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**A SEDIMENTOLOGICAL AND GEOCHEMICAL APPROACH TO
UNDERSTANDING CYCLES OF STRATOVOLCANO GROWTH
AND COLLAPSE AT MT. TARANAKI, NEW ZEALAND**

A thesis presented in partial fulfilment of the requirements
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Frontispiece. Mt. Taranaki viewed from the beach.

ABSTRACT

The long-term behaviour of andesitic stratovolcanoes is characterised by a repetition of edifice growth and collapse phases. This cyclic pattern may represent a natural frequency at varying timescales in the growth dynamics of stratovolcanoes, but is often difficult to identify because of long cycle-timescales, coupled with incomplete stratigraphic records.

The volcanoclastic ring-plain succession surrounding the 2 518 m Mt. Taranaki, New Zealand, comprises a wide variety of distinctive volcanic mass-flow lithofacies with sedimentary and lithology characteristics that can be related to recurring volcanic cycles over >190 ka. Debris-flow and monolithologic hyperconcentrated-flow deposits record edifice growth phases while polyolithologic debris-avalanche and associated cohesive debris-flow units were emplaced by collapse. Major edifice failures at Mt. Taranaki occurred on-average every 10 ka, with five events recognised over the last 30 ka, a time interval for which stratigraphic records are more complete. The unstable nature of Mt. Taranaki mainly results from its weak internal composite structure including abundant saturated pyroclastic deposits and breccia layers, along with its growth on a weakly indurated and tectonically fractured basement of Tertiary mudstones and sandstones. As the edifice repeatedly grew beyond a critical stable height or profile, large-scale collapses were triggered by intrusions preceding magmatic activity, major eruptions, or significant regional tectonic fault movements.

Clasts within debris-avalanche deposits were used as a series of windows into the composition of previous successive proto-Mt Taranaki edifices in order to examine magmatic controls on their failure. The diversity of lithologies and their geochemical characteristics are similar throughout the history of the volcano, with the oldest sample suites displaying a slightly broader range of compositions including more primitive rock types. The evolution to a narrower range and higher-silica compositions was accompanied by an increase in K_2O . This shows that later melts progressively interacted with underplated amphibolitic material at the base of the crust. These gradual changes imply a long-term stability of the magmatic system. The preservation of similar internal conditions during the volcano's evolution, hence suggests that external processes were the main driving force behind its cyclic growth and collapse behaviour and resulting sedimentation pattern.

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Figure 2.42.64

At its type section Waihi 5 (2620264/6175098), the Waingongoro debris-avalanche deposit is c. 5 m thick and characterised by abundant small tip-up clasts of the underlying bedded sands. It is overlain by the Waihi debris-avalanche deposit (A) from which it is separated by a thin paleosol (B).

Figure 2.43.64

In some locations, the Waingongoro debris-avalanche deposit shows a distinct basal layer of subrounded to subangular cobble- to boulder-sized clasts and has a similar appearance as the overlying Waihi.

Figure 2.44. 65

A shows the coastal extent of the Waingongoro debris-avalanche deposit as well as its type section (TS) and reference section (RS). Green circles represent outcrops where the deposit is exposed; white circles mark its absence. The extrapolated distribution of the deposit to the east and its interpreted dispersal axis are similar to the Waihi debris-avalanche deposit and were based on the dispersal of the Ngaere Formation (B).

Figure 2.45. 66

Stratigraphy of the type section for the Waingongoro debris-avalanche deposit (2620264/6175098). The deposit is overlain by the Waihi debris-avalanche unit and several hyperconcentrated –flow deposits. The bottom of the cliff section is made up of bedded sands and Tertiary mudstones.

Figure 2.46. 67

Schematic overview of the stratigraphy at the Waingongoro River mouth and Ohawe Beach. The complex valley sequence is the result of repeated incision and subsequent filling of these river channels with fluvial sediments and debris-avalanche deposits as well as intercalated hyperconcentrated-flow units. The profile is oriented west to east and c. 1.2 km in length. The mudstone sequence underlying the volcanoclastic succession is cut by the c. 127 ka Rapanui Marine Terrace in the eastern part of this cross-section and by the c. 105 ka Inaha Marine Terrace in the western part, resulting in a slight difference in thickness of the Tertiary basement.

