and by traction.

Deposits:

Gravel Dominated Deposits – Poorly sorted, clast supported, often normally graded, lack of reverse grading at the base with a coarse sand and pebble matrix. Large cobbles and boulders with long axis perpendicular to flow direction while small cobbles and gravels parallel to flow direction (Smith, 1986).

Sand Dominated Deposits – Absence of cross stratification, dominated by horizontal bedding, alternating well and poorly sorted fine and coarse beds, and laterally continuous for 2-10m. The laminated sands also contain large clast scattered throughout up to 1m in diameter (Smith, 1986).

Graded Stratified Deposits – Massive, normally graded base grading upward to a horizontally stratified upper. Lower is massive, pebbly, coarse-grained sand, or pebble- to cobble-sized gravel with a texture and fabric as per gravel dominated deposits. Upper is horizontally bedded, poorly sorted, medium to very coarse grained sand with lenses of pebbles and cobbles (Smith, 1986).

2.2.3. Flow Transformation Processes

Dilution:

As a water-supported mass flow moves down active river systems, water is incorporated in to the front of the flow causing dilution, a progressive loss in the flow's carrying capacity and phase changes within the lahar. This process has the most significant effect on smaller flows as the volumes of large flows are significantly greater than the existing river water (Vallance, 2005). In large lahars, size segregation processes become less important with downstream erosion and dilution processes becoming the important mechanisms (Scott, 1988).

Bulking:

Flow bulking is the addition of significant volumes of sediment to an existing flow through the erosion of local clastic material (Oldrich et al., 2005). Erosion is strongest along steep river channels containing loose clastic sediment and weakest in river channels with a gentle gradient or those underlain by strong bedrock (Vallance, 2005). During the erosion process trees and vegetation can also be uprooted. Surficial cover beds including soils occurring at the ground surface can also be incorporated into the body of the flow.

Vallance (2005) found that in any typical river valley water-rich hyperconcentrated flows are more erosive than the more sediment rich debris flows. This is due to the more turbulent flow achieved from the two phased (solid and liquid) hyperconcentrated flow than the single phase debris flow.

2.3. Mass Flow Generation

2.3.1. Edifice-Collapse Related Cohesive Mass Flows

Debris flow transformations can occur from the large volume, catastrophic debris avalanches produced during the large scale collapse of a volcanic edifice. Debris avalanches are a gravity driven rapid movement of incoherent, unsorted masses of rock, soil, water, snow, ice and vegetation (Scott, 1988; Palmer and Neall, 1989). The most likely trigger of these edifice collapses are by the intrusion of magma, resulting in a subsequent over-steepening of the volcanoes flank, magmatic intrusions into the sub-volcanic crust, hydromagmatic or phreatomagmatic processes, and volcanic and/or tectonic earthquakes (Vallance, 2005; Capra et al., 2002).

The potential for catastrophic edifice collapse, and subsequent lahar generation, is increased by the presence of hydrothermally altered rock. Within the hydrothermal systems, acid sulphate leaching removes mobile elements, replaces them with sulfates and forms silica phases (eg. cristobalite and opal) and clay minerals (eg. kaolinite and smectite) (Vallance, 2005). This alteration weakens the rock, resulting in increased disintegration during transportation.

With the very poorly sorted nature, water saturation and high hydrothermally altered clay content of debris avalanches, they commonly laterally transform into cohesive debris flows (>5 wt% clay content). Capra et al. (2002) compiled the process associated with this transformation to a debris flow:

- Failure within a soil, rock or sediment mass.
- Partial or complete liquefaction of the mass by high pore-fluid pressures.
- Conversion of landslide translational energy to internal vibrational energy.
- Transformation during transport of the distal water-saturated portion of the debris avalanche.
- Post-depositional remobilisation of water-saturated parts of the debris avalanche.
- Ruptures of natural dams formed by the debris avalanche deposit.

As these debris flows move downstream, they begin to incorporate exotic debris from the valley floors and adjacent embankments. Due to the size of debris avalanche-sourced debris flows, they very rarely laterally transform to the more dilute hyperconcentrated flows as they migrate downstream (Vallance, 2005).

2.3.2. Pyroclastic Flow Transformation

Pyroclastic flows and surges are a flowing mixture of hot gas and pyroclastic material (Scott, 1988) that move due to gravity down the flanks of a volcano. Pyroclastic surges are a flow that is more dispersed and less likely to approximate steady state conditions than a pyroclastic flow. These highly mobile and super-heated pyroclastic flows can be divided into pumice-and-ash flows and block-and-ash flows. Pumice-and-ash flows are pumice rich flows associated with plinian eruptions where large quantities of juvenile material are ejected. Occurring during rhyolitic eruptions, these pumice-and-ash flows form through the collapse of an eruption column and deposit what are called ignimbrites or rhyolitic tuffs (Sparks and Wilson, 1976; Williams and McBirney, 1979).

Block-and-ash flows on the other hand are gas supported mixtures of large volcanic blocks and ash usually resulting from gravitational collapse of an extruding summit lava dome or eruptive column. Often known as Merapi-style nuees ardentes, block-and-ash flows are a type of gravity driven pyroclastic flow associated with subduction zone andesitic volcanoes such as Unzen (Japan), Montserrat (Lesser Antilles) and Merapi (Indonesia) volcanoes

(Charbonnier and Gertisser, 2008). Block-and-ash flows (commonly less than 1 km³) are low in volume (Michol et al., 2008) but move as successive pulses which can continue for 8 to 20 minutes (observed on Unzen Volcano in 1995) (Ui et al., 1999). Block-and-ash flows move at great velocity and at very high temperatures - velocities calculated for Merapi Volcano events in 2006 range from 62.6m/s (proximal) to 13.5m/s (distal) (Charbonnier and Gertisser, 2008); and temperatures measured from the Soufriere Hills Volcano events in 1997 range from 364⁰C to 640⁰C (Cole et al., 2002).

Block-and-ash flows comprise three different flow parts; (1) a ground-hugging, high concentration basal avalanche; (2) a highly turbulent ash cloud surge; and (3) a billowing ash plume at the top (Hanenkamp, 2011). The path of the flow is controlled by the existing topography, with each flow part associated with different deposits. The deposits reflect the differences in velocity, density, flow volume and particle size between the flow parts.

Block-and-ash flows are generated through the gravitational collapse of an expanding or expanded lava dome (Ui et al., 1999; Charbonnier and Gertisser, 2008). Dome growth can occur through exogenous and endogenous processes (Ui et al., 1999) with gravitational instability occurring both during and after dome growth (Cole et al., 2002). Exogenous dome growth occurs when new lava is squeezed out from the vent and slowly spreads laterally while endogenous dome growth occurs when magma is intruded within the dome and no new lava is extruded on the dome surface. Deposits have been classified into three general facies by Charbonnier and Gertisser (2008). Basal Avalanche – often confined to the valleys and form ground-hugging, high-density granular and/or inertial grain-flow; produce chaotic morphology although ridges and furrows can also be broadly parallel to flow; and have steep, boulder and clast-supported fronts. Ash Cloud Surge – a turbulent and highly mobile deposit which mantles topography; elutriation occurs due to rapid convection and lateral expansion of gas which moved ahead of the ash cloud; and burnt vegetation provides evidence for hot gas transport. Overbank – poorly sorted, decimetre to metre-sized blocks supported in a fine to medium ash.

Block-and-ash flows can laterally transform into lahars as the super-heated pyroclastic material and gas rapidly melts and mixes with snow and ice. When the pyroclastic flow is almost stationary the water within the pyroclastic flow deposit is discharged, along with

adjacent snow melt. As the flow moves down river valleys it further mixes with river water and incorporates existing loose sediment in the valley (a term referred to as bulking) forming a debris flow then redistributes the sediment as the lahar transforms both laterally and downstream through its phases. The incorporation of water occurs at the front of the lahar in active river valleys because the lahar flows faster than the existing river, resulting in a dilution of the lahar and a decrease in the lahars capacity to carry large clasts (Vallance, 2005).

2.3.3. Rainfall-Induced Mass Flows

Debris and hyperconcentrated flows can be triggered by the sediment bulking of flood waters following heavy rainfall events (Hodgson, 1993; Lavigne et al., 2000; Lavigne and Thouret, 2002). Rainfall-induced mass flows are most common in tropical areas due to the high incidence on intense rainfall events as well as the volume and availability of recently erupted unconsolidated pyroclastic material concentrated within tributaries on the flanks of active volcanoes (eg. Mount Merapi and Mt Pinatubo). The triggering of a mass flow is dependant of the rainfall intensity, total amount and duration of rainfall, and other secondary variables (Lavigne and Thouret, 2002; Lavigne et al., 2000) such as:

- Slope and channel gradient.
- Volume and thickness of the source deposits.
- Physical characteristics of the pyroclastic deposits (eg. Permeability, pore pressure and grain size).
- Morphology of the drainage systems.
- Type and abundance of vegetation cover.

It is a known phenomenon that these rainfall-induced mass flows can occur both during and between volcanic events (Hodgson, 1993; Lavigne et al., 2000; Rodolfo and Arguden, 1991). Lavigne et al. (2000) described both syn-and-post eruptive rainfall-induced mass flows at Mount Merapi, Eastern Java, Indonesia:

- *Syn-Eruptive* – Hot lahars are generated by rainfall during or soon after an eruptive event. 8 out of the 61 lahars since 1500's at Merapi were due to this mechanism.

- *Post-Eruptive* – These are generally smaller and more frequent than the hot lahars. Size and frequency depends on the rainfall characteristics and the total volume and grain size characteristics of the pyroclastic material in the source area.

Lavigne and Suwa (2004) and Lavigne et al. (2000) discuss the two main types of rainfall events in tropical areas where rainfall-induced lahars are most common:

- *Stationary Rainfall* – Stationary rainfall triggered one third of the hyperconcentrated flow and stream flow events and triggered 90% of the debris flow events. Lavigne and Suwa (2004) found that as demonstrated on many volcanoes, rainfall intensity is the main factor in lahar generation at Mt Semeru, Indonesia. In most cases lahars were triggered by stationary rainfall over 25mm/hr or where there was a high “working rainfall” (Total rainfall over the 7 days preceding the lahar event).
- *Migratory Rainfall* – This rainfall triggered two thirds of the hyperconcentrated flow and stream flow events. During this rain, lahars are usually triggered by long lasting low intensity rainfall.

At Mount Semeru located in eastern Java, Indonesia – 92% of mass flows were triggered during the rainy season from October to April (Lavigne and Suwa, 2004). This is supported by studies at Merapi where most rainfall events occur between 12:00 and 19:00 with 80% of rainfall events occurring during the rainy season – therefore mass flows are usually generated in the afternoon and during the monsoon season (Lavigne et al., 2000). Although, individually, rainfall-induced lahars are not as voluminous or destructive as other triggering mechanisms (pyroclastic flow transformation, debris avalanche transformation), their high frequency means they can contribute just as much sediment to the surrounding ring-plains (Hodgson, 1993).

3. Case Studies

The study of volcanoes with similar volcanic setting, processes and eruptive history provide an insight and analogue for what could be expected on Egmont Volcano. Mount Ruapehu and Mount St Helens are andesite volcanoes with a very active history encompassing plinian and vulcanian eruptions, debris avalanches, debris flows and hyperconcentrated flows – all of which are observed occurring within the volcanoclastic stratigraphy of Egmont Volcano. The detailed study of these volcanoes provides a template for the study, interpretation and comparison of deposits described at Egmont Volcano.

3.1. Mount Ruapehu, New Zealand

Mount Ruapehu is an andesitic stratovolcano located in the central North Island of New Zealand. At 2,797m high it is the largest stratovolcano in New Zealand (Lecointre et al., 2004) and has a 110 km^3 cone with a volumetrically equivalent ring plain of volcanoclastic sediment (Cronin et al., 1997a). In 1995, from September 18th until October 12th, the eruption began with a series of phreatomagmatic eruptions and ended with the complete

Figure 10: Modified location map of major Mt Ruapehu Lahar courses from Cronin et al. (1997b). Whangaehu River represented in orange.

draining of the Crater Lake. During this eruptive period multiple lahars were triggered, mainly in the Whangaehu River on the eastern flank of the volcano (Figure 10) (Cronin et al., 1997a; Cronin et al., 1997b). The triggering of lahars on Mt Ruapehu is a widely known phenomenon with the risks they pose highlighted in the 1953 Christmas Eve Tangiwhai rail disaster where 151 lives were lost when the natural barriers holding back the Crater Lake collapsed forming a laharic sequence down the Whangaehu River sweeping out the rail bridge (Vignaux and Weir, 1990).

Cronin et al. (1997a) describe four main types of lahars associated with 1995 Mt Ruapehu eruptive sequence:

- **Snow-Slurry Lahars:** Watery slurries of ice, snow and clastic sediment generated when expelled water and debris from the Crater Lake is bulked with sediment from the Whangaehu glacier and subsequent river channel. These lahars extended over 47 km from source. Deposits are massive mixtures of homogeneous sediment, snow and ice. Ice fragments within the deposits were granule to fine pebble-sized with rare ice fragments up to 0.25m. Bulk densities of these deposits ranged from $0.47 - 0.91 \text{ Mg m}^{-3}$.
- **Large Dilute Lahars:** Large, voluminous ($5.6 \times 10^6 \text{ m}^3$ to $2.6 \times 10^6 \text{ m}^3$) hyperconcentrated flows associated with major overflowing of the Crater Lake during phreatomagmatic eruptions. These lahars extended over 84 km from source. Deposits are sand rich, massive, poorly sorted, boulder bearing, muddy sandy gravels in the upper channel (9 km from source) transitioning to slightly gravelly sands and sand (42 km from source). Up to 2m thick, deposits exhibit faint-to-strong planar fabric or weak bedding and concentrations of clasts up to small cobbles.
- **Concentrated Lahars:** Generated by similar means to large dilute lahars, concentrated lahars were less voluminous and had much lower peak discharges. High sediment concentrations of 46-52% by volume were maintained up to 42 km from source due to the bulking of loose sediment in the channels deposited in previous laharic events. Deposits are massive, matrix-supported, boulder bearing slightly gravelly muddy sand (9.5 km from source) transitioning to weakly planar-bedded, fine gravel bearing muddy sand (23.5 km from source) and weakly planar-bedded, slightly gravelly muddy sand (28-42 km from source).

- Remobilised Tephra Lahars: Generated by the collapse of tephra-laden ice and snow on the upper flanks and/or rain-induced reworking of accumulations of fresh tephra. Deposits are massive to weakly planar-bedded, fine gravel-bearing muddy sand (9.5 km from source) transitioning to planar-bedded sandy mud (23.5 km from source). The lahars, and subsequent deposits, contained high percentages of reworked, fresh scoriaceous lapilli.

These findings were supported by Lecointre et al. (2004), Graettinger et al. (2010) (Figure 11) and Cronin et al. (1997b) who described Holocene and recent lahars on Mt Ruapehu and compared these with the laharic sequences from the 1995 eruption.

Figure 11: (A) 1861 mass flow deposit in the Whangaehu Valley exposed beneath the 1945 ash and 1975 lahar deposit. (B) Exposed, crudely stratified lahar deposits located in the Whangaehu Valley 9 km from the Crater Lake – stratification interpreted as pulses or transformations of the mass flow. Photos of the upper main channel of the Whangaehu River- (C) before and (D) after the 18th March 2007 Crater Lake breakout mass flow (Graettinger et al, 2010).

3.2. Mount Merapi, Eastern Java, Indonesia

Merapi Volcano is a 2965m tall andesitic stratovolcano located in eastern Java, Indonesia. On the basis of its composition and eruptive style Merapi Volcano provides probably one of the best analogies for comparison with Egmont Volcano. With 61 reported eruptions since the mid-1500's, Merapi Volcano is the second most active volcano, behind Mt Semeru, and the second most hazardous volcano, behind Kelud Volcano, in Indonesia (Thouret et al., 2000). Volcanic processes associated with Merapi Volcano include lava flows, volcanic blocks and bombs, block-and-ash flows, mass flows and ash plumes (Suryo and Clarke, 1985). Merapi Volcano is particularly prone to mass flow generation, with 23 of the 61 recorded eruptions triggering lahars (Figure 12 and 13) and 280 km² of the slopes comprising laharic material (Lavigne et al., 2000; Lavigne and Thouret, 2002). Lahar generation is common due to the high volume of material produced by pyroclastic flows every 2-4 years, the rainfall intensity during the rainy season (Figure 14) and a very dense drainage system (Lavigne and Thouret, 2002).

Figure 12: Map showing mass flow distribution in 13 rivers around Mt Merapi since AD 1500. The mass flows are concentrated in the south and south western sector of the volcano (Lavigne et al., 2000).

Figure 13: The Boyong River (A) before and (B) after the 22 November 1994 Merapi eruption (Lavigne and Thouret, 2002), and a bridge on the same river (C) before and (D) after the 20 February Merapi eruption (Lavigne et al., 2000). These photos emphasise the rapid and catastrophic deposition of sediment by mass flows on Merapi Volcano.

Figure 14: Monthly distribution of rain triggered mass flows in the Boyong River during two monsoon seasons following the 1994 Merapi eruption. This shows a strong correlation between high rainfall and mass flow generation, and a decrease in mass flow occurrence with time since the eruption occurred (Lavigne and Thouret, 2002).

Pyroclastic flows on Merapi are triggered by almost constantly generated lava domes and their subsequent collapse. The resulting block-and-ash flows can travel up to 13 km from source and laterally transform to water-supported mass flows (Figure 13) where heavy rainfall occurs near the summit following the eruptive event (Suryo and Clarke, 1985). Rainfall is considered to be the dominant mechanism for mass flow generation with rainfall intensities averaging 40mm in 2 hours, the absence of a crater lake and few rivers draining from the edifice having permanent flow (Figure 14) (Lavigne et al., 2000). The intensity of rainfall required to generate mass flows is considered >25mm/h however the actual intensity is also dependant on rainfall duration and permeability of the pyroclastic material (Lavigne et al., 2000; Lavigne and Thouret, 2002).

Lavigne and Thouret (2002) described <1.0m thick, massive to stratified, non-cohesive, clay to boulder size deposits with textures commonly consisting of sandy gravel or gravelly sand. Sedimentary characteristics were used to define the main deposit types:

- Coarse grained ($M_z = -0.5$ to -2.5ϕ), normally graded to ungraded and inversely graded, poorly sorted ($\sigma_G > 3\phi$), coarsely-skewed ($Sk_G > -0.1\phi$) and clast-supported debris flow deposits.
- Less coarsely grained ($M_z = -2.0$ to 0.5ϕ), sorted ($\sigma_G = 1.5$ to 3ϕ), less coarsely skewed ($Sk_G -0.3$ to 0.3ϕ) and matrix-supported debris flow deposits.
- Fine grained ($M_z = 0$ to 2.0ϕ), poorly sorted ($\sigma_G = 1.0$ to 2.0ϕ), sandy hyperconcentrated flow deposits.

3.3. Mount St Helens, United States of America

Mount St Helens is an active andesitic stratovolcano located in Washington State in the United States of America. Standing at 2,550m, the cone and surrounding ring plain were devastated during a catastrophic eruption on May 18th 1980. Mt St. Helens was chosen as a case study in this study since the downstream sedimentological attributes were so well characterised (i.e. see Fig. 15) and provide an important methodological framework for attempting to understand the emplacement of Ngatoro Formation.

During the 1980 eruption of Mt St Helens the adjacent landscape was dramatically transformed in minutes to hours by a voluminous debris avalanche (2.5 km^3) associated with large scale collapse of the volcano's northern flank, a lateral blast, debris flows and associated transformations, pyroclastic flows and ash fall (Scott, 1988; Major et al., 2005). These styles of volcanic processes are not uncommon on Mt St Helens with more than 35 debris and hyperconcentrated flows inundating the north-western river systems more than 50 km from their source (Scott, 1988) (Figure 15 and 16).

Figure 15: Deposits and associated grain size statistics of the 1980 South Fork lahar, 1982 lahar, and associated lahar-runout flows (Scott, 1988).

Figure 16: Map showing the distribution of the 1980 and 1982 Lahars on Mt St Helens. Letter A-F represents deposits identified in Fig 15 (Scott, 1988).

The main mechanisms for lahar formation included (Scott, 1988; Major et al., 2005; Hodgson, 1993):

- Pyroclastic surge transformation: Catastrophically ejected, lithic-rich pyroclastic surge deflated forming a debris flow in the South Fork of the Toutle River. The water source for the transformation from gas-supported to water-supported flows is sourced from snow melt or the incorporation of river water.
- Debris avalanche transformation: Water saturated, poorly sorted debris from the large scale edifice dewatered forming debris and hyperconcentrated flows. The transformation from debris avalanche to debris flow at Mt St Helens was not a direct transformation; this has been attributed to the relatively young age of the modern cone (50,000 years) manifested in its lack of hydrothermally altered rock (Glicken, 1998). The transformation occurred, 5 hours after the main eruption, through the process of liquefaction and subsequent dewatering of the trapped groundwater, glacial ice and locally entrained river water within the debris avalanche. It is suggested that the liquefaction and dewatering was triggered by a succession of “harmonic tremors”.
- Flood surge bulking: Large debris flows formed in the Toutle River system when flood surges were triggered by the collapse of naturally occurring volcanic dams. As the flood waters move downstream the flow is bulked through the erosion and subsequent incorporation of alluvial deposits within the river.

Peak velocities and discharges range from $6.0\text{--}8.0 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ and $6\text{--}12 \text{ ms}^{-1}$ during the largest event in the North and South Fork Toutle River, $2.9 \times 10^4 \text{ m}^3 \text{ s}^{-1}$ during the Pine Creek lahar and $2.2 \times 10^4 \text{ m}^3 \text{ s}^{-1}$ (Hodgson, 1993).

Scott (1988) developed a facies model for the 1980 lahar deposits in the Toutle-Cowlitz River system. This model includes a lahar channel facies, lahar flood-plain facies, lahar-runout facies, transition facies, and lahar related stream flow facies (Figure 17 and 18). This facies model is summarised in table 3.

Figure 17: Representative stratigraphy associated with the Mt St Helens lahar facies model of Scott (1988). This includes the channel facies, flood plain facies, transition facies, lahar-runout facies, and lahar-related stream flow deposits.

Figure 18: (A) Exposed Pine Creek lahars including a large (5 x 12m) egg-shaped mega-clast. (B) Bar deposits of the North Fork lahar. Deposits include hydrothermally altered clasts and rounded alluvial clasts bulked from the existing river bed. (C) Deposits of the 1982 peak runout flow at Kid Valley. Low density clasts are buoyed on the deposits surface. The 'C' marks the position of the largest clasts within the inversely graded unit. (D) Flood-plain facies of 3 older lahars from the Coal Bank section (Scott, 1988).

Table 3 (Next Page): Table describing the features of the facies outlined in the facies model of Scott (1988).

[Includes flows extending tens of kilometers from Mount St. Helens]

Character- istic	Lahar facies		Transition facies	Lahar-runout facies	Lahar-related streamflow deposits
	Lahar channel facies	Lahar flood-plain facies			
Agent of deposition.	Debris flow. Basal part of lahar; locally has coarse clasts in contact and some characteristics of grain flow and nonco- hesive debris flow. Sole layer accreted at debris flow boundary.	Debris flow. Peak flow of lahar flood wave.	Combined hyperconcentrated streamflow (front of wave) and debris flow (tail of wave); debris flow deposits overlies streamflow deposits in a single unit.	Hyperconcentrated stream- flow; grain flow and/or noncohesive debris flow in upper part of hyper- concentrated range.	Streamflow with sediment concentrations mainly below hyperconcentrated range, formed by debulk- ing of hyperconcentrated flow or by erosion of a lahar.
Form of top surface.	Locally forms whaleback bars.	Nearly planar-----	Nearly planar-----	Nearly planar-----	Fluvial bar morphology.
Particles on or near surface.	Wood debris and normal- and low-density boulders on surface or slightly embedded.	Local concentrations of wood debris, pumice, and low-density clasts.	Wood debris and pumice common on surface; low- density clasts embedded.	Wood debris and pumice common on surface; low- density clasts embedded locally.	Local concentrations of wood fragments.
Particle support.	Mainly clast-supported with grain-supported silty sand matrix.	Mainly matrix-supported; local clast support in lower part and at level of maximum clast size.	Clast support at base transitional to matrix support in upper part.	Granular, noncohesive; mainly has openwork structure.	Granular and noncohesive except for surficial silt layer.
Grading-----	Normal in upper 10-80 pct of unit; commonly ungraded in central zone; inverse in basal 20 pct or less.	Normal in upper 50-75 pct of unit; central ungrad- ed zone; basal 15-50 pct inverse (more pronounced than in channel facies).	Commonly inverse in most of unit; commonly normal in uppermost part.	Poorly developed; inverse in subunits or in most of unit; grading may be progressively lost downstream.	Not distinct.
Stratifi- cation.	Poor, except for contact with sole layer and local strata within sole layer.	None-----	Mostly massive, except for local crude strati- fication in lower part and local pumice lenses near flow boundaries.	Appears massive, but may be crudely stratified into inversely graded subunits. Pumice layers seen commonly near lat- eral flow boundary and locally at base of unit.	Good. Cross strata common. Silt layer 5-60 cm thick common at top; silt layer may show convolute lamination.
Modal size class.	Commonly in cobble or boulder size range.	Commonly in pebble size range.	Like lahar flood-plain facies in upper part; like lahar-runout facies in lower part.	Sand size range, commonly 0.2-2.0 ϕ .	Sand size range.
Sorting-----	3.0-4.5 ϕ (main deposit), 3.1-4.3 ϕ (sole layer); matrix also poorly sorted: 2.5 ϕ .	2.0-4.5 ϕ (1.8 ϕ is approximate lower limit approached near point of transition to hypercon- centrated runoff flow).		1.1-1.6 ϕ -----	Variable, but commonly better than runoff depo- sits of the same mean size; as low as 0.7 ϕ in fine-grained strata.
Wood content	Uprooted trees form sub- horizontal molds in older deposits; wood rarely preserved.	Standing trees form vertical molds in older deposits; wood rarely preserved.	Wood preserved in some older deposits, but was originally less abundant than in lahar facies.	Wood commonly preserved in older deposits.	Wood abundant and well preserved in older deposits; charred wood locally abundant.
Sole layer--	Commonly forms basal 10-25 cm; compacted and shows primary foliation in 1980 units.	Poorly developed or absent in 1980 flows, but common in older units.	None-----	None-----	None.
Erosion at base.	Common; local lahar- abraded pavement.	Rare-----	Common-----	Common-----	Common, but usually slight.

Chapter Two: Methodology

1. Field Investigations

To understand the internal architecture and emplacement history of the Ngatoro Formation, the characteristics and stratigraphic context of the deposit must be described from proximal to distal, and flow axes to margin locations. A reconnaissance of prospective study locations was conducted in January 2013 using the Quaternary Geological Map of the Taranaki Peninsula (Neall and Alloway, 2004) as a guideline for the extent of the formation. Eight sites were identified for detailed investigation (Figure 19). These sites are as follows:

Figure 19: Map Egmont Volcano and its ring plain showing the extent of the Ngatoro Formation according to Neall and Alloway (2004), and the location of sections studied in this thesis marked by red dots. Base map 1:250,000 from Land Information New Zealand.

- 1) Eastern Egmont (2.7 km from the modern summit)** (S 39°18'22.20", E 174°05'30.16", 1257m): The section is located on a westward facing escarpment above the Manganui Valley (source tributary of the Manganui River) on the track to the Manganui Ski Field.
- 2) Vickers Quarry (10 km from the modern summit)** (S 39°17'29.99", E 174°10'40.86", 526m): Three sections in pristine, freshly exposed quarry walls (two eastward facing and one north facing) located at Vickers Quarry on York Rd, Stratford. Vickers Quarry is located adjacent to the Manganui River. Sections were mainly confined to the western wall located on the boundary with Egmont National Park.
- 3) Surrey Road Quarry (10 km from the modern summit)** (S 39°16'14.82", E 174°10'28.73", 501m): Three south-facing sections located in a farm quarry located off the end of Surrey Road, at the boundary with Egmont National Park. The quarry is located adjacent an upstream tributary of the Mangatengehu River.
- 4) York Road (13.6 km from the modern summit)** (S 39°16'40.42", E 174°13'08.49", 400m): Two closely-spaced sections (one east and one west facing) located on either side of a road underpass on York Rd, Stratford (1.2 km northeast of the Derby Road intersection).
- 5) Tariki – SH3 (17.1 km from the modern summit)** (S 39°13'28.77", E 174°14'24.22", 276m): Northward-facing section located in an old farm quarry on State Highway 3 at the Mangamawhete River Bridge.
- 6) Tariki Underpass (17.4 km from the modern summit)** (S 39°12'51.86", E 174°14'04.09", 265m): Four sections located on the northern side of the Tariki Underpass on the westward facing cut slope opposite the John's Road junction.
- 7) Suffolk Road Junction (22.8 km from the modern summit)** (S 39°10'07.15", E 174°16'12.82", 158m): Northeast facing section located at the Waitepuke Stream Bridge on Suffolk Road, 50m south of the Norfolk Road junction.
- 8) Kaimata Sawmill (23.8 km from the modern summit)** (S 39°09'30.39", E 174°16'31.25", 144m): Section located on the southwest-facing cut slope at the Manganui River bridge on Tarata Road, next to Kaimata Sawmills.

2. Measured Sections

At each site, one or more sections were measured in detail. This involved clearing the outcrop of vegetation and debris using a spade and trowel. Individual lithostratigraphic units were identified and thickness measured using a standard tape measure. Detailed descriptions using basic geological rock and soil descriptive terms for grain size, colour, mineralogy, sorting, clast features, bedding, sedimentary structures and boundary relationships were made.

At some of the sites, sampling of tephra for Electron Microprobe Analysis (EMP) and sediment for grain size/shape analysis was carried out to help characterise and interpret the lithostratigraphic units.

3. Tephrochronology

Taranaki's Quaternary stratigraphic record contains many tephra beds sourced from Egmont (including Fonthams Peak), Pouakai and Kaitake Volcanoes. These are manifested in the cover-bed stratigraphy as weathered coarse ash and pumiceous and/or lithic lapilli beds. Morphologically distinctive tephra can be recognised in the field on the basis of a combination of colour, bedding and stratigraphic association and therefore are useful as a mappable isochronous horizon that can be used to constrain depositional events both spatially and temporally.

Geochemical characterisation of tephra using major element composition of glass shards and minerals by electron microprobe analysis (EMP) is a commonly used tephra correlation tool employed by tephrochronologists around the world (i.e. Alloway et al, 1995; Cronin et al, 1996; Fenderman and Carey, 1980; Sandiford et al, 2001). Generally, EMP analysis has not been routinely employed on Egmont sourced tephra on account of the rapid weathering of glass to andic material, the occurrence and abundance of crystal microlites in the glassy matrix and the highly vesicular nature of the glass which precludes a 10 um beam obtaining meaningful analysis. This study provides a very comprehensive attempt to correlate Egmont-sourced tephra.

Assuming glass compositional differences between different Egmont-sourced tephra enveloping the Ngatoro Formation, EMP analysis of the major elemental glass composition provides a potential quantitative means for the correlation and discrimination of tephra beds between stratigraphic sections. All tephra interbeds at described localities are correlated with an existing major element glass shard EMP dataset (B.V. Alloway, unpublished data) from two reference sections located on the eastern lower flanks of Egmont Volcano – the first on a roadside cutting on Pembroke Road close to the Manganui ski field car park and at another roadside cutting on Manaia Road in the vicinity of Dawson Falls (Figure 20 and 21). These sections are described by Alloway et al. (1995).

Figure 20: Photos of the sections sampled for Electron Microprobe reference dataset which correspond to the stratigraphic columns presented in figure 21. (A) East Egmont and (B) Dawson Falls sections – Photos courtesy of A/Prof Brent Alloway.

East Egmont

S 39° 18' 26.9"
W 174° 06' 14.2"

Dawson Falls

S 39° 19' 31.7"
W 174° 06' 22.1"

Fig 21: Stratigraphic sections sampled as reference Electron Microprobe dataset. Section photographs presented in figure 20. Reference dataset and stratigraphic sections courtesy of A/Prof Brent Alloway.

3.1. Sample Selection and Processing

Thirty-one tephra beds associated with volcanoclastic sequences containing Ngatoro Formation were selected for laboratory analysis. Samples were collected from key reference sections at Eastern Egmont, Vickers Quarry, York Road, Tariki Underpass, Suffolk Road Junction and Kaimata Sawmill. Each sample was processed using the following method:

- Pumiceous clasts from 26 of the samples were selected based on high glass content, low weathering and sufficient glass preservation (Table 4). The stratigraphic position of each sample is presented with relevant measured sections in Appendix A.
- The pumice was then crushed with wooden blocks and wet sieved between 1 ϕ (500 μ m) and 4 ϕ (63 μ m) then dried at 30⁰C in a laboratory oven. Each sample was then dry sieved into >1 ϕ , 1-2 ϕ , 2-3 ϕ and 3-4 ϕ sub-samples.
- The 1-2 ϕ sub-sample was selected for EMP analysis due to its abundance of well-preserved glass.
- Each sub-sample was set in a 6 sample mount using epoxy resin.
- Each sample mount was then polished to expose the glass.
- Each epoxy mount was carbon coated in preparation for analysis. The carbon coating gives the sample mount a conductive coating that prevents the sample charging up and reducing the effective electron energy.

Location:	Sample Section:	Tephra Sample Number:
East Egmont	EE-1	TS-14, TS-15 and TS-16
Vickers Quarry	VQ-1	TS-19, TS-20, TS-21, TS-22 and TS-28
York Road	YR-1	TS-23, TS-24 and TS-25
	YR-2	TS-31
Tariki Underpass	TU-1	TS-11, TS-12 and TS-13
	TU-2	TS-29 and TS-30
Suffolk Road	SF-1	TS-7, TS-8, TS-9 and TS-10
Kaimata Sawmills	MG-1	TS-1, TS-2, TS-3, TS-4 and TS-5

Table 4: Location and identification numbers of lapilli beds and entrained pumice clasts sampled for EMP analysis. Annotated measured sections for each sample location are presented in Appendix A.

3.2. Measurement and Data Analysis

The major elemental glass composition of the tephra were analysed using JEOL 733 Superprobe equipped with three wavelength dispersive spectrometers located at Victoria University of Wellington, New Zealand (Figure 22). The analysis of SiO_2 , TiO_2 , Al_2O_3 , FeO , MnO , MgO , CaO , Na_2O , K_2O and Cl was performed using a 15 kV accelerating voltage under a static electron beam operating at 8 nA.

The following methodology was used in the Electron Microprobe analysis:

- The Electron Microprobe was calibrated using standards of known chemical composition.
- Measurement drift was corrected for by measuring the ATHO-G and VG-568 glass standards (Table 5) on average every fifteen to twenty sample measurements.
- The vesiculated glass selvages identified within each sample (Figure 23) were measured fifteen to twenty times in order to reduce uncertainty in the resultant major elemental glass composition data.
- Measurements considered outliers were excluded based on qualitative analysis.
- The raw data, excluding statistical outliers, was recalculated using multipliers calculated from the ATHO-G and VG-568 standard measurements.
- The recalculated data was standardised to 100% to allow for direct comparison between samples.

