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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 for the degree of

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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 volcaniclastic 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$_2$O. 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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At this location (Kaupokonui 6B), three debris-avalanche deposits (Otakeho, Rama and Ngaere) are exposed, which represent important lithological markers for correlation of the volcaniclastic sequence.

A: At its type locality Middleton Bay 9, the Hihiwera Peat is c. 1.2 m thick with an upper part consisting of peat and organic soil beds while the lower part is characterised by tephric and silty paleosols. B: At location Otahi 7 it is c. 0.8 m thick and of massive appearance.

A: The Puketapu buried forest is c. 0.5 m thick at location Punehu 4, where it forms a distinct, continuous layer at the bottom of the cliff just above the high tide mark. B-C: Tree stumps in growth position surrounded by beach pebbles mark locations where the actual paleosol occurs below sea level (B: Punehu 13; C: Oeo 4).

The prominent c. 80 ka Manaia Lignite of McGlone et al. (1984) is c. 1.2 m thick at location Waiokura 6B, near the type locality at Inaha Stream.

In coastal sections of south-west Taranaki, the Kawakawa Tephra occurs in a thick soil sequence below the Pungarehu debris-avalanche deposit. The tephra bed is of a distinct creamy colour and can form a continuous horizon (A) or appear patchy (B), probably due to falling on a shrubby vegetation cover. The tephra thickness in both photos is c. 2-3 cm.

Planar and high-angle cross-bedded sets of fine-grained, greyish dune sands with weathered, iron-stained tops (A) overlying three fine-grained pumiceous hyperconcentrated-flow deposits (B) at Punehu 1a.

The Motumate debris-avalanche deposit is exposed near the top of the cliff at its type locality Kaupokonui 5 (2602779/6180288) and separated from the underlying Ngaere Formation by hyperconcentrated-flow deposits and fluvial sediments.

The mapped coastal extent of the Motumate debris-avalanche deposit as well as its type section (TS) and reference sections (RS) are shown in A. Yellow circles represent outcrops where the deposit is exposed; white circles mark its absence. The distribution of the Wr3 lobe (bright yellow) of Neall (1979) and the likely overall distribution of the Motumate debris avalanche-deposit and its dispersal axis are shown in B.
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Figure 2.15. At its type section (2581432/6195939), the Te Namu debris-avalanche deposit is >5 m thick and contains pebble- to boulder-sized clasts as well as abundant rip-up clasts in a clay-rich matrix (A). It is overlain by two distinct organic paleosols that embrace two andesitic tephra beds and a pale pink silt layer (B).

Figure 2.16. At reference locality Okaweu 2, the Te Namu debris-avalanche deposit is overlain by several hyperconcentrated-flow deposits as well as the Opua and Pungarehu Formations near the top of the section (A). Here, the Te Namu debris-avalanche deposit contains abundant ripped-up fragments of the underlying Hihiwera Peat (B).

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Stratigraphy of the type section for the Ihaia debris-flow deposit (2583440/6193829). The deposit is exposed at the bottom of the cliff below the Hihiwera Peat. Above the peat, a thick series of coarse channel fill and hyperconcentrated-flow deposits are exposed with an intercalated lens of the Te Namu and Pungarehu debris-avalanche deposits and a Warea hyperconcentrated-flow deposit and the Opua Formation at the top of the section.

At its type section Kaupokonui 1, the Rama debris-avalanche deposit is c. 5.5 m thick and characterised by coarse clasts, few small rip-up clasts and a large brecciated megaclast in a clay-rich matrix.

Near its type section, the Rama is overlain by stacks of fine-grained hyperconcentrated-flow deposits with interbedded fluvial sediments that are best exposed further inland along the Kaupokonui Stream.

A: Mapped coastal extent of the Rama debris-avalanche deposit, showing its type section (TS) and reference sections (RS). Purple circles represent outcrops where the deposit is exposed; white circles mark its absence. The extrapolated inland distribution of the deposit and the inferred axis of dispersal are shown in B.