Figure 2.47. 68

Overview of the broad Waingongoro River valley at the coast (A), person for scale. Tertiary mudstone sequences form the side walls of an ancient, wider valley in the same location. Tertiary mudstones are c. 7 m thick at the western side (B) and c. 10 m thick at the eastern side (C). The confinement of the Waihi debris avalanche to this paleo-channel and its abrupt contact to the Tertiary basement confirms the long (>70 ka) existence of this valley (B).

Figure 2.48. 70

A c. 4.5 m-thick mound of the otherwise buried Oeo debris-avalanche deposit crops out at the bottom of the cliff at its type section Oeo 7 (A). At this location (2593403/6184081) the deposit is characterised by a brecciated, almost clast-supported fabric (B). Hammer for scale, c. 30 cm long.

Figure 2.49. 71

A second c. 6 m- high mound of the Oeo-debris avalanche deposit crops out at Oeo 4B (A-B). It is overlain by the distinct Puketapu buried forest, which is characterised by a soil with a preserved tree stump in growth position (C). The Oeo debris-avalanche deposit consists of several monolithologic megaclasts with different sedimentological characteristics (D), arrow points to person for scale. The top of the mound is brecciated and clast-supported, while other domains (marked by white dotted line) consist of fine-grained matrix and angular-subangular clasts of various sizes (E).

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The coastal extent of the Oeo debris-avalanche deposit as well as its type section (TS) and reference section (RS) are shown in A. Green circles represent the three outcrops where the deposit is exposed; white circles mark its absence. The distribution of the deposit was extrapolated using the inundation area of the Pungarehu Formation since it is of similar thickness and shows similar deposit characteristics (B). Locations Oeo 4B and 7 most likely mark the course of its dispersal axis.

Figure 2.51.	73
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Stratigraphy of the type section for the Oeo debris-avalanche deposit (2593403/6184081). The deposit forms a mound that crops out at the bottom of the cliff and is overlain by the Puketapu buried forest. The upper part of the section consists of the Otakeho and Rama debris-avalanche deposits that are interbedded with hyperconcentrated-flow units and paleosols.

Figure 2.52.	75
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The Mangati debris-avalanche deposit in north Taranaki is characterised by a basal zone of coarse cobble-to boulder-sized clasts and large protruding tree logs. It occurs above iron-stained cross-bedded sands and is overlain by a thick sequence of peat and andesitic tephra beds.

Figure 2.53.	76
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Figure 2.54.	77
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The mapped extent of the Opuā debris-avalanche deposit in the study area is shown in A. Brown circles represent outcrops where the deposit is exposed; white circles mark its absence. The extrapolated distribution of the deposit based on the observations of this study in comparison to the mapped extent (from Neall & Alloway 2004) and dispersal axis are displayed in B.

Figure 2.55.	78
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Figure 2.56.	79
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Map of the observed coastal extent of the Pungarehu debris-avalanche deposit in the study area (A). Orange circles represent outcrops where the deposit is exposed; white circles mark its absence. The extrapolated distribution of the deposit based on the mapping results of this study in comparison to the mapped extent (from Neall & Alloway 2004) and dispersal axis are shown in B.

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Figure 3.10.133

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Figure 3.12.136

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Figure 4.8.200

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Figure 4.9.202

Variation of $^{87}\text{Sr}/^{86}\text{Sr}$ in relation to SiO_2 content (A) and age (B) of selected Taranaki debris-avalanche samples. Most samples are within a narrow range of $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic compositions but three basalts from the oldest Mt. Taranaki suites are distinct with lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Figure 4.10.202

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Figure 4.11.203

Lead isotope composition of selected Mt. Taranaki and Pouakai debris-avalanche clasts. A: Variation of $^{207}\text{Pb}/^{204}\text{Pb}$ in relation to $^{206}\text{Pb}/^{204}\text{Pb}$. B: Plot of $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$.