Figure 22: The JEOL 733 Superprobe Electron Microprobe at Victoria University used in this study. An Electron Microprobe (EMP) is a specialised Electron Microscope with the primary purpose of major elemental analysis of hard polished surfaces such as mineral thin sections or epoxy mounts. The major elemental composition of a given sample is achieved by measuring the intensities and wavelengths of the x-rays produced by exposing the sample to a focused stationary electron beam. The wavelength of the returned x-rays identifies the element present in the samples, while the intensity of the x-rays is related to the concentration of that mineral using a ZAF-calculation.

	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	Cl	Total
ATHO-SD	75.60	12.20	0.26	3.27	0.10	0.10	1.70	3.73	2.64	0.0	99.65
RAW DATA											
Average	74.71	12.18	0.24	3.29	0.10	0.10	1.76	3.81	2.75	0.00	98.93
SD	0.30	0.09	0.02	0.11	0.01	0.03	0.02	0.29	0.04	0.00	0.44
Multiplier	1.012						0.966	0.980	0.960		
RECALCULATED DATA											
Average	75.61	12.18	0.24	3.29	0.10	0.10	1.70	3.73	2.64	0.00	99.58
SD	0.30	0.09	0.02	0.11	0.01	0.03	0.02	0.29	0.04	0.00	0.44

Table 5: Reference dataset for the ATHO-G standard sample which includes the raw and recalculated data from 90 reference measurements taken during the sample analysis. The full EMP dataset is presented in Appendix B. All EMP data is presented in wt%.

Figure 23: Selected electron microscope images showing four samples with typical vesiculated volcanic glass selvages used for the acquisition of major elemental glass composition data. The highly vesiculated nature and significant weathering of the volcanic glass within the samples made EMP analysis challenging.

4. Sedimentology

Volcaniclastic deposits are very challenging to quantitatively describe due to their coarse-grained texture, rapid lateral and vertical transformations, complex relationships with enveloping formations and very poor sorting - grain sizes range from clay to large boulders (<2.0m) with a wide range of clast shapes. However, a textural analysis of a deposit can provide a useful tool for comparing and contrasting flow deposits, correlating units, and inferring the flow dynamics and origin. The methods employed in this study to quantitatively describe a deposit include grain size, clast roundness and clast form.

- **Grain Size** – This describes the range in intermediate axis length of grains/clast within the deposit. The intermediate axis is selected to correlate with the sieve stack data where the intermediate axis is the determining factor if a particle will pass through the set size mesh (Boggs, 2006).
- **Clast Form** – The clast form is described by the relative lengths of the principal axis (X, Y, Z). The Sneed and Folk (1958) definition of maximum projection sphericity uses the ratio of the maximum projection area of a sphere the same volume as the clast and the maximum projection area of the clast. This classifies clast as compact, platy, bladed or elongated.
- **Clast Roundness** – Clast roundness is the measure of the sharpness of corners and edges of a grain (Boggs, 2006), defined by the ratio of the average ratio of curvature of the particle edges verses the radius of curvature of the largest inscribed sphere (Scott, 1988).

The methods of Scott (1988) were used as a guide for determining the grain size and shape analyses presented in this thesis. Some variation in the methodology occurred due to ongoing developments and refinements in analytical techniques. Scott (1988) quantitatively describes lahar deposits in the Toutle-Cowlitz River System associated with the May 1980, Mount St Helens eruptive sequence. These methods are briefly summarised below:

Grain Size: Lahar deposits containing pebble-size and finer were analysed by wet sieving the sand and coarser constituent and by pipette-analysis of the silt and clay fractions. Grain size distributions of deposits considered too coarse for laboratory analysis were analysed in the field using the grid sampling and point counting method of Wolman (1954). This coarse

constituent data could then be combined with a laboratory matrix analysis to obtain a full size distribution using the frequencies by weight determined in normal laboratory analysis by Kellerhals and Bray (1971).

Clast Form and Roundness: The -3 to -4 ϕ and -4 to -5 ϕ size fractions were selected as they are well represented in both the finer grained peak flow and sole layer, and coarser grained laharic deposits. Each of the reported roundness values is calculated from a minimum of 50 measurements made using reference clasts of known standard roundness. Both scoriaceous and pumiceous clasts were excluded from roundness estimates due to the more rapid rounding compared to the dominant andesite clasts.

Statistics: The graphical statistical method of Folk (1966, 1980) was used to calculate the graphic mean (M_z), graphic standard deviation (σ_G), graphic skewness (Sk_G) and graphic kurtosis (K_G). This method was selected for its comparable graphic standard sorting measure to the widely used σ_ϕ of Inman (1952). Using the Wentworth class size intervals (phi units) the ϕ_{16} and ϕ_{84} could be more easily measured or extrapolated using the Folk (1966, 1980) method. Where possible the inclusive graphical standard deviation (σ_i) and inclusive graphic skewness (Sk_i) were also calculated for comparison.

4.1. Grain Size

The grain size distribution of the Ngatoro Formation was analysed at four different locations ranging from proximal to distal – Vickers Quarry (10 km from the present summit), York Road (13.6 km), Tariki Underpass (17.4 km) and Kaimata Sawmill (23.8 km) sections. This analysis comprised both a field and laboratory component. The grain size analysis uses the grain size scale of Wentworth (1922).

Field Measurement and Sampling

The analysis of grain size distributions was made difficult by the very poorly sorted nature of the proximal Ngatoro Formation. With clasts up to 2.0m, this made the point or grid counting method from Scott (1988) challenging as this is within the range of unit thickness. To address this, a practical approach was taken by classifying and describing units based on:

- Bulk sample of sediment ranging from -5 ϕ to 10 ϕ which encompasses gravel to silt and clay for laboratory analysis.

- Measuring the long axis of the five largest clasts in the field.

At each location, the outcrop was divided into lithostratigraphic units. In coarse-grained proximal deposits the matrix was sampled while in intermediate and fine grained distal deposits, samples were representative of the whole unit. Eighteen samples (-5ϕ to 10ϕ) were collected at the four locations (Figure 25).

Millimeters (mm)	Micrometers (μm)	Phi (ϕ)	Wentworth size class
4096		-12.0	Boulder
256		-8.0	Cobble
64		-6.0	Pebble
4		-2.0	Granule
2.00		-1.0	Very coarse sand
1.00		0.0	Coarse sand
1/2	500	1.0	Medium sand
1/4	250	2.0	Fine sand
1/8	125	3.0	Very fine sand
1/16	63	4.0	Coarse silt
1/32	31	5.0	Medium silt
1/64	15.6	6.0	Fine silt
1/128	7.8	7.0	Very fine silt
1/256	3.9	8.0	Clay
0.00006	0.06	14.0	

Figure 24: Wentworth grain size scale (Wentworth, 1922). Grainsizes are measured in either millimetres (mm) or Phi (ϕ) and divided into gravel, sand, silt and mud size classes.

Figure 25: Photographs of the sections sampled for grain size and shape analysis – (A) Deposits exposed in the quarry wall at Vickers Quarry on York Road (proximal), (B) a cutting at an under-road cow crossing on York Road, (C) a batter slope in the eastern side of Tariki Underpass (intermediate) and (D) the western cutting on Tarata Road near the Manganui River bridge and Kaimata Sawmills (distal).

Laboratory Analysis

In the laboratory, each of the eighteen samples was processed using the following method:

- Sample was dried at 30⁰C in a laboratory oven for approximately 3 days.
- The sample was then split into sub-samples using an aluminium splitter box. Sub-samples ranged from 90.0g to 1300.0g depending on how poorly sorted the sample was.
- Sub-samples were hand-picked to remove organic material.
- The sub-sample was weighed.
- The sub-sample was then wet sieved using 60µm sieve cloth and distilled water. The fine fraction was collected in a glass beaker, with the coarse fraction retained in the sieve cloth. Both the fine and coarse constituents were dried at 40⁰C in a laboratory oven until dry.
- The fine fraction was weighed and recorded.
- The coarse fraction was sieved from -5φ to 5φ using a dry sieve stack at 0.5φ intervals for 10 minutes (Figure 26). Each interval was weighed and recorded.

Figure 26: Coarse sieve stack and laboratory scales used in the grain size analysis.

The initial intention was to analyse the $<4\phi$ ($<63\mu\text{m}$) fraction using a Micrometrics Sedigraph III Plus. However, magnetic flocculation of the fine magnetic particles to the magnetic stirrer in the Sedigraph produced biased grain size distributions. Therefore the fine fraction is recorded simply as a weight percentage (wt%) finer than 4ϕ .

Statistics

The weight of sample in each 0.5ϕ sieve was converted to a weight percentage of the whole sample and plotted on a histogram. The weight percentage and summary statistics were calculated using a MatLab script. The summary statistics included the Graphic Mean (eq. 1.0), Inclusive Graphic Standard Deviation (eq. 2.0), Inclusive Graphic Skewness (eq. 3.0) and Graphic Kurtosis (eq. 4.0) (Folk and Ward, 1957; Boggs, 2006). The inclusive graphic standard deviation is used to estimate the sorting from “Very Well Sorted” to “Extremely Poorly Sorted” (Table 6) and the inclusive graphic skewness describes the grain size distribution from “Strongly Fine Skewed” to “Strongly Coarse Skewed” (Table 7) (Boggs, 2006).

Graphic Mean	$M_z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$	eq. 1.0

Inclusive Graphic Standard Deviation	$\sigma_i = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$	eq. 2.0

Inclusive Graphic Skewness	$SK_t = \frac{(\phi_{84} + \phi_{16} - 2\phi_{50})}{2(\phi_{84} - \phi_{16})} + \frac{(\phi_{95} + \phi_5 - 2\phi_{50})}{2(\phi_{95} - \phi_5)}$	eq. 3.0

Graphic Kurtosis	$K_G = \frac{(\phi_{95} - \phi_5)}{2.44(\phi_{75} - \phi_{25})}$	eq. 4.0

Standard Deviation	
<0.35 ϕ	Very Well Sorted
0.35 – 0.50 ϕ	Well Sorted
0.50 – 0.71 ϕ	Moderately Well Sorted
0.71 – 1.00 ϕ	Moderately Sorted
1.00 – 2.00 ϕ	Poorly Sorted
2.0 – 4.00 ϕ	Very Poorly Sorted
> 4.00 ϕ	Extremely Poorly Sorted

Table 6: Description of grain size sorting based on the inclusive graphic standard deviation (Boggs, 2006).

Skewness	
> +0.30	Strongly Fine Skewed
+0.30 to +0.10	Fine Skewed
+0.10 to -0.10	Near Symmetrical
-0.10 to -0.30	Coarse Skewed
<-0.30	Strongly Coarse Skewed

Table 7: Description of skewness in a grain size distribution based on the inclusive graphic skewness (Boggs, 2006).

4.2. Clast Form and Roundness

Clasts attain characteristic shapes reflecting the erosional history of the clast. This can be used to help interpret the transport and depositional processes which influence a clast in a particular deposit. Two units from the Vickers Quarry section and one unit from the York Road section were sampled. The analysis of clast form and roundness was performed on both field samples and laboratory samples using the method of Sneed and Folk (1958) and Krumbien (1941). The size range targeted for clast form and roundness was -3 ϕ to -8 ϕ . This range includes the -3 ϕ to -6 ϕ range used by Scott (1988) to allow for comparison with laharic deposits on Mt St Helens, Washington, USA. The analysis was also confined to andesite clasts with any pumiceous or scoriaceous clasts excluded from clast shape and

roundness analysis due to their more rapid rates of abrasion and rounding - as per the method of Scott (1988).

The clast form analysis uses the method of Sneed and Folk (1958) (Figure 27) where the long, intermediate and short axis are measured with callipers then plotted with the relative ratios are defined by ten classes: C, Compact; CP, Compact Platy; CB, Compact-Bladed; CE, Compact-Elongate; P, Platy; B, Bladed; E, Elongate; VP, Very Platy; VB, Very Bladed; VE, Very Elongate. The roundness analysis uses the 0.1 to 0.9 scale of Krumbien (1941) (Figure 28) and is plotted as histograms with roundness categories into very-angular, angular, sub-angular, sub-rounded, round and well-rounded according to Waddell (1932).

5.

Figure 27: Ternary diagram showing the clast shape classes defined by Sneed and Folk (1958) based on the ratios of the clasts 3 principal axis.

Figure 28: Clast roundness scale. Ranges from very angular (0.1) to well rounded (0.9) (Krumbien, 1941; Waddell, 1932).

Palaeomagnetic Analysis

As a rock containing magnetic minerals is heated and subsequently cooled in an external magnetic field, it acquires a thermoremanent magnetisation (TRM) whose vector direction is parallel to and intensity is directly proportional to the applied geomagnetic field in which it cooled (Hobblitt and Kellogg, 1979; Butler, 1992). Progressive thermal demagnetization of the TRM preserved volcanic rocks can be used to estimate their emplacement temperatures (Clement et al., 1993) due to magnetic grains of different size and composition within the rock producing a range of blocking temperatures (T_B) below which the magnetic grain preserves its remanence. Blocking temperatures range from ambient temperatures through to the Currie Temperature (T_C) of the magnetic grains within the rock. The remanence acquired within a specific blocking temperature range is considered a Partial Thermal Remanent Magnetisation (pTRM) (Hobblitt and Kellogg, 1979; Butler, 1992). Stepwise thermal demagnetisation progressively removes the pTRM's and enables emplacement temperature estimates (T_E) and insight into the causal events leading up to the emplacement of volcanoclastic deposits such as the Ngatoro Formation.

Previous palaeomagnetic studies on Egmont Volcano have been centred on the lava flows on Egmont's upper cone and Fanthams Peak (Downey et al., 1994) and a preliminary investigation of two flow deposits (Paintin, 1982). An initial study of North Island volcanoes by Cox (1969) included 3 samples from Egmont Volcano. The first significant palaeomagnetic study was carried out by Downey et al. (1994) where samples at 26 sites from 5 different lava flow sequences from both Egmont Volcano and Fanthams Peak were analysed using stepwise thermal demagnetization. Spot directions obtained from the samples were then compared with an established regional palaeosecular variation curve to estimate the emplacement ages of the lava flow sequences.

5.1. The Conglomerate Test

Taranaki andesite is known to contain titanomagnetite (Turner et al., 2008) with T_B ranging up to the Curie temperature of magnetite (585°C). If clasts were emplaced above this temperature and cooled in situ, then:

- All ferromagnetic grains will be magnetized in the direction of the ambient field at the time, so progressive demagnetization through the blocking temperature

spectrum will reveal a unidirectional magnetization (except perhaps in the very lowest blocking temperature grains which may carry a viscous component of magnetization acquired during sampling and handling)

- All clasts will be magnetized in the same direction – the direction of the local geomagnetic field at the time of emplacement.

If the clasts were emplaced at some intermediate temperature, T_E , between ambient temperature and 585°C, then only the grains with $T_B < T_E$ will have been magnetized in situ, and so retain a record of the local field direction– grains with higher T_B will have been magnetized prior to emplacement, and so their magnetization vectors are likely to have been rotated before emplacement. In such a scenario we would expect to see:

- Change(s) in the direction of pTRM within clasts when demagnetized above T_E .
- Agreement of the low T_B component between clasts, but a lack of agreement of the high T_B components.

This approach has been carried out on clasts of varying size collected from proximal deposits of the Ngatoro Formation. These proximal deposits contain in-situ trees with significant charring, suggesting elevated emplacement temperatures. A possible mechanism for this high temperature emplacement is the transformation of high temperature block-and-ash flows generated by effusive dome growth and collapse to debris flows and/or hyperconcentrated flows. In similar investigations Curie temperatures of approximately 580°C have been observed (Clement et al., 1993) and block-and-ash flow emplacement temperatures up to 640°C (Cole et al., 2002) suggest that a uniform palaeomagnetic orientation within the deposit, combined with stratigraphically correlated block-and-ash flow deposits, would support a transformation from block-and-ash flows to debris flows (Scott, 1988). A non-uniform direction would suggest either the flow did not reach Curie-temperature, or a different, colder mechanism is responsible for the lahar formation (Hoblitt and Kellogg, 1979; Butler, 1992; Clement et al., 1993). This palaeomagnetic test is referred to as a 'conglomerate test'.

Palaeomagnetic emplacement temperature estimates have been widely used on lava flows, pyroclastic flows and lahars around the world, but the method has not become a common practice throughout New Zealand. Paterson et al. (2010) emphasises the usefulness of the

method for determining emplacement temperatures of pyroclastic density currents on Mt St Helens, USA; Volcan Lascar, Chile; Volcan de Colima, Mexico; and Mt Vesuvius, Italy. When comparing palaeomagnetic temperature estimates to measured temperatures of pyroclastic density currents, Paterson et al. (2010) found the palaeomagnetic estimates to be very accurate, producing a correlation coefficient (R^2) of 0.996 (Figure 29).

Figure 29: Plot showing the strong correlation between palaeomagnetic temperature estimates and measured temperatures of volcanic mass flows at Mt St Helens and El Chichon (Paterson et al., 2010).

The palaeomagnetic investigation presented in this thesis includes a preliminary alternating field demagnetization investigation, a main thermal demagnetization investigation of a lower flow unit and a further preliminary thermal demagnetization investigation of a second upper flow unit. Alternating field demagnetisation is the processes of exposing the sample to an alternating field that decays from the maximum amplitude (B_{AF}) to zero over a set time. This results in the magnetic grains with magnetic coercivities (h_c) less than the amplitude of the alternating field (B_{AF}) being demagnetised, leaving the Natural Remanent Magnetisation (NRM) of grains with $h_c > H_{AF}$ remaining. This is carried out in three orthogonal directions to expose all grains of different orientations equally.

Thermal demagnetisation involves heating the samples to a specific temperature (T_{demag}) then subsequently cooling to ambient temperatures in a zero magnetic field. During the cooling, magnetic grains with blocking temperatures ($T_B \leq T_{\text{demag}}$) are remagnetised randomly, thereby no longer contributing to the overall remaining magnetisation. Between demagnetisation steps the direction and intensity of the remanent magnetisation, and the magnetic susceptibility was measured. The direction and intensity measurements provide insight into the emplacement history of the sampled clasts and susceptibility measurements will identify thermal alteration of the magnetic grains during the heating and cooling process.

5.2. Sampling and Drilling

The palaeomagnetic investigation involved sampling at Vickers Quarry and Surrey Road Quarry (Figure 30). These are proximal locations near the Egmont National Park boundary; both with excellent exposure of the Ngatoro Formation with cobble/boulder deposits in the quarry walls providing ideal material for a palaeomagnetic conglomerate test.

Andesitic cobbles and boulders (0.2m to 1.4m in diameter) were cored using a water cooled, 25mm diameter diamond tipped core drill bit driven by a modified chainsaw engine (Figure 30b). A minimum core length of 40mm was required to ensure at least two specimens could be recovered. An X, Y and Z axis was used to describe the cores orientation where the Z axis is the core's axis and the Y axis is the plane perpendicular to the Z axis (Figure 31). The core orientation was then measured with respect to the modern geomagnetic field using a geological compass mounted on an adjustable stage (Figure 30c and d). The azimuth of the cores Y axis with respect to magnetic north was measured with both the geological compass and with respect to the sun with a sun compass mounted on the same stage. The plunge of the Z axis relative to horizontal was measured using an inclinometer. Due to the young and undeformed nature of the sediment, no bedding correction was required for dipping bedding planes. Clasts were selected on the basis of stratigraphic position; appropriate size, minimal weathering and, most importantly, in-situ position (Any post-depositional rotation of the clast produces erroneous palaeomagnetic directions).

Figure 30: (A) Water cooled, diamond tipped palaeomagnetic drill being used to sample a large andesite boulder at Vickers Quarry. (B) The palaeomagnetic drill used to collect the core samples. (C) The orienting stage and magnetic compass being used to orient a sample. (D) The stage, magnetic compass and sun compass used to orient samples. Photo "A" courtesy of A/Prof Brent Alloway.

Figure 31: Example of a labelled palaeomagnetic core and specimen. (Inset) A schematic of the palaeomagnetic specimen labelling system used with respect to the X, Y and Z axis.

The following drilling program was carried out:

- Preliminary Investigation (September, 2012): 3x Clasts – 9 x Cores
- Lower Flow Unit Investigation (April, 2013): 15 x Clasts – 45 x Cores
- Preliminary Upper Flow Unit Investigation (November, 2013): 4 x Clasts – 12 x Cores

5.3. Sample Processing

Each labelled and named core was cut into 22mm long specimens using a liquid cooled rock saw. Each specimen was subsequently given a specific specimen number and remarked to preserve its known orientation.

The room temperature magnetic susceptibility of each sample was measured after each demagnetisation step and susceptibility with temperature of representative samples using a Bartington Instruments Ltd MS2 Magnetic Susceptibility Meter. Room temperature susceptibility measurements will reveal any thermally induced alteration of the magnetite mineralogy (eg. Inversion or oxidisation) - this results in a loss in the original magnetisation (Butler, 1992). Susceptibility with temperature measurements indicates the composition of the magnetic grains within the rock. The intensity and direction of the remanent magnetisation was measured using an Agico's JR6 Spinner Magnetometer. Thermal demagnetisation was carried out in a quartz glass tube lined, thermostatically-controlled oven with separate air cooled cooling chamber with zero ambient magnetic field.

For each stage of the investigation a representative suite of the specimens from each core and clast were selected for processing.

- Preliminary Lower Flow Unit Investigation: Alternating field demagnetisation was carried out on 3 specimens sampled from two different clasts. The alternating field demagnetisation ranged from 0 to 80mT at 5mT intervals.
- Main Lower Flow Unit Investigation: Thermal demagnetisation was carried out on 32 specimens from 16 cores sampled from 8 clasts. This included 5 clasts from the Vickers Quarry site and 3 from the Surrey Road Quarry site. The thermal demagnetisation ranged from 0 to 550°C at 50°C intervals. Magnetic susceptibility was measured after each demagnetisation step.

- Preliminary Upper Flow Unit Investigation: Thermal demagnetisation was carried out on 16 specimens from 8 cores sampled from 4 clasts. The thermal demagnetisation ranged from 0 to 550⁰C at 50⁰C intervals. Magnetic susceptibility was measured after each demagnetisation step.

5.4. Data Processing

The remanent magnetisation direction and intensity data were analysed using Remasoft 3.0: Palaeomagnetic data browser and analyser. The remanent magnetisation direction data is presented as Equal Area Stereographic Projections and Zijderveld Diagrams are used to present the direction and intensity of the remanent magnetisation throughout the demagnetisation steps (Figure 32). The magnetic susceptibility is presented in plots of susceptibility versus demagnetisation level. The best estimate of the remanent magnetisation direction was found using principal component analysis (Kirschvinck, 1980) and a 95% confidence limit expressed as an angular radius from the calculated mean direction (alpha-95).

Figure 32: Typical stepwise thermal demagnetisation results from Mt St Helens. Results presented in Zijderveld Diagrams (top), Equal Area Stereographic Projections (Middle) and Intensity vs Temperature Plots (Bottom). This figure shows both (a) single component of magnetisation and (b) two components of magnetisation within the samples (Paterson et al., 2010).

Chapter Three: Investigation Results and Interpretation

A summary of the volcanoclastic stratigraphy, associated tephrostratigraphy and sedimentology of each location with appropriate interpretations are presented in this chapter. Each measured section is divided into lithostratigraphic units (ie. EE-1, Unit 1) with detailed measured sections, lithostratigraphic descriptions, grain size and shape analysis results and electron microprobe analyses results presented in Appendix A. The complete datasets from the Electron Microprobe Analysis and grain size/shape analysis is presented in Appendix B and Appendix C respectively.

The palaeomagnetic results and appropriate interpretations are also included separately at the end of the chapter. These are presented separately as palaeomagnetic sampling only occurred at two key proximal sections (Vickers (VQ) and Surrey Road (SQ) Quarries). The complete palaeomagnetic results and data are presented in Appendix D.

The following notation is used to distinguish between stratigraphic sections, EMP tephra samples and grain size samples:

- Measured Sections: East Egmont, Section One [EE-1]
Tariki Underpass, Section Three [TU-3]
- EMP Samples: Tephra Sample One [TS-1]
Tephra Sample Twenty [TS-20]
- Grain size Samples: Vickers Quarry, Sample One [VQ-S1]
York Road, Sample Two [YR1-S2]

1. East Egmont (EE-1)

The East Egmont section is located 2.7 km east from the present-day summit of Egmont Volcano on the margins of the Manganui Valley (Figure 33). At this site one measured section (Figure 34) and tephra sampling for EMP analysis was carried out.

Figure 33: Aerial photograph showing the location of section EE-1 relative to the Manganui River and Ski Field. Photo courtesy of Taranaki Regional Explorer (2014).

Figure 34: Stratigraphy of section EE-1.

Figure 35: Photograph of section EE-1 with relevant lithostratigraphic units described in Appendix A.

1.1. Stratigraphy

The EE-1 (Appendix A) section exposes four cm- to dm-thick scoriaceous and/or pumiceous ash and lapilli beds overlying a >70m thick unit of extremely poorly sorted and consolidated, massive, boulder-rich sands and gravel (Figure 35). The first unit (EE-1, Unit 1) comprises cm scale bedded fine sand and silt with few andesite pebbles and pumiceous lapilli. The first lapilli bed (EE-1, Unit 2) is a $\leq 0.1\text{m}$ thick, fine to medium, pumiceous lapilli in a coarse sandy ash matrix overlain by a $< 0.2\text{m}$ thick, laminated to massive, fine coarse sand and silt with lenses (0.01m) of fine to coarse pumiceous sand (EE-1, Unit 3 & 4).

The second lapilli bed (EE-1, Unit 5) is a $< 0.4\text{m}$ thick, poorly sorted, fine to very coarse pumiceous lapilli with few dispersed angular to sub-angular coarse to very coarse lithic lapilli overlain by a $< 0.05\text{m}$ thick, well sorted, fine sand and silt (EE-1, Unit 6).

The third lapilli bed (EE-1, Unit 7) is a $< 0.1\text{m}$ thick, fine to coarse pumiceous lapilli with few to common, angular, grey lithic lapilli overlain by a $\leq 0.2\text{m}$ thick stratified and low-angle cross stratified, alternating silty fine sand and fine to medium sand (EE-1, Unit 8). This is overlain by a $< 0.4\text{m}$ thick, faintly stratified to massive, fine to coarse, basaltic, scoriaceous lapilli (EE-1, Unit 9) then a $> 0.15\text{m}$ thick, massive, very poorly sorted, fine to coarse, basaltic, scoriaceous lapilli and blocks (EE-1, Unit 10).

1.2. Tephrochronology

Glass shards of the three pumiceous lapilli beds at the base of EE-1 were analysed for major element composition and then correlated with the reference tephra dataset (Section B1, Appendix B) and stratigraphic logs published in Alloway et al (1995). Major element glass analyses from the first pumiceous lapilli bed (EE-1, TS-14) is indistinguishable from those determined for Korito Tephra (c. $4,100^{14}\text{C}$ yrs B.P). The second and third pumiceous lapilli beds (EE-1, TS-15 & -16 respectively) correlate with the lower and upper sub-units (Inglewood.a and b, respectively) of Inglewood Tephra dated at c. $3,600^{14}\text{C}$ yrs B.P (Alloway et al., 1995). The upper-most basaltic, scoriaceous lapilli bed correlates with the Manganui.a subunit of the Manganui Tephra dated at c. $3,100^{14}\text{C}$ yrs B.P (Section 1: Alloway et al., 1995).

1.3. Interpretation

The basal coarse-grained deposits underlying Unit 1 are interpreted to be undifferentiated block-and-ash flow deposits. Similar deposits are observed nearby within the valley walls of the Manganui Gorge adjacent to the ski-field (Figure 36), with some deposits exceeding 70m thick overlying lava flow and autobreccia deposits. Constrained by the overlying Korito Tephra (EE-1, Unit 2), the block-and-ash flows have a minimum age of c. 4,100 ^{14}C yrs B.P.

The three basal pumiceous lapilli beds (EE-1, Units 2, 5 & 7) are interpreted to correlate with the Korito Tephra and the lower and upper subunits of the Inglewood Tephra, respectively, based on stratigraphic associations and confirmed by glass shard chemistry (Figure 37). Beds EE-1, Units 3, 4, 6 & 8 are typically moderate to well-sorted, fine to coarse-grained ashy textured with mm- to cm-planar to low angle cross-laminations. Laterally these beds pinch and swell in overall thickness, and perceptibly thin up-elevation. Combined these features indicate pyroclastic surge emplacement and are likely associated with the passage of ash-elutriating, valley-confined block-and-ash-flow units that now form prominent but discontinuously exposed remnants of decimetre to metre-thick faintly stratified to massive deposits visible on either side of the present-day stream valley. The basaltic, scoriaceous lapilli, containing ballistic bombs at the top of the section (EE-1, Unit 9) is interpreted to be the Manganui.a bed of the Manganui Tephra based on direct stratigraphic correlation with Alloway et al. (1995) (Figure 37).

The pyroclastic surge deposit (EE-1, Unit 8), enveloped by the Inglewood.b (EE-1, Unit 7) and Manganui.a (EE-1, Unit 9) beds, appears to occur in a similar stratigraphic position with debris and hyperconcentrated flow deposits of Ngatoro Formation as described by Alloway et al (1989) beyond the confines of Egmont National Park (10 km from Egmont Volcano summit) (Figure 38). Therefore this pyroclastic surge deposit could represent a co-eruptive event closely associated with the generation and emplacement of Ngatoro Formation. The enveloping tephra constrain the age of the pyroclastic surge deposit (EE-1, Unit 8) to between c. 3,100 ^{14}C yrs and c. 3,600 ^{14}C yrs B.P.

Figure 36 (Above): View up the Manganui Valley towards section EE-1. The valley walls comprise <100m thick block-and-ash flow deposits overlying lava flow and autobreccia deposits.

Figure 37 (Below): Interpretation of lithostratigraphic units (see figure35) at section EE-1. This section exposes the Korito, Inglewood and Manganui Tephra. Upper pyroclastic surge deposits stratigraphically correlate with the Ngatoro

2. Vickers Quarry (VQ-1, VQ-2 and VQ-3)

The Vickers Quarry sections are located 10 km east from the present-day summit of Egmont Volcano on the banks of the Manganui River (Figure 38). At this site three measured sections, and sampling for EMP analysis and grain size/shape analysis was carried out.

Figure 38 (Right): Aerial photograph showing the location of sections VQ-1, VQ-2 and VQ-3. Photo courtesy of Taranaki Regional Explorer (2014).

Figure 39 (Left): Stratigraphy of section VQ-1, VQ-2 and VQ-3.

Figure 40 (Below Right): Photograph of the basal pumiceous lapilli sequence at section VQ-1 with relevant lithostratigraphic units presented in Appendix A.

Figure 41 (Top): Photograph of section VQ-1 with relevant lithostratigraphic units presented in Appendix A. Photo courtesy of A/Prof Brent Alloway

Figure 42 (Above): Photograph of section VQ-2 with relevant lithostratigraphic units presented in Appendix A. Photo courtesy of A/Prof Brent

Figure 43 (Above Left): Photograph of section VQ-3 basal pumiceous lapilli sequence and paleosol with relevant lithostratigraphic units presented in Appendix A.

2.1. Stratigraphy

The stratigraphy described at Vickers Quarry sections VQ-1, 2 & 3 (Appendix A) comprises up to 10m of cobble-and boulder-rich deposits overlying a basal pumiceous lapilli sequence (Figure 41, 42 & 43). There are three closely-spaced cm-scale basal lapilli beds (VQ-1, Units 1, 3 & 5) observed at the base of the Vickers Quarry section. The first of the basal lapilli beds (VQ-1, Unit 1) is a <0.2m thick, massive, fine to coarse pumiceous lapilli with few lithic lapilli. The second basal tephra bed (VQ-1, Unit 3) is a ≤ 0.05 m thick, fine to medium pumiceous lapilli with few lithic lapilli. The third basal lapilli bed (VQ-1, Unit 5) is a <0.15m thick, fine to coarse pumiceous lapilli bed. At Vickers Quarry, these basal lapilli beds are separated from the overlying boulder-rich volcanoclastic deposits by a <0.05m thick, dark blackish-brown, highly carbonaceous silts (VQ-1, Units 2 & 4). The uppermost pumiceous lapilli bed is overlain at VQ-3 by a 0.04m thick, organic-rich, firm and semi-deformable silt (VQ-3, Unit 7) (Figure 44) – this bed is not preserved at VQ-1 and VQ-2.

Overlying these basal lapilli beds is a <0.05m thick, laterally discontinuous, massive, normally graded, fine sand to silt unit (Figure 42) overlain by a 1.9-4.4m thick, laterally variable, massive, faintly reverse graded, pebbles, cobbles and boulders, clast-supported in a sandy matrix (VQ-1, Unit 6). This vertically grades to a fine to coarse, cobble and boulders clast-supported in a sand matrix (VQ-1, Unit 7). The upper 1.0m of Units 6 & 7 laterally transforms to massive pebble-rich fine to coarse sand with two beds of fine sandy silt. The cobble-and boulder-rich deposits are overlain by a <0.05m thick, leaf litter accumulation (VQ-1, Unit 8) that laterally transforms to a dark brown, organic-rich silt. This is subsequently overlain by a <0.5m thick, massive to faintly stratified, fine to medium pebbly sand deposit (VQ-1, Unit 9). This deposit laterally transforms to a massive, gravel and pebble rich sandy deposit. The upper boundary of this unit is marked by a ≤ 0.03 m thick accumulation of dark blackish brown leaf litter and wood fragments (VQ-1, Unit 10).

Overlying the leaf litter accumulation is a <5.0m thick unit of massive, poorly sorted, reversely graded lower to ungraded middle, fine to coarse pebbles, cobbles and boulders, clast-supported in a sand matrix (VQ-1, Unit 12) grading to fine to coarse pebbly sand (VQ-1, Unit 13 & 14). These deposits laterally vary in thickness with in-filled erosional channels (VQ-2, Unit 8) comprising massive, poorly sorted, fine to coarse, cobbles and boulders in a fine to coarse pebble and sand matrix (Figure 42).

The top of VQ-1 and VQ-2 is marked by a laterally continuous, <0.05m thick, massive, medium to coarse pumiceous lapilli in a silty ash matrix (VQ-1, Unit 15) overlain by a <0.05m thick, massive, moderately sorted, silty fine to medium sand with few charred wood fragments (VQ-1, Unit 16), and a <0.5m thick, massive, poorly sorted, reversely graded to ungraded, fine to coarse pebbles and cobbles clast-and/or matrix-supported in fine to coarse sand (VQ-1, Unit 17).

2.2. Tephrochronology and ^{14}C Chronology

Glass shards of the four pumiceous lapilli beds and entrained pumice clasts from VQ-1/VQ-2 were analysed for major element composition and then correlated with the reference tephra dataset (Section B1, Appendix B) and stratigraphic logs published in Alloway et al. (1995). Major element glass analyses from the first pumiceous lapilli bed (VQ-1, TS-19) is indistinguishable from those determined for Korito Tephra (c. 4,100 ^{14}C yrs B.P). The second and third pumiceous lapilli beds (VQ-1, TS-20 & 21 respectively) correlate with the lower and upper subunits (Inglewood.a and b, respectively) of Inglewood Tephra dated at c. 3,600 ^{14}C yrs B.P (Alloway et al., 1995).