Stratigraphy of the type section for the Rama debris-avalanche deposit. The deposit is exposed at the top of the cliff and underlain by the Ihaia debris-flow and the Otakeho debris-avalanche deposit. The bottom of the cliff section is made of stacks of pumice- and andesite-rich hyperconcentrated-flow deposits and intercalated cross-beded fluvial sands and gravels.

At reference locality Waikura 5C, the Rama dominates the cliff section. It is separated from the Tertiary mudstones by bedded marine and fluvial sands and several peat layers, including the Manaia Lignite (A). The debris-avalanche deposit is overlain by a prominent equivalent of the Hihiwera Peat (B).

An unnamed c. 1.3 m thick cohesive debris-flow deposit is exposed at Kaupokonui 1. It occurs above the Otakeho debris-avalanche deposit and is separated from the overlying Rama by cross-beded fluvial sands.

Mapped coastal extent of the unnamed debris-flow deposit and extrapolated inland distribution along a proto-Kaupokonui catchment.
The Otakeho debris-avalanche deposit is c. 2.5 m thick at its type section Wahamoko 10 (2600243/6181996).

At Oeo 1, the deposit is only c. 1 m thick and overlies a distinct peat layer and a thick paleosol.

At reference locality Kaupokonui 5, the Otakeho debris-avalanche deposit is very matrix-rich and contains several large tree logs (A) and large stratified rip-up clasts >2.5 m in diameter (B).

A: Map showing the coastal extent of the Otakeho debris-avalanche deposit as well as its type section (TS) and reference sections (RS). Blue circles represent outcrops where the deposit is exposed; white circles mark its absence. The extrapolated distribution of the deposit inland and the inferred axis of dispersal are shown in B.

Stratigraphy of the type section for the Otakeho debris-avalanche deposit (2600243/6181996). The deposit overlies hyperconcentrated flow-deposits and dune sands. The top part of the cliff consists of the prominent Rama debris-avalanche deposit and several sheet-like and channelled hyperconcentrated-flow deposits.

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In the Punehu catchment, the unnamed debris-flow deposit below the Otakeho debris-avalanche deposit is c. 0.6 m thick, very matrix-rich and characterised by small, granule- to pebble-sized clasts.

In the Kaupokonui catchment, a c. 0.8 m thick unnamed debris-flow deposit occurs below the Otakeho. It is underlain by fluvial sands and hyperconcentrated-flow deposits.

The Tokaora debris-avalanche deposit thickens in a small channel at its type section Waingongoro 5 (2614414/6178412) is shown in A. It is characterised by small, predominantly pebble-sized clasts in a dark brownish matrix and typically has a yellowish weathered top (B-C).

A: Map of the coastal extent of the Tokaora debris-avalanche deposit as well as its type section (TS) and reference section (RS). Blue circles represent outcrops where the deposit is exposed;
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Figure 2.38. The Waihi debris-avalanche deposit shows a distinct coarse basal layer is at its type section Waihi 2 (2617078/6176430) and is sedimentologically similar to the underlying Waingongoro debris-avalanche deposit.

Figure 2.39. At reference locality Waihi 5A, the Waihi debris-avalanche deposit is c. 5 m thick and characterised by large, rounded megaclasts (A) and abundant rip-up clasts (B; white arrow points to a large rip-up clast). At Waingongoro 4A, the deposit thickens in a small channel and consists of a coarse bottom unit with large cobble- to boulder-sized clasts and abundant brecciated megaclasts and a thinner upper part characterised by smaller clasts and small rip-up clasts (C).

Figure 2.40. The coastal extent of the Waihi debris-avalanche deposit as well as its type section (TS) and reference sections (RS) are shown in A. Blue 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 was based on the dispersal of the Ngaere Formation (B).

Figure 2.41. Stratigraphy of the type section for the Waihi debris-avalanche deposit (2617078/6176430). The deposit is exposed near the top of the cliff. The sequence below is made of bedded sands with two thick intercalated peat/soil layers. Marine sands and a prominent shellbed form the coverbeds of the Rapanui marine bench and separate the volcaniclastic succession from the underlying Tertiary mudstone sequence.

