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Understanding Aspects of Andesitic Dome-forming Eruptions Through the Last 1000 yrs of Volcanism at Mt. Taranaki, New Zealand

A dissertation presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Earth Science

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The summit of Mt. Taranaki. Photographed by G. Lube.
Dedicated to my parents,
to Katrin and my son August
Abstract

Andesitic volcanoes are notorious for their rapid and unpredictable changes in eruptive style between and during volcanic events, a feature normally attributed to shallow-crustal and intra-edifice magmatic processes. Using the example of eruptions during the last 1000 yrs at Mt. Taranaki (the Maero Eruptive Period), deposit sequences were studied to (1) understand lava dome formation and destruction, (2) interpret the causes of rapid shifts from extrusive to explosive eruption styles, and (3) to build a model of crustal magmatic processes that impact on eruption style.

A new detailed reconstruction of this period identifies at least 10 eruptive episodes characterised by extrusive, lava dome- and lava flow-producing events and one sub-Plinian eruption. To achieve this, a new evaluation procedure was developed to purge glass datasets of contaminated mineral-glass analyses by using compositional diagrams of mineral incompatible-compatible elements. Along with careful examination of particle textures, this procedure can be broadly applied to build a higher degree of resolution in any tephrostratigraphic record. Geochemical contrasts show that the products of the latest Mt. Taranaki eruption, the remnant summit dome (Pyramid Dome) was not formed during the Tahurangi eruptive episode but extruded post-AD1755. Its inferred original maximum volume of 4.9×10⁶ m³ (DRE) was formed by simultaneous endogenous and exogenous dome growth within days. Magma ascent and extrusion rates are estimated at ≥0.012 ms⁻¹ and ≥6 m³s⁻¹, respectively, based on hornblende textures. Some of the Maero-Period dome effusions were preceded by a vent-clearing phase producing layers of scattered lithic lapilli around the edifice [Newall Ash (a), Mangahume Lapilli, Pyramid Lapilli]. The type of dome failure controlled successive eruptive phases in most instances. The destruction of a pressurised dome either caused instantaneous but short-lived magmatic fragmentation (Newall and Puniho episodes), or triggered a directed blast-explosion (Newall episode), or initiated sustained magmatic fragmentation (Burrell Episode). The transition from dome effusion to a sustained, sub-Plinian eruption during the Burrell Lapilli (AD1655) episode was caused by unroofing a conduit of stalled magma, vertically segregated into three layers with different degrees of vesiculation and crystallisation. The resultant ejecta range from brown, grey and black coloured vesicular clasts to dense grey lithics. Bulk compositional variation of erupted clasts can be modelled by fractionation of hornblende, plagioclase, clinopyroxene, and Fe-Ti oxides. Pre-eruption magma ascent for the Maero Period events is assumed to begin at depths of c.9.5 km.
Acknowledgements

I wish to thank every person who contributed to the outcome of this study.

I went back to New Zealand to study one of the most fascinating phenomena nature has to offer: volcanoes. Of the North Island volcanoes, Mount Taranaki stands out as being the most imposing, and to me the most striking. Despite its dormancy, it proved a real challenge, to climb, find samples and sections, and to draw out some of its secrets.

For the opportunity to work again on Mt. Taranaki I am indebted to my chief-supervisor Dr Shane J. Cronin. Through him I learnt much about how to observe volcanic deposits and to understand the various processes involved in generating them. His aid in my receiving a Massey University Doctoral scholarship is highly appreciated. In past years Dr Cronin supported numerous overseas trips, which offered me the opportunity to meet other scientists, either on conferences or at the institutions where my overseas supervisors are based. I also benefited from his extraordinary skills in writing and presenting ideas and thoughts.

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# Table of Contents

Abstract

Acknowledgements

List of Tables

List of Figures

## Chapter 1  Introduction

1.1  Introduction  
1.2  Objectives and Strategy  
1.3  Thesis Outline  
1.4  Background Geology  
1.4.1  Regional Geological Setting  
1.4.2  Taranaki Basin  
1.4.3  Taranaki Volcanic Lineament  
1.4.4  Mount Taranaki/Egmont  
1.4.5  Petrology of Mt. Taranaki Rocks  
1.5  References

## Chapter 2  Methodology

2.1  Brief Outline  
2.2  Field Studies  
2.3  Mineralogy  
2.3.1  Sample Preparation  
2.3.2  Microscopic Studies
2.4 Geochemistry 34
2.4.1 X-ray Fluorescence Spectroscopy 34
2.4.2 Electron Microprobe Analysis 35
2.4.3 Laser Inductively Coupled Plasma Mass Spectrometry 36

2.5 Porosity and Permeability 37

2.6 Scanning Electron Microscopy 41

2.7 Fourier Transform Infrared Spectroscopy 41

2.8 Thermal Analysis 43

2.9 References 46

Chapter 3 The Maero Eruptive Period 49

3.1 Introduction 49
3.1.1 Previous Studies 51
3.1.1.1 Previous Work on Lava Flow Stratigraphy 54

3.2 Results 57
3.2.1 Stratigraphic Type and Reference Sections 57
3.2.1.1 Type Section of the Maero Formation 58
3.2.1.2 Reference Sections of the Maero Formation 64
3.2.2 Block-and-Ash Flow Deposits 68
3.2.2.1 Distribution and Flow Paths 68
3.2.3 Lava Flows 71
3.2.4 Glass Chemistry 75
3.2.4.1 Special Characteristics of Some Erupted Units 76
3.2.4.2 Correlation of Tephra and Pyroclastic Flow Deposits 77