Pumiceous clasts sampled from within the cobble and boulder rich deposits (VQ-1, TS-22) show a much broader range of major elemental compositions than the basal lapilli beds and are indistinguishable from the Korito and Inglewood Tephra. The pumiceous lapilli analysed from the top of the section (VQ-1, TS-28) is geochemically indistinguishable from the Inglewood.a and Inglewood.b subunits of the Inglewood Tephra. The lapilli's stratigraphic position 9.5m above the Inglewood.a and Inglewood.b subunits (VQ-1, Units 3 & 5) makes the correlation of this lapilli bed with the existing stratigraphic framework more complicated (for possible explanations see Section 2.4).

A prominent feature of the Vickers Quarry site is the presence of truncated large (< 2-m diameter) podocarp-hardwood trees extending upwards from a paleo-ground surface that includes Inglewood Tephra close to the ground surface contact. This forested paleosurface was buried by rapid and catastrophic emplacement of the cobble-and boulder-rich deposits (VQ-1, Units 6 & 7). These trees were radiocarbon dated at $3,236 \pm 35$ ^{14}C yrs B.P by Neall et al. (2012) indicating the paleoforest prior to the emplacement of the Inglewood Tephra.

2.3. Sedimentology

Sample VQ-S1 (VQ-1, Unit 6) exhibits a bimodal distribution with a major peak at -4.0ϕ and a minor peak at 1.0ϕ , and a mean of -1.53ϕ . The sample is very poorly sorted ($S.D = 3.16\phi$), coarse skewed ($SK_t = -13.54$) and has a fine constituent of $6.79 \text{ wt\%} < 4\phi$. Field measurements from this unit show the largest five clasts range in diameter from 0.75m to 3.2m. This very coarse deposit vertically grades to a finer grained and less poorly sorted unit (VQ-1, Unit 7). Sample VQ-S2 (VQ-1, Unit 7) exhibits a broad, bimodal grain size distribution with a major peak at -2.0ϕ and a minor peak at $0.5-1.0\phi$, and a mean of 0.00ϕ . The sample is very poorly sorted ($S.D = 2.56\phi$), fine skewed ($SK_t = 0.13$) and has a fine constituent of $7.97\text{wt\%} < 4\phi$. Sample VQ-S3 from the fine to coarse pebbly sand (VQ-1, Unit 9) bound by accumulations of organic material (VQ-1, Units 8 & 10) exhibits a broad, single modal peak at 1.0ϕ and a mean of 0.07ϕ . The sample is very poorly sorted ($S.D = 2.30$), fine skewed ($SK_t = 0.13$) and has a fine constituent of $4.46\text{wt\%} < 4\phi$. Sample VQ-S4 (VQ-S1, Unit 11) taken from the thin, fine textured, pebbly sand unit overlying the second organic layer (VQ-1, Unit 10) exhibits a single modal peak at 1.0ϕ and a mean of 1.44ϕ . The sample is very poorly sorted ($S.D = 2.35\phi$), fine skewed ($SK_t = 0.73$) and has a fine constituent of $13.53\text{wt\%} < 4\phi$. Sample VQ-S5 taken from the second, cobble and boulder rich unit (VQ-1, Unit 12) exhibits a bimodal distribution with a major peak at -4.5ϕ and a minor peak at $1.0-2.0\phi$, and a mean at 2.15ϕ . This vertically grades to a fine grained unit shown by sample VQ-S6 (VQ-1, Unit 14) which exhibits a modal peak at $1.0-2.0\phi$ with a single, outlying peak at -5.0ϕ .

Clast form analysis of the two main cobble and boulder rich units VQ-S1 (VQ-1, Unit 6) and VQ-S5 (VQ-1, Unit 12) indicate that both the deposits at Vickers Quarry comprise dominantly Compact-Bladed and sub-rounded clasts. Analysis of VQ-S1 (VQ-1, Unit 6) shows a shape distribution of Compact bladed (30%), Compact-Elongate (19%) and Bladed (19%) with a range from compact to very-bladed. The roundness estimates exhibit a peak in the rounded class (0.5) with a mean and median of 0.5, and a range from sub-angular (0.3) to rounded (0.7). Analysis of VQ-S5 (VQ-1, Unit 12) shows a main shape distribution of Compact-Bladed (28%), Compact (18%) and Compact-Elongate (14%) with a range from compact to very-bladed. The roundness estimates for VQ-S5 exhibit a peak at rounded (0.5) but has a mean and median of sub-rounded (0.4), and a range from angular (0.2) to rounded (0.6).

2.4. Interpretation

The interbedded, basal pumiceous lapilli beds (VQ-1, Units 1, 3 & 5) are interpreted to be the Korito Tephra (c. 4,100 ^{14}C yrs B.P) and the Inglewood.a and Inglewood.b subunits of the Inglewood Tephra (c. 3,600 ^{14}C yrs B.P) based on stratigraphic position and geochemical composition. This is overlain by an organic rich silt unit interpreted to be a paleosol (VQ-3, Unit 7). The paleosol is variable in both thickness and composition with the same paleosol expressed as a <0.2m thick, fibrous peat deposit near VQ-3.

Overlying the paleosol, the normally graded, fine sand to silt unit is interpreted to be a basal sole layer (Figure 45) deposited by the wave of water pushed in front of the head of the debris flow. At Vickers Quarry the paleosol and basal sole layer are often absent with the overlying coarse grained deposits unconformably overlying the Inglewood.b subunit (e.g. VQ-1 and VQ-2). The <5.0m thick, massive, monolithologic, coarse textured, pebble, cobble and boulder unit (VQ-1, Unit 6; VQ-2, Unit 7; VQ-3, Unit 8) is interpreted to be proximal debris flow deposits. This unit vertically grades to a massive, monolithologic, pebble and cobble-rich debris flow deposits (VQ-1, Unit 7). Based on the underlying Inglewood Tephra (c. 3,600 ^{14}C yrs B.P), the debris flow deposits are interpreted to be proximal exposures of the Ngatoro Formation (Figure 46). The top of these debris flow deposits is marked by a leaf litter accumulation that laterally transforms to an organic rich silt (VQ-1, Unit 8) interpreted to be a paleosol. This represents a period of stability in the landscape after the emplacement of the Ngatoro Formation. Overlying the leaf litter accumulation, the normally graded, and massive to stratified sand unit is interpreted to be fluvial reworked deposits (VQ-1, Unit 9) (Figure 47). The fluvial reworked deposits are laterally discontinuous suggesting an alluvial system formed on the upper surface of the Ngatoro Formation. This is supported by another leaf litter accumulation on the upper contact of the fluvial reworked deposits (VQ-1, Unit 10).

The paleosol and fluvial reworking sequence (VQ-1, Units 8, 9 & 10) is laterally variable with the fluvial reworked deposits expressed as a massive, monolithologic, pebble and sand rich debris flow deposit overlain by a laterally continuous fine textured, fine sand to silt unit (VQ-1, Unit 11) interpreted to be a sole layer. The sole layer is overlain by another <4.0m thick, massive, monolithologic, reversely graded, pebble, cobble and boulder unit (VQ-1, Unit 12) vertically grading to gravelly fine to coarse sand unit (VQ-1, Units 13 & 14) are interpreted to

be proximal debris flow deposits of the Te Popo Formation (Figure 46). These deposits laterally vary in thickness from <4.0m (VQ-1, Unit 12) to 7.0m thick (VQ-2, Units 7 & 8) where it infill's erosional channels into the underlying deposits.

The top of the Vickers Quarry sections are marked by a laterally continuous, medium to coarse pumiceous lapilli with some charred wood fragments (VQ-1, Unit 15; VQ-2, Unit 9). This is overlain by a massive, silty, fine to medium sand unit (VQ-1, Unit 16) interpreted to be a sole layer overlain by another >0.5m thick, monolithologic, reversly graded, sandy pebble and cobble unit (VQ-1, Unit 17) interpreted to be a proximal debris flow deposit. Major element composition analysis (VQ-1, TS-28) indicates the pumiceous lapilli has a composition indistinguishable from the Inglewood Tephra; however its stratigraphic position 9.6m above the Inglewood.a and Inglewood.b subunits (VQ-1, Units 3 & 5) does not fit within the existing stratigraphic framework (Alloway et al., 1995; Lowe, 1988). There are three possible explanations for the occurrence of TS-28 with its Inglewood glass chemistry. It may represent: 1) a layer of reworked Inglewood pumice occurring higher in the volcanoclastic stratigraphy; 2) an additional Inglewood eruptive subunit not recognised at other sections; or 3) an incorrectly labelled or inadvertently swapped sample during preparation and analysis. Irrespective of these possible explanations to account for the position of TS-28, Korito and Inglewood subunits a and b are identified in the correct sequence in the lower stratigraphy of the same vertical section. This issue is expected to be resolved after submission of this thesis by tephra resampling and further EMP analysis as well as submission of associated wood fragments for radiocarbon dating.

Figure 44 (Left): Photograph showing the Korito Tephra and Inglewood.a and Inglewood.b subunits at the base of sections VQ-1 and VQ-2.

Figure 45 (Above): Photograph showing the discontinuous basal sole layer at Vickers Quarry.

Figure 46: Photograph show the Ngatoro Formation overlying the Korito Tephra and Inglewood.a and Inglewood.b subunits at sections VQ-1 and VQ-2. The upper boundary is marked with a laterally discontinuous paleosol and fluvial reworked deposits. The overlying Te Popo Formation has eroded and infilled a channel into the underlying Ngatoro Formation. Note the charred tree truncated at the boundary between the Ngatoro Formation and Te Popo Formation. Photo courtesy of A/Prof Brent Alloway.

As previously discussed, a prominent feature of the Vickers Quarry site is the presence of truncated large podocarp-hardwood trees extending upwards from a paleosurface buried by rapid and catastrophic emplacement of the Ngatoro Formation (VQ-1, Units 6 & 7) (Figure 47). The trees show two key features that provide insight into the emplacement of the Ngatoro Formation:

- **Charred Outer Veneer** – The outer edge of the truncated tree trunks are superficially charred to a penetration depth of <0.1m. The charred outer is dark black in colour, with prominent desiccation cracks. This is evidence for an emplacement of the Ngatoro Formation or any pre-cursor event above ambient temperature – hot enough to char the trees but not enough to completely burn them. The outside and top of the truncated trees also show evidence of impacts from debris including rounded off tops, upslope removal and downslope preservation of bark, and fine material encased around the trunks.

- Correlation of Truncation Height – The height at which the trees have been truncated ranges from 1.9m to 3.3m above the buttress of the tree. This height correlated with the boundary between the upper and lower flow units exposed in the quarry walls (VQ-1 and VQ-2).

Vickers Quarry - Truncated Trees			
Tree	Height (From Base)	Height (From Top of Buttress)	Circumference (m)
1	3.8	-	5.2
2	4.3	-	3.4
3	3.1	2.0	1.8
4	4.5	3.5	4.2
5	4.1	2.9	3.3
6	3.9	3.3	5.9
7	3.3	2.5	2.0
8	3.5	2.0	5.2
9	3.2	2.5	2.8
10	3.9	3.3	3.8
11	2.3	1.9	2.4

Figure 47: Table of truncated tree heights with accompanying photographs showing the excavated charred and desiccated in situ trees. Note the rounded tops and sand/cobbles forming a veneer around the upslope side of trunk. Photographs courtesy of A/Prof Brent Alloway.

3. Surrey Road Quarry (SQ-1, SQ-2 and SQ-3)

The Surrey Road Quarry sections are located 10 km east from the present-day summit of Egmont Volcano on the banks of the Mangamawhete Stream (Figure 48). At this site three measured sections were carried out (Figure 49).

Figure 48: Aerial photograph showing the location of sections SQ-1, SQ-2 and SQ-3. Photo courtesy of Taranaki Regional Explorer (2014).

Figure 49: Stratigraphy of sections SQ-1, SQ-2 and SQ-3.

Figure 50 (Above): Photograph of section SQ-2 with relevant lithostratigraphic units described in Appendix A. Photo courtesy of A/Prof Brent Alloway.

Figure 51 (Left): Photograph of section SQ-3 with relevant lithostratigraphic units described in Appendix A. Photo courtesy of A/Prof Brent Alloway.

3.1. Stratigraphy

The stratigraphy described at Surrey Road Quarry sections VQ-1, 2 & 3 (Appendix A) comprises up to 10m of cobble-and boulder-rich deposits overlying a basal pumiceous lapilli sequence with interbedded basaltic, scoriaceous lapilli beds. Two closely spaced, cm-to dm-scale pumiceous lapilli beds (SQ-2, Units 1 & 3) were observed at the base of the Surrey

Road Quarry walls (Figure 50). These pumiceous lapilli beds are separated by a <0.1m thick, massive sand unit (SQ-2, Unit 2). The first lapilli bed (SQ-2, Unit 1) is <0.2m thick, very coarse (up to 0.3m) pumiceous lapilli and blocks, with the second lapilli bed (SQ-2, Unit 3) a 0.1m thick, fine to medium, pumiceous lapilli in a sandy matrix. This is overlain by a <0.1m thick, dark brown, organic rich, fine to medium, sandy silt with common wood fragments (SQ-2, Unit 4). The two lapilli beds are only observed at section SQ-2.

The basal pumiceous lapilli sequence is typically overlain by a <2.0m thick, massive, monolithologic, pebble, cobble-and boulder-rich unit containing wood fragments (0.2m), exhibiting a reversely graded lower to ungraded middle and normally graded upper (SQ-2, Unit 5) (Figure 50). In places the base of this unit is marked by a <0.3m thick, massive, poorly sorted fine to coarse sand. The cobble-and boulder-rich unit is subsequently overlain by a ≤0.15m thick cross-stratified, sandy deposit normally grading to massive, dark brown sandy silt (SQ-2, Unit 6) and a <0.1m thick, massive to faintly stratified, fine to medium basaltic, scoriaceous lapilli in a sandy/silt matrix (SQ-1, Unit 2; SQ-2, Unit 7; SQ-3, Unit 2).

The basaltic lapilli is overlain by a laterally and vertically variable unit of massive, homolithologic, clast-supported, angular to sub-rounded, fine to coarse pebble-rich to pebble, cobble-and boulder-rich deposits (SQ-1, Units 3 & 4; SQ-2, Units 8 & 9; SQ-3, Units 3, 5 & 8) with two <0.2m thick, interbedded basaltic, scoriaceous lapilli beds (SQ-3, Units 4 & 6). The two lapilli beds (SQ-3, Units 4 & 6) are comprised of massive, fine to medium basaltic, scoriaceous lapilli with the uppermost in a dark brown silt matrix. The sandy pebble, cobble and boulder units are channelised with erosional lower boundaries cutting into underlying units, and lateral textural and thickness variations (0.3 – 2.5m thick). This is evident in the three scoriaceous lapilli beds exposed at SQ-3 (Units 2, 4 & 6), whereas only one scoriaceous lapilli bed is preserved at SQ-1 (Unit 2) where overlying units have incised and eroded out the second and third scoriaceous lapilli beds.

3.2. Tephrochronology

The pumiceous and scoriaceous lapilli beds (SQ-2, Units 1 & 3; SQ-3, Units 2, 4 & 6) exposed at Surrey Road Quarry were correlated with the existing tephrostratigraphic record on the basis of stratigraphic association augmented by glass shard chemistry (Section B1, Appendix B). The basal pumiceous lapilli beds (SQ-2, Unit 1 & 3) are correlated with the lower and

upper subunits of the Inglewood Tephra (c. 3,600 ¹⁴C yrs B.P). The three basaltic, scoriaceous lithic lapilli beds (SQ-3, Units 2, 4 & 6) have been correlated with the Manganui.a, Manganui.b and Manganui.c beds of the Manganui Tephra (c. 3,100 ¹⁴C yrs B.P) (Alloway et al., 1995).

3.3. Interpretation

The basal pumiceous lapilli beds (SQ-2, Units 1 & 3) are interpreted to be the Inglewood.a and Inglewood.b subunits of the Inglewood Tephra (c. 3,600 ¹⁴C yrs B.P) based on stratigraphic position, colour and coarse texture. The Inglewood Tephra is subsequently overlain by an organic-rich, sandy silt interpreted to be a paleosol (SQ-2, Unit 4) representing a period of stability in the landscape following the Inglewood eruptive event. The massive, poorly sorted sandy unit rarely preserved at Surrey Road Quarry (Figure 52) is interpreted to be a basal sole layer deposited by the wave of alluvial water pushed in front of the head of the debris flow.

Figure 52: Interpretation of the lithostratigraphic units (Figure 50). This section exposes the Inglewood.b subunit, organic rich paleosol with wood fragments and the basal sole layer.

The lower massive, pebble, cobble-and boulder-rich unit (SQ-1, Unit 1; SQ-2, Unit 5 & 6; and SQ-3, Unit 1) is interpreted to be a proximal debris flow deposit based on its coarse-grained texture, homogeneous composition, massive structure and poorly sorted nature. This is unconformably overlain by a cross-stratified, fine to coarse sandy unit (SQ-2, Unit 6) interpreted to be hyperconcentrated flow deposits vertically transforming into a massive, dark brown silt with abundant basaltic, scoriaceous lapilli (SQ-1, Unit 2; SQ-2, Unit 7; and SQ-3, Unit 2). The scoriaceous lapilli bed stratigraphically correlates with the Manganui.a subunit of the Manganui Tephra (c. 3,100 ¹⁴C yrs B.P) and as a paleosol. This palaeosol

represents a period of stability in the landscape following the first Manganui eruptive event. The enveloping Inglewood and Manganui Tephra correlate the proximal debris flow deposits and hyperconcentrated flow deposits (SQ-2, Units 5 & 6) with the Ngatoro Formation (c. 3,600 ^{14}C yrs B.P) (Figure 53).

Figure 53 (Above): Photograph showing the Ngatoro Formation enveloped by the Inglewood.b subunit and paleosol and the overlying Manganui.a subunit interpreted from lithostratigraphic units (Figures 50 and 51) section SQ-2. The upper most debris flow deposits are proximal Te Popo Formation. Photo courtesy of A/Prof Brent Alloway.

Figure 54: Photograph showing the Manganui.b and Manganui.c subunits with interbedded overbank pebbly sand debris flow deposits interpreted from lithostratigraphic units (Figure 51) at section SQ-3

Above the Manganui.a subunit, the pebble, cobble-and boulder-rich unit (SQ-1, Unit 3; SQ-2, Unit 9; and SQ-3, Unit 3) is interpreted to be proximal debris flow deposits of the Te Popo Formation (c. 2.9 to 3.1 kyr B.P) based on its coarse gravelly texture, homogeneous composition, massive structure and poorly sorted nature. This unit varies in thickness from 0.8m (SQ-3, Unit 3) to <2.5m thick (SQ-2, Unit 9) as it basally erodes and forms channels in the underlying volcanoclastic deposits. Within the channels, the debris flow deposits are typically massive, clast-supported, and have cobble-and boulder-dominated textures (SQ-1, Unit 3; SQ-2, Unit 9), whereas the thinner overbank deposits are massive, matrix-supported and have sand-and pebble-dominated textures (SQ-3, Unit 3) (Figure 54). At section SQ-2, the base of the debris flow deposit (SQ-2, Unit 9) is marked by a massive, pebbly coarse sand layer (SQ -2, Unit 8) interpreted as a sole layer deposited by the wave of alluvial water pushed downstream at the head of the debris flow. The sole layer is not preserved at SQ-1 and SQ-3 through subsequent erosion by the main body of the debris flow.

At sections SQ-1 and SQ-2, the debris flow deposits extend up to the top of the quarry walls, however at section SQ-3 a second and third basaltic scoriaceous lapilli bed (SQ-3, Units 5 & 6) are interbedded between the volcanoclastic deposits (Figure 54). The second scoriaceous lapilli bed (SQ-3, Unit 4) stratigraphically correlates with the Manganui.b subunit of the Manganui Tephra (c. 3,100 ¹⁴C yrs B.P). This Manganui Tephra is not laterally continuous and variable in thickness where overlying deposits have eroded it out (Figures 55 and 56). The Manganui.b subunit is overlain by a laterally variable pebbly sand to pebble, cobble-and boulder-rich unit (SQ-3, Unit 5) is interpreted to be proximal debris flow deposits of the Te Popo Formation based on its coarse-grained texture, homogeneous composition, massive structure and poorly sorted nature. The debris flow deposits vary in thickness with coarse-textured infilled channels and finer textured overbank deposits (Figure 55 and 56) similar to the previous Te Popo Formation debris flow deposits (SQ-2, Unit 9; SQ-3, Unit 3).

The debris flow deposits (SQ-3, Unit 5) vertically transform into a basaltic, scoriaceous lapilli in a dark brown silt matrix (SQ-3, Unit 6) which stratigraphically correlates with the Manganui.c subunit of the Manganui Tephra (c. 3,100 ¹⁴C yrs B.P) within a paleosol. This paleosol represents a period of stability in the landscape following the third Manganui eruptive event. Overlying the Manganui.c subunit, is another pebble, cobble-and boulder-rich unit (SQ-3, Unit 8) interpreted to be proximal debris flow deposits of the Te Popo

Formation based on its coarse-grained texture, homogeneous composition, massive structure and poorly sorted nature. The base of the debris flow deposits are marked by a massive silt layer (SQ-3, Unit 7) interpreted to be a sole layer deposited by the wave of alluvial water pushed in front of the head of the debris flow.

Figure 55 (Top): Photograph showing a debris flow deposit of the Te Popo Formation incised (orange line) into the underlying Ngatoro Formation and Manganui.a subunit forming a boulder-rich channel deposit.

Figure 56 (Bottom): Photograph showing the subunits of the Manganui Tephra (light blue) eroded away by channel deposits of the overlying Te Popo Formation.

4. York Road (YR-1 and YR-2)

The York Road sections are located 13.6 km east from the present-day summit of Egmont Volcano at the cut slopes of a cow underpass on York Road (Figure 57). At this site two measured sections (Figure 58), and sampling for EMP analysis and grain size/shape analysis was carried out.

Figure 57 (Left): Aerial photograph showing the location of sections YR-1 and YR-2. Photo courtesy of Taranaki Regional Explorer (2014).

Figure 58: Stratigraphy of sections YR-1 and YR-2.

Figure 59: Photograph of the basal pumiceous lapilli sequence at YR-1 with relevant lithostratigraphic units described in Appendix A.

4.1. Stratigraphy

The stratigraphy described at York Road sections YR-1 and 2 (Appendix A) comprises 2m of sandy pebble- and cobble-rich deposits overlying a basal pumiceous lapilli sequence. Section YR-1 exposes three cm-scale pumiceous lapilli beds (YR-1, Units 2, 4 & 6) overlying a massive, yellow-brown soil (YR-1, Unit 1) (Figure 60). The first basal lapilli bed (YR-1, Unit 2) is a <0.2m thick, fine to medium, pumiceous lapilli in a sandy ash matrix overlain by massive, yellow-brown silt with few, fine to medium pumiceous clasts (YR-1, Unit 3). The second lapilli bed (YR-1, Unit 4) is a <0.1m thick, massive, fine to medium pumiceous lapilli and sub-angular, fine to medium lithic lapilli in a silty ash matrix. This is overlain by massive, yellow-brown silt with few, fine to medium, pumiceous clasts (YR-1, Unit 5). The third basal lapilli bed (YR-1, Unit 6) is a ≤ 0.1 m thick, massive, dominantly coarse, pumiceous lapilli and fine lithic lapilli in a brown sandy ash matrix.

The basal lapilli beds are overlain by a <0.05m thick, massive, monolithologic, fine to medium, pebbly sand (YR-1, Unit 7) and a <0.5m thick sequence of faintly stratified, pebble-rich, fine to coarse sand (YR-1, Unit 8). This is subsequently overlain by a <0.4m thick, massive, monolithologic, fine to coarse sand and sub-angular to sub-rounded, fine to coarse pebbles (YR-1, Unit 9).

Approximately 5.0m along section, Units 8 and 9 from section YR-1 laterally transform to a >0.5m thick, massive, monolithologic, channelised, clast-supported, fine to coarse sand with some angular to sub-angular, fine to coarse pebbles with some cobbles (YR-2, Unit 1) (Figure 60). This unit erodes into the underlying pumiceous lapilli beds (YR-1, Units 2, 4 & 6) and is overlain by a <0.25m thick, massive, fine to medium, sandy silt with abundant, medium to very coarse, pumiceous lapilli in the upper 0.1m (YR-2, Unit 2). This pumiceous lapilli bed is subsequently overlain by a >1.5m thick, massive, monolithologic, faintly normally graded, matrix-supported, fine to coarse sand with angular to sub-angular, fine to coarse pebbles and cobbles (YR-2, Unit 3) (Figure 61). Along section YR-2 Unit 1 correlates with YR-1 Units 9 and 10.

Figure 60: Photograph showing the two pebble- and cobble-rich sand units with interbedded pumiceous lapilli at section YR-2 with relevant lithostratigraphic units described in Appendix A.

Figure 61: Photograph showing the pumiceous lapilli overlain by a pebble and cobble-rich sand unit at section YR-2 with relevant lithostratigraphic units described in Appendix A.

4.2. Tephrochronology

Glass shards of the three basal pumiceous lapilli beds (YR-1, Units 2, 4 & 6) were analysed for major element composition and then correlated with the reference tephra dataset (Section B1, Appendix B) as well as stratigraphic logs published in Alloway et al., (1995). Major element glass analyses from the first pumiceous lapilli bed (YR-1, TS-25) is indistinguishable from those determined for Korito Tephra (c. 4,100 ^{14}C yrs B.P). The second and third pumiceous lapilli beds (YR-1, TS-24 & 23 respectively) correlate with the lower and upper subunits (Inglewood.a and b, respectively) of Inglewood Tephra dated at c. 3,600 ^{14}C yrs B.P (Alloway et al., 1995). The lapilli bed exposed at YR-2 (Unit 2) correlates with the unknown uppermost lapilli bed at Vickers Quarry (VQ-1, Unit 15).

4.3. Sedimentology

Grain size analysis from sample YR1-S1 within the thin, fine-textured sand unit (YR-1, Unit 7) overlying the basal lapilli sequence exhibits a modal peak at -0.5ϕ showing near normal distribution and has a mean of -0.05ϕ . The sample is very poorly sorted ($S.D = 2.15\phi$), fine skewed ($SK_t = 0.26$) and has a fine constituent of 7.59wt% $< 4\phi$. Sample YR1-S2 sampled from the overlying pebbly sand unit (YR-1, Unit 8) exhibits a modal peak at -0.5ϕ showing normal distribution and a mean of -0.08ϕ . The sample is poorly to very poorly sorted ($S.D = 2.00\phi$), near symmetrical ($SK_t = 0.02$) and has a fine constituent of 4.74wt% $< 4\phi$. The top of

the section exhibits an upwards coarsening and more poorly sorted nature with sample YR1-S3 (YR-1, Unit 9) exhibiting a poorly defined peak at -4.5ϕ and a mean of -1.23ϕ . The sample is very poorly sorted ($S.D = 2.67\phi$), fine skewed ($SK_t = 2.99$) and has a fine constituent of $5.00\text{wt}\% < 4\phi$

Clast form analysis of YR1-S3 (YR-1, Unit 9) indicates the deposit comprises dominantly bladed and sub-rounded clasts. The analysis shows a main shape distribution of bladed (33%), compact-bladed (23%) and compact-elongate (18%) with a range from compact-platy to very-elongate. The roundness estimates for YR1-S3 (YR-1, Unit 9) exhibit a peak, mean and median of sub-rounded (0.4), and a range from angular (0.2) to well-rounded (0.8).

4.4. Interpretation

The basal pumiceous lapilli beds (YR-1, Units 2, 4 & 6) are interpreted to be the Korito Tephra (c. 4,100 ^{14}C yrs B.P) and Inglewood.a and Inglewood.b subunits of the Inglewood Tephra (c. 3,600 ^{14}C yrs B.P) based on stratigraphic interpretation and geochemical composition. The andic soils that separate the pumiceous lapilli beds represent a period of stability in the landscape between the three eruptive events. The Inglewood Tephra constrains the overlying deposits to a maximum age of c. 3,600 ^{14}C yrs B.P.

The <20mm thick, pebbly sand deposit (YR-1, Unit 7) overlying the basal tephra is interpreted to be a sole layer deposited by the wave of alluvial water pushed in front of the head of the debris flow. This is overlain by the cm-scale bedded to massive, sandy pebble deposits (YR-1, Units 8, 9 & 10) interpreted to be coarse-textured marginal debris flow deposits exhibiting multiple cut and fill sequences. At section YR-2, the coarse-grained sand, pebble-and cobble-rich deposits exposed at the base of the section (YR-2, Unit 1) are interpreted to be debris flow deposits based on the coarse-texture, homogeneous composition, and massive structure and poorly sorted nature of the deposits. These coarse-grained debris flow deposits stratigraphically correlate with the Ngatoro Formation (Figure 62). Overlying the Ngatoro Formation is a massive, sandy silt soil with the upper boundary marked by a pumiceous lapilli bed (YR-2, Unit 2) which stratigraphically correlates with the unknown uppermost tephra at the Vickers Quarry sections (VQ-1, Unit 15 and VQ-2, Unit 10) based on texture, colour and relative stratigraphic position within enveloping volcanoclastic deposits. The soil beneath and within the tephra (YR-2, Unit 2) indicates a

period of quiescence and stability in the landscape leading up to the deposition of the tephra and the deposition of the overlying volcanoclastic deposits (YR-2, Unit 3). The massive, fine to coarse pebble and cobble unit at the top of the section (YR-2, Unit 3) is interpreted to be a debris flow deposit based on coarse-grained texture, homogeneous composition, massive structure and poorly sorted nature.

The deposits described at YR-2 are much more coarsely grained in comparison to those at YR-1, in particular YR-2 Unit 2, which has cut into the underlying debris flow deposits (YR-1, Units 9 & 10; YR-2, Unit 1) and basal tephra sequence (YR-1, Units 2, 4 & 6) depositing a cobble-rich, massive, channelised debris flow unit (YR-2, Unit 3). This suggests that deposits at YR-1 are marginal deposits whereas YR-2 exposes deposits within a debris flow channel.

Figure 62: Interpretation of lithostratigraphic units (Figure 59) exposed at section YR-1. This section exposed the marginal debris flow deposits of the Ngatoro Formation overlying the Korito Tephra, and Inglewood.a and Inglewood.b sub-units.

5. Tariki – SH3 (TR-1)

The Tariki – SH3 section is located 17.1 km east from the present-day summit of Egmont Volcano near the SH3 Mangmawhete Stream Bridge (Figure 63). At this site one measured section (Figure 64) was carried out.

Figure 63: Aerial photograph showing the location of section TR-1. Photo courtesy of Taranaki Regional Explorer (2014).

Figure 64 (Far Left): Stratigraphy of section TR-1

Figure 65: Photograph of section TR-1 with relevant lithostratigraphic units described in Appendix A.

5.1. Stratigraphy

The stratigraphy described at Tariki-SH3 section (Appendix A) comprises <3.0m of pebble- and sand-rich deposits overlying a basal pumiceous lapilli sequence (Figure 65). Two cm-scale pumiceous lapilli beds (TR-1, Units 1 & 3) are observed at the base of the section separated by a ≤ 0.1 m thick massive, dark brown, fine to coarse sandy silt (TR-1, Unit 2). The lower lapilli bed (TR-1, Unit 1) is a <0.2m thick, massive, normally graded, fine to medium pumiceous lapilli. The second lapilli bed (TR-1, Unit 3) is a <0.15m thick, massive, fine to coarse lapilli in a clayey silt matrix. This is overlain by 0.02m thick, organic rich, dark brown silty clay (TR-1, Unit 4) (Figure 66).

Figure 66: Photograph of the basal pumiceous lapilli and overlying organic-rich clay at section TR-1 with relevant lithostratigraphic units described in Appendix A. The arrow used for scale is 0.15m long.

The basal pumiceous lapilli sequence is overlain by a <0.03m thick, massive, silty fine sand (TR-1, Unit 5) and <0.7m sequence of stratified/cross-stratified, fine to medium sand and channelised, fine to coarse pebbly sand (TR-1, Unit 6, 7 & 8). This sequence is overlain by a <0.03m thick, massive, silty fine sand (TR-1, Unit 9). This is subsequently overlain by ≤ 0.5 m of stratified, fine to medium sand (TR-1, Unit 10) vertically grading to massive, pebbly fine to medium sand (TR-1, Unit 11 & 13), interbedded with a laterally discontinuous accumulation of fine to medium pumice clasts in a pebbly sand matrix (TR-1, Unit 12). Above this is a <0.1m thick, massive, fine to medium pumiceous lapilli in a silty sand matrix (TR-1, Unit 14) overlain by cross-stratified, fine to medium sand (TR-1, Unit 15) vertically grading to

massive, channelised, alternating fine to coarse sand and fine to coarse, pebbly sand (TR-1, Unit 16). Approximately 10m eastward of TR-1, Unit 16 is exposed as a massive, poorly sorted, clast-supported, gravel and cobble unit with a fine to coarse sand matrix.

5.2. Tephrochronology

The pumiceous lapilli beds exposed at the Tariki-SH3 section were correlated with the existing tephrostratigraphic record on the basis of stratigraphic association augmented by glass shard chemistry (Section B1, Appendix B). The two basal pumiceous lapilli beds (TR-1, Units 1 & 3) are correlated with the Inglewood.a and Inglewood.b subunits of the Inglewood Tephra (c. 3,600 ¹⁴C yrs B.P). The pumiceous lapilli at the top of the section (TR-1, Unit 14) within a silty sand matrix stratigraphically correlates with the tephra described at the top of the York Road (YR-2, Unit 2) and Vickers Quarry (VQ-1, Unit 15) sections.

5.3. Interpretation

The two basal pumiceous lapilli beds (TR-1, Units 1 & 3) are interpreted to be the Inglewood.a and Inglewood.b subunits of the Inglewood Tephra (c. 3,600 ¹⁴C yrs B.P) separated by a paleosol (TR-1, Unit 2) based on relative stratigraphic position and field description. The Inglewood.a subunit is overlain by an organic rich, sandy silt paleosol (TR-1, Unit 4) (Figure 67) indicating a period of time between the Inglewood eruptive event and the emplacement of the overlying units.

The paleosol is overlain by a silty, fine sand layer (TR-1, Unit 5) interpreted to be a sole layer deposited by the wave of alluvial water pushed in front of the head of the next debris/hyperconcentrated flow (Figure 67). This vertically grades to stratified/low-angle cross-stratified to channelised, pebbly, fine to coarse sand units (TR-1, Units 6, 7 & 8)

Figure 67: The interpretation of the lithostratigraphic units (Figure 66) at section TR-1. This section exposes the basal Inglewood Tephra overlain by the organic-rich paleosol. This is subsequently overlain by hyperconcentrated flow deposits of the Ngatoro Formation.

interpreted to be hyperconcentrated flow deposits (Figure 68). This is subsequently unconformably overlain by a second silty, fine sand sole layer (TR-1, Unit 9). Above the second sole layer is a sequence of stratified, fine to medium sandy hyperconcentrated flow deposits (TR-1, Unit 10) vertically grading to the massive, fine to coarse, pebbly sand units (TR-1, Units 11 & 13) interpreted to be debris flow deposits. These debris flow deposits are interbedded with a laterally discontinuous accumulation of pumiceous clasts (TR-1, Unit 12) (Figure 68).