Figure 4.12.205

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Figure 4.13.206

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Figure 4.14.207

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Figure 4.15.208

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Figure 4.16.208

Debris-avalanche samples from Pouakai show lower concentrations in Pb than the Mt. Taranaki suites and a constant trend with increasing SiO_2 (A). Barium contents are lower for low-silica compositions but overlap with the oldest suites from Mt. Taranaki towards higher SiO_2 abundances (B). The Maitahi suite also shows a steeper fractionation trend than the other sample suites.

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Plots showing the differences in HFSE between Mt. Taranaki and Pouakai sample suites. A: The Maitahi suite has distinctly lower contents of Hf and marks a relatively constant trend with increasing SiO_2 . B: Pouakai samples have distinctly lower contents of Zr and Hf than Mt. Taranaki rocks, resulting in a distinct cluster for each volcano with only minor overlap. C: The differences in Nb and Ta contents are less distinct, with Pouakai samples plotting towards lower concentrations but overlapping with Mt. Taranaki rocks. Within ring-plain samples, Nb and Ta are linearly correlated, in contrast to the youngest eruptives that have relatively constant Nb at varying Ta abundances.

Figure 4.18.215

Distinction between Pouakai and Mt. Taranaki sample suites based on LREE contents. The Maitahi samples have distinctly lower contents of Ce (A) and Nd (B) compared to Mt. Taranaki rocks. Pouakai and Mt. Taranaki sample suites form separate clusters with only minor overlap on plots of Pr versus Ce (C) and Sm versus Nd (D).

Figure 4.19.218

A: The plot of K/Nb ratios versus Ce/Pb ratios highlights the increasing slab influences or lower crustal interactions with time within the Mt. Taranaki sample suites. The oldest Mt. Taranaki debris-avalanche samples show the highest Ce/Pb and lowest K/Nb ratios, while Pouakai samples overlap with the 80-10 ka sample suites. One Pouakai rock and one Otakeho clast plot at unusually high Ce/Pb ratios. B: The generally higher Ba/Yb ratios of Mt. Taranaki and Pouakai eruptives indicate lower degrees of partial melting and more interaction with

underplated lower crustal material than at Ruapehu although there is some overlap with older Taranaki samples. Mt. Taranaki data from Price et al. (1999), Platz (2007) and Turner (2008); Mt. Ruapehu data from Gamble et al. (1993 & 1999) and Waight et al. (1999).

Figure 4.20.220

$^{86}\text{Sr}/^{87}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ diagram for Mt. Taranaki and Pouakai sample suites in comparison with data from Ruapehu as well as fields defined by rhyolites and basalts from the Taupo Volcanic Zone (TVZ) and Kermadec/Tonga lavas (K/T). Data sources: Graham & Hackett 1986; Gamble et al 1993, 1999; Ewart et al. 1998; Price et al. 1999; Waight et al 1999.

Figure 4.21.222

Trace element characteristics of distinct samples from Mt. Taranaki compared to the rest of the sample suites. They show a range of LREE abundances and depletion of HREE compared to NMORB with the exception of andesite sample AZ06-83 from the Ngaere Formation (A). Various degrees of arc signature suggest more than one mantle source for Taranaki magmas (B).

Figure 4.22.223

The influence of the slab component increases from the Kermadec/Tonga to the Taranaki volcanoes and Ruapehu. Taranaki eruptives show a wide range in Nb/Yb ratios, which reflects variations in the mantle source, and some overlap with Ruapehu. Mt. Taranaki data from Price et al. 1999, Platz 2007 and Turner 2008. Ruapehu data from Gamble et al. 1993, 1999 and Waight et al. 1999. Kermadec/Tonga data from Ewart et al. 1998.