3.3 Discussion 81
3.3.1 Eruption Frequency of the Maero Eruptive Period 81
3.3.2 Comparison to the Previously Known Stratigraphy 86
3.3.3 Tephrostratigraphy of the Maero Eruptive Period 87

3.4 References 91
## Chapter 4  Improving the Reliability of Microprobe-based Glass Analyses

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Abstract</td>
<td>97</td>
</tr>
<tr>
<td>4.2 Introduction</td>
<td>97</td>
</tr>
<tr>
<td>4.2.1 Andesitic Volcanism, Tephra Generation and Dispersal</td>
<td>100</td>
</tr>
<tr>
<td>4.2.2 Sample Sites</td>
<td>103</td>
</tr>
<tr>
<td>4.3 Results</td>
<td>103</td>
</tr>
<tr>
<td>4.3.1 Contrasts in Particle Texture</td>
<td>103</td>
</tr>
<tr>
<td>4.3.2 Glass Chemistry and Data Evaluation</td>
<td>105</td>
</tr>
<tr>
<td>4.3.3 Estimating Plagioclase Proportions in Contaminated Analyses</td>
<td>111</td>
</tr>
<tr>
<td>4.4 Discussion</td>
<td>112</td>
</tr>
<tr>
<td>4.5 Conclusions</td>
<td>116</td>
</tr>
<tr>
<td>4.6 References</td>
<td>117</td>
</tr>
</tbody>
</table>

## Chapter 5  Non-explosive, Dome-forming Eruptions

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Introduction</td>
<td>121</td>
</tr>
<tr>
<td>5.1.1 Lava Domes</td>
<td>122</td>
</tr>
<tr>
<td>5.1.1.1 Lava Dome Distribution in Taranaki</td>
<td>124</td>
</tr>
<tr>
<td>5.2 Field Observations</td>
<td>124</td>
</tr>
<tr>
<td>5.2.1 Tahurangi Eruptive Deposits</td>
<td>124</td>
</tr>
<tr>
<td>5.2.2 The Present Summit Lava Dome</td>
<td>128</td>
</tr>
<tr>
<td>5.2.3 Rock-Avalanche Deposit</td>
<td>130</td>
</tr>
<tr>
<td>5.3 Sample Sites and Methods</td>
<td>131</td>
</tr>
<tr>
<td>5.4 Results</td>
<td>132</td>
</tr>
<tr>
<td>5.4.1 Dome Volume Calculations</td>
<td>132</td>
</tr>
<tr>
<td>5.4.2 Mineralogy and Mineral Chemistry</td>
<td>134</td>
</tr>
<tr>
<td>5.4.3 Bulk Rock Composition</td>
<td>139</td>
</tr>
<tr>
<td>5.4.4 Microstructure, Density and Permeability of Dome Rocks</td>
<td>142</td>
</tr>
<tr>
<td>5.5 Discussion</td>
<td>142</td>
</tr>
</tbody>
</table>
Chapter 7    Reconstruction of Eruption Mechanisms Using Physico-chemical Data

7.1    Introduction
7.1.1    Viscosity of Magmas

7.2    Methods and Approach

7.3    Results
7.3.1    Petrography
7.3.1.1    Pyroclastic Flow Deposits
7.3.1.2    Lava Flows
7.3.2    Bulk Rock Chemistry
7.3.2.1    Pyroclastic Flow Deposits
7.3.2.2    Lava Flows
7.3.3 Physical Properties 232
7.3.3.1 Water Estimates of Volcanic Glasses 233
7.3.3.2 Viscosity 234

7.4 Discussion 238
7.4.1 Comparison of Physico-chemical Properties 238
7.4.1.1 Bulk Rock Composition 238
7.4.1.2 Melt and Magma Viscosities 239
7.4.2 Course and Eruption Styles of the Maero Eruptive Period 243
7.4.2.1 Types of Lava Domes 243
7.4.2.2 Causes of Dome Collapse and Associated Deposits 244
7.4.2.3 Reconstruction of the Maero Eruptive Period 247

7.5 Conclusion 251

7.6 References 252

Chapter 8 Conclusions 259

8.1 Avenues of Future Research 263

Appendices I
List of Tables

Table 2-1…………………………………………………………………………………………………..36
Detection limit of element oxides measured at the EMP (University of Auckland) including the deviation from a reference glass composition.

Table 2-2…………………………………………………………………………………………………..43
Water and carbon dioxide peaks on the FTIR spectra including their bonds within glasses.

Table 3-1…………………………………………………………………………………………………..52
Stratigraphy of the youngest deposits of Mt. Taranaki (Druce, 1966).

Table 3-2…………………………………………………………………………………………………..53
Stratigraphy of the youngest deposits at Mt. Taranaki until 2003 (Druce, 1966; Neall, 1972; Neall, 1979; McGlone et al., 1988; Lees and Neall, 1993).

Table 3-3…………………………………………………………………………………………………..54
Stratigraphy of the last 1000 yrs of activity at Mt. Taranaki established in 2003 (modified after Cronin et al., 2003).

Table 3-4…………………………………………………………………………………………………..73
Sample list, description and stratigraphy of studied lava flows and scoria-and-ash flow deposits.

Table 3-5…………………………………………………………………………………………………..83
New tephrostratigraphy of the Maero Eruptive Period.