The debris flow deposits are overlain by the massive, fine to medium, pumiceous lapilli (TR-1, Unit 14) interpreted to be a pumiceous tephra which stratigraphically correlates with the tephra described at the top of the York Road (YR-2, Unit 2) and Vickers Quarry (VQ-1, Unit 15) sections. The silty, fine to medium sandy matrix is interpreted to be a paleosol indicating a period of time between the deposition of the tephra and the deposition of the overlying units. Above the tephra, the cross-stratified, fine to medium sand (TR-1, Unit 15) overlain by channelised, alternating pebbly, fine to coarse sand and gravelly, fine to coarse sand (TR-1, Unit 16) are interpreted to be hyperconcentrated flow deposits overlain by cut and fill debris flow deposits.

Figure 68: The interpretation of the lithostratigraphic units (Figure 65) at section TR-1. This section exposes hyperconcentrated flow deposits and debris flow deposits. Note the entrained pumice clasts and unknown pumiceous tephra at the top of the section.

6. Tariki Underpass (TU-1, TU-2, TU-3 and TU-4)

The Tariki Underpass sections are located 17.4 km east from the present-day summit of Egmont Volcano at the junction of Johns Road and SH3 (Figure 69). At this site four measured sections (Figure 71), and sampling for EMP analysis and grain size/shape analysis was carried out.

Figure 69: Aerial photograph showing the location of sections TU-1, TU-2, TU-3 and TU-4. Photo courtesy of Taranaki Regional Explorer (2014).

Figure 70: Stratigraphy of sections TU-1, TU-2, TU-3 and TU-4.

6.1. Stratigraphy

The Tariki Underpass location exposes three distinct and stratigraphically variable sections (Appendix A) - TU-1 & 2, TU-3 and TU-4 (Figure 69).

Southern Sections (TU-1 and TU-2)

The southern TU-1 and TU-2 sections expose three cm-scale pumiceous lapilli beds with interbedded massive, dark brown, sandy/silty loam soils (TU-2, Units 1, 3 & 5) (Figure 71). The first lapilli bed (TU-1, Unit 2; TU-2, Unit 2) is a <0.07m thick, massive, faintly normally graded, fine to coarse pumiceous lapilli in a coarse pumiceous sandy ash matrix. The second lapilli bed (TU-1, Unit 4; TU-2, Unit 4) is a <0.07m thick, massive, fine to coarse pumiceous lapilli and few pale grey fine to medium lithic lapilli in a dark brown silt/sand ash matrix. The third lapilli bed (TU-1, Unit 6; TU-2, Unit 6) is a <0.05m thick, massive, fine to coarse pumiceous lapilli.

Overlying the basal pumiceous lapilli sequence is a <0.04m thick, massive, well sorted silt with organic fragments (TU-1, Unit 7; TU-2, Unit 7) overlain by a 0.1m thick, massive, fine sand with few pumiceous clasts and rip-ups of the underlying silt (TU-2, Unit 8).

Approximately 1.0m along section from TU-1, the <0.04m thick silt unit (TU-1, Unit 7) becomes deformed, forming convolute dewatering structures (Figure 71). Units 7 & 8 at section TU-2 is overlain by a <0.02m thick, massive silt (TU-2, Unit 9) and a <0.7m thick, mm- to cm-scale stratified and channelised, fine to coarse sand with rare, medium pumiceous clasts (TU-2, Unit 10). Approximately 2.0m along section from TU-1, the stratified sandy unit erodes down into the underlying sand units and pumiceous lapilli beds (TU-2, Units 1 to 9).

Overlying the stratified sandy unit (TU-2, Unit 10) is a <0.05m thick, massive, fine to medium sand vertically grading to silt (TU-2, Unit 11). This laterally transforms along section to massive, dark brown, organic rich sand with preserved leaf litter (TU-1, Unit 10) (Figure 72). This is overlain by a <0.5m thick, channelised lower to laminated upper, fine to coarse sand (TU-2, Unit 12). This unit exhibits sharp erosional scour features and silt rip-ups at the basal contact, flame dewatering structures within the lower part of the unit and vertically grades to a <0.03m thick, massive, fine sandy silt (TU-2, Unit 13) (Figure 73). This silt unit is overlain

by a <0.1m thick, massive, medium sand with few pumiceous clasts (TU-2, Unit 14) vertically grading to a <0.2m thick, massive, abundant fine to coarse pumiceous clasts in a medium to coarse sand matrix (TU-2, Unit 15). The top of the sections comprise stratified and channelised, fine to coarse sand with some pebbles (TU-2, Unit 16).

Figure 71 (Above): Photograph showing the basal pumiceous lapilli sequence at section TU-1 with relevant lithostratigraphic units described in Appendix A. Note the overlying deposits incised into the lapilli sequence. Photo courtesy of A/Prof Brent Alloway.

Figure 72 (Right): Photograph showing the organic-rich sand unit at section TU-1. Photo courtesy of A/Prof Brent Alloway.

Figure 73 (Left): Photograph showing the stratified sandy units overlying the basal pumiceous lapilli sequence at section TU-2 with relevant lithostratigraphic units described in Appendix A. Photo courtesy of A/Prof Brent Alloway.

Central Section (TU-3)

The central TU-3 section exposes a <1.0m thick, faintly mm-to-cm scale stratified, poorly sorted, fine to coarse sand with some sub-angular to sub-rounded pebbles with rare boulders and wood fragments (TU-3, Unit 1). This is overlain by a <1.2m thick, massive, monolithologic, poorly sorted, fine to coarse pebbles and cobbles matrix supported in fine to coarse sand (TU-3, Unit 2) vertically grading to a 4.0m thick, massive to faintly stratified, medium to coarse sand with some fine to medium pebbles and few boulders (TU-3, Unit 3). The top of the section is marked by the modern topsoil (TU-3, Unit 4) formed following the cutting and construction of the existing batter slopes.

Northern Section (TU-4)

The northern TU-4 section exposes a >0.1m thick, low angle cross-stratified, fine to coarse sand (TU-4, Unit 1) overlain by 0.02m thick, massive silt with fibrous organic material (TU-4, Unit 2) (Figure 74). Above this is a 0.1m thick, massive, medium to coarse sand with some coarse to very coarse pumiceous lapilli (TU-4, Unit 3) overlain by a 0.1m thick, faintly stratified, fine to medium sand grading to fine to coarse sand (TU-2, Unit 4). Unconformably overlying the sandy unit is a massive, fine to coarse sandy, fine to medium pebbles with the upper boundary marked by a 0.02m thick, massive, silt (TU-4, Unit 5). Above this a 1.3m thick, massive, fine to medium sand with fine to coarse pebbles, some cobbles and boulders vertically grades to faintly cross-stratified, fine to medium sand (TU-4, Unit 6). The top of this unit is marked by massive silt.

Above the lower sandy units, TU-4 exposes a sequence of three cm-to-dm thick, basaltic, scoriaceous lapilli beds (TU-4, Units 8, 10 & 12) (Figure 74). The base of the sequence is marked by a <0.1m thick, massive, sandy silty soil (TU-4, Unit 7) overlain by the first 0.03m thick lapilli bed (TU-4, Unit 8) comprised of massive, fine basaltic, scoriaceous lapilli. Overlying this is a <0.1m thick, massive, fine to medium sandy soil (TU-4, Unit 9) and the second 0.15m thick, massive, fine, basaltic, scoriaceous lapilli (TU-4, Unit 10). The third lapilli bed (TU-4, Unit 12) is a <0.2m thick, massive, normally graded, fine to medium basaltic, scoriaceous lapilli with the upper 0.02m marked by an orange iron pan. The third lapilli is subsequently overlain by a <0.15m thick, massive, fine sandy silt with lenses of clay (TU-4, Unit 13) then unconformably overlain by a >1.1m thick, massive, matrix supported, fine to

coarse sand with fine to coarse pebbles, some cobbles and boulders (TU-4, Unit 14). The lower 0.2m has rip-ups of silt with fibrous organics.

Figure 74 (Left): Photograph showing the three basaltic, scoriaceous lapilli beds overlying pebbly sand basal deposits at TU-4 with relevant lithostratigraphic units described in Appendix A.

6.2. Tephrochronology

Glass shards of the three pumiceous lapilli beds at the base of TU-1 were analysed for major element composition and then correlated with the reference tephra dataset (Section B1, Appendix B) and stratigraphic logs published in Alloway et al (1995). Major element glass analyses from the first pumiceous lapilli bed (TU-1, TS-12) and second pumiceous lapilli bed (TU-1, TS-11) correlate with the lower and upper subunits (Inglewood.a and b, respectively) of Inglewood Tephra dated at c. 3,600 ^{14}C yrs B.P (Alloway et al., 1995). The three basaltic, scoriaceous lapilli beds (TU-4, Units 8, 10 & 12) stratigraphically correlate with the Manganui.a, Manganui, b and Manganui,c subunits of the Manganui Tephra dated at c. 3,100 ^{14}C yrs B.P (Section 1: Alloway et al., 1995).

6.3. Sedimentology

Sample TU2-S1 (TU-2, Unit 10) exhibits a single modal peak at 2.0ϕ to 2.5ϕ , with a mean of 2.16ϕ . The sample is poorly sorted ($S.D = 1.20\phi$), strongly fine skewed ($SK_t = 0.70$) and has a fine constituent of $6.89\text{wt}\% < 4\phi$. Sample TU2-S2 (TU-2, Unit 11) taken from the thin, fine sandy silt unit exhibits an asymmetric, single modal peak at 4.0ϕ , with a mean of 4.49ϕ . The sample is poorly sorted ($S.D = 1.49\phi$), strongly fine skewed ($SK_t = 0.99$) and has a fine constituent of $53.97\text{wt}\% < 4\phi$. Sample TU2-S3 (TU-2, Unit 12) exhibits a well-defined, single modal peak at 2.0ϕ and has a mean of 2.02ϕ . The sample is poorly sorted ($S.D = 1.29\phi$), strongly fine skewed ($SK_t = 0.65$) and has a fine constituent of $7.90\text{wt}\% < 4\phi$. This sandy unit vertically grades to a pumice and sand unit where sample TU2-S4 (TU-2, Unit 15) exhibits a bimodal distribution with peaks at -4.5ϕ and 2.0ϕ , and a mean of -0.31ϕ . The sample is very poorly sorted ($S.D = 3.02\phi$), strongly fine skewed ($SK_t = 2.55$) and has a fine constituent of $5.38\text{wt}\% < 4\phi$. Sample TU2-S5 from the upper most unit (TU-2, Unit 16) exhibits a single, broad modal peak at 1.0ϕ and has a mean of 1.44ϕ . The sample is poorly sorted ($S.D = 1.33\phi$), strongly fine skewed ($SK_t = 0.71$) and has a fine constituent of $5.26\text{wt}\% < 4\phi$.

6.4. Interpretation

Southern Sections (TU-1 and TU-2)

The first basal pumiceous lapilli bed (TU-2, Unit 2) is interpreted to be the Korito Tephra (c. 4,100 ^{14}C yrs B.P) based on stratigraphic position. The overlying second and third lapilli beds (TU-2, Unit 4 & 6) are interpreted to be the Inglewood.a and Inglewood.b subunits of the Inglewood Tephra (c. 3,600 ^{14}C yrs B.P) (Figure 75) based on stratigraphic interpretation and geochemical composition. This is overlain by a massive, organic rich silt unit (TU-2, Unit 7) interpreted to be a sole layer deposited by the wave of alluvial water pushed in front of the head of the debris/hyperconcentrated-flow. This is overlain by a massive, fine sand unit with few fine pumice clasts (TU-2, Unit 8). This unit has an erosional lower contact with rip-ups of the underlying sole layer. Above this is a second massive silt unit (TU-2, Unit 9) interpreted to be another sole layer (Figure 75).

Figure 75: Interpretation of the lithostratigraphic units (Figure 73) at section TU-2. This section exposes sandy hyperconcentrated-flow deposits of the Ngatoro Formation overlying the Korito Tephra, and the Inglewood.a and Inglewood.b subunits. Note the three interbedded sole layers.

Figure 76: Interpretation of the lithostratigraphic units (Figure 71) at section TU-1. This section exposes load deformation of the sole layer and the incised hyperconcentrated-flow deposits of the Ngatoro Formation in to the basal lapilli. Photo courtesy of A/Prof Brent Alloway.

The overlying <0.7m thick sequence of stratified and channelised fine to coarse sand unit (TU-2, Unit 10) interpreted to be hyperconcentrated-flow deposits of the Ngatoro Formation. The deposition of this unit resulted in the deformation of the underlying sole layers forming convolute dewatering structures and the erosion of the underlying basal pumiceous lapilli beds (Figure 77). Above the hyperconcentrated-flow deposits, the massive, normally graded fine to medium sand to silt unit (TU-2, Unit 11) is interpreted to be a third sole layer which laterally transforms to an organic rich, sandy paleosol (TU-1, Unit 10). The overlying channelised to laminated fine to coarse sand unit (TU-2, Unit 12) is interpreted to be a sequence of debris-flow deposits vertically grading to laminated hyperconcentrated flow deposits. This unit has rip-ups of the underlying sole layer and flame dewatering structures (Figure 77) which develop as the flow transitions from a single phase debris flow to the two

phased hyperconcentrated flow phase. This unit vertically grades to a massive, fine sandy silt unit (TU-2, Unit 13) interpreted to be a fourth sole layer.

The overlying, laterally discontinuous accumulation of pumice clast in a medium to coarse sand matrix (TU-2, Units 14 & 15) are interpreted to be a pumice “train” deposited on the margins of the mass flow. This is subsequently overlain by stratified and channelised, fine to coarse sand with few pebbles (TU-2, Unit 16) interpreted to be hyperconcentrated flow deposits.

Figure 77: Photograph showing the flame dewatering structures in the hyperconcentrated flow deposits at section TU-1. Photo courtesy of A/Prof Brent Alloway.

Central Section (TU-3)

The lower faintly stratified, fine to coarse sandy unit with pebbles and rare boulders (TU-3, Unit 1) is interpreted to hyperconcentrated flow deposits based on the stratification formed indicative of a flow with a solid and fluid phase. This is unconformably overlain by a massive matrix supported pebble and cobble unit (TU-3, Unit 2) interpreted to be a debris flow deposit. This unit vertically grades to a massive to faintly stratified, medium to coarse sand

unit with some gravel and few boulders (TU-3, Unit 4) is interpreted to be a hyperconcentrated flow deposit with its upper contact forming the modern day topsoil (TU-3, Unit 4).

Northern Section (TU-4)

The low angle cross-stratified, fine to coarse sand unit (TU-4, Unit 1) at the base of the section is interpreted to be a hyperconcentrated flow deposit overlain by a massive silt with some fine sand and fibrous organics (TU-4, Unit 2) interpreted to be a basal sole layer. Above this, a massive, medium to coarse sand unit with some pumiceous lapilli (TU-4, Unit 3) interpreted to be a debris flow deposit is unconformably overlain by faintly stratified sandy (TU-4) hyperconcentrated flow deposits. Overlying this is a massive, sandy pebble unit (TU-4, Unit 5) interpreted to a debris flow deposit with an upper contact marked by a second massive, silt sole layer.

Overlying the second sole layer is a 1.3m thick, massive lower to stratified upper, fine to medium sand unit with common pebbles, some cobbles and few boulders (TU-4, Unit 6). This is interpreted to be a massive debris flow deposit vertically grading to stratified hyperconcentrated flow deposits. This is overlain by a sequence of three basaltic, scoriaceous lapilli beds (TU-4, Units 8, 10 & 12) with interbedded silty, fine to medium sandy soils (TU-4, Units 7 & 9) (Figure 78). The lapilli beds are interpreted to be the Manganui.a, Manganui.b and Manganui.c subunits of the Manganui Tephra (c. 3,100 ¹⁴C yrs B.P) based on stratigraphic interpretation and field descriptions. These soils indicate a period of stability in the landscape between the Manganui.a and Manganui.b eruptive events. Above the Manganui.c lapilli is massive, fine sandy silt paleosol with lenses of clay (TU-4, Unit 13). This indicates a period of time between the Manganui.c eruptive event and the emplacement of the overlying massive, pebble, cobble and boulder unit (TU-4, Unit 14) interpreted to be a debris flow deposit.

The complex stratigraphic relationships between the stratigraphic sections at the Tariki Underpass makes correlation between stratigraphic units complicated. However the hyperconcentrated flow deposits (TU-2, Unit 10; TU-1, Unit 9) incising into the underlying basal lapilli beds indicates that an erosional channel is observed at this location with TU1

and TU-2 indicating the southern margin, TU-3 indicating the axis and TU-4 indicating the northern margin of the mass flow channel.

Figure 78: Interpretation of the lithostratigraphic units (Figure 74) at section TU-4. This section exposes the Manganui.a, Manganui.b and Manganui.c subunits overlying hyperconcentrated flow deposits of the Ngatoro Formation.

7. Suffolk Road Junction (SF-1)

The Suffolk Road section is located 22.8 km north-east from the present-day summit of Egmont Volcano near the Waitepuke Stream Bridge (Figure 79). At this site one measured section (Figure 80) and sampling for EMP analysis was carried out.

Figure 79 (Right): Aerial photograph showing the location of section SF-1.
Photo courtesy of Taranaki Regional Explorer (2014).

Figure 80: Stratigraphy of section SF-1.

Figure 81: Photograph of section SF-1 with relevant lithostratigraphic units described in Appendix A.

7.1. Stratigraphy

The stratigraphy described at Suffolk Road section (Appendix A) comprises >1.0m thick sand and pebbly sand deposits overlying a basal pumiceous lapilli sequence (Figure 81). The SF-1 section exposes two laterally continuous, cm-scale pumiceous lapilli beds overlying >0.3 thick massive, firm, friable fine to medium sand and silt. The first pumiceous lapilli bed (SF-1, Unit 1) is a <0.5m thick, massive, firm and friable, fine to medium sand and silt with fine to coarse pumiceous lapilli and few lithic lapilli concentrated at the upper boundary. The second lapilli bed (SF-1, Unit 2) is a ≤0.1m thick, massive, fine to coarse pumiceous lapilli with few fine to coarse lithic lapilli.

The basal tephra sequence is overlain by a lower unit comprising massive, fine sand that laterally pinches and swells (SF-1, Unit 3) (Figure 81). This is subsequently overlain by massive, fine to coarse sand with few pebbles grading to laminated, medium sand (SF-1, Unit 4) and channelised, fine to coarse sand with pumiceous and lithic clasts in the channels (SF-1, Unit 5). The lower unit is overlain by massive, fine to coarse sand with some fine to medium pebbles grading to channelised, stratified, fine to medium sand (SF-1, Unit 6). The top of the section is marked by massive, loamy fine sand (SF-1, Unit 7).

7.2. Tephrochronology

Glass shards of the two pumiceous lapilli beds and entrained pumice clasts from SF-1 were analysed for major element composition and then correlated with the reference tephra dataset (Section B1, Appendix B) and stratigraphic logs published in Alloway et al., (1995). Major element glass composition from the first pumiceous lapilli bed (SF-1, TS-7) is indistinguishable from the Korito Tephra (c. 4,100 ¹⁴C yrs B.P). The second lapilli bed (SF-1, TS-8) correlates with the Inglewood Tephra (c. 3,600 ¹⁴C yrs B.P).

Pumice clasts sampled from within Unit 6 (SF-1, TS-9) have a broader range of major element compositions but are generally indistinguishable from the Inglewood Tephra (c. 3,600 ¹⁴C yrs B.P). Pumice clasts sampled from within the soil in Unit 7 at the top of the section (SF-1, TS-10) has a well constrained major element composition indistinguishable from the Burrell Lapilli (A.D. 1655).

7.3. Interpretation

The first basal pumiceous lapilli bed (SF-1, Unit 1) is interpreted to be the Korito Tephra (c. 4,100 ^{14}C yrs B.P) based on stratigraphic interpretation and geochemical composition. The vertical accumulation of pumiceous lapilli within the laterally continuous lapilli bed is most likely an in-filled tree root or a localised depression in the paleotopography. The second basal pumiceous lapilli bed (SF-1, Unit 2) is interpreted to be a distal deposit of the Inglewood Tephra (c. 3,600 ^{14}C yrs B.P). At these distal distances the Inglewood.a and Inglewood.b subunits have been described as merging into a single lapilli bed (Alloway et al., 1995). A thin bed of reddish brown andic soil separates the Korito and Inglewood Tephra distinguishing the eruptive events both stratigraphically and temporally. Constrained by the basal tephra (Figure 83), the overlying deposits are interpreted to have a maximum age of c. 3,600 ^{14}C yrs B.P.

The <0.05m thick, fine sand bed (SF-1, Unit 3) is interpreted to be a fine grained sole layer deposited by the wave of alluvial water pushed in front of the head of the debris/hyperconcentrated flow. The overlying lower sandy deposits (SF-1, Unit 4) are interpreted to be an erosional cut and fill debris flow deposit vertically grading to laminated hyperconcentrated stream flow deposits indicating a transition from en masse sediment deposition to grain by grain deposition from a solid and liquid phased flow. The overlying massive, poorly sorted, pebbly sand (SF-1, Unit 5) is interpreted to be a fine textured distal debris flow deposit vertically grading to channelised to laminated hyperconcentrated flow deposits (SF-1, Unit 6). The basal Inglewood Tephra, and entrained pumice clasts sourced from the Inglewood Tephra, indicates that Units 3 to 6 are distal deposits of the Ngatoro Formation (Figure 82). The pumice clasts within the soil at the top of the section (SF-1, Unit 7) geochemically correlated with the Burrell Lapilli gives a minimum age of the underlying deposits of 1600 A.D. When compared to the reference stratigraphy (Alloway et al., 1995) several tephra were not identified at the Suffolk Road section (eg. Manganui and Maketawa Tephra). This could be due to deposition then subsequent erosion or that these distal tephra have been dispersed by biological agents (vegetation and/or invertebrate insects) in the andic soil coverbeds and are no longer recognisable as discrete layers.

Figure 82: Interpretation of the lithostratigraphic units (Figure 81) at section SF-1. This section exposes sandy hyperconcentrated flow and pebbly sand debris flow deposits of the Ngatoro Formation overlying the Korito and Inglewood Tephra.

8. Kaimata Sawmills (MG-1)

The Kaimata Sawmills section is located 23.8 km north-east from the present-day summit of Egmont Volcano on the banks of the Manganui River (Figure 83). At this site one measured section (Figure 84), and sampling for EMP analysis and grain size analysis was carried out.

Figure 83 (Right): Aerial photograph showing the location of section MG-1. Photo courtesy of Taranaki Regional Explorer (2014).

Figure 84: Stratigraphy of section MG-1.

Figure 85: Photograph of section MG-1 with relevant lithostratigraphic units described in Appendix A.

8.1. Stratigraphy

The stratigraphy described at Kaimata Sawmills section (Appendix A) comprises >1.5m thick sand and pebbly sand deposits overlying a basal pumiceous lapilli sequence (Figure 85). The MG-1 section exposes two cm-scale, pumiceous lapilli beds (MG-1, Units 1 & 3) separated by a <0.05m thick, massive, loamy silt (MG-1, Unit 2) (Figure 86). The lower lapilli bed (MG-1, Unit 1) is a <0.1m thick, massive, fine to coarse pumiceous lapilli and very fine to fine lithic lapilli in an ash matrix. The second lapilli bed (MG-1, Unit 3) is a ≤ 0.05 m thick, massive, fine to coarse pumiceous lapilli and few fine lithic lapilli in a fine ash matrix.

These pumiceous lapilli beds are overlain by a <0.05m thick, massive, fine sand and silt vertically grading to silt (MG-1, Unit 4) (Figure 86). This is subsequently overlain by a 0.7m thick sequence of alternating channelised, fine to coarse sand and very fine to fine sand vertically grading to laminated, fine to very coarse sand (MG-1, Unit 5). The lower sandy deposits are overlain by a 1.0m thick unit (MG-1, Unit 6) comprising massive, medium to coarse sand with few pebbles vertically grading to massive, medium to coarse sandy pebble deposits and fine to very coarse sand. This unit is gradationally overlain by massive, friable, fine to very coarse sand (MG-1, Unit 7).

Figure 86: Photograph showing the basal pumiceous lapilli sequence at section MG-1 with relevant lithostratigraphic units described in Appendix A.

8.2. Tephrochronology

Glass shards of the two basal lapilli beds at the base and three samples from within the sandy deposits at MG-1 were analysed for major element composition and then correlated with the reference tephra dataset (Section B1, Appendix B) and stratigraphic logs published by Alloway et al., (1995). Major element glass analysis from the first pumiceous lapilli bed (MG-1, TS-4) is indistinguishable from those determined for the Korito Tephra (c. 4,100 ^{14}C yrs B.P). The second lapilli bed (MG-1, TS-3) can be geochemically correlated with the Inglewood Tephra (c. 3,600 ^{14}C yrs B.P). Pumice clasts sampled from the basal silt layer, Unit 4 (MG-1, TS-2) and lower unit sandy deposits, Unit 5 (MG-1, TS-1) can be geochemically correlated with the underlying Inglewood Tephra. Pumice clasts sampled from the upper fine to very coarse sandy deposits, Unit 7 (MG-1, TS-5) has a broader major elemental composition but can be correlated with the underlying Inglewood Tephra (c. 3,600 ^{14}C yrs B.P).

8.3. Sedimentology

Sample MG-S1 (MG-1, Unit 4) exhibits a single modal peak at 3.0ϕ and has a mean of 3.23ϕ . The sample is poorly sorted ($S.D = 1.41\phi$), strongly fine skewed ($SK_t = 0.82$) and has a fine constituent of $20.17\text{wt}\% < 4\phi$. Sample MG-S2 taken from the first sand and pebbly sand unit (MG-1, Unit 5) exhibits a broad, single modal peak from 1.0ϕ to 2.0ϕ and has a mean of 1.53ϕ . The sample is poorly sorted ($S.D = 1.59\phi$), strongly fine skewed ($SK_t = 0.62$) and has a fine constituent of $7.69\text{wt}\% < 4\phi$. Sample MG-S3 (MG-1, Unit 6) exhibits a broad, single modal peak at 1.0ϕ with a mean of 0.96ϕ . The sample is very poorly sorted ($S.D = 2.01\phi$), strongly fine skewed ($SK_t = 0.64$) and has a fine constituent of $6.93\text{wt}\% < 4\phi$. This vertically grades to sample MG-S4 (MG-1, Top of Unit 6) which exhibits a bimodal distribution with peaks at -2.5ϕ and 1.0ϕ , and a mean of -0.24ϕ . The sample is very poorly sorted ($S.D = 2.50\phi$), strongly fine skewed ($SK_t = 1.17$) and has a fine constituent of $4.79\text{wt}\% < 4\phi$. Sample MG-S5 taken from the top of the section (MG-1, Unit 7) exhibits a well-defined, single modal peak at 2.5ϕ and has a mean of 1.10ϕ . The sample is poorly sorted ($S.D = 1.40\phi$), strongly fine skewed ($SK_t = 0.80$) and has a fine constituent of $4.12\text{wt}\% < 4\phi$.

8.4. Interpretation

The two basal pumiceous lapilli beds (MG-1, Unit 1 & 3) are correlated with Korito Tephra (c. 4,100 ¹⁴C yrs B.P) and Inglewood Tephra (c. 3,600 ¹⁴C yrs B.P) based on stratigraphic association and confirmed by the reference dataset (Section B1, Appendix B). The interbedded loamy silt represents a period of andic soil formation and site stability. The basal pumiceous lapilli beds constrain the base of section (MG-1) to a maximum age of c.3,600 ¹⁴C yrs B.P. with the overlying Units 5, 6 and 7 being interpreted as the Ngatoro Formation.

The base of the Ngatoro Formation is marked by massive, fine sandy silt (MG-1, Unit 4) unconformably overlying the Inglewood Tephra. This unit is interpreted to be a basal sole layer deposited by the wave of alluvial water pushed in front of the head of the debris/hyperconcentrated flow. The lowermost sandy deposits of the Ngatoro Formation (MG-1, Unit 5) are interpreted to be hyperconcentrated flow deposits based on the cut and fill, and laminated sedimentary structures within the fine grained sandy deposit indicative of flows with both a solid and fluid phase. The vertical transition from cut and fill structures to laminations indicate transformation to a higher flow regime. The overlying units 6 & 7 are interpreted to be distal debris flow deposits with a dominantly massive, sandy texture.

Figure 87: Interpretation of the lithostratigraphic units (Figure 86) at section MG-1. This section exposes hyperconcentrated flow and debris flow deposits.

9. Palaeomagnetic Analysis

The following section presents the results of the magnetic susceptibility and thermal demagnetisation studies carried out on andesite clasts sampled at Vickers Quarry and Surry Road Quarry.

- Preliminary Investigation (VQ-1, Unit 6)
- Main Lower Unit Investigation (VQ-1, Unit 6 and SQ-1, Unit 1)
- Preliminary Upper Unit Investigation (VQ-1, Unit 12)

This includes identification and calculation of distinct components of natural remanent magnetisation (NRM) by principal component analysis (PCA) of progressive specimen demagnetisation data, averaging these components by clast and estimation of emplacement temperatures. Full specimen analysis with relevant Zijderveld plots and plots of magnetisation intensity versus temperature are presented in Appendix D.

9.1. Preliminary Investigation

The preliminary alternating field demagnetisation investigations show the andesite clasts having a strong, stable remanent magnetisation suitable for palaeomagnetic studies, with intensities ranging from 5.43 to 9.28A/m. Throughout the demagnetisation, specimen VQ2-3C exhibits a north east ($D = 66.0^\circ$) and downward ($I = 20.8^\circ$) trending component of magnetisation with a Maximum Angular Deviation (MAD) of 2.0° (Figure 88). Specimens VQ3-1C and VQ3-2B exhibit a north and downward component. All three specimens showed a slight deviance from the ChRM at low field strength demagnetisation steps (NRM and 5mT) but this can be attributed to a viscous component rather than a secondary component of magnetisation formed during emplacement. These results (being alternating field demagnetisation) do not give any direct indication of thermal history or emplacement temperature, but they do suggest a simple emplacement history.

● Figure 88: Zijderveld diagram and magnetic intensity plots showing the demagnetisation of specimen VQ2-3C. The specimen exhibits a single component of magnetisation.

9.2. Main Lower Unit Investigation (S3, S4, S5, S7, S10, S11, S12 & S14)

9.2.1. Magnetic Susceptibility

The magnetic susceptibility with temperature measurements indicate that the ferrimagnetic minerals in the sample (S10.3, S11.2 and S12.1) lose their magnetic susceptibility by 550°C suggesting curie temperatures in the order of 550°C and a composition within the titanomagnetite series (20% Fe₃O₄ to 80% Fe₂TiO₄) (Butler, 2004). The results of temperature susceptibility analysis are presented in Section D1, Appendix D.

The room temperature magnetic susceptibility results cluster into four distinct susceptibility groups centred around 0.065-0.1 SI, 0.06 SI, 0.4 SI and 0.002 SI (Figure 89). Although there is a range between specimens, there are no significant changes in room temperature magnetic susceptibility over the thermal demagnetisation temperature range (0-550°C). This suggests no major thermally induced alteration of the ferrimagnetic minerals during the demagnetisation and a Curie temperature (T_c) higher than 550°C. The range in magnetic susceptibility between specimens could be attributed to varying concentrations of titanomagnetite, however the high Curie temperature (>550°C) suggests a dominantly low titanium (Ti) content with compositions close to magnetite. Clast S12 has the lowest susceptibility and also is the most mafic clast sampled; dark grey in colour rather than light grey.

Figure 89: Room temperature magnetic susceptibility versus temperature plot for the main lower unit investigations specimens. Specimens plots are distinguished by colour based on clast.

9.2.2. Palaeomagnetic Directions

Specimens sampled exhibit strong and stable remanent magnetisations, with NRM intensities ranging from 1.07 to 10.6 A/m. During thermal demagnetisation 90% of the NRM was generally removed after the 550°C step. The NRM intensity decreased with each temperature step in two main ways (Figure 90) – Specimens from clasts S3, S4 and S15 exhibited an almost linear decrease in intensity with temperature whereas specimens from clasts S5, S7, S10, S11 and S12 only lost 30-40% of their TRM intensity up to 450-500°C before decreasing rapidly by the final 550°C heating step. The former, more linear (un)blocking temperature spectrum could be attributed to a greater range of ferrimagnetic grain size.

Figure 90: Remanent magnetisation intensity versus temperature plots showing examples of a gradual, almost linear loss in intensity (S3.3A) and a relatively stable intensity before a rapid loss at 450°C (S10.3A).

Principal component analysis (PCA) was carried out on the demagnetisation data of thirty two specimens to identify components of magnetisation carried in different intervals of the blocking temperature spectrum. The suite of specimens predominantly exhibits a well-defined C_i and C_h component. The C_i components have MAD's ranging from 2.2° to 10.3° and the C_c components have MAD's ranging from 0.4° to 4.7°. This is exhibited by twenty of thirty two specimens. Demagnetisation data of typical specimens are shown in figure 91 and discussed below:

- S3.3A has an NRM intensity of 2.48 A/m. It has a C_i component in a north-easterly and downward direction (declination, $D = 17.1^\circ$, inclination, $I = -51.9^\circ$, intensity of remanence analysed by PCA = 0.42A/m), isolated between 50 and 200°C, and a C_h

component in a more easterly and shallower direction ($D = 79.3^{\circ}$, $I = -19.6^{\circ}$, intensity = 1.82A/m) isolated between 200 and 550°C . Overall the remanence exhibits a near linear decrease with temperature.

- S4.3C has an NRM intensity of 2.59 A/m . It has a C_i component in a north-westerly and downward direction ($D = 312.3^{\circ}$, $I = -64.1^{\circ}$, intensity of remanence analysed by PCA = 0.64A/m), isolated between 50 and 200°C , and a C_h component in a south-westerly and steeper direction ($D = 213.1^{\circ}$, $I = -73.5^{\circ}$, intensity = 1.69A/m) isolated between 250 and 550°C . Overall the remanence exhibits a near linear decrease with temperature, except for the 350 and 400°C steps where it remains stable.
- S7.1A has an NRM intensity of 9.81A/m . It has a C_i component in a south-westerly and downward direction ($D = 231.7^{\circ}$, $I = -64.4^{\circ}$, intensity of remanence analysed by PCA = 0.99A/m), isolated between 50 and 250°C , and a C_h component in a southerly and upwards direction ($D = 164.0^{\circ}$, $I = 39.5^{\circ}$, intensity = 9.35A/m) isolated between 300 and 550°C . The overall remanence remains stable until 450°C , after which 90% has been removed by 550°C .
- S15.3A has an NRM intensity of 2.68A/m . It has a C_i component in a westerly and downward direction ($D = 291.0^{\circ}$, $I = -73.3^{\circ}$, intensity of remanence analysed by PCA = 0.79A/m), isolated between 100 and 300°C , and a C_h component in a south-westerly and downward direction ($D = 225.0^{\circ}$, $I = -72.5^{\circ}$, intensity = 1.16A/m) isolated between 350 and 550°C . Overall the remanence exhibits a near linear decrease with temperature, except for the 500 and 550°C steps where it remains stable.