Figure 2.42. 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. 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.
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Figure 2.45. 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. 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 volcaniclastic 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. 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. 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. 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 monolithic 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).
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.

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.

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.

At Okaweu 10, the Opua debris-avalanche deposit is c. 4 m thick and characterised by cobble-to boulder-sized clasts in a clay-rich matrix.

The mapped extent of the Opua 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.

In the second, marginal lobe of distribution, the Pungarehu debris-avalanche deposit is characterised by an orange-reddish matrix and few, predominantly pebble-sized clasts. It is c. 2 m thick at Mangahume 4.

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.
At Kaupokonui 6, the Ngaere debris-avalanche deposit is c. 3.5 m thick and characterised by coarse clasts pebble- to boulder-sized clasts. It is overlain by the Motumate debris-avalanche deposit and separated from the underlying Rama by a thick hyperconcentrated-flow deposit.

Within the Waingongoro River valley, the Ngaere debris-avalanche deposit fills a small fluvial channel that was cut into the underlying Waihi debris-avalanche deposit and older fluvial sediments (A). The arrow marks the location of the cut and fill inset, which is shown as close-up in B.

Map of the observed coastal extent of the Ngaere 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 inland complements the mapped extent by Neall & Alloway (2004) as shown in B.

Cross-section of the medial Mt. Taranaki ring-plain succession, exposed in coastal cliff sections of the western to southern Taranaki peninsula. Displayed are the dominant marker horizons, including debris-avalanche and cohesive debris-flow deposits, prominent peat and soil layers that could be laterally correlated as well as Hauriri dune sands and the underlying Tertiary mudstone. The extent of the Opunake and Lizzie Bell river systems is also marked. Individual lahar deposits and channels could not be displayed due to their limited lateral extent. Pu = unnamebd debris-flow deposit in Punehu catchment, Kau = unnamebd debris-flow deposit in Kaupokonui catchment, Pbf = Puketapu buried forest, ML = Manaia lignite.

New stratigraphic concept for the Mt. Taranaki volcanic succession, which combines a chronostratigraphic framework and lithostratigraphically defined units.

Composite stratigraphic overview of the Mt. Taranaki volcanic succession. The chronostratigraphic units are defined based on the volcano's cyclic behaviour and represent phases of growth and collapse. Within this chronostratigraphic framework, the identified lithostratigraphic units from this and previous studies (Neall 1979; Neall et al. 1986; Alloway 1989; Alloway et al. 1995; Neall 2003; Alloway et al. 2005; Platz 2007) are distinguished based on their origin and emplacement mechanism. Volcanic units comprise edifice-building lava flows, pyroclastic flow deposits and tephra as well as satellite lava domes. The volcaniclastic units comprise lahar (hyperconcentrated-flow and debris-flow) and debris-avalanche deposits, which are shown based on their dispersal within the northeastern, southeastern and southwestern sector of the ring plain. Nonvolcanic sediments include flood deposits, fluvial sediments and aeolian sand dunes as well as peat layers. St = stage, SS = sub-stage, EP = eruptive period, EE = eruption episode, PF = pyroclastic flow.
Figure 3.1. Schematic illustration of sediment/water ratio, corresponding flow type, transport and depositional mechanisms (from Smith & Lowe 1991).

Figure 3.2. Rheologic classification of sediment-water flows from Pierson & Costa (1987).

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Figure 3.4. Characteristic lithofacies types and facies variations in Taranaki debris-avalanche deposits from source to medial/distal areas are illustrated in A (adapted from Palmer & Neall 1991). Photographs show the corresponding geomorphologic characteristics of axial-A (A), axial-B (B) and marginal facies (C) of unconfined debris-avalanche deposits at Mt. Taranaki.

Figure 3.5. Fabric of axial-A (A-B), axial-B (C-D) and marginal (E-F) facies of Mt. Taranaki debris-avalanche deposits. The transition from axial-A to marginal facies is characterised by a decrease in overall clast size and thickness and an increase in matrix and megaclasts and large lava blocks are gradually disaggregated. Secondary rip-up clasts become more common.