Table 4-1…………………………………………………………………………………………………106
Glass EMPA of Taranaki (Burrell Lapilli eruption) and Ruapehu (14. October 1995 eruption) sorted by classed uncontaminated and contaminated data points. Detection limits for Taranaki glass EMPA only. All data in wt. %.

Table 4-2…………………………………………………………………………………………………108
Plagioclase microlite rim and centre compositions (Burrell Lapilli eruption, Mt. Taranaki). All data in wt. %.

Table 4-3…………………………………………………………………………………………………112
Calculation of various plagioclase mixing proportions within Taranaki hybrid glass EMPA. EMPA data in wt. %. See text for explanation.

Table 5-1…………………………………………………………………………………………………132
Sample location and description of studied summit dome rocks.

Table 5-2…………………………………………………………………………………………………134
Comparison of the modelled summit dome to other Taranaki flank lava domes.

Table 5-3…………………………………………………………………………………………………156
Historic lava dome eruptions compiled from Newhall and Melson (1983) and the Smithsonian Institution Catalogue.

Table 5-4…………………………………………………………………………………………………158
Physical parameters and results for equations 5-4 to 5-6.

Table 5-5…………………………………………………………………………………………………160
Physical parameters used for conductive cooling and rainfall-quenching of the lava dome.
Table 5-6…………………………………………………………………………………………………163
Selected eyewitness reports of the 18th and 19th century.

Table 6-1…………………………………………………………………………………………………186
Minimum volume and mass calculations of erupted tephra.

Table 6-2…………………………………………………………………………………………………191
XRF bulk rock geochemistry of Burrell Lapilli clasts. Samples are mostly from pumice flow deposits with one BAF deposit sample (P10).

Table 6-3…………………………………………………………………………………………………193
Mass balance calculation for the inferred fractionation process for pumice-lithics.

Table 6-4…………………………………………………………………………………………………195
Representative normalised matrix glass compositions. All data in wt. %.

Table 6-5…………………………………………………………………………………………………214
Location of pyroclastic flow deposits on the NW and S sector of Mt. Taranaki.

Table 7-1…………………………………………………………………………………………………226
Sample list and description of studied pyroclastic flow deposits.

Table 7-2…………………………………………………………………………………………………228
Summary of petrographic studies of BAF samples.
List of Figures

Figure 1-1. Tectonic setting and its relation to Holocene volcanism in the North Island, New Zealand. Area between the Hikurangi Trough and the axial ranges is the forearc. Arrow indicates Pacific Plate movement with a rate of 42 mm yr⁻¹. AVF – Auckland Volcanic Field; TgVC – Tongariro Volcanic Centre; TVL – Taranaki Volcanic Lineament; TVZ – Taupo Volcanic Zone. AD and RD refers to andesite and rhyolite dominance within TVZ, respectively. Modified after Reyners et al. (2006) and Wilson et al. (1995).

Figure 1-2. Regional tectonic setting of the Taranaki peninsula. The Taranaki Volcanic Lineament comprises the Sugar Loaf Islands (SLI), Kaitake (K), Pouakai (P) and Mt. Taranaki (T). Major onshore (thick lines) and offshore (thin lines) faults are indicated: IF-Inglewood Fault, MF-Manaia Fault, NF-Norfolk Fault, OF-Oaonui Fault. Contours are at 300 m intervals for the volcanic edifices only. New Plymouth (NP) as the major settlement is identified. Modified after Sherburn and White (2005).

Figure 1-3. Orthophotograph of Mt. Taranaki including the lower northwestern flanks. Inset shows upper cone area including Fanthams Peak. Major morphological features are indicated by letters: a-summit crater of Mt. Taranaki, b-Fanthams Peak, c-the Beehives (two lava domes), d-scarp of the Opua amphitheatre, e-Big Pyramid, f-The Dome, g-Skinner Hill (probably a buried dome structure), h-Pyramid Stream, i-Maero Stream, j-Waieruanui Stream, k-Hangatahua River, l-Egmont National Park boundary (forest/pasture border, here 390 m), m-Kapuni Gorge (marks the eastern border of the amphitheatre), n-Sharks Tooth (second highest peak, 2510 m), o-Fanthams Peak (comprising multiple vents), p-remnant summit dome, q-Turtle, r-Bobs Ridge (western border of the Opua amphitheatre), s-NW flank and main path for BAFs.

Figure 1-4. Classification of Mt. Taranaki and Mt. Ruapehu rocks after Gill (1981). Modified after Price et al. (1999).

Figure 1-5. Trace element patterns of selected Mt. Taranaki rocks. Warwicks/Staircase refers to lava flow groups of the main cone of Mt. Taranaki; Fanthams describes lava flows of the satellite vent Fanthams Peak. Data compiled from Price et al. (1992, 1999). Normalisation after Sun and McDonough (1989).

Figure 2-1. The specimen illustrates how pumice cores were obtained. As in this case, six cores in three mutually perpendicular orientations were drilled.

Figure 2-2. Standard deviations for diameter and length of the cores (a) and for volumes Vc and VHe (b). It is noted that one sample in (a) is off the chart at a standard deviation of 0.1321 cm. b) Samples are differentiated into those drilled in Oregon and at Massey. Oregon samples show small variations for both Vc and VHe.

Figure 2-3. Standard deviation for connected porosities. The limit of 0.3 cm³ for Vc and VHe in Fig. 2-2b is used as maximum limit. Cores drilled in Oregon are shown for comparison.

Figure 2-4. Permeability measurements of individual cores were performed three to six times, partially using multiple flow rates, in order to assess reproducibility. In this case, the red graph suggests higher flow rates compared to the other three runs and was excluded from further calculations.