Figure 91: Lambert (equal area) stereoplots and Zijderfeld diagrams showing the predominant styles of behaviour of specimens during thermal demagnetisation

Some specimens exhibit behaviour which differs from this predominant behaviour. Eight of the thirty two specimens exhibit a poorly-defined C_i and a well-defined C_h component. The C_i components have Maximum Angular Deviations (MAD) ranging from 12.5° to 23.0° and the C_h components have MAD's ranging from 1.9° to 8.9° . Three of specimens sampled from clast S3 exhibit curvature between the C_i and C_h components. The curvature is attributed to the overlapping blocking temperature ranges of the two components. These include (Figure 92):

- S5.1A has an NRM intensity of 2.05 A/m. It has a C_i component in a north-westerly and downward direction (declination, $D = 348.4^\circ$, inclination, $I = -61.9^\circ$, intensity of remanence analysed by PCA = 0.11A/m), isolated between 50 and 200°C , and a C_h component in a more north-westerly and shallower direction ($D = 329^\circ$, $I = -5.2^\circ$, intensity = 1.62A/m) isolated between 300 and 550°C . The overall remanence remains stable until 300°C after which it exhibits a near-linear decrease with temperature until 85% is lost by the 550°C demagnetisation step.
- S11.1C has an NRM intensity of 1.15 A/m. It has a C_i component in a north-westerly and downward direction (declination, $D = 319.6^\circ$, inclination, $I = -66.5^\circ$, intensity of remanence analysed by PCA = 0.10A/m), isolated between 50 and 200°C , and a C_h component in a more south-westerly and shallower direction ($D = 214.2^\circ$, $I = -20.1^\circ$, intensity = 0.26A/m) isolated between 250 and 550°C . The overall remanence exhibits a near-linear decrease with temperature until 450°C after which it decreases rapidly with 90% lost by 550°C .
- S3.1A has an NRM intensity of 2.87A/m. It has a C_i component in a northerly and downward direction (declination, $D = 23.7^\circ$, inclination, $I = -57.2^\circ$, intensity of remanence analysed by PCA = 0.51A/m), isolated between 50 and 200°C , and a C_h component in a more easterly and shallower direction ($D = 80.9^\circ$, $I = -20.2^\circ$, intensity = 1.80A/m) isolated between 250 and 550°C . The overall remanence exhibits a near-linear decrease with temperature until 450°C after which it decreases rapidly with 85% lost by 550°C .

In most specimens there is a short interval of the blocking temperature spectrum between the removal of the C_i component and the clear isolation of the C_h component. In only a few specimens (e.g. S10.3A, Figure 92) is it possible to isolate and determine a

distinct component of remanence in this blocking temperature interval. However, the presence of such an intermediate interval suggests an intermediate stage in the thermal history of the clasts. This is thought to represent a time interval between the acquisition of the high and low blocking temperature components, during which the clasts were in a state of turbulent transport. This intermediate component is clearly seen in Figure 93:

- S10.3A has an NRM intensity of 8.34A/m. It has a C_i component in a south-easterly and upwards direction (declination, $D = 154.8^\circ$, inclination, $I = 15.7^\circ$, intensity of remanence analysed by PCA = 0.51A/m) isolated between 50 and 150°C, a C_i component in a south-westerly and downward direction ($D = 248.7^\circ$, $I = -16.6^\circ$, intensity of remanence analysed by PCA = 1.42A/m) isolated between 150 and 450°C, and a C_h component in a in a south-westerly and downward direction ($D = 216.1^\circ$, $I = -11.4^\circ$, intensity of remanence analysed by PCA = 3.22A/m) isolated between 450 and 550°C.

Figure 92: Lambert (equal area) stereoplots and Zijderveld diagrams showing the behaviour of specimens which differs from the predominant behaviour shown in Figure 91.

Of the thirty two specimens, S12.2A was excluded from the suite as it exhibited unstable behaviour during thermal demagnetisation - PCA did not identify any coherent component of magnetisation. Specimen S12.1A was only used in the analysis of high temperature components as it exhibits a well-defined high temperature component (C_h) but an undefined low temperature component (C_l).

The presence of two and in some cases three, components of magnetisation suggests that the thermal history of the clasts involves more than simply one cooling episode. This is more complicated than the preliminary alternating field demagnetisation investigation suggested. The directions of the C_h components show strong correlation between specimens within clasts but no correlation between clasts. The C_l components are generally less well-determined, but show some correlation, both within and between clast (Figure 93).

Figure 93: Lambert (equal area) stereoplots showing the low temperature (C_l) (left) and high temperature (C_h) (right) components of each specimen (top) and as a clast mean (bottom) – Clast S3 (yellow); S4 (black); S5 (purple); S7 (light blue); S10 (red); S11 (dark blue); S12 (green); and S15 (orange).

The lower quality of the C_I components of magnetisation can be attributed to (1) a low blocking temperature viscous component of magnetisation (VRM) overprinting the thermoremanent magnetisation (TRM) acquired during emplacement and/or (2) statistical limitations of analysis due to the small number of demagnetisation steps (generally ≤ 5) used to calculate the low temperature component of magnetisation.

- (1) VRM: Acquired gradually overtime, VRM is due to the relaxation of the ferrimagnetic moments of magnetic grains to align with the ambient field. The VRM is dependent on the relaxation of time of the magnetic grains, with the magnetic moments of any grains having a relaxation time (τ) shorter than the age of the deposit sampled tending to become unblocked and realigned with earth's modern geomagnetic field.
- (2) The maximum angular deviation (MAD) of a component is increased by both increased deviation of points from the calculated mean but also by reductions in points used in the calculation of the mean. With the low temperature component generally removed by 100°C to 300°C leaving minimal data points available to calculate a statistically reasonable low temperature component.

9.2.3. Thermal History

As previously discussed a modification of the conglomerate test is being used to decipher the thermal history and estimate the temperature at which clasts were deposited. This is considered the lowest temperature at which the T_h component has been removed. To estimate the temperature at which the whole deposit was emplaced Paterson et al (2010) recommends the equilibrium temperature method of Bardot and McClelland (2000). The equilibrium temperature is considered the lowest emplacement of the sampled clasts. This method however commonly underestimates true deposit temperature in thin deposits or where clasts at flow boundaries experience adverse cooling (Cioni et al, 2004).

Based on the behaviour of the specimens and the PCA I consider a single emplacement event does not adequately describe the variability in the palaeomagnetic demagnetisation data. This variability can be attributed to differing thermal histories, clast incorporation temperatures and time of deposition during the flow process. I have taken the approach of

determining separately, a mean incorporation and emplacement temperature based on the C_i and C_h components. The three temperature intervals and two remanence components identified in these specimens represent three stages of the clasts thermal history. These have been interpreted as the following (Figure 94):

Figure 94: Idealised illustration providing a visual representation of the high, intermediate and low temperature components of magnetisation.

- The lowest temperature at which the C_h component is preserved as an estimate of the temperature at which the clast was incorporated into the flow. The high temperature component is the component remaining from the parent rock's formation or a previous process which heated the clast above the Curie temperature of the magnetic minerals (c. 585⁰). This component has been removed from lower blocking temperature grains during the deposition of the Ngatoro Formation.
- The temperature range over which the randomly defined C_i component is preserved as an estimate of the clasts cooling during incorporation and transport. The component is poorly defined as it represents the clast cooling during transport within the flow from the time of its incorporation until emplacement.
- The highest temperature at which the C_l component is preserved as an estimate of the emplacement temperature of that clast. This is interpreted to be the temperature at which the clast became stationary within the flow deposit, resulting in a well-defined C_l component.

The emplacement temperature of the deposit is based on principal component analysis from 31 specimens representing 8 clasts from two locations. The stepwise thermal demagnetisation limits the maximum accuracy of any temperature estimate to the minimum demagnetisation step, which in this study is 50⁰C. The highest temperature at which the C_i component is preserved ranges from 100⁰C to 350⁰C (Table 8) and has a modal peak, mean and median of 200⁰C. The lowest temperature at which the C_h component is preserved ranges from 100⁰C to 450⁰C (Table 8) and has a modal peak, mean and median of 300⁰C. Based on these results, the Ngatoro Formation is considered to have a mean incorporation temperature estimate of 300⁰C and a mean emplacement temperature estimate of 200⁰C (Figure 95). The mean amount the clast cooled between incorporation and emplacement is estimated to be 80⁰C.

Main Lower Unit Investigation - Principal Component Analysis												
Specimen	Declination	Inclination	MAD	Intensity	Temperature	Declination	Inclination	MAD	Intensity	Range	Cl	Ch
S3.1A	23.7	-57.2	10.5	0.51	50-200	80.9	-20.2	2.7	1.83	250-550	200	250
S3.1D	24.3	-45.8	4.2	0.55	50-200	79.1	-28.3	2.3	2.75	250-550	200	250
S3.3A	17.1	-51.9	2.2	0.42	50-200	79.3	-19.6	2.6	1.82	200-550	200	200
S3.3C	21.4	-56.9	8	0.45	50-200	80	-23.1	1.4	2.25	250-550	200	250
S4.2A	28.3	-47.1	3.3	0.4	50-150	221.1	-73.7	4.9	1.65	200-550	150	200
S4.2C	46.4	-14.9	14.5	0.43	0-100	157.8	-82.8	6.3	1.89	200-550	100	200
S4.3A	160.3	-49	5.2	1.15	50-250	183.2	-69.5	4.5	1.36	300-550	250	300
S4.3C	312.3	-64.1	5.2	0.64	50-200	213.1	-73.5	3.7	1.69	250-550	200	250
S5.1A	348.4	-61.9	23	0.11	50-200	329	-5.2	3	1.62	300-550	200	300
S5.1B	285.3	-35.8	12.5	0.29	50-200	337.2	-2	6.4	1.59	300-550	200	300
S5.2A	82.9	18.2	12.8	0.23	50-250	330.4	-4.3	2.6	1.19	300-550	250	300
S5.2B	47.6	-3.1	8.4	0.28	50-200	332.7	-5.5	4.4	1.57	300-550	200	300
S7.1A	231.7	-64.4	5.8	0.99	50-250	164	39.5	1.6	9.35	300-550	250	300
S7.1C	330.9	57	4.4	1.09	50-200	178.4	45.3	2.3	9.07	400-550	200	400
S7.3A	191.3	-43.8	4.4	1.6	50-250	159.9	30.6	3.2	8.28	300-550	250	300
S7.3B	193.1	-56	5.5	1.02	50-200	160.5	26	4.6	9.09	250-550	200	250
S10.1A	212.3	-12.9	5.7	1.08	50-250	220.4	-13.5	2	7	300-550	250	300
S10.1B	269.6	-33	3.5	0.58	50-150	219.9	-10.3	1.1	7.37	300-550	150	300
S10.3A	154.8	15.7	5.6	0.51	50-150	216.1	-11.4	0.7	3.22	450-550	150	450
S10.3C	284.1	-28.5	5.8	0.36	50-150	218.8	-14.9	0.4	3.58	450-550	150	450
S11.1A	208.1	-73.9	16.7	0.13	50-150	215.8	-19.6	2.9	0.82	300-550	150	300
S11.1C	319.6	-66.5	17.8	0.1	50-200	214.2	-20.1	8.9	0.26	250-550	200	250
S11.2A	266	-15.4	7.2	0.21	50-200	221.4	-18.3	5.7	0.28	350-550	200	350
S11.2D	165.8	-62.2	13.4	0.25	50-250	227.9	-13.7	1.9	1	300-550	250	300
S12.1A	-	-	-	-	-	318.3	25.2	0.9	6.2	400-550	-	400
S12.1C	262.6	-16	19.5	0.85	50-350	314.9	23.8	2.1	6.48	400-550	350	400
S12.2A	-	-	-	-	-	-	-	-	-	-	-	-
S12.2B	267.7	-28.4	5.1	1.52	50-300	328.1	28.3	2.5	6.53	350-550	300	350
S15.1A	85.7	-31.3	-	0.39	50-100	215.1	-70.6	3.4	2.46	100-550	100	100
S15.1C	322.3	-69.5	2.9	0.57	50-200	183.1	-77.3	3.6	1.71	250-550	200	250
S15.3A	291	-73.3	10.3	0.79	100-300	225	-72.5	8.1	1.16	350-550	300	350
S15.3C	323.1	-58.5	3.2	0.47	0-200	191.5	-74.9	2.9	1.87	200-550	200	200

Specimen	Declination	Inclination	$\alpha 95$	Declination	Inclination	$\alpha 95$
S3	21.7	-53	6.5	79	-24	3.9
S4	44.3	-63.5	66.9	198.4	-78.8	15.2
S5	28.7	-35.9	127.6	331.5	-4.2	3.9
S7	219.9	-49.3	124.7	165.5	35.9	12.4
S10	230.5	-22.6	89.7	221.7	-12.2	3.7
S11	249.6	-66.5	50.3	220.7	-17.8	6.4
S12	-	-	-	319.9	26.2	9
S15	315.2	-67.8	15.5	192.6	-75.9	6.1
Mean	306.7	-78.7	36.5	-	-	-

Table 8: Table of the Principle Component Analysis (PCA) results for the main lower unit investigation. The table includes the C_l and C_h components with their declination, inclination and $\alpha 95$ angles.

Figure 95: Plot showing the incorporation and emplacement temperature estimates based on PCA outlined in Table 8.

9.3. Preliminary Upper Unit Investigation (S16, S17, S18 & S19)

9.3.1. Magnetic Susceptibility

The magnetic susceptibility with temperature measurements indicates that the ferrimagnetic minerals in the sample (S19.1) loses its magnetic susceptibility by 550°C suggesting a Curie temperatures in the order of 550°C and a composition within the titanomagnetite series (20% Fe₃O₄ to 80% Fe₂TiO₄) (Butler, 2004). The results of temperature susceptibility analysis are presented in Section D1, Appendix D.

The room temperature magnetic susceptibility results show no significant changes in susceptibility with demagnetisation temperature (Figure 96). The samples show a range from 0.03 SI to 0.09 SI and exhibit a ≈ 0.01 SI decrease in susceptibility above 400°C. These results suggest no major thermally induced alteration of the ferrimagnetic minerals. As with the Main Lower Unit investigation, the high Curie temperature ($>550^{\circ}\text{C}$) suggests a low titanium (Ti) content with compositions close to magnetite.

Figure 96: Room temperature magnetic susceptibility versus temperature plot for the preliminary upper unit investigations specimens. Specimens plots are distinguished by colour based on clast.

9.3.2. Palaeomagnetic Directions

The 16 specimens demagnetised from the upper unit exhibit strong, stable magnetisations with NRM intensities ranging from 1.31 to 2.27A/m. During thermal demagnetisation, 80-90% of the TRM was generally removed after the 550°C step and the NRM intensity generally decreasing with each demagnetisation step, however some specimens show small increases at certain demagnetisation temperature steps (Figure 97). Clasts S16 and S18 have

a stable NRM at low temperatures, only losing 20-40% of their TRM intensity prior to the 450°C demagnetisation step after which the intensity is rapidly lost with each temperature step (Figure 97). Clasts S17 gradually lose 10-20% of their NRM intensity by 300°C, after which the intensity decreases almost linearly until the 550°C demagnetisation step (Figure 97).

Figure 97: Remanent magnetisation intensity versus temperature plots showing demagnetisation behaviour exhibited by the specimens.

Figure 98 (below): Lambert (equal area) stereoplots and Zijderveld diagrams showing the predominant behaviour of specimens during thermal demagnetisation.

Principal component analysis (PCA) was carried out on sixteen specimens to identify high and/or low temperature components of magnetisation. The predominant behaviour of the suite of specimens is well-defined with a C_i and C_h component. The C_i components have MAD's ranging from 6° to 9.9° and T_h components have MAD's ranging from 0.5° to 9.9° (Figure 98):

- S16.1A has an NRM intensity of 1.45 A/m. It has a C_i component in a north-westerly and downward direction (declination, $D = 311.5^\circ$, inclination, $I = -30.8^\circ$, intensity of remanence analysed by PCA = 0.26A/m), isolated between 50 and 200°C , and a C_h component in a more north-easterly and steeper direction ($D = 32.5^\circ$, $I = -37.7^\circ$, intensity = 1.28A/m) isolated between 300 and 550°C . Overall the remanence exhibits an increase at the 250 and 300°C temperature intervals before rapidly decreasing with temperature after the 450°C temperature step.
- S19.3A has an NRM intensity of 2.27 A/m. It has a C_i component in an easterly and downward direction ($D = 115.1^\circ$, inclination, $I = -6.7^\circ$, intensity of remanence analysed by PCA = 0.49A/m), isolated between 50 and 200°C , and a C_h component in a more easterly and upward direction ($D = 82.5^\circ$, $I = 1.5^\circ$, intensity = 1.36A/m) isolated between 300 and 550°C . Overall the remanence exhibits a near linear decrease with temperature.

Some specimens do exhibit behaviour which differs from this predominant behaviour. Six of the 16 specimens exhibit a poorly-defined C_i but well-constrained C_h component. The C_i components have MAD's ranging from 9.6° to 17.1° and the C_h components have MAD's ranging from 0.5° to 3.9° . All sixteen of the specimens exhibit some form of C_i component, in most cases just a poorly-defined component occupying a blocking temperature interval of at least 50°C between the C_i and C_h components. Two of the specimen (S18.2B and S18.2C) exhibit well-defined C_i components with MAD's of 1.9° and 4.3° . Exceptions to the predominant behaviour include (Figure 99):

- S16.3A has an NRM intensity of 1.61 A/m. It has a C_i component in a north-westerly and downward direction (declination, $D = 286.1^\circ$, inclination, $I = -56.6^\circ$, intensity of remanence analysed by PCA = 0.31A/m), isolated between 50 and 200°C , and a C_h component in a more easterly and shallower direction ($D = 30.8^\circ$, $I = -37.7^\circ$,

intensity = 1.47A/m) isolated between 300 and 550°C. Overall the remanence exhibits an increase at the 250 and 300°C temperature intervals before rapidly decreasing with temperature after the 450°C temperature step.

- S17.1B has an NRM intensity of 2.08 A/m. It has a C_i component in a easterly and downward direction ($D = 72.2^\circ$, $I = -18.2^\circ$, intensity of remanence analysed by PCA = 0.16A/m), isolated between 50 and 150°C, and a C_h component in a more northerly and upward direction ($D = 30.0^\circ$, $I = 51.5^\circ$, intensity = 1.41A/m) isolated between 300 and 550°C. Overall the remanence remains stable until 100°C after which it exhibits a near linear decrease with temperature.
- S18.2B has an NRM intensity of 1.83A/m. It has a C_i component in a north-easterly and downwards direction (declination, $D = 39.4^\circ$, inclination, $I = -60.2^\circ$, intensity of remanence analysed by PCA = 0.27A/m) isolated between 50 and 150°C, a C_i component in a southerly and upward direction ($D = 197.9^\circ$, $I = 43.2^\circ$, intensity of remanence analysed by PCA = 0.48A/m) isolated between 300 and 450°C, and a C_h component in a in a south-easterly and upward direction ($D = 154.7^\circ$, $I = 46.0^\circ$, intensity of remanence analysed by PCA = 1.34A/m) isolated between 450 and 550°C.

As with the Lower Unit Investigation, the presence of two and in some cases three, components of magnetisation suggests that the clasts have a three stage thermal history. The C_h components show strong correlation between specimens within clasts but no correlation between clasts, where the C_i components show some correlation both within and between clast but is much less well-defined (Figure 100). The C_i component has a mean direction of 28.6° declination and -66.6° inclination with an $\alpha-95$ of 37.3° . It is most probably that this represents the ambient geomagnetic field at the time of emplacement (c. 3,600 ^{14}C yr B.P). There is no published palaeomagnetic data for this date from New Zealand, however one would expect a direction that deviates from that of a Geocentric Axial Dipole (GAD) field by no more than the generally accepted amplitude of secular variation i.e. declination of $0 \pm 15^\circ$ and an inclination of $58.5 \pm 15^\circ$. Despite the large $\alpha-95$, the mean C_i component is consistent with this.

Figure 99: Lambert (equal area) stereoplots and Zijderveld diagrams showing the behaviour of specimens which differs from the predominant behaviour shown in figure 98.

Figure 100: Stereoplots showing the low temperature (C_l) (left) and high temperature (C_h) (right) components of each specimen (top) and as a clast mean (bottom) – Clast S16 (orange); S17 (light blue); S18 (green); and S19 (black).

9.3.3. Thermal History

As with the Lower Unit Investigation, the thermal history of the deposit is based on principal component analysis from 16 specimens representing 4 clasts from Vickers Quarry. The stepwise thermal demagnetisation limits the maximum precision of any temperature estimate to the minimum demagnetisation step, which in this study is 50°C. As previously discussed a modification of the conglomerate test is being used to determine the temperature at which a clast was deposited. This is considered the lowest temperature at which the C_h component has been removed.

The temperature estimates are based of the method outline in the Lower Unit Investigation (Section 9.2.3) where an incorporation and emplacement temperature is estimated based on the C_l , C_i and C_h components. The highest temperature at which the C_l component is preserved ranges from 100°C to 200°C (Table 9) and has a modal peak of 200°C, mean of

Preliminary Upper Unit Investigation - Principal Component Analysis												
Specimen	Declination	Inclination	MAD	Intensity	Temperature	Declination	Inclination	MAD	Intensity	Temperature	Cl	Ch
S16.1A	311.50	-30.80	6.00	0.26	50-200	32.50	-37.70	2.80	1.28	300-550	200	300
S16.1B	23.90	-43.20	6.40	0.34	50-200	23.70	-39.10	1.70	1.43	250-550	200	250
S16.3A	286.10	-56.60	10.20	0.31	50-200	30.80	-37.70	2.50	1.47	300-550	200	300
S16.3B	1.90	-62.40	11.20	0.21	50-200	34.30	-35.10	2.40	1.43	300-550	200	300
S17.1B	72.20	-18.30	17.10	0.16	50-150	30.10	51.50	2.90	1.41	300-550	150	300
S17.1C	68.30	-41.80	7.80	0.53	50-150	30.90	45.50	3.20	0.98	250-550	150	250
S17.3B	118.40	-83.50	11.50	0.23	50-150	28.40	45.30	1.90	1.66	200-550	150	200
S17.3C	341.60	-60.60	11.80	0.22	50-200	32.40	49.20	3.90	1.27	300-550	200	300
S18.1A	348.10	-9.90	0.00	0.19	50-100	166.20	48.70	2.30	1.31	250-550	100	250
S18.1C	18.20	-30.50	9.60	0.35	50-200	158.70	50.40	0.50	2.02	350-550	200	350
S18.2B	39.40	-60.20	19.20	0.27	50-150	154.70	46.00	1.80	1.34	450-550	150	450
S18.2C	11.70	-74.30	6.00	0.27	50-150	161.90	52.00	4.30	1.17	300-550	150	300
S19.1A	216.80	-52.40	9.90	0.24	50-150	74.30	-3.00	3.50	0.85	350-550	150	350
S19.1B	113.30	-59.00	9.20	0.57	50-200	91.80	-3.50	7.30	1.54	300-550	200	300
S19.3A	115.10	-6.70	8.30	0.49	50-200	82.50	1.50	9.90	1.36	300-550	200	300
S19.3B	1.80	-68.50	0.00	0.15	50-100	81.10	2.90	1.50	1.40	300-550	100	300

Specimen	Declination	Inclination	$\alpha 95$	Declination	Inclination	$\alpha 95$
S16	335.00	-55.00	37.90	30.40	-37.50	4.60
S17	-57.60	-57.30	46.70	30.40	47.90	3.60
S18	10.20	-45.50	39.90	160.30	49.40	4.70
S19	126.30	-64.90	65.70	82.40	-0.50	9.00
Mean	28.60	-66.60	37.30	68.20	22.80	107.00

Table 9: Table of the Principle Component Analysis (PCA) results for the main lower unit investigation. The table includes the C_i and C_h components with their declination, inclination and $\alpha 95$ angles.

170⁰C and median of 175⁰C. The lowest temperature at which the C_h component is preserved ranges from 200⁰C to 450⁰C (Table 9) and has a modal peak, mean and median of 300⁰C. Based on these results, the Te Popo Formation is considered to have a mean incorporation temperature estimate of 300⁰C and a mean emplacement temperature estimate of 170-200⁰C (Figure 101). The mean amount the clast cooled between incorporation and emplacement is estimated to be 130⁰C.

Figure 101: Plot showing the incorporation and emplacement temperature estimates based on PCA outlined in Table 9.

Chapter Four: Discussion

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1. Internal Architecture

1.1. Distribution

In this study, deposits of the Ngatoro Formation were described at eight locations within Egmont National Park and the surrounding ring plain ranging between 2 and 24 km from the present day Egmont Volcano summit (Figure 20, Section 1, Chapter Two). These included catchments of the:

- Manganui River from the Manganui Ski Field, down through Vickers Quarry to the Manganui River Bridge on Tarata Road.
- Mangawhete Stream from the boundary of Egmont National Park on Surrey Road to the junction of the Mangawhete Stream with the Manganui River.

These locations confirm the distribution of the Ngatoro Formation outlined by Alloway et al. (1989) and presented by Neall and Alloway (2004) who described the Ngatoro Formation within the Ngatoro, Ngatoroiti, Maketawa, Mangatengehu Streams and the Manganui River.

1.2. Deposit Characteristics

The textural and bedding characteristics of mass flow deposits provide a means for determining the emplacement mechanisms, flow types and transformations, and stratigraphic correlation of the Ngatoro Formation. These characteristics include stratigraphic position, texture, sorting, bedding, sedimentological features and contact geometry. The characteristics of deposits of the Ngatoro Formation are presented in the Table 10 below:

Table 10: Block-and-ash, debris and hyperconcentrated flow deposit characteristics of the Ngatoro Formation described in this study. Modification of the Table 2 presented in Section 2, Chapter One.

Deposit Type	Sedimentary Characteristics	Other Features
Block and Ash Flows Channel Overbank Surge	- Dominantly clast supported. - Predominantly monolithologic. - Angular to sub-angular pebble-to boulder-sized clasts. - Massive structured. - Fine to medium sand and silt - Well sorted - Low angle cross-stratified - Alternating silt/fine to medium sand and fine to medium sand. <0.3m thick.	Basally erosive contact overlying lava flow and auto-breccia deposits. Repeating undifferentiated units. Sharp and irregular basal contact. Deposited on margins of the Manganui Valley.
Debris Flow Deposits (Non-cohesive mass flow deposits)	- Dominantly clast supported but some matrix supported deposits. - Predominantly monolithologic. Common wood fragments up to 0.5m in diameter. - Pebble to boulder sized clasts in a fine to coarse sand matrix. - Sub-angular to rounded clasts (-3φ to -8φ sampled range mean of sub-rounded to rounded). - Poorly to very poorly sorted (S.D = 2.0-3.16) - Mm-wide striations up to 15cm long on boulders. - Massive. - Ungraded or faintly reverse graded lower, ungraded middle and normally graded upper. 1.0 to 4.5m thick. - Deposits can reflect transformation of debris-to-hyperconcentrated flow: deposits consist of a massive, matrix supported, sand, pebble and cobble unit grading to low-angle cross stratified, fine to coarse pebbly sand.	
Debris Flow – Channel Facies	- Dominantly clast supported with subordinate pebble and sand matrix. - Very coarse, pebble to boulder sized clasts (up to 2.0m). - Very poorly to extremely poorly sorted. - Massive. - Up to 5.0m thick. - Grades upwards to weakly low angle cross-stratified sand (Hyperconcentrated flow deposits). - Lenses of massive to faintly stratified, normally graded, pebbly fluvial sand deposits due to rapid post-depositional reworking.	Erosional basal contact. Confined to the erosive channels.
Debris Flow – Marginal Facies	- Moderately to poorly sorted, sandy pebble and pebbly sand deposits becoming progressively coarser and more poorly sorted towards the channel. - Faintly stratified to massive repeating units. - Ungraded - Up to 1.0m thick – becoming thinner with distance from the channel.	Non-erosive. Wedge shaped – thins away from channel.
Hyperconcentrated Flow Deposits HCF - Channel Facies	- Fine to coarse sand with some pebbles and rare boulders (0.5m). - Moderately to poorly sorted. - Massive to faintly stratified. >0.5m thick.	Erosional basal and contacts. Confined to erosional channels.

HCF – Marginal Facies	• Fine to coarse sand with some pebbles and few cobble sized clasts. • Poorly to moderately sorted. • dm to cm-bedded cross-stratified to planar parallel sands. • Normally graded to ungraded. • Typically 0.1 to 0.8m thick • Occurrence of pumice “trains” and aligned clasts. • Flame and convolute dewatering structures. • Rip-ups of underlying deposits.	Typically non-erosive, although rip-up indicate minor erosion.
Sole Layer	• Massive to low angle cross stratified. • Fine to coarse sand (proximal) to silty fine sand (intermediate/distal). • Ungraded to normally graded. • Repeated within Ngatoro Formation.	Non-erosional and typically at the base of a debris/hyperconcentrated flow deposit. Discontinuous and often truncated by overlying df and hcf deposits

1.2.1. Debris Flow Deposits

Debris flow deposits of the Ngatoro Formation are generally confined to the proximal locations within 14 km from source (Vickers Quarry, Surrey Road Quarry and York Road). These deposits are typically massive, poorly to very poorly sorted ($S.D = 2.0-3.16$), clast supported, monolithologic. pebble to boulder sized, sub-angular andesite clasts in a fine to coarse sand matrix (VQ-1, Unit 6; VQ-2, Unit 7; SQ-2, Unit 5). Deposits have an ungraded or faintly reverse graded lower, ungraded middle and normally graded upper, ranging from 1.0 to 4.5m in thickness and associated with charred wood, both entrained and as *in situ* tree trunks. Deposits can reflect the transformation from debris-to-hyperconcentrated flows with massive, matrix-supported, sand-, pebble- and cobble-rich deposits grading to low-angle cross stratified, fine to coarse pebbly sand (SQ-2, Unit 6). The base of debris flow deposits are commonly underlain by a sole layer comprising massive to low angle cross-stratified, fine to coarse sand and silt (Figure 102). These layers are typically less than 0.1m thick but in some instances up to 0.3m thick. The sole layer is not preserved at all locations either due to non-deposition but more commonly through erosion by the downstream passage of subsequent debris flow events. Sandy-textured debris flow deposits are also observed at distal locations (Suffolk Road and Kaimata Sawmills). These distal deposits are typically massive, poorly sorted, pebbly fine to very coarse sand (MG-1, Unit 6). Deposits are normally graded to ungraded and up to 0.5m in thickness.

Figure 102 (Left): Normally graded, fine sand to silt, sole layer at the base of the Ngatoro Formation

1.2.2. Hyperconcentrated Flow Deposits

Hyperconcentrated flow deposits of the Ngatoro Formation are constrained to the intermediate and distal localities >10 km from the modern summit (Tariki-SH3, Tariki Underpass, Suffolk Road and Kaimata Sawmills). These deposits are typically poorly to moderately sorted sands with some pebbles and a few cobble-sized clasts. Deposits are 0.1 to 0.8m thick, repeated units of channelised, cross-stratified lower to laminated upper, normally graded to ungraded with sedimentary structures such as flame dewatering structures, convolute bedding, rip-ups of underlying deposits, pumice ‘trains’ and aligned clasts (TR-1, Units 6, 7 & 8; TU-2, Units 10 & 12). The repeated units are underlain and interbedded with <0.05m thick, massive, fine sandy silt sole layers that exhibit load deformation structures (TU-2, 7, 9 & 11; SF-1, Unit 3; MG-1, Unit 4).

1.3. Lateral and Longitudinal Variability

1.3.1. Proximal

Deposits of the Ngatoro Formation exhibit lateral textural variability with distance from Egmont Volcano. Within the confines of the Manganui Valley inside Egmont National Park (EE-1, 2.7 km from the modern summit) the Ngatoro Formation is manifested as a <0.2m thick, bedded to low angle cross-stratified, alternating silt/fine sand and fine to medium sand interpreted to be an overbank surge deposits (EE-1, Unit 8) (Figure 103). These surge deposits mantle the topographically high margins of the Manganui River and extend down

the valley towards the ring plain. At the boundary of Egmont National Park at the Vickers Quarry (VQ-1, VQ-2 & VQ-3, 10 km from the modern summit) and Surrey Road Quarry (SQ-1, SQ-2 and SQ-3, 10 km from the modern summit) the Ngatoro Formation is manifested as a 2.0 to 5.0m thick, massive, poorly to very poorly sorted, monolithologic, pebble to boulder (up to 2.0m) channel debris flow deposits with common charred wood fragments (VQ-1, Unit 6; SQ-2, Unit 5) (Figure 103 and 104). The debris flow deposits typically overly a <0.1m thick, organic rich well-developed paleosol and in places a massive, normally graded, fine sand to silt sole layer. In places the debris flow deposits are overlain by <0.15m thick, low angle cross-stratified, fine to coarse sand with some pebbles interpreted to be hyperconcentrated flow deposits (SQ-2, Unit 6).

Marginal deposits of the proximal Ngatoro Formation (800m from Vickers Quarry) occur at York Road as <2.0m thick, massive, poorly sorted, fine to coarse sand with some matrix-supported sandy deposits (YR-1, Unit 9 & 10) (Figure 104). The basal contact is non-erosive with the debris flow deposits overlying <0.05m thick, massive, fine to coarse sand and fine pebble sole layer (YR-1, Unit 7).

The marginal deposits are typically thinner, matrix supported, better sorted and finer textured with a unimodal grainsize peak and predominantly bladed clasts in comparison to the clast supported, very coarse textured, channel deposits which exhibit a bimodal grainsize distribution and comprise predominantly of compact-bladed clasts (Figure 104). Both channel and marginal deposits are massive and poorly sorted without sedimentary structures indicative of a single phase flow.

1.1.1. Intermediate

On the Egmont ring plain (TU-1, TU-2, TU-3 & TU-4, 17.1 to 17.3 km from the modern summit) Ngatoro Formation at Tariki Underpass occurs predominantly as channel deposits comprising 1.0 to 2.0m thick, massive to faintly stratified, poorly sorted fine to coarse sandy hyperconcentrated flow deposits with some pebbles, cobbles and a few boulders (0.5m) (TU-3, Units 1 & 3) (Figure 105). In places the channel deposits are massive, poorly sorted, pebble and cobble debris flow deposits, matrix-supported in a fine to coarse sand matrix (TU-3, Unit 2). The channel deposits typically have erosional lower contacts.

Figure 103: Measured sections indicating the transition from proximal pyroclastic surge and debris flow deposits to intermediate and distal hyperconcentrated flow deposits. Grain size histograms show the deposits becoming more sorted and fine grained with distance from Egmont Volcano.

Figure 104: Measured sections indicating the transition from thick, axial cobble and boulder rich debris flow deposits to thin, marginal pebbly sand debris flow deposits. Grain size histograms show the deposits becoming more sorted and fine grained with distance from the channel axis.

Figure 105: Measured sections indicating the transition from massive, coarse textured channel deposits to massive-to-stratified, fine textured marginal deposits. Grainsize histograms for the marginal deposits indicate they are sorted, fine grained, pebbly sand deposits.

The marginal deposits of the intermediate Ngatoro Formation (TU-1 & TU-2) are typically 0.1 to 0.8m thick, low angle cross-stratified to laminated, poorly to moderately sorted, sandy deposits with some pebbles (TR-1, Units 6, 7 & 8; TU-2, Units 10 & 12) (Figure 105). These marginal deposits exhibit unimodal and bimodal grain size distributions, and sedimentary structures such as flame dewatering structures, convolute bedding, rip-ups of underlying deposits, pumice 'trains' and aligned clasts that are interpreted as hyperconcentrated flow deposits. These deposits are underlain and interbedded with massive to normally graded, well sorted, unimodal fine sand to silt sole layers.