Figure 3.6. Facies types of lahar and lahar-related streamflow deposits (from Scott 1988a).

Figure 3.7. Sedimentary features of Mt. Taranaki and Pouakai debris-avalanche deposits. A: Te Namu debris-avalanche deposit thickening in channel at Te Namu Pa. B-C: Basal shearing and deformation of the Maitahi debris-avalanche deposit at Oakura Beach. Camera cases for scale each c. 10 cm long. D: Basal bouldery layer of the Mangati debris-avalanche deposit near Bell Block. E: Close up of D showing the pumice-rich top of the Mangati debris-avalanche deposit. F: The Otakeho debris-avalanche deposit has a greenish base and brownish top half near Kaupokonui Stream.

Figure 3.8. Characteristic components of Mt. Taranaki and Pouakai debris-avalanche deposits. A. Matrix-rich fabric of the Opua Formation with coarse clasts as example of the granular type debris-avalanche deposit. Hammer for scale, handle c. 30 cm long. B. Fractured clast with jigsaw cracks surrounded by clustered clasts of the same lithology within the Maithai Formation. Camera lens cap for scale c. 5 cm across. C. Close-up of a fractured block with jigsaw cracks within the Pungarehu Formation. Lens cap for scale. D. Large brecciated megaclast observed in the Opua Formation close to its main axis of dispersal. E. Small “brecciated clast” within the Maithai Formation. F. Stratified megaclast in the Maitahi Formation, which preserved the original stratigraphy of the edifice. Circled hammer for scale.
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Figure 3.10. Cohesive-type debris-avalanche deposits are characterised by a matrix-rich fabric with only few and relatively small clasts (A). The Otakeho Formation also contains abundant pieces of ripped-up wood up to log-size (B). Megaclasts are rare, considerably rounded and small in size, like this example from the Otakeho debris-avalanche deposit (C). Rip-up clasts are typically small and rounded and are often fragments of peat beds with interbedded tephras (D).

Figure 3.11. Channelised debris-flow deposits are characterised by a clast-supported fabric and large boulders (A). Towards the channel margins they grade into thinner and finer-grained overbank deposits, marked by the white arrow (B).

Figure 3.12. Photographs of the different types of hyperconcentrated-flow deposits observed in Taranaki. Hammer c. 30 cm long; pencil in B c. 15 cm long. A-B. Coarse- and fine-grained pumice-/scoria-rich hyperconcentrated-flow deposits were generated during or shortly after Plinian/subplinian eruptions. C. Hyperconcentrated-flow deposits that contain dense andesite clasts represent the runout of block-and-ash-flow reworking lahars. D. Juvenile breadcrust bombs in monolithologic hyperconcentrated-flow deposits indicate syneruptive origin or generation shortly after eruptive activity. E. Polyolithologic hyperconcentrated-low deposits do not seem to be directly related to eruptive periods.

Figure 3.13. Sediment-rich hyperconcentrated flows at Mt. Taranaki emplaced coarse and reverse to normally graded, (A) or massive and ungraded units, the latter showing transitions to debris-flow deposits (B). More dilute flows produced bedded, fine-grained hyperconcentrated-low deposits (C). Pumice trains are common in finer-grained, faintly bedded, pumiceous hyperconcentrated-flow deposits (D). Pebble-sized clasts transported as bedload, cluster in front of larger clasts, which represented a barrier during flow (E). Dish and pillar structures (F) and load-induced flame structures (G-H) are common in Mt. Taranaki hyperconcentrated-flow deposits and are produced by post-depositional deformation and dewatering processes. Hammer c. 30 cm long; shovel handle in C c. 1 m long; lens cap in G c. 5 cm across.
Flows transitional between hyperconcentrated flow and normal streamflow produce deposits with laminar bedding (A) or lenticular, cross-bedded units that can often steep channels.