Figure 2-5. Separated groundmass glass fraction from a pumice clast (SD32).
Thermal analysis of volcanic glass to 850 °C. The change in weight (green axis) was measured after the isothermal break at 110 °C.

Distribution of lava flows on the Mt. Taranaki main cone and Fanthams Peak. Sampled lava flows and scoria-and-ash flow units are highlighted. The thick solid line represents the Opua amphitheatre scarps. The map has been modified after Neall (2003); map details were kindly provided by J.N. Procter.

Location of type and reference sections around the edifice of Mt. Taranaki. TS-type section, P-Pembroke Road, W-Waingongoro Stream, M-Manaia Road. Numbered black squares refer to reference sections. Black diamonds mark distal locations of pyroclastic flow deposits in the area of Saunders Road – Wiremu Road – Waiweranui Stream.

Type section of the Maero Formation located in Maero Stream, NW sector of Mt. Taranaki. Reference sections Nos. 1 and 2 are located in Pyramid Stream and Hangatuhua River, respectively. The outcrops comprise deposits of BAFs, surges and pumice flows as well as co-ignimbrite ashes. Debris flow-, lahar-, and fluvial deposits are also exposed but not always differentiated. For further details see text and appendices. Labels Py7 etc refer to sample numbers. See also Fig. 3-4 for field photographs.

Field photographs of deposits from the NW sector of Mt. Taranaki. a) NW sector of Mt. Taranaki as viewed from the summit. Note the depression in vegetation caused by an avalanche (see Chapter 5). H. R. - Hangatuhua River. b) exposure in the upper right Pyramid fork. Cliff section is approx. 30 m high and shows mainly lahar and hyperconcentrated flow deposits. Note Shane Cronin for scale (arrow). c) outcrop on the true left side of the Maero Stream near the intersection of Puniho and Holly Hut track. The upper unit shows the Tahurangi Block-and-Ash Flow deposit (unit a) with its upper matrix-supported and lower clast-supported zones. d) reference section No.1, lower Pyramid Stream, true right side. Only major units are labelled. Discolouration of units IV-Bb and II-B is caused by a raised iron-rich water table. Note the black bar has same height as the spate (arrow). e) close-up of c); basal portion of Tahurangi BAF (unit a) which consists of fine to medium ash. Dashed line marks the boundary between main body of the BAF and its basal portion. f) close-up of d); finely laminated and cross-bedded fine to medium ash surge deposit. Some pumice clasts (arrows) are present. g) exposure on the true right side of Maero Stream. Major units are labelled. The reworked section is 2.5 m thick and represents predominantly fluvial deposits. h) close-up of g); unit IV-Bb. Noteworthy are boulder trains and weak reverse grading of the lower to middle portion. i) distal blast deposit [Newall Breccia (a)] showing its typical pocketing appearance. j) stream exposure of a BAF deposit with pervasive red coloured top portion and grey bottom portion (Waiweranui Stream). k) in situ charcolised tree at a distal BAF exposure [Burrell Breccia (A)] near Saunders Road. l) degassing pipe originating at a charred log within the BAF deposit (same unit as in k). Note that the pipe branches at the centre of the photograph. Same unit as in k). Labelled units in c, d and g refer to the lithostratigraphic code. See discussion of Chapter 3 for further details. Detailed description of reference section No.1 can be found in the appendix. Photographs of f) and i) were taken by Shane Cronin.

Reference sections Nos. 3 and 4 located on the east flank of Mt. Taranaki. Reference site: No.3–Pembroke Road cutting; No.4–intersection of Waingongoro Stream and Round-The-Mountain-Track. E02-72 etc are sample numbers.
Figure 3-6
Reference sections Nos. 5 and 6 located on the south flank of Mt. Taranaki. Reference site: No.5—at the site of the Old Mangahume Hut; No.6—near the Old Mangahume Hut, upslope of No.5. Labels E03-35 etc are sample numbers.

Figure 3-7
Reference sections Nos. 7, 8 and 9 located on the west and north sector of Mt. Taranaki. Reference site: No.7—Ahukawakawa Swamp; No.8—Marupakoko Stream near Kahui Hut; No.9—Parihaka Road cutting. Labels E02-4 etc refer to sample numbers.

Figure 3-8
Crater rim stratigraphy as exposed on its SW side at the entrance of Okahu Gorge. Four lava flows are identifiable with the youngest flow (4) being known as South Flow.

Figure 3-9
Composite photograph of the upper NW flank of Mt. Taranaki showing named and described morphological features.

Figure 3-10

Figure 3-11
Histogram of all glass chemical analyses for SiO₂ (a) and K₂O (b).

Figure 3-12
Backscatter-electron microscopy images of individual glass shards. Different glass shard shapes within individual samples are illustrated (top: vesicular, partially deformed; bottom: dense and angular). Label in images gives analysis number and approximate beam location (black dot). Grey=glass; light grey=minerals; black=epoxy. a-b) Tahurangi Ash sample (T04-98) with chemically homogenous glass shards but of different texture; a) deformed vesicles, b) dense angular. Note that the presence of large minerals (bottom) may alter vesicle distribution. c-d) Newall Ash sample (E02-75) with distinct shard textures; glass chemistry of shard (d) is similar to those of scoria-and-ash flow shard (c). Note regular to irregular vesicles in c). e-f) Burrell Lapilli sample (E03-35) with Taranaki glass shard (f) and Taupo volcano-derived glass shard (e), which shows a deformed vesicle.