Marginal deposits are typically thinner, cross-stratified to laminated, better sorted and finer textured with single and bimodal grainsize distributions in comparison to the thicker, massive to faintly stratified, poorly sorted, coarser textured channel deposits (Figure 105). In comparison to the proximal debris flow deposits at Vickers Quarry and Surrey Road Quarry (Figure 103), the intermediate deposits are thinner, finer textured, better sorted, stratified and exhibit sedimentary structures indicative of a flow with both a solid and fluid phase.

1.1.2. Distal

At distal locations (SF-1 & MG-1, c. 22 km from the modern summit) the Ngatoro Formation occurs as a <0.7m thick, stratified fine to coarse sandy deposit with some entrained fine to coarse pumice lapilli eroded from the underlying Inglewood Tephra and repeating cut and fill structures, interpreted as hyperconcentrated flow deposits (SF-1, Unit 6; MG-1, Unit 5). The deposits exhibit a generally unimodal and fine textured grain size distribution. These are overlain by a massive, fine textured, bimodally distributed, poorly sorted fine to medium pebbly sand debris flow deposit (SF-1, Unit 5; MG-1, Units 6 & 7). The distal Ngatoro Formation is typically underlain by a <0.05m thick, massive, fine sand and silt normally grading to silt deposit interpreted as a sole layer (SF-1, Unit 3; MG-1, Unit 4). The sole layer is well-sorted and exhibits a fine textured, unimodal grainsize distribution. In comparison to the intermediate deposits at Tariki-SH3 and Tariki Underpass (Figure 103), distal deposits are typically thinner, finer textured and better sorted.

2. Emplacement History

2.1. Precursory Events

The existing tephra framework for Holocene eruptive events on Egmont Volcano indicates that the Ngatoro Formation is underlain by two closely spaced pumiceous lapilli beds (Alloway et al., 1995; Neall, 1972). These lapilli beds are the widely dispersed informal Inglewood.a and Inglewood.b subunits of the Inglewood Tephra (c. 3,600 ^{14}C yrs B.P.). The Inglewood tephra is associated with two closely spaced plinian eruptions from Egmont Volcano that deposited juvenile pumiceous material throughout north-east Taranaki and extending to the Waikato (Lowe, 1988). The Inglewood Tephra was described at all eight of the locations studied, either as the Inglewood.a and Inglewood.b subunits at proximal sections (East Egmont, Vickers Quarry, Surrey Road Quarry and York Road) and intermediate sections (Tariki – SH3 and Tariki Underpass) or as a single, pumiceous lapilli bed at distal sections (Suffolk Road and Kaimata Sawmills). The current understanding of the deposition of the Ngatoro Formation is that is “closely followed” the eruption of the Inglewood Tephra (Alloway et al., 1995). However, well-developed paleosols consistently identified between the Inglewood Tephra and overlying Ngatoro Formation suggests that that these events are closely related in time but represent separate events (Figure 106).

Figure 106: Photographs of the well-developed paleosol between the underlying Inglewood.b subunit and overlying Ngatoro Formation debris flow deposits. The paleosol is shown at Surrey Road Quarry (Left) at the base of the spade and at Vickers Quarry marked by the camera lense cap (Photo courtesy of B. Alloway).

This paleosol represents an intervening hiatus between deposition of Inglewood and Ngatoro Formation where pedogenic processes predominated in favour of volcanigenic deposition. Organic rich paleosols were described at Vickers Quarry (VQ-1, Unit 7), Surrey Road Quarry (SQ-2, Unit 4) and Tariki-SH3 (TR-1, Unit 4), and at the remaining sections the Inglewood Tephra was expressed as a pumiceous lapilli within a silty, ash soil (e.g. MG-1, Unit 3). As this prominent paleosol is observed at multiple locations, both proximal and distal, it is evidence to suggest the emplacement of the Ngatoro Formation is not a syn-eruptive process directly related to the deposition of the Inglewood Tephra, but rather a separate volcanoclastic event and may be attributed to a hitherto previously unrecognised extended phase of the Inglewood eruption event.

2.2.   Emplacement Mechanism

With evidence such as the underlying paleosol and absence of juvenile pumiceous clasts within its deposits suggesting the emplacement of the Ngatoro Formation occurred sometime after the emplacement of the Inglewood.a and Inglewood.b lapilli beds an emplacement mechanism must be determined. Common mass flow generating mechanisms outlined in Section 2.3, Chapter One include; transformation of edifice collapse generated debris avalanches; lateral transformation of pyroclastic flows; and rainfall-induced destabilisation of unstable volcanoclastic material.

Within Egmont National Park at section EE-1 the Ngatoro Formation is expressed as fine grained pyroclastic surge deposit (EE-1, Unit 8) enveloped by the Inglewood.b and Manganui.a subunits (EE-1, Units 7 & 9). The pyroclastic surge deposit may be an overbank surge deposits associated with one of the many undifferentiated, massive, monolithologic, cobble- and boulder-rich block-and-ash flow deposits within the Manganui Valley. This suggests that the debris and hyperconcentrated flow deposits described beyond the confines of Egmont National Park transformed from proximal block-and-ash flows. Debris flow deposits described at Vickers Quarry (VQ-1, Units 6 & 7) and Surrey Road Quarry (SQ-2, Unit 5) indicate the block-and-ash flows within the Manganui and Mangatenghu Rivers transformed to water supported debris flows within 10 km of the summit of Egmont Volcano.

The generation of block-and-ash flows not directly related to volcanic events such as the emplacement of the Inglewood Tephra is generally through the gravitational collapse of an effusive lava dome. The collapse of lava domes is identified in the eruptive history of Egmont Volcano (Platz et al., 2007) and also has been observed at Soufriere Hills Volcano (Cole et al., 2002; Stinton et al., 2014; Wadge et al., 2014), Merapi Volcano (Charbonnier and Gertisser, 2008) and Unzen Volcano (Ui et al., 1999). The period of lava dome growth and subsequent collapse observed at Unzen Volcano, Japan, between 1990 and 1995 can be used as an analogue for the generation of the proximal block-and-ash flow deposits of the Ngatoro Formation. The generated lava dome formed exogenous lobes up to 300m long, 150m wide and advanced less than 20m per day (Ui et al., 1999). Prior to the collapse, gas plumes were observed on the lobes at the points where the block and ash flows emanated (Figure 107 A). As the dome collapsed lava blocks from the frontal cliffs of the lobes or from the cliffs formed as new lava is extruded from the vent separated (Figure 107 B-C) and disintegrated instantaneously resulting in catastrophic block and ash flows (Figure 107 D-F). In photo G (Figure 107) the ash cloud and pyroclastic surge is clearly visible moving down the flanks of the cone. This is similar the type of surge that would have deposited the overbank surge deposits described within Egmont National Park (EE-1, Unit 8).

Figure 107: Photographs of block-and-ash flow generation from the collapse of an effusive lava dome on Unzen Volcano, February 25 1992 (Ui et al., 1999). This generated block-and-ash flows similar to the proximal pyroclastic surge deposits of the Ngatoro Formation at section EE-1 (A, B & C). The frontal lobe of the lava dome detached (indicated by arrows), disintegrated and subsequently generated a block-and-ash flow followed by the collapse (D & E) of a second slab of lava (F & G). Close up and distant view of the generated block and ash flow and (H) the remains of the lava dome 10 minutes after the collapse.

2.3. Emplacement Temperature

Initial evidence for elevated emplacement temperatures for the Ngatoro Formation was the charred and desiccated outer podocarp-hardwood tree trunks observed at Vickers Quarry. The charring is limited to a <0.1m thick veneer on the outside of the tree stumps while the interior remains well preserved. This suggests that the debris flow was hot enough to char the trees but not hot enough, or lacked the oxygen supply to completely burn the trees. This is a phenomenon associated with other mass flows that have originated as pyroclastic flows. Crandell (1971) and Scott (1988) both describe charred or carbonised wood associated with lahars on Mt Rainier and Mt St Helens respectively. Crandell (1971) also references the observations of Kemmerling (1921) on Mt Merapi where a temperature of 92⁰C was measured one foot below the surface of the mass flow deposit a few days after deposition. Kemmerling also observed a gas vent from the mass flow deposits with a temperature of 360⁰C and subsequent temperature of 100⁰C at the same point one year later. This same heat retention within volcanoclastic deposits is observed in block-and-ash flow deposits on Volcan de Colima, Mexico where a temperature of 128⁰C was recorded 0.3m below the surface six days after deposition (Rodriguez-Elizarraras et al., 1991).

The results of the palaeomagnetic investigation of the Ngatoro Formation and overlying Te Popo Formation (Section 9, Chapter Three) give both incorporation and emplacement temperature estimates for the sampled clasts. For sampled clasts from Ngatoro Formation, the incorporation temperature is considered the temperature of the clasts at the time they were entrained within the block and ash flow, and the emplacement temperature refers to the temperature at which the clasts were deposited at the Vickers Quarry and Surrey Road Quarry.

The main lower unit investigation (VQ-1, Unit 6; SQ-1, Unit 1) gives a mean incorporation temperature estimate of 300⁰C for the proximal block-and-ash flow phase of the Ngatoro Formation. This indicates a lower temperature block-and-ash flow generated the Ngatoro Formation than comparable pyroclastic flows on typical andesitic volcanoes (Table 11):

Table 11: Incorporation temperature estimate of the Ngatoro Formation from this study compared with block and ash flow temperatures from comparable volcanoes.

Event / Location	Temperature	Method	Reference
Ngatoro Formation, Egmont Volcano	Incorporation Temperature of 300 ⁰ C.	Palaeomagnetic temperature estimates.	This study.
Te Popo Formation, Egmont Volcano	Incorporation Temperature of 300 ⁰ C.	Palaeomagnetic temperature estimates.	This study.
Merapi Volcano, Central Java	Minimum temperatures range from 400 ⁰ C for the basal avalanche and 165 ⁰ C for the ash cloud.	Fourier-transform infrared spectro-scopic measurement of plastic buried in the flow deposits and from direct temperature measurements of the flow deposits.	Charbonnier and Gertisser (2008)
Soufriere Hills Volcano, Montserrat	365-640 ⁰ C	Direct measurement with a thermocouple and temperature patches.	Cole et al. (2002)
Unzen Volcano, Japan	300-600 ⁰ C	Palaeomagnetic temperature estimates.	Tanaka et al. (2004)
Mt St Helens, Washington	550-600 ⁰ C	Palaeomagnetic temperature estimates.	Hoblitt and Kellogg (1979)

The main lower unit investigation also gives a mean emplacement temperature estimate of 200⁰C for the proximal block-and-ash flow phase of the Ngatoro Formation. As with the incorporation temperature, this temperature estimate is lower than the palaeomagnetic temperature estimate of 375±25⁰C for comparable mass flows at Mt St Helens, Washington (Hoblitt and Kellogg, 1979).

Based on palaeomagnetic analysis and field observations of proximal deposits at Vickers Quarry and Surrey Road Quarry, the Ngatoro Formation was initiated as a low temperature block-and-ash flow with an estimated temperature of 300⁰C. As this mass flow laterally transformed into a water-supported debris flow it was emplaced with an estimated temperature of 200⁰C. As the trees in the vicinity of Vickers Quarry were inundated and buried, the Ngatoro Formation retained sufficient heat to surfically burn and desiccate the exterior of mature podocarp-hardwood tree trunks but did not have sufficient heat or oxygen to completely burn them.

2.4. Flow Transformations

The transformation from gas-supported block and ash flows to water-supported debris flows requires the incorporation of large volumes of water, sufficient unconsolidated debris, steep slopes and a triggering mechanism. With the proposed mechanism of gravitational collapse of an effusive lava dome and the abundant unconsolidated block and ash flow deposits within the steep Manganui Valley, the question of source water remains.

The most likely source of water for the transformation of the Ngatoro Formation was the incorporation of steam and water from the source rocks, ice and snow from the flanks of the volcano and alluvial water within the catchments down which the pyroclastic flows travelled (Scott, 1988; Vallance, 2000; Vallance 2005). The block and ash flows typically come to rest and form the melt water which subsequently erodes the pyroclastic material forming the water-supported mass flows (Vallance, 2000).

The transition from gas-supported block-and-ash flows to water supported debris flows occurs within the upper confinements of the Manganui Valley and Mangawhete Stream <2.0 km from the modern day summit. Evidence for the bulking or incorporation of previously deposited loose sediment is generally evident in the presence of foreign clasts within the flow deposits. Determining the amount of sediment bulking for the Ngatoro Formation is challenging due to the >70m thick, monolithologic, undifferentiated, block-and-ash flow deposits upstream within the Manganui Valley. This material makes it challenging to differentiate between andesite cobbles and boulders sourced from the dome collapse event and the same type of andesite clasts incorporated into the Ngatoro debris flow from the underlying deposits. The use of palaeomagnetic investigations however provide some insight into the sediment bulking during the emplacement of the Ngatoro Formation. The clasts sampled in the main lower unit Investigation (VQ-1, Unit 6; SQ-2, Unit 5) exhibit a range in incorporation and emplacement temperatures (100-450°C and 100-350°C respectively) as discussed in Chapter Three, Section 9.0. These results suggest differing thermal histories, and therefore differing incorporation and emplacement processes between the sampled clasts. For example, specimen S15.1A has an incorporation and emplacement temperature of 100°C, much lower than clast S7.1C which has incorporation and emplacement temperatures of 400°C and 200°C. This suggests that clasts S15 was incorporated or bulked into the debris flow at a lower temperature and did not significantly

cool during transportation, in comparison to clast S7 which was incorporated at a high temperature and subsequently cooled during transportation.

The coarse-textured deposits exposed at Vickers Quarry (VQ-1, Unit 6) and Surrey Road Quarry (SQ-2, Unit 5) contain clasts up to 2.0 in diameter, are predominantly cobble and boulder and lack any internal stratification or sedimentary structures. This type of mass flow deposit is indicative of a single phase debris flow with very high sediment concentrations (>80wt%) and sufficient energy to transport these large clasts in its primary axis of flow. The largest boulders are located at the top of the debris flow deposit (VQ-1, Unit 6) indicating that these clasts were buoyed on top of the sediment water mixture until which point the flow no longer has sufficient energy, sediment concentration, and yield strength to support them any longer. At Surrey Road Quarry there is an upward transformation from coarse-textured debris flow deposits (SQ-2, Unit 5) to cross-stratified sandy deposits interpreted as hyperconcentrated flow deposits in the dilute waning stage of flow (Zernack et al., 2009).

Downstream there is evidence to indicate a progressive reduction in the carrying capacity of the mass flow with the predominance of stratified, sandy and pebbly sand-textured deposits at Tariki – SH3 and Tariki Underpass sections 17 km from the modern day summit. These features are indicative of a hyperconcentrated stream flow, with intermediate sediment concentrations (40-80wt%) and a solid and fluid phase. The hyperconcentrated flows deposited sediment in multiple pulses indicated by multiple intervening sole layers (TU-2, Units 7, 9 & 11; TR-2, Units 5 & 9) and repeated stratified units (TU-2, Unit 10), and in variable flow regimes depositing features from low angle cross-stratified (TR-1, Unit 8) to laminated sands (TU-2, Unit 12).

2.5.   **Emplacement of the Manganui Tephra and Te Popo Formation**

The existing tephra framework for Holocene eruptive events on Egmont Volcano indicates that the Ngatoro Formation is overlain by four basaltic, scoriaceous lapilli beds (Alloway et al., 1995; Neall, 1972). These lapilli beds are considered informal subunits of the Manganui Tephra (c. 3,100 ¹⁴C yrs B.P.) related to a period of activity on Fanthams Peak (Alloway et al., 1995). Associated with these lapilli beds are mass flow deposits of the Te Popo Formation. The Manganui.a, Manganui.b and Manganui.c subunits were described at three of the locations in this study (East Egmont, Surrey Road Quarry and Tariki Underpass). At proximal

locations (Surrey Road Quarry) the Manganui subunits are associated with massive, poorly sorted, cobble and boulder rich debris flow deposits. A preliminary palaeomagnetic study on the Te Popo Formation at Vickers Quarry (VQ-1, Unit 12) gives an incorporation temperature estimate of 300⁰C and emplacement temperature estimate of 170-200⁰C. These are comparable temperature estimates to those of Ngatoro Formation.

The stratigraphy described in this thesis supports the existing stratigraphic framework of Alloway et al., 1995, however as with the Ngatoro Formation paleosols the Manganui.a and Manganui.c subunits (SQ-3, Units 2 & 6) indicate a separation in time between the Manganui eruptive events and subsequent emplacement of the Te Popo debris flow deposits. This suggests that eruptive events such as the Inglewood and Manganui events being followed sometime after by low temperature, water supported mass flows are not an isolated sequence of events on Egmont Volcano but repeated in the stratigraphic record.

2.6. Summary of Emplacement

The summary of precursor events and emplacement of the Ngatoro Formation is as follows:

1. Emplacement of the Inglewood.a lapilli during the first eruptive phase of the Inglewood eruptive event at c. 3,600 ¹⁴C yrs B.P (e.g. VQ-1, Unit 3; Tu-2, Unit 4).
2. Period of quiescence and stability in the landscape enabling the formation of andic soils (e.g. VQ-1, Unit 4; TU-2, Unit 5).
3. Emplacement of the Inglewood.b lapilli during the second phase of the Inglewood eruptive event at least several decades after c. 3,600 ¹⁴C yrs B.P (e.g. VQ-1, Unit 5; TU-2, Unit 6).
4. Period of quiescence and stability in the landscape enabling the formation of a well-developed, organic rich paleosol (e.g. VQ-3, Unit 7).
5. Effusive growth of a post-Inglewood lava dome - presumably near the summit of the present-day Egmont Volcano
6. Subsequent collapse of this effusive lava dome generating a block-and-ash flow at a temperature of 300⁰C. This deposited cobble- and boulder-rich block-and-ash flow deposits in the Manganui Valley and overbank surge deposits of the valley margins (e.g. EE-1, Unit 8).

7. Snow, ice and alluvial water incorporated into the flow transformed the block-and-ash flow into single phase, water-supported, sediment rich, coarse-textured debris flows with temperatures of 200⁰C (e.g. VQ-1, Units 6-7; SQ-2, Units 5-6). This event inundated, buried and partially burned the podocarp-hardwood forest occurring on the lower eastern flanks in the vicinity of Vickers Quarry (e.g. VQ-1, Units 6 & 7).
8. Syn-depositional lateral transformation from debris flows to finer-textured, more dilute, solid and fluid phase hyperconcentrated flows (e.g. TR-1, Units 6-8; TU-2, Unit 10; MG-1, Unit 5).
9. Period of quiescence then the emplacement of the Fanthams Peak sourced Manganui.a scoriaceous lapilli of the Manganui Tephra at 3,100 ¹⁴C yrs B.P. (e.g. EE-1, Unit 9; SQ-2, Unit 7; TU-4, Unit 8).
10. Following the emplacement of the Manganui.a lapilli was a period of quiescence enabling the formation of a well-developed paleosol (e.g. SQ-3, Unit 6 & 7).
11. Emplacement of the first coarse-textured, water-supported debris flow deposit of the Te Popo Formation (e.g. SQ-2, Units 8 & 9). This unit decapitated the partially buried and burnt podocarp-hardwood forest remnants at Vickers Quarry (e.g. VQ-1, Unit 12).
12. Subsequently deposition of another two scoriaceous lapilli beds, Manganui.b and Manganui.c lapilli (e.g. SQ-3, Units 4 & 6; TU-4, Units 10 & 12), and associated debris flow units of the Te Popo Formation (e.g. SQ-3, Units 5, 7 & 8).

3. Hazards

Egmont Volcano is an active andesite stratovolcano with 76 Egmont-sourced tephra intermittently erupted between c. 3,000 and c. 28,000 ^{14}C yrs B.P. and an eruptive periodicity of c. 330 years (Alloway et al., 1995). Recent work by Turner et al. (2009) identified 138 separate ash-forming eruptions between 96 and 10,150 yrs B.P. Using this record Turner et al. (2009) used the Weibulls renewal model to forecast a probability of 0.52 for an eruption in the next 50 years on Egmont Volcano. Along with tephra emission, Egmont Volcano also has a history of pycroclastic flows, water-supported debris/hyperconcentrated flows, lava flows and edifice collapse induced debris avalanches (Alloway, 1989; Neall and Alloway, 2004). In order to assess the risk posed by these range of processes requires an understanding of:

- The emplacement mechanisms.
- Spatial extent and duration of the event.
- The return period.
- The amount of forewarning.
- Potential social and economic effects.

Water-supported mass flows similar to the Ngatoro Formation are recorded throughout the eruptive history of Egmont Volcano (Alloway, 1989; Zernack et al., 2009). The many truncated and charred trees exposed at Vicker Quarry (circumferences up to 5.9m) and the rapid accumulations of coarse-textured cobble- and boulder-rich (up to 2.0m in diameter) deposits depict the extreme risk posed to any person or structure directly in the path of water-supported mass flow events such as the Ngatoro event. The catastrophic effects of debris/hyperconcentrated flows was highlighted in the 1985 inundation of the town of Armero, Colombia by a lahar following the eruption of Nevado del Ruiz volcano, resulting in 22,000 deaths (Voight, 1996). This was a disaster that with a better understanding of the hazards and behaviour of mass flows, and adequate warning systems in place could have been avoided.

The current hazard monitoring system on Egmont Volcano by GNS Science includes 1 continuous feed web cam, 9 seismographs and 1 continuous GPS site (Figure 108) (Johnston et al., 2011). This is a less comprehensive monitoring than on Mt Ruapehu, New Zealand

which is equipped with 2 continuous feed web cameras, 10 seismographs, 6 microphones, 9 continuous GPS stations and regular water and gas monitoring visits to the Crater Lake as well as airborne gas surveys (www.gns.cri.nz). This comprehensive monitoring system was implemented in response to an eruptive history, including the 1953 Tangiwai disaster in which the Christmas Eve Wellington to Auckland express train crashed into the Whangaehu River killing 151 people after a water-supported mass flow destroyed the rail bridge (Neall, 1976).

Figure 108: Schematic map indication the positions of the seismographs and continuous GPS site as part of the Egmont Volcano monitoring program (Johnston et al., 2011)

However Egmont Volcano and Mt Ruapehu both have a highly active and intermittent eruptive record comprising pyroclastic flows, debris/hyperconcentrated flows and debris avalanches. The difference in monitoring system between Egmont Volcano and Mt Ruapehu may indicate an underestimation of the risk posed by Egmont Volcano due to the most recent eruption occurring in 1755 A.D. (Alloway et al., 1995), before anecdotal or written record.

A combined volcanic hazard zone map published by the Taranaki Regional Council (Figure 109) indicates areas to the north-east, north-west and south-west of Egmont Volcano at risk of water-supported mass flows (in purple) - This includes the area of the Ngatoro Formation. The distribution of the Ngatoro Formation described in this thesis supports that of Alloway et al. (1995) and Neall and Alloway (2004), and reinforces the existing understanding of hazards posed by debris/hyperconcentrated flow distribution. The findings of this thesis add to the current understanding of these mass flow events and the timing of mass flow emplacement relative to precursory eruptive events. The emplacement of the Ngatoro Formation has been found to occur sometime after the emplacement of the Inglewood Tephra (c. 3,600 ^{14}C yrs B.P) as part of an extended and previously unidentified phase of the Inglewood eruptive event involving the steady growth and subsequent collapse of an effusive lava dome. This timing suggests that for future eruptions there is still significant risk of catastrophic emplacement of gas- to water-supported mass flows for an extended period of time after a paroxysmal eruptive event similar to that which emplaced the Inglewood Tephra.

Figure 109: Combined volcanic hazard zone map (Neall and Alloway, 1995). The areas classified as being at risk of debris/hyperconcentrated flows and associated flood flows are identified in purple to the north-east, north-west and south-west of Egmont Volcano.

Chapter Four: Conclusions

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1. Conclusions

This thesis has used a combination of field mapping, stratigraphic descriptions, grain size and shape analysis, tephrochronology and palaeomagnetic analysis to determine the stratigraphy, facies architecture and emplacement history of the c. 3.6 ka B.P. Ngatoro Formation on the eastern flanks of Egmont Volcano, western North Island, New Zealand.

Based on this the following conclusions have been drawn:

- The Ngatoro Formation comprises two closely spaced mass flow events whose flow & emplacement characteristics have undergone both proximal to distal and axial to marginal transformations. On surfaces adjacent the Manganui Valley on the incised flanks of Egmont Volcano the Ngatoro Formation is identified as <0.2m thick overbank surge deposits. These surge deposits mantle the topographically high margins of the Manganui River and extend down-valley towards the ring plain. Within the Manganui River valley itself Ngatoro Formation deposits couldn't be identified with any certainty on account of intra-channel cut and fill and the lack of any intervening stratigraphic marker beds. At the boundary of Egmont National Park the Ngatoro Formation occurs as 2.0 to 5.0m thick, pebble- to boulder-rich debris flow deposits with common charred wood fragments laterally transforming to <2.0m thick, massive, poorly sorted, fine to coarse sand with some matrix-supported pebble marginal debris flow deposits. At intermediate and distal sections the Ngatoro Formation occurs as <0.8m thick sequence of at least two, low angle cross-stratified to laminated, pebbly sandy hyperconcentrated flow deposits. These deposits exhibit sedimentary structures such as flame dewatering structures, convolute bedding, rip-ups of underlying deposits, pumice 'trains' and aligned clasts.
- This lateral and longitudinal variability in the Ngatoro Formation reflects the transformation from gas-supported block and ash flows within the valley confines of Egmont National Park to transitional gas/water-supported debris flows at the Vickers

Quarry, Surrey Road Quarry and York Road sections. These debris flows had high sediment concentrations, flowed as a single phase and deposited sediment en-masse as evidenced by the massive, very coarse-textured deposits. The debris flows laterally transformed to turbulent finer grained, gravelly sand-dominated hyperconcentrated flows with a solid and fluid phase and lower yield strength than the debris flow from which it transformed. This is evident in the stratified, finer textured deposits with flame dewatering structures, convolute bedding, rip-ups of underlying deposits, pumice 'trains' and aligned clasts.

- Palaeomagnetic temperature estimates for Ngatoro Formation in the vicinity of the National Park boundary (c.9.6 km from the present day summit; Vickers Quarry and Surrey Road Quarry sites) indicate clast incorporation temperatures of c. 300⁰C and emplacement temperatures of c. 200⁰C.
- The Ngatoro Formation manifests as a single pyroclastic deposit within Egmont National Park, has an underlying well-developed paleosol and monolithologic composition, and an above ambient incorporation temperature. This evidence suggest the Ngatoro Formation was emplaced by the lateral transformation of a block and ash flow generated by collapse of an effusive lava dome sometime after the Inglewood eruptive event (c. 3,600 ¹⁴C yrs B.P.).
- The overlying Te Popo Formation exhibits similar debris and hyperconcentrated flow deposits overlying well-developed andic paleosols with ash and lapilli interbeds with comparable incorporation and emplacement temperatures. This suggests that eruptive events such as the Inglewood and Manganui tephra events being followed sometime after by low temperature, rapidly transforming water-supported mass flows are not isolated occurrences on Egmont Volcano but apparently are repeated in the aftermath of sustained eruptive activity or paroxysmal eruption. On this basis, such similar events could conceivably be expected in the years and decades following a future Egmont Volcano eruptive phase.

2. Future Work

The complex and laterally variable nature of volcaniclastic deposits and their spatial and temporal relationship with enveloping tephra generally leads to a wide range of potential future work. Upon completion of this study some specific recommendations for future work are summarised below:

- The key to describing and correlating rapidly transforming volcaniclastic deposits between sections is through the correlation of tephra units. In this study, Korito, Inglewood and Manganui Tephra were successfully correlated using a combination of field descriptions as well as major element glass composition determined from EMP analysis. Some stratigraphic complexity encountered in the upper part of the Vickers Quarry and York Road sections do not currently fit within the existing stratigraphic framework (Alloway et al., 1995). This issue is expected to be better clarified after submission of this thesis by tephra resampling, further EMP analysis and the submission of associated wood fragments for radiocarbon dating.
- This thesis has identified that the emplacement of the Ngatoro Formation does not strictly correspond in age with the Inglewood Tephra eruption (c. 3,600 yrs ^{14}C B.P.), with sufficient intervening time between the two events as evidenced by the formation of a prominent intervening soil. The challenge from this revelation is to precisely estimate the time between the emplacement of the Inglewood Tephra and the Ngatoro Formation. This may be best done through more intensive radiocarbon dating of the interval that separates the Inglewood Tephra from the closely overlying Ngatoro Formation.
- This thesis has successfully used palaeomagnetic analysis to estimate clast incorporation and emplacement temperatures for Ngatoro Formation using a modification of the conglomerate test. We suggest the comparison of the Ngatoro Formation temperature estimates to those calculated at similar volcanoes elsewhere in order to understand the temperatures at which water-supported mass flows are initially generated and emplaced.

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Appendix A: Stratigraphy, Sedimentology and Electron Microprobe Results

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A1 – Field and laboratory Results

Sixteen measured sections, field descriptions, Electron Microprobe results and grain size and shape analysis result presented by stratigraphic section.

EMP Analysis

East Egmont Reference:

Samples:

- △ Burrell Lapilli
- ▲ Kaupokonui Tephra
- unnamed Vulcanian tephra
- Maketawa Tephra
- ◇ Mg.d, Manganui Tephra
- ◆ Mg.c, Manganui Tephra
- ☆ Mg.b, Manganui Tephra
- ★ Mg.d, Manganui Tephra
- II.b, upper Inglewood Tephra
- II.a, upper Inglewood Tephra
- ⊕ Korito Tephra

EE-1: Measured section showing relevant descriptions and sample locations. Electron Microprobe Analysis results compared with East Egmont and Dawson Falls reference sections (Section B1, Appendix B).

VQ-1: Measured section with relevant descriptions and sample locations. Grain size histograms, clast shape and roundness histograms, and Electron Microprobe Analysis results compared with the East Egmont and Dawson Falls reference Section (Section B1, Appendix B).

VQ-2: Measured section with relevant descriptions and sample locations.

VQ-3

VQ-3: Measured section with relevant descriptions and sample locations.

SQ-1

SQ-1: Measured section with relevant descriptions and sample locations.

SQ-2: Measured section with relevant descriptions and sample locations.

SQ-3

SQ-3: Measured section with relevant descriptions and sample locations.

YR-1: Measured section with relevant descriptions and sample locations. Grain size histograms, clast shape and roundness histograms, and Electron Microprobe Analysis results compared with the East Egmont and Dawson Falls reference Section (Section B1, Appendix B).

YR-2

Descriptions

UNIT 3, 0.75m: Lower boundary is sharp and wavy. Massive, monolithologic, faintly normally graded, matrix supported, dark grey, fine to coarse sand with angular to sub-angular, pebbles and cobbles (25.0cm). [DEBRIS FLOW DEPOSITS]

UNIT 2, 0.5m: Lower boundary is distinct and wavy. Massive, orange brown, fine to medium sandy silt. Upper boundary marked with abundant, medium to very coarse, yellowish white pumiceous lapilli. [PUMICEOUS TEPHRA/ANDIC SOIL]

UNIT 1, 0.0m: Lower boundary not observed. Massive, monolithologic, poorly sorted, clast supported, dark grey, fine to coarse sand with some angular to sub-angular, fine to coarse pebbles. [DEBRIS FLOW DEPOSITS]

YR-2: Measured section with relevant descriptions and sample locations.

TR-1

TR-1: Measured section with relevant descriptions and sample locations.

TU-1: Measured section with relevant descriptions and sample locations. Electron Microprobe Analysis results compared with the East Egmont and Dawson Falls reference Section (Section B1, Appendix B).

TU-2: Measured section with relevant descriptions and sample locations. Grain size histograms and Electron Microprobe Analysis results compared with the East Egmont and Dawson Falls reference Section (Section B1, Appendix B).

TU-3

TU-3: Measured section with relevant descriptions and sample locations.

TU-4

Descriptions

UNIT 14, 2.39m: Lower boundary is indistinct. Massive, poorly sorted, matrix supported, brownish grey, fine to coarse sand with few sub-angular to sub-rounded, fine to coarse pebbles, cobbles and boulders (50.0cm). Few rip ups of light grey silt with fibrous organics. [DEBRIS FLOW DEPOSITS]

UNIT 13, 2.27m: Lower boundary gradational (5.0cm). Massive, light brown with orange mottled, fine sandy silt with lenses of some clay. [PALEOSOL]

UNIT 12, 2.09m: Lower boundary is distinct and wavy. Massive, normally graded, dark brownish black, fine to medium basaltic, scoriaceous lapilli. Upper 2.0cm marked by brownish orange iron pan. [SCORIACEOUS TEPHRA]

UNIT 11, 2.05m: Lower boundary is distinct and wavy. Massive, moderately sorted, orange, fine to medium sandy silt iron pan.

UNIT 10, 1.9m: Lower boundary is distinct and wavy. Massive, fine, black basaltic, scoriaceous lapilli. [SCORIACEOUS TEPHRA]

UNIT 9, 1.83m: Lower boundary abrupt and smooth. Massive, light brown with orange mottled, silty fine to medium sandy soil. [ANDIC SOIL]

UNIT 8, 1.8m: Lower boundary sharp and planar. Massive, fine, black basaltic, scoriaceous lapilli. [SCORIACEOUS TEPHRA]

UNIT 7, 1.74m: Lower boundary abrupt and smooth. Massive, light brown, fine to medium sandy silty soil. [ANDIC SOIL]

UNIT 6, 0.44m: Lower boundary is sharp and irregular. Massive, poorly sorted, light grey with orange mottled and streaked, fine to medium sand with common sub-angular to sub-rounded, fine to coarse pebbles, some cobbles and few boulders (50.0cm). Graded to faintly cross-stratified, moderately sorted, orange, fine to medium sand. Upper boundary marked with sharp and wavy, massive, light brown, silt. DEBRIS/HCF DEPOSITS

UNIT 5, 0.32m: Lower boundary is distinct and irregular. Massive, poorly sorted, fine to coarse sandy, angular to sub-angular, fine to medium pebbles. Erosive channels at base with upper boundary marked with 2.0mm light grey silt bed. [SOLE LAYER]

UNIT 4, 0.22m: Lower boundary sharp and planar. Faintly stratified, moderately sorted, fine to medium sand grading to fine to coarse sand.

UNIT 3, 0.12m: Lower boundary is sharp and irregular. Massive, moderately sorted, grey, medium to coarse sand with some, coarse to very coarse, creamy white pumiceous lapilli.

UNIT 2, 0.1m: Lower boundary sharp and planar. Massive, light grey, silt with some fine sand and a few, fine, dark brown, fibrous organics. [SOLE LAYER]

UNIT 1, 0.0m: Lower boundary not observed. Low angle cross-stratified, moderately sorted, dark grey with orange streaked, fine to coarse sand. HCF DEPOSITS]

TU-4: Measured section with relevant descriptions and sample locations.