Figure 4.23.224

Lead isotopic data for Mt. Taranaki and Pouakai samples in comparison with Ruapehu, data fields of TVZ and Kermadec-/Tonga-arc (K/T) and the Northern Hemisphere Reference Line (NHRL) from Hart (1984). Magmas from both volcanoes form a continuous trend of increasing $^{207}\text{Pb}/^{204}\text{Pb}$ (A) and $^{208}\text{Pb}/^{204}\text{Pb}$ (B) ratios at slightly increasing $^{206}\text{Pb}/^{204}\text{Pb}$. Ruapehu rocks are more radiogenic and cluster in a small field, while Taranaki magmas show a wider range of $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios and extend to less radiogenic compositions. Circles W and M represent average data (from Price et al. 1999) for Taranaki basement rocks of Waipapa terrane and Median Tectonic Zone. The square labelled T represents Ruapehu basement made of Torlesse terrane. Other data sources: Gamble et al 1993, 1999 and Price et al. 1999.

Figure 5.1.228

Composition of feldspars in Mt. Taranaki rocks. A: Compositional range of plagioclase in 100-130 ka debris-avalanche clasts. B: Rim and core analyses of plagioclase in debris-avalanche samples. C: Comparison of plagioclase composition in >100 ka and <10 ka rocks (data from Platz 2007, Turner 2008).

Figure 5.2.231

Composition of pyroxenes in Mt. Taranaki rocks. A: Clinopyroxene and orthopyroxene compositions in 100-130 ka debris-avalanche clasts. B: Rim and core analyses of clinopyroxenes in debris-avalanche samples. Comparison of clinopyroxene and orthopyroxene compositions in

>100 ka and 10 ka rocks is shown in C and D, respectively (data from Stewart et al. 1996, Platz 2007, Turner 2008).

Figure 5.3.234

Composition of hornblende in Mt. Taranaki rocks. A: Compositional range of hornblende in 100-130 ka debris-avalanche clasts (classification after Leake et al. (1997a, b, 2003) based on Si versus Mg#*). B: Rim and core analyses of hornblende in debris-avalanche samples. C: Comparison of hornblende composition in old and young rocks. (data from Stewart et al. 1996, Platz 2007, Turner 2008). *Mg#=100[Mg²⁺/(Mg²⁺+Fe²⁺)]minimum Fe³⁺ after Schumacher (1997).

Figure 5.4.235

Comparison of Ti and Al proportions in hornblende within 100-130 ka debris-avalanche clasts and rocks <10 ka. A: TiO₂ (wt.%) versus Al₂O₃ (wt.%) of hornblende crystals. B: Ti versus tetrahedral Al^{IV} and C: Ti versus octahedral Al^{VI}.

Figure 5.5.238

Composition of olivine in Mt. Taranaki rocks. A: Compositional range of olivine in >100 ka debris-avalanche clasts. B: Rim and core analyses of olivine in debris-avalanche samples. C-D: Comparison of olivine composition in 100-130 ka and <10 ka rocks in a plot of forsterite versus CaO(C).

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Plots displaying the compositional range of titanomagnetite in >100 ka debris-avalanche clasts in comparison to <10 ka samples. Molecular Al plotted versus Fe²⁺ (A) and Mg (C). B shows a plot of Fe³⁺# versus Ti/Al ratios (cations per formula unit).

Figure 6.1.268

Simplified model of cyclic behaviour of stratovolcanoes in general and associated volcanic and volcanoclastic sedimentation as observed at Mt. Taranaki.

Figure 6.2.277

DEM of the Taranaki peninsula showing the direction of collapse that produced the identified debris-avalanche deposits in the Mt. Taranaki ring-plain succession. Failures have occurred on similar sectors of the edifice during certain time periods, indicating that different parts of the edifice were more unstable and thus vulnerable to collapse at different times throughout the volcanic history. Dashed axes are based on assumed dispersal of the south-eastern and the oldest northern debris-avalanche deposits. Shaded areas illustrate the direction of the two main volcanic alignments. Grid references are NZ map grid.

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