Figure 3-13
Glass chemistry of Burrell Lapilli-erupted deposits. The SiO₂ vs. K₂O diagram shows a general positive correlation. Highest mean silica and potassium contents are observed for BAF and surge deposits. The crosses represent the 95% confidence interval of the sample mean. The tephra sample E03-35 is bimodal containing glass shards with a signature similar to Taupo volcano (or atypical of Taranaki). If foreign glass shard analyses are excluded the sample mean is located within the field of BAF/surges (=E03-35'). Also included are sample means of a surge deposit pre-dating the Maero Eruptive Period showing a rhyolitic glass chemistry. It is noted that one sample (WW19) shows large variations and a bimodal sample population.

Figure 3-14
Comparison of mean sample values of scoria-and-ash flow units (T04-53, T04-56) to pyroclastic pumice flow deposits of the Burrell episode (units 1-3) and Puniho Ash, and other Maero deposits (crosses). Individual glass shards (small black squares) within deposits, other than T04-53 and T04-56, that have compositions similar to scoria-and-ash flows. a) SiO₂ vs. K₂O, b) CaO vs. FeO.
Correlation of individual tephra and pyroclastic flow units based on field studies and glass chemistry (SiO₂ vs. K₂O). a) Waingongoro and Waieranui episodes, b) Newall and Puniho episodes, c) Tahrangi and Te Popo episodes.

Locations of Holocene volcanic centres in the North Island of New Zealand: Auckland Volcanic Field, Taupo Volcanic Zone (TVZ), Tongariro Volcanic Centre (TgVC), Mt. Taranaki. Numbers 1-4 refer to distal andesite tephra sites: 1-Onepoto Basin/Pukaki Lagoon/Lake Pupuke (Sandiford et al., 2001; Shane and Hoverd, 2002; Shane, 2005), 2-Waikato lakes (Lowe, 1988b), 3-Kaipo Bog (Lowe et al., 1999), 4-Lake Tutira (Eden and Froggatt, 1996), 5-Lake Poukawa (Shane et al., 2002), 6-Kaimanawa Mts. and Ruahine Ranges (Froggatt and Rogers, 1990).

Particle textures found in Burrell Lapilli sub-Plinian fall deposits. a) pumice clast, type 1, with clear to pale brownish glass; b) hypocrystalline groundmass texture of type 2 clast showing plagioclase, Fe-Ti oxide and minor clinopyroxene microlites; c) semi-vesicular type 3 clast with brown groundmass glass, large crystals are hornblende; d) for comparison, hypocrystalline groundmass of the present summit dome of Mt. Taranaki with abundant microlites of plagioclase, Fe-Ti oxides and minor clinopyroxene. Scale bars are in μm.

Standard deviations of all major oxides are shown for the original glass EMPA dataset and the glass dataset classed as uncontaminated by plagioclase for the Taranaki (a) and Ruapehu (b) samples. A clear reduction in SiO₂, Al₂O₃ and CaO variations is observed. See text for further details. All Fe expressed as FeO.

Bivariate plots of Al₂O₃ and K₂O vs. SiO₂ for Burrell Lapilli (Taranaki) and Ruapehu glass data. Data points with lowest SiO₂ show linear relationship towards mean plagioclase compositions (dashed lines).

Bivariate oxide plots for Burrell Lapilli eruption, Taranaki (a-d) and 14. October 1995 eruption, Ruapehu (e-f) demonstrate how contaminated glass analyses were identified. Open symbols are classed uncontaminated, closed symbols represent hybrid glass-plagioclase analyses. Dashed lines point towards mean plagioclase compositions.

The glass evaluation procedure cannot be directly applied to BAF deposits as demonstrated for the Burrell Lapilli equivalent BAF deposit. Although data points above a threshold value of 17.9 wt.% Al₂O₃ clearly embrace contaminated glass analyses, the transitional data between 17.1 and 17.9 wt.% Al₂O₃ cannot be uniquely classified. Dashed line points toward mean plagioclase composition.

Glass compositions of Taranaki and TgVC tephras (Lowe 1988b; Lowe et al., 1999; Eden and Froggatt, 1996 and Shane and Hoverd, 2002) show large variations, here only shown the means and standard deviations for K₂O and Al₂O₃. Contaminated plagioclase-glass analyses and/or the analysis of two or more particle types may have caused the apparent glass compositional heterogeneity. The small variation in the unmodified Burrell Lapilli dataset (Taranaki) is shown for comparison (in grey).

Lava dome types: a) spiny (Rock Mesa ENE, Oregon), b) spiny-lobate (Mt. St. Helens lava dome, Washington, July 2004), c) lobate-platy (Big Obsidian Flow, Newberry, Oregon).
Figure 5-2………………………………………………………………………………………………...125
NW sector of Mt. Taranaki showing the main deposition area of Maero BAF deposits. The extent of the Tahunangi BAF A is outlined (light grey); unit B is only observed in the Maero Stream and is omitted for clarity. The rock-avalanche deposit (RAD) is outlined as observed on aerial photographs from 1959 (mid-grey) with an additional area based on field observations (dark grey). Contour interval is 20 m. The upper right inset shows the general slope inclinations.

Figure 5-3………………………………………………………………………………………………...127
Correlation of Tahurangi BAF A and B units and the rock-avalanche deposit across the Pyramid-Maero-Hangatuhua area. The exposures are sorted by stream and planimetric distance from source (filled squares in Fig. 5-2). See figure legend for further details (RAD – rock-avalanche deposit). Magnetism was measured by a portable fluxgate magnetometer. For clarity, older exposed units were omitted. Outcrop numbers and profiles refer to Platz (2001) except S04-133.