SF-1

Descriptions

UNIT 7, 1.1m: Lower boundary is diffuse. Massive, weak, friable, loamy fine sand. [TOPSOIL]

UNIT 6, 0.72m: Lower boundary sharp and smooth, marked by thin (2mm), discontinuous, fine to medium sand bed. Masive, poorly sorted, grey, fine to coarse sand with some sub-rounded, fine to medium pebbles grading to stratified, sorted, grey with orange streaked medium to coarse channelised sand. [HCF DEPOSITS]

UNIT 5, 0.66m: Lower boundary is sharp and smooth, marked by an orange iron pan (<0.01cm). Channelised, poorly sorted, friable, grey, fine to coarse sand with some abundant pumice and lithic pebbles in channels. [DEBRIS FLOW DEPOSITS]

UNIT 4, 0.63m: Lower boundary is sharp and wavy. Massive, poorly sorted, fine to coarse sand with few pebbles vertically grading to a laminated, well sorted, grey with orange streaked medium sand. [HCF DEPOSITS]

UNIT 3, 0.6m: Lower boundary is sharp and irregular. Massive, well sorted, friable, orange brown fine sand. Laterally swells and pinches. [SOLE LAYER]

UNIT 2, 0.5m: Lower boundary is distinct and irregular. Abundant, moderately sorted, reddish brown coated creamy white, fine to coarse pumiceous lapilli and few fine, grey, sub-angular to sub-rounded, fine to coarse lithic lapilli in a reddish brown sandy ash matrix. [PUMICEOUS TEPHRA]

UNIT 1, 0.0m: Lower boundary not observed. Massive, firm, friable, reddish brown fine to medium sand and silt. Few fine to coarse pale brownish white pumiceous lapilli and grey, sub-angular to sub-rounded lithic lapilli. Vertical infilled accumulation of pale brownish white, medium to coarse pumiceous lapilli. [PUMICEOUS TEPHRA]

SF-1: Measured section with relevant descriptions and sample locations. Electron Microprobe Analysis results compared with the East Egmont and Dawson Falls reference Section (Section B1, Appendix B).

EMP Analysis

East Egmont Reference:

- △ Burrell Lapilli
- ▲ Kaupokonui Tephra
- unnamed Vulcanian tephra
- Maketawa Tephra
- ◇ Mg.d, Manganui Tephra
- ◆ Mg.c, Manganui Tephra
- ☆ Mg.b, Manganui Tephra
- ★ Mg.d, Manganui Tephra
- Il.b, upper Inglewood Tephra
- Il.a, upper Inglewood Tephra
- ✕ Korito Tephra

Samples:

- ✕ TS-7
- ✕ TS-8
- ✕ TS-9
- ✕ TS-10

MG-1: Measured section with relevant descriptions and sample locations. Grain size histograms and Electron Microprobe Analysis results compared with the East Egmont and Dawson Falls reference Section (Section B1, Appendix B).

A2 – Stratigraphic Correlation

The measured sections presented in section A1 are correlated using well-developed paleosols and laterally continuous tephra marker beds supported by EMP analysis.

Appendix B: Electron Microprobe Dataset

B1 – Reference Major Elemental Glass Composition

Presented is the reference Electron Microprobe Analysis dataset showing the major elemental glass compositions of the sampled reference tephra sections at East Egmont and Dawson Falls. This is unpublished data provided by A/Prof Brent Alloway for the correlation of tephra beds identified in this study with the existing stratigraphic and tephrochronologic framework.

East Egmont EMP Reference Dataset

Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	Na ₂ O+K ₂ O	Correlative
498	66.22	17.13	0.46	2.94	0.88	0.11	2.87	4.61	4.57	9.18	Burrell_1
485	66.13	16.50	0.71	3.19	1.20	0.15	2.59	4.55	4.71	9.26	Burrell_2
486	65.93	16.82	0.49	3.21	1.00	0.13	2.60	4.95	4.63	9.58	Burrell_3
489	66.16	17.13	0.60	2.93	0.88	0.15	2.66	4.53	4.75	9.28	Burrell_4
490	66.35	17.13	0.38	2.77	0.90	0.00	2.72	4.74	4.76	9.50	Burrell_5
493	66.32	17.11	0.48	2.89	0.92	0.10	2.64	4.63	4.64	9.27	Burrell_6
494	66.47	16.95	0.37	2.87	0.86	0.18	2.61	4.73	4.65	9.38	Burrell_7
495	65.51	17.40	0.53	3.10	0.93	0.11	3.09	4.55	4.57	9.11	Burrell_8
404	62.56	18.25	0.77	3.88	1.13	0.19	4.28	5.25	3.59	8.84	Kp-1
405	63.04	17.19	0.83	4.41	1.43	0.19	3.75	4.90	4.09	8.99	Kp-2
406	63.17	17.11	0.80	4.42	1.49	0.26	3.74	4.78	4.01	8.79	Kp-3
407	63.41	17.18	1.00	4.01	1.33	0.14	3.39	5.00	4.35	9.36	Kp-4
408	62.11	17.35	0.57	4.86	1.64	0.23	4.18	4.88	4.01	8.89	Kp-5
409	61.56	17.91	0.76	4.62	1.64	0.16	4.59	5.24	3.39	8.64	Kp-6
410	63.17	16.77	0.73	4.82	1.72	0.12	3.71	4.79	4.12	8.91	Kp-7
411	60.93	19.50	0.58	3.53	1.13	0.12	5.46	5.88	2.74	8.62	Kp-8
413	63.31	17.25	0.80	4.65	1.50	0.12	3.55	4.50	4.06	8.57	Kp-9
414	63.42	17.07	0.81	4.58	1.55	0.16	3.54	4.62	4.01	8.62	Kp-10
415	63.93	17.04	0.61	4.38	1.51	0.03	3.58	4.57	4.20	8.76	Kp-11
417	64.17	17.19	0.56	4.30	1.16	0.16	3.39	4.52	4.34	8.86	Kp-12
418	61.22	18.38	0.75	4.43	1.25	0.09	4.89	5.51	3.31	8.82	Kp-13
420	63.73	16.98	0.53	3.92	1.43	0.10	3.25	5.11	4.70	9.81	Vulc_1
422	65.90	17.27	0.46	3.10	0.99	0.14	2.83	4.88	4.16	9.04	Vulc_2
423	65.80	17.13	0.72	3.14	0.88	0.19	2.87	4.89	4.19	9.08	Vulc_3
424	65.25	16.28	0.70	3.81	1.16	0.11	2.68	5.30	4.45	9.75	Vulc_4
425	69.58	16.17	0.39	1.99	0.43	0.00	1.85	4.43	4.89	9.32	Vulc_5
426	65.93	16.93	0.46	3.29	1.05	0.11	2.86	4.89	4.21	9.10	Vulc_6
427	65.44	17.38	0.48	3.21	0.92	0.25	2.89	4.83	4.42	9.26	Vulc_7
428	69.28	16.14	0.23	2.04	0.41	0.08	2.10	4.66	4.82	9.49	Vulc_8
429	65.12	17.77	0.43	2.93	0.81	0.14	3.82	5.28	3.52	8.80	Vulc_9
432	69.78	15.89	0.39	1.98	0.40	0.19	1.96	4.38	4.78	9.15	Vulc_10
438	68.31	16.60	0.50	2.33	0.61	0.13	2.11	4.71	4.46	9.17	Mk_1
443	68.44	16.62	0.41	2.36	0.56	0.11	2.19	4.63	4.49	9.12	Mk_2
510	56.84	17.34	0.68	6.86	2.66	0.25	7.26	5.08	2.86	7.94	Mg4_1
506	57.20	17.29	0.90	7.19	2.84	0.19	6.22	5.03	2.98	8.02	Mg4_2
508	58.16	17.72	1.17	6.33	1.69	0.12	5.12	5.67	3.87	9.53	Mg4_3
513	58.17	15.84	1.21	7.30	2.46	0.32	5.76	5.01	3.77	8.78	Mg4_4
514	58.28	16.31	1.16	7.32	2.24	0.26	5.71	4.67	3.79	8.46	Mg4_5
530	60.37	18.72	0.85	4.60	1.05	0.12	4.43	5.98	3.66	9.63	Mg3_1
525	59.36	19.26	0.63	4.99	1.15	0.14	5.12	6.41	2.82	9.24	Mg3_2
528	62.87	17.25	0.95	4.53	1.04	0.18	3.16	5.25	4.56	9.81	Mg3_3
523	59.17	20.26	0.67	4.12	0.95	0.15	5.39	6.18	2.92	9.10	Mg3_4
537	56.57	16.24	1.29	8.26	2.46	0.31	5.18	5.16	4.31	9.47	Mg2_1
540	56.58	17.47	1.52	7.70	1.58	0.16	5.31	5.57	3.86	9.43	Mg2_2

Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	Na ₂ O+K ₂ O	Correlative
551	59.63	16.14	1.03	7.26	1.93	0.20	4.41	4.93	4.24	9.16	Mg1_1
552	59.07	16.93	1.09	6.87	1.96	0.15	4.58	5.03	4.11	9.14	Mg1_2
560	58.82	16.54	1.29	6.71	1.97	0.18	4.88	5.38	3.95	9.33	Mg1_3
561	59.12	16.42	1.24	7.05	1.91	0.28	4.48	5.09	4.16	9.26	Mg1_4
558	58.89	17.45	1.00	6.14	1.75	0.36	5.01	5.61	3.68	9.29	Mg1_5
553	57.63	18.73	1.00	5.85	1.57	0.21	5.97	5.50	3.33	8.83	Mg1_6
454	72.65	14.71	0.41	1.46	0.25	0.07	1.26	4.25	4.63	8.88	II2.1
455	72.35	15.05	0.30	1.49	0.24	0.16	1.35	4.17	4.67	8.84	II2.2
457	72.17	15.28	0.35	1.57	0.29	0.02	1.36	4.31	4.43	8.74	II2.3
459	72.45	14.62	0.32	1.65	0.32	0.15	1.44	4.27	4.60	8.87	II2.4
460	72.44	14.89	0.41	1.39	0.25	0.10	1.30	4.13	4.79	8.92	II2.5
463	72.47	14.76	0.39	1.40	0.30	0.15	1.30	4.36	4.57	8.93	II2.6
464	73.14	14.89	0.26	1.48	0.32	0.05	1.36	3.63	4.68	8.31	II2.7
465	73.32	14.79	0.40	1.44	0.28	0.06	1.31	3.59	4.63	8.22	II2.8
466	72.42	14.82	0.21	1.55	0.32	0.14	1.34	4.26	4.72	8.98	II2.9
468	72.49	14.93	0.32	1.58	0.30	0.09	1.48	4.16	4.42	8.58	II1_1
469	72.45	14.97	0.43	1.57	0.27	0.19	1.39	3.94	4.48	8.42	II1_2
470	72.77	14.95	0.35	1.42	0.33	0.09	1.33	3.81	4.66	8.47	II1_3
471	72.52	14.92	0.02	1.61	0.29	0.21	1.41	4.10	4.59	8.69	II1_4
472	72.68	14.87	0.43	1.47	0.27	0.01	1.26	4.12	4.63	8.75	II1_5
474	72.68	14.95	0.29	1.66	0.23	0.05	1.39	3.98	4.50	8.49	II1_6
476	72.08	15.12	0.56	1.49	0.27	0.11	1.38	4.01	4.66	8.66	II1_7
478	72.74	14.85	0.41	1.40	0.27	0.02	1.35	3.97	4.70	8.67	II1_8
479	72.17	14.89	0.29	1.48	0.27	0.14	1.42	4.30	4.77	9.07	II1_9
481	72.75	14.58	0.34	1.48	0.27	0.18	1.28	4.16	4.67	8.83	II1_10
482	72.91	14.76	0.30	1.35	0.28	0.05	1.20	4.01	4.84	8.85	II1_11
567	71.96	15.15	0.18	1.65	0.34	0.11	1.43	4.31	4.64	8.95	J_1
568	71.89	15.19	0.36	1.61	0.31	0.05	1.45	4.36	4.55	8.91	J_2
569	71.85	15.14	0.39	1.68	0.34	0.15	1.52	4.11	4.54	8.64	J_3
570	72.04	15.23	0.30	1.53	0.28	0.19	1.51	4.17	4.52	8.69	J_4
571	72.13	15.20	0.60	1.54	0.29	0.15	1.50	3.94	4.43	8.37	J_5
572	72.01	14.89	0.34	1.54	0.29	0.17	1.57	4.25	4.63	8.88	J_6
573	71.75	15.11	0.59	1.60	0.28	0.23	1.52	4.32	4.40	8.72	J_7
574	72.11	15.04	0.32	1.47	0.27	0.05	1.43	4.44	4.68	9.13	J_8
575	72.09	14.93	0.39	1.58	0.28	0.15	1.52	4.31	4.51	8.82	J_9
578	72.14	15.23	0.28	1.60	0.30	0.09	1.47	4.13	4.54	8.67	J_10
579	71.87	15.12	0.35	1.64	0.34	0.20	1.41	4.27	4.61	8.88	J_11
580	72.09	15.15	0.23	1.72	0.31	0.03	1.58	4.26	4.38	8.64	J_12

Dawson Falls EMP Reference Dataset

Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	NA ₂ O+K ₂ O	Correlative
396	65.99	16.94	0.73	2.91	0.92	0.11	2.73	4.79	4.61	9.40	Burrell_2
383	65.69	17.21	0.78	2.85	0.80	0.16	2.73	4.99	4.57	9.56	Burrell_3
387	66.00	16.82	0.54	3.08	0.88	0.10	2.80	4.84	4.71	9.55	Burrell_4
393	65.81	17.12	0.57	2.97	0.85	0.10	3.00	4.69	4.64	9.33	Burrell_5
394	67.01	16.93	0.34	2.63	0.73	0.12	2.36	4.93	4.74	9.67	Burrell_6
295	62.24	17.55	0.89	4.75	1.72	0.21	3.83	4.67	3.93	8.60	Kp-1
296	62.16	16.74	0.96	5.16	1.95	0.10	4.03	4.69	4.00	8.69	Kp-2
297	61.78	17.49	0.78	5.07	1.57	0.01	4.45	4.98	3.72	8.70	Kp-3
298	61.21	17.54	0.65	4.98	1.79	0.10	4.71	5.04	3.79	8.83	Kp-4
299	62.14	17.03	0.66	5.20	1.64	0.19	4.23	4.80	3.95	8.75	Kp-5
301	62.03	17.32	0.62	4.93	1.77	0.15	4.42	4.95	3.67	8.63	Kp-6
303	61.95	17.71	0.88	4.62	1.61	0.19	4.09	4.69	4.06	8.74	Kp-7
304	62.41	17.63	0.67	4.61	1.59	0.09	4.12	4.86	3.81	8.67	Kp-8
305	63.15	17.75	0.73	4.29	1.56	0.03	3.85	4.75	3.71	8.47	Kp-9
308	63.50	17.00	0.71	4.56	1.54	0.11	3.42	4.68	4.32	9.00	Kp-10
309	61.88	19.05	0.59	3.68	1.03	0.09	4.81	5.39	3.25	8.64	Kp-11
310	62.02	19.41	0.50	3.32	0.98	0.12	4.84	5.64	3.13	8.77	Kp-12
311	60.60	19.03	0.43	4.10	1.55	0.22	5.68	5.48	2.73	8.21	Kp-13
320	61.58	19.15	0.55	3.35	1.10	0.12	5.18	5.78	3.00	8.79	Up-Un-1
321	62.08	17.08	0.75	4.45	2.02	0.13	3.92	4.46	4.90	9.36	Up-Un-2
318	63.31	16.59	0.50	4.79	1.46	0.16	3.68	5.88	3.39	9.26	Up-Un-3
326	65.61	16.80	0.67	3.37	1.06	0.12	2.75	5.21	4.19	9.41	Up-Un-4
327	63.22	17.17	0.81	3.90	1.41	0.09	3.42	6.05	3.72	9.76	Up-Un-5
328	61.50	17.52	0.65	3.76	2.34	0.19	5.81	5.56	2.56	8.12	Up-Un-6
345	66.03	16.90	0.47	3.21	1.01	0.24	2.75	4.91	4.33	9.24	Lwr-Un-1
330	66.41	17.30	0.29	2.61	0.68	0.08	3.56	5.26	3.54	8.80	Lwr-Un-2
334	66.49	17.14	0.38	3.07	0.72	0.09	2.68	5.01	4.12	9.13	Lwr-Un-3
337	66.73	16.79	0.76	2.92	0.84	0.16	2.52	4.74	4.26	8.99	Lwr-Un-4
341	66.04	16.90	0.54	3.51	0.76	0.12	2.55	5.26	4.09	9.34	Lwr-Un-5
364	67.79	16.64	0.38	2.47	0.65	0.09	2.34	4.82	4.53	9.35	Mk-1
365	68.29	16.77	0.25	2.38	0.60	0.10	2.17	4.87	4.36	9.22	Mk-2
351	67.40	16.90	0.52	2.79	0.60	0.15	2.19	4.93	4.30	9.24	Mk-3
353	66.50	17.70	0.63	2.42	0.58	0.13	3.06	4.95	3.86	8.80	Mk-4
354	68.31	16.75	0.39	2.33	0.62	0.08	2.14	4.73	4.41	9.14	Mk-5
355	68.39	16.66	0.30	2.38	0.57	0.12	2.19	4.70	4.44	9.14	Mk-6
357	68.49	16.25	0.57	2.36	0.58	0.01	2.15	4.89	4.46	9.35	Mk-8
358	68.46	16.62	0.48	2.30	0.58	0.05	2.20	4.64	4.42	9.07	Mk-9
361	68.64	16.51	0.38	2.22	0.55	0.09	1.92	4.83	4.51	9.34	Mk-10
362	67.29	16.52	0.55	2.42	0.65	0.06	3.31	4.71	4.31	9.02	Mk-11

B2 – Study Electron Microprobe Dataset

Presented is the Electron Microprobe Analysis dataset showing the major elemental glass compositions of tephra beds sampled at East Egmont (TS-14, TS-15 and TS-16), Vickers Quarry (TS-19, TS-20, TS-21, TS-22 and TS-28), York Road (TS-23, TS-24 and TS-25), Tariki Underpass (TS-11, TS-12, TS-13, TS-29 and TS-30), Suffolk Road (TS-7, TS-8, TS-9 and TS-10) and Kaimata Sawmills (TS-1, TS-2, TS-3, TS-4 and TS-5) sections. The alternating blue and white cells discriminate between each tephra sample (i.e. TS-1, TS-2).

Study EMP Dataset												
Section	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	NA ₂ O+K ₂ O	Correlative
MG-1	108	71.87	14.84	0.36	1.84	0.40	0.18	1.62	4.28	4.60	8.89	TS1_1
MG-1	110	71.39	15.48	0.35	1.63	0.23	0.15	1.90	4.31	4.53	8.84	TS1_2
MG-1	115	70.62	15.91	0.34	1.74	0.22	0.11	2.06	4.68	4.30	8.98	TS1_3
MG-1	119	71.93	14.72	0.41	1.92	0.28	0.13	1.69	4.32	4.58	8.90	TS1_4
MG-1	120	71.37	15.34	0.35	1.62	0.27	0.10	2.14	4.73	4.07	8.80	TS1_5
MG-1	122	72.80	14.67	0.35	1.51	0.28	0.08	1.28	4.33	4.69	9.02	TS2_1
MG-1	123	72.98	14.80	0.34	1.48	0.30	0.08	1.23	4.29	4.48	8.78	TS2_2
MG-1	124	71.49	14.87	0.33	1.56	0.33	0.15	2.15	4.44	4.65	9.09	TS2_3
MG-1	125	72.85	14.92	0.31	1.42	0.26	0.16	1.23	4.25	4.59	8.83	TS2_4
MG-1	128	72.54	14.72	0.31	1.58	0.28	0.08	1.25	4.67	4.56	9.23	TS2_5
MG-1	129	73.18	14.83	0.33	1.38	0.25	0.05	1.29	3.90	4.76	8.66	TS2_6
MG-1	130	73.24	14.85	0.33	1.46	0.29	0.10	1.27	3.79	4.64	8.42	TS2_7
MG-1	131	73.07	14.89	0.31	1.53	0.27	0.11	1.29	3.97	4.54	8.51	TS2_8
MG-1	132	73.10	14.82	0.33	1.60	0.24	0.05	1.26	3.87	4.73	8.59	TS2_9
MG-1	134	72.02	14.92	0.35	1.66	0.32	0.08	1.70	4.24	4.68	8.92	TS2_10
MG-1	135	72.91	14.93	0.34	1.50	0.28	0.11	1.27	4.03	4.62	8.65	TS2_11
MG-1	136	73.01	14.78	0.31	1.45	0.30	0.10	1.28	4.16	4.58	8.74	TS2_12
MG-1	143	73.26	14.82	0.36	1.52	0.30	0.10	1.17	3.62	4.80	8.43	TS3_1
MG-1	144	72.46	14.44	0.37	1.71	0.29	0.09	1.12	4.41	5.09	9.51	TS3_2
MG-1	145	73.39	14.46	0.36	1.60	0.30	0.11	1.04	3.94	4.79	8.73	TS3_3
MG-1	146	73.28	14.53	0.37	1.65	0.30	0.13	1.09	3.94	4.69	8.63	TS3_4
MG-1	148	72.54	15.00	0.34	1.45	0.35	0.14	1.23	4.29	4.64	8.93	TS3_5
MG-1	150	73.37	14.50	0.32	1.60	0.29	0.10	1.02	4.15	4.64	8.79	TS3_6
MG-1	152	73.10	14.63	0.35	1.53	0.30	0.18	1.03	4.09	4.76	8.85	TS3_7
MG-1	153	72.83	14.97	0.37	1.53	0.27	0.07	1.36	4.23	4.36	8.58	TS3_8
MG-1	154	73.33	14.69	0.36	1.65	0.30	0.09	1.01	3.81	4.75	8.56	TS3_9
MG-1	155	71.13	16.46	0.29	1.37	0.26	0.09	1.91	4.40	4.08	8.47	TS3_10
MG-1	157	70.68	15.88	0.43	1.91	0.38	0.11	1.74	4.50	4.36	8.86	TS4_1
MG-1	158	71.78	16.04	0.40	1.75	0.39	0.15	1.63	3.44	4.40	7.84	TS4_2
MG-1	159	70.55	15.69	0.42	1.79	0.41	0.12	1.74	4.72	4.54	9.27	TS4_3
MG-1	164	70.58	15.69	0.39	1.85	0.37	0.12	1.56	5.13	4.30	9.43	TS4_4
MG-1	165	70.60	15.84	0.40	1.78	0.42	0.10	1.77	4.71	4.36	9.07	TS4_5
MG-1	166	70.59	15.74	0.41	1.99	0.41	0.10	1.78	4.60	4.36	8.96	TS4_6

Section	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	Na ₂ O+K ₂ O	Correlative
MG-1	167	70.58	15.75	0.40	1.71	0.44	0.11	1.74	4.87	4.38	9.25	TS4_7
MG-1	169	71.39	15.64	0.37	1.68	0.39	0.10	1.42	4.99	4.02	9.01	TS4_8
MG-1	171	70.98	15.76	0.43	1.91	0.36	0.11	1.73	4.26	4.43	8.69	TS4_9
MG-1	157	70.68	15.88	0.43	1.91	0.38	0.11	1.74	4.50	4.36	8.86	TS5_1
MG-1	158	71.78	16.04	0.40	1.75	0.39	0.15	1.63	3.44	4.40	7.84	TS5_2
MG-1	159	70.55	15.69	0.42	1.79	0.41	0.12	1.74	4.72	4.54	9.27	TS5_3
MG-1	164	70.58	15.69	0.39	1.85	0.37	0.12	1.56	5.13	4.30	9.43	TS5_4
MG-1	165	70.60	15.84	0.40	1.78	0.42	0.10	1.77	4.71	4.36	9.07	TS5_5
MG-1	166	70.59	15.74	0.41	1.99	0.41	0.10	1.78	4.60	4.36	8.96	TS5_6
MG-1	167	70.58	15.75	0.40	1.71	0.44	0.11	1.74	4.87	4.38	9.25	TS5_7
MG-1	169	71.39	15.64	0.37	1.68	0.39	0.10	1.42	4.99	4.02	9.01	TS5_8
MG-1	171	70.98	15.76	0.43	1.91	0.36	0.11	1.73	4.26	4.43	8.69	TS5_9
MG-1	188	71.95	15.34	0.34	1.56	0.26	0.14	1.51	4.24	4.66	8.90	TS5_10
MG-1	190	72.32	14.67	0.36	1.86	0.30	0.19	1.35	4.04	4.88	8.93	TS5_11
MG-1	191	72.44	14.79	0.38	1.70	0.24	0.08	1.29	4.26	4.80	9.06	TS5_12
SF-1	192	70.77	15.72	0.39	1.87	0.38	0.13	1.63	4.92	4.18	9.10	TS-7_1
SF-1	193	70.12	15.92	0.43	2.19	0.49	0.14	1.76	4.68	4.25	8.93	TS-7_2
SF-1	194	70.81	15.55	0.44	1.75	0.38	0.16	1.65	4.93	4.31	9.24	TS-7_3
SF-1	196	70.63	15.87	0.39	1.83	0.42	0.11	1.74	4.71	4.27	8.98	TS-7_4
SF-1	197	70.04	15.98	0.40	1.96	0.40	0.12	1.79	4.97	4.31	9.28	TS-7_5
SF-1	198	70.59	15.64	0.44	1.91	0.42	0.12	1.79	4.83	4.23	9.05	TS-7_6
SF-1	199	70.77	15.66	0.43	1.86	0.40	0.13	1.71	4.61	4.38	9.00	TS-7_7
SF-1	200	70.97	15.52	0.42	1.91	0.38	0.04	1.76	4.81	4.17	8.98	TS-7_8
SF-1	201	70.66	15.63	0.43	1.93	0.40	0.14	1.71	4.85	4.23	9.08	TS-7_9
SF-1	81	70.88	15.45	0.44	1.88	0.39	0.15	1.71	4.77	4.30	9.07	TS8_1
SF-1	82	70.85	15.69	0.40	1.82	0.40	0.10	1.68	4.76	4.28	9.05	TS8_2
SF-1	83	70.88	15.43	0.41	1.78	0.40	0.20	1.77	4.70	4.41	9.11	TS8_3
SF-1	84	70.39	16.01	0.37	1.91	0.39	0.14	2.20	4.66	3.89	8.56	TS8_4
SF-1	85	71.22	15.60	0.42	1.82	0.41	0.08	1.67	4.49	4.28	8.77	TS8_5
SF-1	86	71.06	15.54	0.42	1.79	0.39	0.08	1.73	4.67	4.32	8.98	TS8_6
SF-1	87	70.48	15.70	0.40	1.78	0.36	0.15	1.69	5.01	4.42	9.43	TS8_7
SF-1	89	70.73	15.71	0.42	1.87	0.38	0.10	1.71	4.76	4.29	9.05	TS8_8
SF-1	90	71.01	15.58	0.41	1.80	0.41	0.14	1.71	4.52	4.41	8.93	TS8_9
SF-1	91	72.62	15.17	0.30	1.26	0.23	0.08	1.33	4.28	4.71	9.00	TS9_1
SF-1	92	68.22	18.77	0.22	0.93	0.08	0.04	3.58	4.80	3.36	8.16	TS9_2
SF-1	93	73.52	14.53	0.34	1.42	0.25	0.06	1.17	3.69	5.01	8.70	TS9_3
SF-1	94	74.77	13.73	0.38	1.39	0.15	0.10	0.68	3.49	5.29	8.79	TS9_4
SF-1	95	73.67	14.19	0.35	1.47	0.20	0.12	1.03	3.85	5.09	8.94	TS9_5
SF-1	96	72.90	14.93	0.32	1.35	0.19	0.05	1.53	4.13	4.58	8.71	TS9_6
SF-1	99	72.20	15.32	0.33	1.37	0.14	0.12	1.72	4.69	4.10	8.79	TS9_7
SF-1	100	73.28	14.18	0.35	1.57	0.25	0.10	1.08	3.99	5.18	9.17	TS9_8
SF-1	105	67.83	18.31	0.23	1.30	0.48	0.08	3.45	5.28	3.05	8.33	TS9_9
SF-1	112	65.03	17.04	0.61	4.00	1.15	0.17	2.88	4.91	4.18	9.09	TS10_1
SF-1	113	65.60	17.18	0.63	3.37	1.08	0.17	2.74	4.94	4.28	9.22	TS10_2
SF-1	114	65.61	17.08	0.59	3.49	1.18	0.15	2.99	4.74	4.17	8.91	TS10_3

Section	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	Na ₂ O+K ₂ O	Correlative
SF-1	115	65.39	17.33	0.61	3.44	1.20	0.15	2.72	4.94	4.21	9.15	TS10_4
SF-1	116	65.43	16.81	0.64	3.57	1.21	0.15	3.08	4.86	4.22	9.08	TS10_5
SF-1	117	64.01	16.59	0.47	2.87	2.19	0.14	5.71	4.32	3.69	8.01	TS10_6
SF-1	119	69.22	15.90	0.45	2.53	0.59	0.09	1.58	4.53	5.10	9.63	TS10_7
SF-1	121	65.36	17.12	0.61	3.64	1.18	0.15	3.00	4.87	4.05	8.92	TS10_8
SF-1	122	65.30	17.17	0.63	3.49	1.24	0.07	3.07	4.85	4.16	9.01	TS10_9
SF-1	123	65.47	17.08	0.62	3.61	1.19	0.20	3.00	4.64	4.18	8.82	TS10_10
SF-1	124	65.26	17.03	0.66	3.51	1.28	0.14	2.92	5.00	4.19	9.19	TS10_11
SF-1	125	65.46	16.97	0.64	3.63	1.13	0.15	2.86	4.94	4.20	9.14	TS10_12
SF-1	126	64.60	17.03	0.65	4.07	1.21	0.13	3.00	5.13	4.18	9.30	TS10_13
SF-1	127	65.23	17.02	0.61	3.62	1.19	0.18	2.98	4.96	4.19	9.15	TS10_14
SF-1	128	65.49	17.19	0.63	3.56	1.17	0.19	2.96	4.67	4.14	8.80	TS10_15
SF-1	129	65.36	17.22	0.69	3.51	1.15	0.08	2.82	4.92	4.25	9.16	TS10_16
SF-1	130	64.91	17.01	0.62	3.73	1.29	0.13	3.10	5.02	4.17	9.19	TS10_17
SF-1	131	65.34	17.01	0.65	3.69	1.21	0.11	2.93	4.91	4.13	9.03	TS10_18
TU-1	137	72.99	14.71	0.32	1.55	0.31	0.11	1.26	4.08	4.64	8.72	TS11_1
TU-1	138	72.75	14.69	0.34	1.65	0.27	0.11	1.26	4.04	4.85	8.89	TS11_2
TU-1	139	73.05	14.65	0.32	1.53	0.28	0.12	1.17	4.04	4.83	8.87	TS11_3
TU-1	140	73.00	14.60	0.38	1.45	0.29	0.13	1.12	4.19	4.82	9.01	TS11_4
TU-1	141	73.35	14.82	0.33	1.68	0.29	0.11	1.23	3.57	4.61	8.18	TS11_5
TU-1	142	74.84	15.04	0.36	1.65	0.28	0.11	1.37	1.63	4.71	6.34	TS11_6
TU-1	144	72.51	14.96	0.32	1.57	0.29	0.09	1.35	4.17	4.71	8.89	TS11_7
TU-1	146	72.20	15.17	0.34	1.67	0.30	0.12	1.32	4.41	4.45	8.86	TS11_8
TU-1	147	72.41	14.95	0.34	1.58	0.31	0.12	1.32	4.41	4.56	8.97	TS11_9
TU-1	148	72.99	14.45	0.38	1.49	0.27	0.18	1.17	4.16	4.89	9.05	TS11_10
TU-1	149	72.28	15.12	0.32	1.73	0.27	0.08	1.46	3.99	4.73	8.72	TS11_11
TU-1	150	71.33	15.81	0.30	1.69	0.30	0.10	1.54	4.32	4.61	8.93	TS11_12
TU-1	158	71.72	15.34	0.45	1.86	0.30	0.13	1.59	4.23	4.37	8.60	TS12_1
TU-1	159	71.12	15.72	0.44	1.91	0.33	0.04	1.82	4.11	4.49	8.60	TS12_2
TU-1	160	70.29	16.07	0.39	1.99	0.27	0.09	1.87	4.48	4.53	9.01	TS12_3
TU-1	163	71.18	15.55	0.38	1.67	0.34	0.10	1.64	4.65	4.47	9.13	TS12_4
TU-1	164	70.89	15.59	0.42	1.87	0.38	0.07	1.68	4.73	4.33	9.07	TS12_5
TU-1	165	71.11	15.50	0.40	1.88	0.39	0.14	1.70	4.45	4.40	8.85	TS12_6
TU-1	167	70.73	15.47	0.44	1.93	0.30	0.14	1.79	4.79	4.40	9.18	TS12_7
TU-1	175	74.81	13.83	0.36	1.08	0.16	0.13	0.74	3.63	5.22	8.85	TS13_1
TU-1	176	74.71	13.52	0.35	1.35	0.14	0.16	0.62	3.75	5.36	9.12	TS13_2
TU-1	177	70.84	16.02	0.28	1.25	0.30	0.15	2.03	5.08	4.06	9.13	TS13_3
TU-1	178	73.36	14.33	0.41	1.83	0.21	0.11	1.04	3.50	5.20	8.69	TS13_4
TU-1	180	73.00	14.42	0.41	1.82	0.22	0.17	1.16	3.86	4.93	8.79	TS13_5
TU-1	181	71.76	14.77	0.30	1.88	0.83	0.18	1.65	4.32	4.30	8.61	TS13_6
TU-1	183	73.08	13.34	0.33	1.89	0.80	0.26	1.45	3.78	5.06	8.83	TS13_7
TU-1	184	74.43	13.99	0.36	1.30	0.14	0.09	0.80	3.70	5.18	8.87	TS13_8
TU-1	186	65.47	17.27	0.67	3.91	0.93	0.10	2.42	4.88	4.34	9.22	TS13_9
TU-1	187	73.34	13.92	0.42	1.79	0.32	0.15	0.92	3.72	5.40	9.12	TS13_10
TU-1	188	69.08	17.51	0.25	1.35	0.22	0.09	3.05	4.84	3.60	8.44	TS13_11