Figure 5-4………………………………………………………………………………………………...129
The remnant present summit dome. a) hemispherical shape of the dome as viewed from the SE; arrow points to a person for scale. Photographed by S.J. Cronin. b) dome amphitheatre as viewed from the W; the arrow points to the summit marker (2518 m); the dashed lines mark the hydrothermally altered central dome portion. c) northern scar of the amphitheatre showing listric faults. d) the summit marker is a sub-vertical extrusion penetrating the carapace; note weak columnar jointing; summit marker is highest point of the dome. e) orthophotograph of the summit region of Mt. Taranaki; outline shows mapped deposits associated with the lava dome; note the blocky lava flow to the N; crosses mark sample locations. f) the ‘Three Sisters’ (background) mark the NW border of the intra-crater collapse zone with resulting deposit still preserved in the crater (foreground).

Figure 5-5………………………………………………………………………………………………...130
Black and white photograph taken between 1898 and 1901 showing the fresh bouldery rock-avalanche deposit (centre to right). The photograph is taken from the Round-The-Mountain-Track just west of Maero Stream from the top of a buried lava ridge. The view is NNW towards Pouakai. Photographed by the surveyor H.M. Skeet.

Figure 5-6………………………………………………………………………………………………...133
Reconstruction of the Pyramid Dome geometry. a) dashed white line illustrates the former ideal crater wall position; the solid line marks the inferred dome outline; the black dot is the assumed vent location at the break in slope. b) view of the remnant summit dome from the W. c) top view of the combined paraboloid with a composite elliptical base; dimensions of elliptical radii are given. d) side view of the inferred dome geometry; the dome remnants are in dark grey; the inferred underlying slope on the upper flank is estimated to be c.20°.

Figure 5-7………………………………………………………………………………………………...135
Hornblende types. a) type 1 with continuous reaction rim. b) type 2 with discontinuous reaction rim; present only in sample SD1; note individual Fe-Ti oxide crystals are visible. c) type 3 partial to fully replaced hornblende crystals. d) type 1 with observed brown glass fringing the reaction rim; only observed in sample SD6. Scale bar is 100 µm in a) otherwise 25 µm.

Figure 5-8………………………………………………………………………………………………...136
Histogram of type 1 hornblende reaction rim thicknesses averaged for crystals and entire samples.
Hornblende compositions of the summit lava dome, Mt. Taranaki. a) Na+K (A-site) vs. AlIV. b) Mg# vs. Si; (c.p.f.–cation per formula unit). For comparison are shown recalculated pargasitic hornblende compositions of Unzen volcano, Japan (Sato et al., 1999; Browne et al., 2006; Nakada and Motomura, 1999) [Unzen matrix refers to groundmass crystals], Soufrière Hills Volcano, Montserrat (Barclay et al., 1998; Rutherford and Devine, 2003), Mt. St. Helens, USA (Rutherford and Hill, 1993), Colima, Mexico (Luhr, 2002) and Cerro la Pilita, Mexico (Barclay and Carmichael, 2004).

Compositions of Fe-Ti oxide phenocrysts and inclusions in clinopyroxene and hornblende. a) Al vs. Ti. b) Ti/Al vs. Fe3+# (c.p.f.–cations per formula unit). Cations are calculated on the basis of 32 oxygens.

Glass compositions of inclusions in clinopyroxene and hornblende. Silica is used as differentiation index. Note that inclusions in different host minerals form separate groups.

Bulk rock compositions of the summit lava dome and the Tahurangi BAF A and B deposits. Dome compositions are distinct to Tahurangi rocks as illustrated for Al2O3 (a), Mg# (b, d) Fe2O3 (e) and Zr (f).

Trace element patterns of the Pyramid Dome and Tahurangi BAF deposits normalised to N-MORB (a) and chondrite (b). Pyramid Dome rocks and Tahurangi BAF deposits show nearly identical trace element patterns. For the light rare earth elements slightly higher abundances in Tahurangi BAF deposits are noted. Normalisation after Sun and McDonough (1989).

Texture of rock sample SD6. a) photograph shows sub-vertical, near parallel crack patterns and cavities. b) modified image of a) highlighting cracks and cavities in black.

Lava dome growth patterns are illustrated in a-e. Exogenous and endogenous dome growth occurred simultaneously. f) demonstration of the inferred exogenously (dark grey) and endogenously (light grey) formed surfaces as observed on the dome remnants.

Reconstruction of the summit dome failure. a) erosion scars on upper flank (white arrows) as well as the curvatures of the amphitheatre, and the scars to the SW and S define the geometry of individual collapse sectors. b) dome geometry with individual sectors I-IV and their flow directions. c) cross-section of the dome showing the dome remnants (grey), and the disintegration of dome rocks along listric faults.

Aluminium-in-hornblende geobarometer shown as histogram for hornblende phenocrysts (core and rim) and microphenocrysts. Calculated after Johnson and Rutherford (1989) and corrected by -1.5 kbar.

Comparison of calculated hornblende crystallisation pressures for various Mt. Taranaki rocks and xenoliths. Granodiorite xenoliths contain all required mineral phases for the Al-in-hornblende geobarometer (Johnson and Rutherford, 1989) and therefore were not corrected. Note that some hornblende crystals of hornblende gabbros and hornblende-pyroxene gabbros indicate crystallisation below (<1 kbar) the inferred hornblende stability limit.
Mount Taranaki (lower right) has produced mainly lava dome eruptions in the past 800 years with Block-and-Ash Flow deposits making up the fan between the Maero and Pyramid Stream and in the Hangatahua River (BAF – Block-and-Ash Flow, ppf – pumice pyroclastic flow). Star (top left) indicates the most distal outcrop discussed in the text. To the NNW of Mt. Taranaki are the south flanks of Pouakai volcano. The inset shows the Taranaki peninsula with the Taranaki Volcanic Lineament (SLI-Sugar Loaf Islands, K-Kaitake, P-Pouakai, T-Taranaki). Major onshore and offshore faults: IF-Inglewood Fault, MF-Manaia Fault, NF-Norfolk Fault, OF-Oanui Fault. Contours are 300 m. Modified after Sherburn and White (2005).

Figure 6-2
Variations in bulk vesicularity and connected porosity of single clasts for grey pumice (a), banded pumice (b), and black and brown pumice (c). Crosses represent the range in vesicularity per clast using minimum, mean and maximum values (see inset in a). Variations in bulk vesicularity refer to single cores cut in two ($\varphi_{core}$) and overall clast variations with multiple cores ($\varphi_{clast}$). Note different scale in b). See text for details.

Figure 6-3
Field photographs of a) succession of three pumice pyroclastic flow deposits on the upper south flanks; sketch shows a general assembly of pumice types and grey dense lithics, b) grey pumice clasts of unit 3, c) eroded surface into unit 2 showing the scattered grey pumice [1] from airfall, brown pumice [2], banded pale grey to dark brown pumice [4], and the dense fractured andesite clasts [L]; d) lower contact of a distal BAF deposit, c.13.5 km from source (star in Fig. 1). See text for field description.

Figure 6-4
Distribution of Burrell Lapilli deposits: a) isopachs in cm including the BAF deposit (black) to the NW for reference, black squares represent mapping locations for fall deposits only, P-Pouakai, contours 100 m; b) isopleths for pumice clasts and pumice pyroclastic flow deposits on the upper flanks (black), see inset in a) for location; c) isopleths for lithic clasts, same outline as in b). Numbers in b) and c) are clast diameters in cm.

Figure 6-5
Thin-section photographs illustrating basic vesicularity differences of juvenile clasts. a) dense grey lithic, b) semi-vesicular black pumice, c) vesicular black pumice with isolated and coalesced vesicles, crosses mark plagioclase crystals; d) grey pumice with isolated large single vesicles as well as larger coalesced vesicle. Scale bar is 100 µm in a-c and 500 µm in d. See text for details.

Figure 6-6
SEM images of grey (a) and brown (b) pumice (note a and b are binarised; black=vesicles, white=glass + crystals); c) shows a large coalesced vesicle; d) consists of three SEM images showing the transition from grey to brown in banded pumice. Scale bar is 10 µm in c), otherwise 100 µm.

Figure 6-7
Hornblende reaction textures in different clast types: a) fresh hornblende with no reaction rims in pumice, b) single Fe-Ti oxide crystals are attached to the hornblende rims in black semi-vesicular pumice, c) hornblende in dense grey lithic clast shows resorption textures and is partially replaced by clinopyroxene, plagioclase and Fe-Ti oxide crystals or is fully replaced (lower left); note abundant plagioclase microlites in groundmass. Scale bar is 100 µm.

Figure 6-8
Bulk rock geochemistry of pumice and grey andesite clasts in a multi element oxide vs. SiO₂ diagram. The calculated fractionation trend pumice – grey lithics is in good agreement for the majority of clasts (solid line) with some variation for the most evolved clast (dashed line). See Table 6-3 for details.
Groundmass glass compositions of pumice types presented in the Al$_2$O$_3$ vs. SiO$_2$ diagram. Modelled glass composition changes due to plagioclase and clinopyroxene crystallisation (thick solid line) and is in good agreement with linear regression line (thin solid line). The small inset shows six data points of one lapillus (SD20) demonstrating relative glass homogeneity. The dimensions of the box are 1 wt. % for Al$_2$O$_3$ and SiO$_2$.

Figure 6-10. Connected porosity vs. bulk vesicularity of all pumice types. Brackets represent 95% confidence limit for the mean of each pumice population. Solid lines represent 0% and 10% and dashed line 5% isolated pore volume.

Figure 6-11. Connected and bulk vesicularity vs. permeability. a) data of this study with upper and lower data limits (black lines) of $y=5 \times 10^{-19} x^{4.5314}$ and $y=6 \times 10^{-21} x^{4.5314}$, respectively. Note there are six specimens with three cores cut in three mutually perpendicular directions. Upper inset shows cores cut in two perpendicular directions. b) comparison of our data with published literature: Montserrat (Melnik and Sparks, 2002), Big and Little Glass Mountains (Rust and Cashman, 2004), Pichincha (Wright et al., 2007); grey lines are limits of Klug and Cashman (1996).

Reconstruction of eruptive events during the Burrell Lapilli eruption. Changes in bulk rock silica contents are illustrated in Stage a. Bubble nucleation levels 1-3 correspond with erupted units 1-3. See text for further details.