Section	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	Na ₂ O+K ₂ O	Correlative
EE-1	191	72.64	14.81	0.33	1.65	0.31	0.14	1.37	4.01	4.74	8.74	TS14_1
EE-1	192	72.87	14.81	0.32	1.54	0.28	0.12	1.39	4.02	4.61	8.63	TS14_2
EE-1	193	72.42	14.97	0.32	1.62	0.29	0.05	1.37	4.37	4.58	8.95	TS14_3
EE-1	194	72.90	14.95	0.31	1.32	0.28	0.10	1.33	4.15	4.66	8.81	TS14_4
EE-1	195	74.65	15.04	0.32	1.56	0.30	0.10	1.38	2.06	4.58	6.63	TS14_5
EE-1	196	72.58	14.78	0.32	1.68	0.32	0.10	1.37	4.26	4.58	8.84	TS14_6
EE-1	197	72.65	14.86	0.31	1.44	0.30	0.14	1.41	4.18	4.71	8.88	TS14_7
EE-1	198	72.79	14.86	0.31	1.42	0.30	0.11	1.39	4.25	4.56	8.80	TS14_8
EE-1	199	72.48	14.85	0.31	1.69	0.30	0.13	1.36	4.20	4.66	8.86	TS14_9
EE-1	200	72.65	14.84	0.31	1.50	0.30	0.08	1.39	4.25	4.66	8.91	TS14_10
EE-1	201	72.40	14.81	0.33	1.56	0.31	0.15	1.37	4.43	4.64	9.06	TS14_11
EE-1	202	72.31	14.78	0.34	1.62	0.28	0.09	1.41	4.35	4.79	9.13	TS14_12
EE-1	203	72.86	14.86	0.33	1.46	0.29	0.11	1.39	4.08	4.60	8.67	TS14_13
EE-1	204	72.75	14.72	0.31	1.45	0.31	0.07	1.41	4.41	4.57	8.98	TS14_14
EE-1	210	72.56	14.96	0.30	1.57	0.28	0.08	1.34	4.32	4.57	8.90	TS15_1
EE-1	211	72.32	14.92	0.37	1.76	0.30	0.17	1.47	4.13	4.54	8.67	TS15_2
EE-1	212	73.05	14.70	0.33	1.47	0.28	0.13	1.32	4.01	4.70	8.71	TS15_3
EE-1	213	72.70	14.76	0.32	1.55	0.29	0.12	1.38	4.26	4.61	8.87	TS15_4
EE-1	214	72.51	14.84	0.32	1.47	0.31	0.11	1.40	4.42	4.57	8.99	TS15_5
EE-1	215	72.84	14.97	0.34	1.49	0.30	0.14	1.34	3.92	4.66	8.59	TS15_6
EE-1	216	72.81	14.84	0.32	1.50	0.28	0.04	1.36	4.19	4.62	8.82	TS15_7
EE-1	217	72.60	14.82	0.34	1.65	0.32	0.10	1.41	4.19	4.55	8.74	TS15_8
EE-1	218	72.90	14.87	0.32	1.42	0.26	0.10	1.41	4.09	4.61	8.70	TS15_9
EE-1	220	72.75	14.88	0.30	1.52	0.28	0.12	1.39	4.13	4.59	8.72	TS15_10
EE-1	221	72.78	14.88	0.33	1.59	0.28	0.11	1.34	4.18	4.51	8.69	TS15_11
EE-1	222	72.63	14.71	0.33	1.60	0.32	0.14	1.39	4.31	4.53	8.84	TS15_12
EE-1	223	72.63	14.82	0.35	1.64	0.25	0.07	1.39	4.34	4.49	8.83	TS15_13
EE-1	224	72.62	14.97	0.34	1.60	0.32	0.11	1.34	4.15	4.52	8.67	TS15_14
EE-1	225	72.73	14.91	0.30	1.55	0.29	0.13	1.37	4.04	4.68	8.72	TS15_15
EE-1	226	72.53	14.86	0.31	1.55	0.29	0.09	1.43	4.40	4.53	8.94	TS15_16
EE-1	227	72.29	15.02	0.32	1.56	0.31	0.16	1.52	4.16	4.64	8.80	TS15_17
NA	247	67.81	16.34	0.50	2.71	0.76	0.10	1.93	4.90	4.90	9.80	TS17_1
NA	248	67.43	16.97	0.45	2.68	0.65	0.14	2.35	4.67	4.66	9.33	TS17_2
NA	250	67.90	16.22	0.52	2.67	0.73	0.13	1.82	4.97	5.00	9.97	TS17_3
NA	251	66.30	17.73	0.50	2.55	0.66	0.12	3.02	4.86	4.25	9.11	TS17_4
NA	252	67.61	16.42	0.56	2.93	0.71	0.16	1.96	4.66	4.96	9.62	TS17_5
NA	254	67.92	16.65	0.54	2.54	0.64	0.14	2.36	4.50	4.69	9.18	TS17_6
NA	258	67.84	16.40	0.54	2.80	0.69	0.12	1.98	4.80	4.82	9.62	TS17_7
SQ-1	260	72.61	14.98	0.31	1.60	0.31	0.06	1.37	4.19	4.56	8.75	TS18_1
SQ-1	261	72.37	14.96	0.33	1.58	0.29	0.13	1.48	4.11	4.73	8.84	TS18_2
SQ-1	262	72.38	14.91	0.30	1.53	0.29	0.12	1.41	4.04	5.01	9.06	TS18_3
SQ-1	263	72.30	15.06	0.32	1.67	0.30	0.04	1.36	4.15	4.77	8.93	TS18_4
SQ-1	264	72.60	14.86	0.33	1.65	0.27	0.13	1.37	3.89	4.89	8.78	TS18_5
SQ-1	265	72.14	15.05	0.33	1.81	0.29	0.06	1.51	3.98	4.80	8.78	TS18_6
SQ-1	266	71.98	15.07	0.31	1.65	0.31	0.06	1.53	4.26	4.79	9.05	TS18_7

Section	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	Na ₂ O+K ₂ O	Correlative
SQ-1	267	72.72	14.82	0.33	1.56	0.29	0.12	1.42	3.74	4.96	8.70	TS18_8
SQ-1	268	72.52	14.78	0.31	1.64	0.28	0.09	1.42	4.01	4.92	8.93	TS18_9
SQ-1	269	70.40	16.90	0.27	1.24	0.23	0.10	2.47	4.40	3.97	8.37	TS18_10
SQ-1	270	72.17	14.95	0.33	1.72	0.33	0.09	1.48	4.23	4.68	8.91	TS18_11
SQ-1	271	72.61	14.95	0.30	1.51	0.33	0.10	1.41	4.03	4.73	8.76	TS18_12
SQ-1	272	71.88	15.11	0.36	1.81	0.30	0.12	1.59	3.93	4.88	8.81	TS18_13
SQ-1	273	72.20	15.03	0.35	1.69	0.35	0.18	1.41	4.19	4.58	8.77	TS18_14
SQ-1	274	72.02	15.18	0.37	1.68	0.30	0.19	1.47	4.08	4.70	8.78	TS18_15
SQ-1	275	72.56	15.01	0.33	1.48	0.28	0.07	1.40	4.13	4.72	8.85	TS18_16
VQ-1	281	69.95	15.83	0.42	2.08	0.50	0.13	1.87	4.80	4.40	9.20	TS19_1
VQ-1	282	70.26	15.95	0.44	2.06	0.47	0.13	1.80	4.44	4.42	8.86	TS19_2
VQ-1	283	70.15	15.84	0.42	2.07	0.51	0.12	1.77	4.70	4.40	9.10	TS19_3
VQ-1	284	69.83	15.93	0.44	2.07	0.48	0.10	1.81	4.78	4.56	9.33	TS19_4
VQ-1	285	70.25	15.79	0.46	2.11	0.49	0.13	1.81	4.52	4.42	8.94	TS19_5
VQ-1	286	69.98	15.95	0.46	2.14	0.47	0.15	1.79	4.62	4.42	9.04	TS19_6
VQ-1	287	69.82	15.83	0.42	2.20	0.53	0.15	1.87	4.74	4.42	9.16	TS19_7
VQ-1	288	69.96	15.89	0.45	2.15	0.48	0.09	1.86	4.83	4.28	9.11	TS19_8
VQ-1	289	70.01	15.94	0.41	2.11	0.54	0.09	1.82	4.61	4.43	9.05	TS19_9
VQ-1	290	69.84	16.04	0.39	2.14	0.48	0.10	1.87	4.65	4.46	9.11	TS19_10
VQ-1	291	70.33	15.93	0.43	1.91	0.46	0.07	1.86	4.63	4.37	9.00	TS19_11
VQ-1	292	69.82	15.97	0.45	1.98	0.49	0.11	1.88	4.82	4.46	9.29	TS19_12
VQ-1	294	68.88	16.18	0.47	2.54	0.60	0.15	2.18	4.86	4.13	8.99	TS19_13
VQ-1	295	69.99	15.99	0.42	2.16	0.47	0.12	1.83	4.58	4.43	9.01	TS19_14
VQ-1	6	69.44	15.89	0.50	2.51	0.53	0.18	2.06	4.32	4.53	8.86	TS20_1
VQ-1	7	69.87	15.79	0.43	2.21	0.47	0.13	1.96	4.79	4.32	9.11	TS20_2
VQ-1	8	69.90	15.90	0.47	2.26	0.50	0.15	2.04	4.28	4.46	8.74	TS20_3
VQ-1	9	70.45	15.87	0.42	2.13	0.48	0.15	1.94	4.11	4.41	8.52	TS20_4
VQ-1	13	70.13	15.62	0.44	2.21	0.46	0.13	1.94	4.70	4.34	9.05	TS20_5
VQ-1	14	70.18	15.77	0.43	2.21	0.46	0.09	1.96	4.47	4.38	8.85	TS20_6
VQ-1	15	69.90	15.76	0.41	2.12	0.48	0.09	2.00	4.85	4.38	9.22	TS20_7
VQ-1	16	70.01	15.85	0.42	2.03	0.48	0.12	1.94	4.87	4.27	9.13	TS20_8
VQ-1	17	69.95	15.76	0.42	2.16	0.51	0.14	1.98	4.81	4.26	9.07	TS20_9
VQ-1	18	69.82	15.70	0.44	2.37	0.48	0.14	2.00	4.67	4.37	9.04	TS20_10
VQ-1	20	72.47	14.88	0.45	2.07	0.33	0.13	1.08	3.26	5.29	8.55	TS20_11
VQ-1	21	73.76	16.33	0.44	2.06	0.44	0.14	2.08	1.05	3.68	4.72	TS20_12
VQ-1	22	68.32	16.59	0.41	2.14	0.43	0.20	2.91	4.84	4.13	8.98	TS20_13
VQ-1	24	72.32	15.03	0.32	1.64	0.29	0.12	1.42	4.13	4.68	8.81	TS21_1
VQ-1	25	72.58	14.97	0.33	1.57	0.31	0.11	1.36	4.20	4.55	8.75	TS21_2
VQ-1	29	72.06	14.97	0.35	1.60	0.35	0.18	1.41	4.31	4.74	9.06	TS21_3
VQ-1	30	72.20	14.93	0.34	1.63	0.30	0.05	1.39	4.52	4.62	9.13	TS21_4
VQ-1	31	72.77	15.03	0.34	1.80	0.30	0.06	1.36	3.68	4.63	8.31	TS21_5
VQ-1	32	72.44	15.05	0.35	1.63	0.34	0.09	1.35	4.22	4.51	8.74	TS21_6
VQ-1	33	72.61	14.86	0.34	1.45	0.31	0.11	1.34	4.32	4.65	8.97	TS21_7
VQ-1	34	72.42	14.96	0.36	1.64	0.32	0.10	1.37	4.23	4.59	8.81	TS21_8
VQ-1	35	72.27	15.01	0.35	1.53	0.28	0.11	1.38	4.55	4.51	9.07	TS21_9

Section	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	Na ₂ O+K ₂ O	Correlative
VQ-1	44	70.92	15.17	0.40	2.22	0.63	0.09	2.04	4.16	4.35	8.51	TS22_1
VQ-1	46	71.15	15.58	0.42	2.11	0.44	0.12	1.66	4.25	4.25	8.50	TS22_2
VQ-1	47	70.67	15.69	0.42	1.93	0.47	0.09	1.80	4.56	4.32	8.88	TS22_3
VQ-1	48	72.07	14.44	0.35	2.08	0.40	0.18	1.71	4.36	4.33	8.69	TS22_4
VQ-1	50	72.06	15.98	0.40	1.81	0.32	0.06	1.52	3.88	3.93	7.81	TS22_5
VQ-1	53	71.32	15.08	0.39	2.08	0.56	0.11	1.69	4.14	4.62	8.75	TS22_6
YR-1	56	72.94	15.03	0.32	1.53	0.30	0.07	1.34	3.86	4.59	8.45	TS-23-1
YR-1	58	72.41	14.83	0.33	1.57	0.31	0.07	1.40	4.56	4.50	9.06	TS-23-2
YR-1	59	72.54	15.01	0.34	1.56	0.25	0.11	1.38	4.22	4.56	8.78	TS-23-3
YR-1	61	72.38	14.61	0.38	1.71	0.27	0.13	1.36	4.30	4.84	9.14	TS-23-4
YR-1	62	72.57	14.94	0.33	1.65	0.30	0.16	1.42	4.02	4.58	8.60	TS-23-5
YR-1	63	72.60	14.79	0.38	1.62	0.27	0.14	1.29	4.34	4.54	8.88	TS-23-6
YR-1	64	72.57	14.79	0.32	1.48	0.27	0.10	1.32	4.60	4.53	9.13	TS-23-7
YR-1	65	72.58	15.02	0.35	1.47	0.29	0.06	1.32	4.31	4.59	8.90	TS-23-8
YR-1	72	72.55	14.82	0.33	1.36	0.29	0.12	1.37	4.58	4.56	9.14	TS24_1
YR-1	73	72.21	14.82	0.34	1.73	0.31	0.11	1.40	4.44	4.61	9.05	TS24_2
YR-1	75	72.77	14.77	0.35	1.48	0.29	0.09	1.33	4.30	4.59	8.89	TS24_3
YR-1	76	72.80	14.77	0.37	1.54	0.29	0.10	1.28	4.26	4.58	8.84	TS24_4
YR-1	77	72.74	14.87	0.38	1.53	0.29	0.08	1.32	4.14	4.64	8.78	TS24_5
YR-1	78	73.89	15.50	0.28	1.40	0.28	0.13	1.11	2.98	4.42	7.40	TS24_6
YR-1	79	72.83	14.97	0.31	1.41	0.27	0.12	1.56	4.12	4.39	8.51	TS24_7
YR-1	80	72.82	14.68	0.33	1.49	0.29	0.09	1.36	4.18	4.74	8.92	TS24_8
YR-1	81	72.07	14.87	0.33	1.89	0.31	0.11	1.33	4.51	4.55	9.06	TS24_9
YR-1	82	72.45	14.71	0.38	1.72	0.26	0.13	1.38	4.23	4.70	8.93	TS24_10
YR-1	85	73.24	15.18	0.36	1.38	0.27	0.05	1.21	3.77	4.51	8.28	TS24_11
YR-1	86	72.58	14.55	0.37	1.88	0.27	0.13	1.35	4.16	4.71	8.87	TS24_12
YR-1	89	71.85	15.09	0.42	1.90	0.36	0.14	1.23	4.09	4.89	8.98	TS-25_1
YR-1	93	68.64	16.45	0.45	2.49	0.53	0.15	2.43	4.88	3.92	8.81	TS-25_2
YR-1	95	69.31	16.04	0.44	2.31	0.53	0.16	2.04	4.91	4.23	9.14	TS-25_3
YR-1	96	69.50	16.36	0.38	2.25	0.55	0.09	2.18	4.44	4.23	8.67	TS-25_4
YR-1	97	70.41	15.55	0.40	2.01	0.45	0.13	1.71	4.77	4.54	9.30	TS-25_5
YR-1	98	69.39	16.10	0.46	2.32	0.51	0.12	2.19	4.48	4.42	8.89	TS-25_6
YR-1	100	69.84	15.89	0.45	2.22	0.50	0.09	1.94	4.57	4.48	9.04	TS-25_7
YR-1	101	69.61	15.94	0.46	2.32	0.51	0.09	2.01	4.63	4.42	9.04	TS-25_8
VQ-1	296	73.07	14.72	0.34	1.41	0.26	0.05	1.31	4.01	4.80	8.82	TS28_1
VQ-1	297	72.80	14.71	0.34	1.48	0.30	0.07	1.29	4.12	4.87	8.99	TS28_2
VQ-1	299	72.98	14.64	0.35	1.53	0.26	0.11	1.29	4.17	4.63	8.80	TS28_3
VQ-1	300	72.74	14.87	0.31	1.42	0.26	0.12	1.31	4.18	4.77	8.96	TS28_4
VQ-1	301	72.70	14.64	0.33	1.47	0.29	0.12	1.28	4.46	4.68	9.15	TS28_5
VQ-1	302	73.01	14.70	0.34	1.34	0.28	0.10	1.29	4.22	4.69	8.91	TS28_6
VQ-1	303	72.63	14.83	0.35	1.45	0.30	0.14	1.31	4.26	4.70	8.96	TS28_7
VQ-1	304	72.71	14.70	0.38	1.59	0.23	0.14	1.32	4.25	4.66	8.90	TS28_8
VQ-1	305	72.99	14.59	0.30	1.52	0.28	0.08	1.34	4.23	4.64	8.88	TS28_9
VQ-1	306	72.91	14.71	0.35	1.49	0.27	0.05	1.33	4.30	4.56	8.86	TS28_10
TU-2	313	73.44	14.20	0.37	1.62	0.17	0.10	1.01	4.09	4.98	9.07	TS29_1

Section	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	Na ₂ O+K ₂ O	Correlative
TU-2	314	72.47	15.21	0.33	1.55	0.16	0.13	1.50	4.15	4.48	8.63	TS29_2
TU-2	316	69.69	17.40	0.26	1.14	0.11	0.07	2.64	5.04	3.66	8.69	TS29_3
TU-2	318	67.62	18.69	0.17	0.99	0.15	0.07	3.37	5.77	3.17	8.94	TS29_4
TU-2	319	69.46	17.56	0.27	1.17	0.13	0.08	2.86	4.72	3.75	8.47	TS29_5
TU-2	320	70.36	17.01	0.25	1.16	0.12	0.07	2.50	4.68	3.84	8.53	TS29_6
TU-2	323	74.27	13.70	0.39	1.40	0.21	0.09	0.81	3.86	5.24	9.11	TS29_7
TU-2	325	74.20	13.94	0.35	1.43	0.19	0.09	0.72	3.75	5.33	9.07	TS29_8
TU-2	326	73.80	13.88	0.33	1.55	0.48	0.14	1.03	3.91	4.87	8.78	TS29_9
TU-2	329	69.95	15.88	0.43	2.29	0.47	0.10	1.86	4.63	4.38	9.01	TS30_1
TU-2	330	70.02	16.29	0.38	1.91	0.38	0.07	2.10	4.72	4.12	8.84	TS30_2
TU-2	331	70.46	15.80	0.43	1.96	0.50	0.11	1.71	4.58	4.44	9.02	TS30_3
TU-2	332	70.44	15.57	0.41	1.94	0.48	0.12	1.70	4.74	4.59	9.33	TS30_4
TU-2	333	70.48	15.67	0.43	2.09	0.46	0.14	1.71	4.43	4.58	9.01	TS30_5
TU-2	334	70.13	15.71	0.42	2.16	0.39	0.05	1.80	4.72	4.61	9.33	TS30_6
TU-2	335	70.15	15.72	0.42	1.95	0.46	0.19	1.75	4.85	4.48	9.33	TS30_7
TU-2	336	70.10	15.96	0.40	1.88	0.50	0.15	1.86	4.68	4.45	9.13	TS30_8
TU-2	337	69.96	15.84	0.43	2.16	0.48	0.09	1.84	4.79	4.38	9.17	TS30_9
TU-2	338	70.12	15.87	0.46	1.99	0.49	0.15	1.87	4.64	4.39	9.02	TS30_10
TU-2	339	70.06	15.71	0.47	2.05	0.52	0.14	1.70	4.81	4.52	9.32	TS30_11
TU-2	340	69.92	16.04	0.42	2.03	0.47	0.08	1.81	4.86	4.37	9.22	TS30_12
TU-2	341	70.17	15.80	0.43	1.95	0.46	0.15	1.82	4.81	4.37	9.18	TS30_13
TU-2	342	70.06	15.85	0.41	1.97	0.50	0.12	1.80	4.85	4.42	9.28	TS30_14
TU-2	343	70.32	15.83	0.39	2.09	0.43	0.11	1.71	4.61	4.50	9.11	TS30_15
TU-2	344	70.10	15.88	0.41	1.90	0.38	0.14	1.81	4.87	4.48	9.35	TS30_16
TU-2	345	70.01	15.76	0.46	2.05	0.48	0.09	1.69	4.91	4.52	9.43	TS30_17
TU-2	346	69.66	15.94	0.49	2.24	0.43	0.14	1.83	4.85	4.39	9.24	TS30_18

Appendix C: Sedimentological Data

C1 – Clast Shape and Roundness field data including Largest Clasts.

The a, b and c axis are measured in mm and roundness measured using the Krumbein roundness scale for two samples Vickers Quarry and one sample from York Road sites according to the method outlined in Section Four – Chapter Two. Each group of measurements are divided into 2 ϕ categories (e.g. -6 to -7 ϕ). For each sample, the largest five clasts from the lithostratigraphic unit were measured. For sample stratigraphic positions see A1 – Appendix A.

VQ-S1												
-6 to -7				-7 to -8				> -8				
a	b	c	roundness	a	b	c	roundness	a	b	c	roundness	Largest Clasts (m)
90	65	50	0.3	230	180	120	0.5	270	160	140	0.5	3.2
115	75	70	0.5	150	120	95	0.5	290	210	170	0.4	0.75
80	45	40	0.5	140	125	60	0.3	300	220	170	0.5	1.8
100	90	65	0.4	145	115	70	0.4	350	280	170	0.6	1.6
110	85	65	0.5	220	150	130	0.5	280	200	120	0.4	0.8
80	65	45	0.5	150	110	100	0.5	300	230	190	0.6	1
90	50	40	0.3	210	160	120	0.6	340	260	200	0.6	
100	90	45	0.5	250	150	120	0.4	320	280	200	0.7	
110	100	60	0.4	180	130	110	0.5	410	326	280	0.5	
120	80	50	0.5	150	80	80	0.5	460	320	200	0.4	
80	65	35	0.5	150	65	60	0.6	270	200	150	0.5	
110	90	55	0.5	150	80	70	0.6	520	370	220	0.5	
80	55	30	0.5	220	170	160	0.5	540	400	240	0.4	
115	95	55	0.3	250	170	160	0.4	350	280	170	0.5	
120	85	80	0.6	230	170	90	0.5	380	230	190	0.5	
75	60	60	0.3	160	120	110	0.5	340	290	190	0.5	
85	65	65	0.4	190	120	40	0.3	300	270	130	0.5	
75	70	35	0.3	150	90	80	0.4	350	210	100	0.4	
95	70	50	0.4	220	170	120	0.4	380	300	260	0.6	
105	75	55	0.5	170	140	120	0.4	340	270	230	0.4	

VQ-S5							
-6 to -7				>7			
a	b	c	roundness	a	b	c	roundness
90	80	60	0.4	240	220	90	0.4
90	50	40	0.5	170	110	90	0.5
110	100	90	0.4	210	140	110	0.5
120	80	60	0.5	170	150	120	0.5
65	45	40	0.3	150	100	70	0.4
110	90	50	0.5	190	150	100	0.5
110	80	60	0.4	160	140	120	0.5
110	90	70	0.5	110	80	60	0.4
100	90	60	0.3	150	110	80	0.4
60	55	40	0.3	230	190	150	0.5
90	80	70	0.3	230	190	170	0.5
90	80	50	0.4	140	100	90	0.6
65	50	40	0.5	150	120	90	0.5
100	80	70	0.5	130	90	70	0.4
80	65	30	0.3	220	160	120	0.5
65	55	40	0.6	210	200	160	0.5
70	60	50	0.4	170	150	100	0.3
60	55	40	0.3	150	110	80	0.4
65	50	30	0.5	140	80	70	0.5
90	60	55	0.6	230	140	130	0.5

YR-1								
-5 to -6				-6 to -7				
a	b	c	roundness	a	b	c	roundness	Largest Clasts (m)
45	30	20	0.2	65	55	40	0.4	0.3
33	20	20	0.4	70	50	30	0.3	0.25
45	35	20	0.6	105	65	40	0.6	0.2
55	35	30	0.5	100	60	40	0.6	0.4
50	25	20	0.5	80	80	30	0.5	0.18
35	25	20	0.5	80	65	40	0.8	
45	40	20	0.4	115	75	50	0.7	
40	35	15	0.5	120	100	70	0.5	
50	30	20	0.4	110	55	30	0.3	
50	40	30	0.5	75	50	40	0.4	
50	35	25	0.3	100	75	55	0.3	
60	35	20	0.3	65	45	40	0.4	
50	25	20	0.3	70	45	40	0.3	
40	30	15	0.5	65	50	40	0.3	
60	40	40	0.6	75	55	35	0.3	
45	40	25	0.3	85	65	45	0.4	
60	40	35	0.4	90	65	40	0.5	
40	30	25	0.4	90	50	40	0.4	
35	30	15	0.6	110	100	65	0.5	
55	30	10	0.4	120	95	70	0.4	

C2 – Laboratory Sieve Stack Dataset

Twenty samples were analysed using laboratory sieve stack analysis. The samples were collected from Vickers Quarry, York Road, Tariki Underpass and Kaimata Sawmills sections. The samples were analysed at 0.5 ϕ increments as set out in Section Four –Chapter Two and presented in weight percentage of the sample.

	Laboratory Sieve Stack Data (Weight %)																			
Size (φ)	TU2-S1	TU2-S2	TU2-S3	TU2-S4	TU2-S5	YR1-S1	YR1-S2	YR1-S3	MG-S1	MG-S2	MG-S3	MG-S4	MG-S5	VQ-S1	VQ-S2	VQ-S3	VQ-S4	VQ-S5	VQ-S6 (A)	VQ-S6 (B)
-5														3.39				13.71	23.56	
-4.5				13.25				11.55				4.46		12.51	2.91			20.34		4.43
-4				3.48								2.30		13.53	0.00	8.08		10.44	0.99	3.36
-3.5				5.36			1.54	8.33				1.42		9.64	1.04			5.48	2.81	4.42
-3				4.23			1.73	7.47			0.59	3.57		4.79	3.93	0.46	1.44	3.47	2.83	1.33
-2.5				4.06		3.06	4.89	9.21			2.39	8.31	0.70	4.66	7.16	3.30	1.35	2.67	2.50	3.73
-2				4.47		7.50	7.33	7.22		0.15	3.20	7.84	1.11	3.48	9.54	6.37	3.12	2.00	2.42	3.72
-1.5	0.33		0.09	3.36	0.23	13.47	8.81	7.87		0.23	4.38	6.42	2.28	2.66	8.74	5.78	3.71	1.73	2.54	3.52
-1	0.32	0.02	0.18	2.15	0.78	14.44	9.30	5.39		1.01	4.89	5.43	2.73	2.42	6.53	6.03	3.84	2.04	2.58	3.52
-0.5	0.57	0.05	0.72	2.16	3.53	18.06	10.61	5.73	0.03	4.54	5.82	6.11	5.02	3.21	6.21	7.40	6.62	2.57	3.51	4.89
0	1.06	0.06	1.65	1.95	6.89	11.28	10.20	5.44	1.17	8.20	7.40	6.58	6.56	3.38	6.32	8.82	8.08	3.10	4.56	5.56
0.5	3.04	0.08	4.13	2.91	10.55	6.01	8.88	4.56	1.67	10.65	9.66	7.61	10.76	4.72	6.76	8.66	2.59	4.11	5.79	7.26
1	7.77	0.45	10.28	7.24	16.66	4.10	9.34	5.57	1.77	12.68	11.49	7.86	16.46	4.98	6.77	10.84	10.67	4.34	6.58	8.49
1.5	12.97	1.44	16.72	9.88	16.02	2.53	6.64	4.58	2.16	12.78	11.11	7.19	17.62	4.60	5.97	9.00	10.46	4.08	6.44	7.73
2	19.19	2.63	18.33	11.68	14.57	2.11	5.42	3.86	5.96	13.14	10.58	6.76	14.49	4.61	5.88	7.39	9.54	4.06	6.78	7.86
2.5	19.40	2.26	16.41	8.02	10.86	2.13	3.91	2.89	15.35	11.30	8.06	5.32	8.72	3.61	5.02	5.31	8.19	3.85	5.78	6.91
3	15.19	4.55	13.17	5.51	8.08	2.51	3.24	2.47	23.51	9.15	6.70	4.18	5.40	3.38	4.32	4.14	7.16	3.83	5.17	6.22
3.5	8.30	16.69	6.31	2.91	4.21	2.34	1.88	1.49	15.24	5.32	4.06	2.39	2.42	2.50	2.91	2.30	5.11	2.85	3.71	4.00
4	4.97	17.82	4.10	1.98	2.35	2.95	1.56	1.36	12.96	3.16	2.72	1.47	1.61	0.98	2.03	1.66	4.59	0.59	3.10	3.23
<4	6.89	53.97	7.90	5.38	5.26	7.53	4.74	5.00	20.17	7.70	6.93	4.79	4.12	6.97	7.97	4.46	13.53	4.74	8.35	9.82

Appendix D: Palaeomagnetic Data

D1 – Magnetic Susceptibility with Temperature

The magnetic susceptibility was measured between ambient temperature and 700°C was carried out on three samples from the Main Lower Unit Investigation (S10.3, S11.2 and S12.1) and one sample from the Preliminary Upper Unit Investigation (S19.1). The change in magnetic susceptibility with temperature measurements indicate that the ferrimagnetic minerals in the sample lose their magnetic susceptibility by 550°C suggesting a curie temperatures in the order of 550°C and a composition within the titanomagnetite series (20% Fe_3O_4 to 80% Fe_2TiO_4).

D2 – Room Temperature Palaeomagnetic Susceptibility Dataset

Room temperature magnetic susceptibility measurements were carried out between each thermal demagnetisation step. The following tables present the dataset from the Main Lower Unit Investigation and Preliminary Upper Unit Investigation. Data was collected using a Bartington Instruments Ltd MS2 Magnetic Susceptibility Meter.

Main Lower Unit Investigation - Magnetic Susceptibility												
Sample	0	50	100	150	200	250	300	350	400	450	500	550
S3.1A		0.045	0.046	0.045	0.046	0.048	0.049	0.049	0.049	0.049	0.048	0.047
S3.1D		0.045	0.046	0.046	0.046	0.046	0.047	0.048	0.049	0.049	0.048	0.049
S3.3A		0.041	0.041	0.042	0.043	0.043	0.043	0.042	0.042	0.041	0.041	0.040
S3.3C		0.044	0.044	0.044	0.044	0.045	0.045	0.044	0.045	0.044	0.044	0.045
S4.2A		0.096	0.097	0.097	0.097	0.096	0.096	0.098		0.094	0.090	0.085
S4.2C		0.097	0.098	0.098	0.098	0.098	0.098			0.097	0.091	0.087
S4.3A		0.093	0.093	0.094	0.094	0.094	0.094	0.096	0.099	0.093	0.088	0.083
S4.3C		0.090	0.092	0.091	0.091	0.091	0.091	0.093	0.095	0.091	0.085	0.080
S5.1A		0.091	0.092	0.090	0.089	0.086	0.084	0.081	0.081	0.078	0.075	0.073
S5.1B		0.088	0.089	0.087	0.087	0.085	0.083	0.081	0.081	0.077	0.075	0.073
S5.2A		0.087	0.087	0.086	0.085	0.082	0.080	0.078	0.078	0.075	0.072	0.072
S5.2B	0.087	0.087	0.087	0.087	0.085	0.083	0.080	0.079	0.079	0.075	0.071	0.069
S7.1A	0.088	0.088	0.089	0.089	0.088	0.088	0.087	0.084	0.082	0.078	0.078	0.076
S7.1C	0.089	0.089	0.089	0.089	0.089	0.089	0.087	0.084	0.082	0.077	0.077	0.074
S7.3A	0.075	0.076	0.076	0.075	0.075	0.075	0.075	0.072	0.071	0.068	0.070	0.068
S7.3B	0.077	0.077	0.077	0.077	0.077	0.077	0.076	0.074	0.072	0.069	0.071	0.069
S10.1A	0.079	0.080	0.080	0.080	0.079	0.078	0.075	0.072	0.073	0.071	0.071	0.070
S10.1B	0.080	0.080	0.080	0.080	0.079	0.079	0.077	0.073	0.073	0.071	0.072	0.070
S10.3A	0.075	0.075	0.076	0.076	0.074	0.074	0.071	0.069	0.068	0.067	0.068	0.066
S10.3C	0.082	0.083	0.082	0.082	0.082	0.081	0.079	0.076	0.077	0.073	0.075	0.073
S11.1A	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.038	0.040	0.042
S11.1C	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.040	0.040	0.039	0.039	0.042
S11.2A		0.037	0.038		0.037	0.037	0.037	0.037	0.037	0.035	0.037	0.038
S11.2D		0.042	0.042		0.042	0.042	0.042	0.042	0.041	0.040	0.042	0.043
S12.1A		0.003	0.003		0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
S12.1C		0.002	0.002		0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
S12.2A		0.002	0.003		0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
S12.2B		0.002	0.002		0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
S15.1A		0.075	0.075		0.076	0.076	0.075	0.077	0.077	0.074	0.071	0.065
S15.1C		0.062	0.062		0.063	0.062	0.063	0.064	0.064	0.063	0.059	0.055
S15.3A		0.072	0.073		0.073	0.073	0.072	0.074	0.074	0.072	0.068	0.064
S15.3C		0.060	0.059		0.060	0.059	0.059	0.060	0.061	0.060	0.057	0.054

Preliminary Upper Unit Investigation - Magnetic Susceptibility

Sample	0	50	100	150	200	250	300	350	400	450	500	550
S16.1A	0.088	0.088	0.089	0.089	0.089	0.089	0.088	0.088	0.087	0.083	0.079	0.078
S16.1B	0.085	0.084	0.086	0.086	0.087	0.085	0.085	0.083	0.083	0.079	0.075	0.074
S16.3A	0.090	0.091	0.090	0.092	0.093	0.090	0.090	0.087	0.088	0.083	0.079	0.078
S16.3B	0.079	0.079	0.080	0.081	0.081	0.080	0.079	0.077	0.077	0.073	0.070	0.068
S17.1B	0.083	0.083	0.085	0.086	0.087	0.088	0.087	0.086	0.087	0.086	0.079	0.072
S17.1C	0.064	0.064	0.065	0.066	0.067	0.065	0.065	0.065	0.066	0.065	0.060	0.054
S17.3B	0.087	0.086	0.088	0.090	0.089	0.090	0.089	0.089	0.089	0.085	0.079	0.071
S17.3C	0.083	0.082	0.083	0.084	0.085	0.085	0.084	0.083	0.083	0.080	0.073	0.066
S18.1A	0.052	0.052	0.053	0.055	0.057	0.056	0.056	0.053	0.052	0.052	0.053	0.050
S18.1C	0.077	0.077	0.078	0.079	0.079	0.078	0.077	0.068	0.067	0.065	0.062	0.056
S18.2B	0.066	0.066	0.067	0.070	0.071	0.070	0.068	0.062	0.061	0.060	0.058	0.055
S18.2C	0.054	0.053	0.055	0.058	0.058	0.057	0.056	0.053	0.053	0.053	0.051	0.051
S19.1A	0.073	0.072	0.073	0.074	0.072	0.070	0.072	0.071	0.070	0.066	0.063	0.062
S19.1B	0.090	0.090	0.092	0.093	0.093	0.091	0.092	0.093	0.089	0.086	0.080	0.078
S19.3A	0.093	0.092	0.094	0.095	0.096	0.092	0.093	0.092	0.088	0.086	0.078	0.075
S19.3B	0.088	0.089	0.089	0.090	0.090	0.087	0.088	0.088	0.083	0.078	0.073	0.071

D3 – Main Lower Unit Investigation Results

Lambert (equal area) stereoplots, Zijderveld diagrams and Remanent magnetisation intensity versus temperature plots for the specimens analysed in the Main Lower Unit Investigation.

S3-1A

S3-3A

S3-1D

S3-3C

S7-1A

S7-3A

S7-1C

S7-3B

S10-1A

S10-3A

S10-1B

S10-3C

S15-1A

S15-3A

S15-1C

S15-3C

D4 – Preliminary Upper Unit Investigation Results

Lambert (equal area) stereoplots, Zijderveld diagrams and Remanent magnetisation intensity versus temperature plots for the specimens analysed in the Preliminary Upper Unit Investigation.

S16-1A

S16-1B

S16-3A

S16-3B

S17-1B

S17-3B

S17-1C

S17-3C