Correlation of pyroclastic flow deposits associated with the Burrell episode. Note that the major unit from medial to distal represents the Burrell Breccia (A). In section S04-133, the thin pyroclastic pumice flow deposits represent Burrell Breccia (B) units 1-3. Exposures are sorted by stream and planimetric distance from source. See figure legend for further details (RAD – rock-avalanche deposit). Magnetism was measured by a portable fluxgate magnetometer. For clarity, older exposed units were omitted. Outcrop numbers and profiles refer to Platz (2001) except S04-133. For list of samples and coordinates of outcrops see Appendix B.

Estimates of total water and carbon dioxide contents in melt inclusions. a) total H$_2$O at 3550 cm$^{-1}$ vs. molecular H$_2$O at 1630 cm$^{-1}$, and b) molecular CO$_2$ at 2350 cm$^{-1}$ vs. total H$_2$O at 3550 cm$^{-1}$.

Different shapes of melt inclusions in clinopyroxene. a) overview of crystal 2 (sample SD20); note the many inclusions of glass, plagioclase, apatite and Fe-Ti oxide which are mostly oriented along crystallographic planes, b) two close-ups as marked in a); I - represents common but very small melt inclusions found in clinopyroxene, which are unsuitable for FTIR analysis. Their shape is near spherical to ovate; II - the bottle-neck shape is typical for leaked melt inclusions, c) overview of crystal 11 (sample SD32) showing a large irregular shaped melt inclusion, d) close-up of c) showing the impossibility of using these inclusions for FTIR analysis; their shape is near spherical to ovate, e) section of crystal 4 (sample SD20) showing two types of melt inclusions, the reddish-brown coloured inclusions are probably altered in comparison to the brown inclusions to the right; note again the irregular outline of the inclusions, f) section of crystal 8 (sample SD9D); abundant sheet-like inclusions probably oriented along crystallographic planes; the inclusions around the Fe-Ti oxide inclusions (black) appear to be connected. Scale bars are 100 µm in a), c), and e), 50 µm in d) and f), and 10 µm in b).
Preliminary results of the thermal analysis studies. a) trial and error series of sample SD20, b) reproducibility results of different pumice samples; it is noted that for the same sample the maximum weight loss is often observed at similar temperatures.

Groundmass texture (a-d) and crystallinity (e-h) of clasts from pyroclastic flow deposits. a and c) two groundmass glasses, b-d) differences in degree of groundmass crystallisation in clear translucent and brown glasses, e) semi- to hyaline, clear translucent glass; note microvesicularity, f) same image as in e) under crossed polarised light, g) semi- to holocrystalline brown glass, h) same image as in g) under crossed polarised light.

Bulk rock composition of selected Maero eruptives. Block-and-Ash Flow deposits are not differentiated and the Pyramid Dome and the Turtle are omitted for clarity. For comparison, selected lava flows of the upper main cone and Fanthams Peak are plotted. Mg#={Mg2+/(Mg2++Fe2+)}; all iron as Fe2+.

Analytical totals of all EMP glass analyses (a) and sample averages (b) are plotted against silica content. Estimated glass water contents using the water-by-difference method (WBD) are shown on the right axis. The terms andesite, dacite, and rhyolite refer to the TAS-classification scheme of Le Maitre et al. (1989).

Calculated melt viscosities, $\eta$, are plotted against silica abundances. Values of the models of Shaw (1972) and Hui and Zhang (2007) are shown for H2O contents of 0.1 wt.%, 1 wt.% and WBD at T=900 °C and P=1 bar. Solid and dashed lines are regression lines of $\eta$ at WBD for the Hui-and-Zhang- and Shaw-models, respectively.

Calculated magma viscosities, $\eta_a$, are plotted against SiO2 contents. Lower and upper crystal volume fractions of 30% (a) and 55% (b), respectively are used for the calculation based on the calculated melt viscosities (see Fig. 7-4). Viscosities are calculated using H2O contents of 0.1 wt.%, 1 wt.% and WBD at constant T=900 °C and P=1 bar. Solid and dashed lines are regression lines of $\eta_a$ at WBD for the Hui-and-Zhang- and Shaw-models, respectively.

Bulk SiO2 contents (a) and Mg# (b) are plotted against K2O in chronological appearance of eruption episodes.

Calculated Mt. Taranaki melt viscosities are compared to calculated melt viscosities of Merapi volcano (Indonesia), Soufrière volcano (St. Vincent), and Soufrière Hills Volcano (Montserrat), using the same parameters. Solid lines are regression lines for Taranaki data.
Calculated Mt. Taranaki magma viscosities plotted against SiO$_2$ are compared to other andesite to rhyolite volcanoes. Since Taranaki viscosity calculations are based on glass chemical compositions of the Maero Eruptive Period, the range in bulk silica contents of rocks erupted during this period are used to allow comparison to published data. Upper and lower viscosity abundances are taken from Fig. 7-5. Taranaki data are illustrated by two parallelograms with upper and lower limits representing crystal volume fractions of 55% and 30%, respectively. The grey parallelogram corresponds to 1 wt.% melt water content, whereas the dashed parallelogram relates to water contents determined by WBD. Data source: silicic lava flows (Murase and McBirney, 1973; Fink, 1980; Navarro-Ochoa et al., 2002; Manley, 1996; Harris et al., 2004; and McKay et al., 1998); Mt. St. Helens (Murase et al., 1985; Scandone and Malone, 1985); Unzen volcano (Suto et al., 1993; Goto, 1999; Sato et al., 1999); Soufrière Hills Volcano, Montserrat (Voight et al., 1999; Sparks et al., 2000); Soufrière volcano, St. Vincent (Huppert et al., 1982); Merapi volcano (Siswowidjoyo et al., 1995).