Fluvial deposits are common in the Taranaki ring-plain succession and typically consist of cross-bedded lenses of sand and beds of rounded pebbles (A-B). Aggradational river sequences are more poorly sorted and coarser, consisting of pebble- to boulder-sized rounded to subrounded volcanic clasts with intercalated cross-bedded lenses of small pebbles and sand (C-D). Pencil for scale in D is c. 15 cm long.

Paleo-sand dunes within the ring-plain succession consist of alternating thin beds of dark grey, very well-sorted fine sands and thicker beds of coarser, light yellow to brownish, well-sorted sands (A). They form sequences of >12 m thickness with individual sets of dune sands typically being tens of cm to c. 1.5 m thick and showing planar or high-angle cross-stratification (B).

Sequence of stacked debris-avalanche (Rama and Otakeho) and debris-flow (DFD, unnamed) units at Kaupokonui 1 with little fluvial accumulation (Flu) between events.

Cliff section at Middleton Bay 3, which contains the Opua Formation near the top and the Ihaia debris-flow deposit at the bottom of the cliff. Channels were cut into the Pungarehu (Pu) and Te Namu (TN) debris-avalanche deposits and subsequently filled by debris-flow, hyperconcentrated-flow and fluvial deposits.

Deposit sequence of a central channel area filled by coarse debris flow and finer-grained hyperconcentrated flow deposits towards the top. The coarser channel-fill grades into finer-grained overbank deposits near the channel margins.

Cliff section dominated by stacks of coarse- and fine-grained hyperconcentrated flow deposit. Persons for scale.

Fluvial deposit sequence characterised by aggradational, coarse sediments in the bottom half that are separated from overlying cross-bedded fluvial gravel and sands by several thin hyperconcentrated-flow deposits (HF). The cliff section is capped by the Opua debris-avalanche deposit.
Deposit sequence dominated by several sets of cross- and planar bedded grey dune sands. Here, no paleosols formed within the sequence but some layers are characterised by weathered iron-stained tops.

Stratigraphic columns of the different types of lithofacies associations occurring in the Taranaki ring-plain succession: debris-avalanche dominated sequence (A), channel system capped by hyperconcentrated-flow deposits (B), series of sheet-like hyperconcentrated-flow deposits with interbedded fluvial sediments (C) and sequence of dune sands with interbedded peat layers or sandy paleosols (D). Lithofacies elements B-D are typically found between debris-avalanche deposits, indicating different types of deposition between collapse events (as indicated by the dotted lines).

Correlation of debris-avalanche (DA) events with prevailing climate in Taranaki. Climate conditions from Newnham & Alloway (2004) and planctonic $\delta^{18}$O isotope record at DSDP site 594 from Nelson et al. (1993).

Warm climates are characterised by reddish-brown organic-rich paleosols with strongly developed soil structures (A). In contrast, yellowish loess-rich tephric paleosols reflect cold climates (B); the 22.5 ka Kawakawa Tephra is marked by a white arrow. Thick laminated peat deposits are common in the ring-plain succession and often preserve interbedded tephra beds (C). The Hihiwera Peat is the most prominent peat accumulation of the south-western ring plain and at several locations it is interbedded with organic-rich and tephric soils (D). Hammer for scale is c. 30 cm long.

Map of the Taranaki peninsula showing distinct physiographic units: Taranaki ring plain, Pouakai ring plain, Old Surface, remnants of Kaitake and Pouakai Volcanoes, Mt. Taranaki edifice above 1100 m, marine terraces, and Taranaki hill country/Tertiary marine sediments (A). Swamp areas are shown in white. A digital elevation model (DEM) of the present-day geomorphology with these physiographic units is presented in B.

A large channel with wavy basal and erosive lateral contacts is shown in photograph A. It is filled by a series of coarse channelised debris-flow deposits (Ch), which are overlain by several hyperconcentrated-flow units (HFD). A close-up of the channel shows the rectangular lateral contact (marked by black arrow) to the Otakeho debris-avalanche deposit (B). Vertical erosion stopped, when the channel encountered slightly cemented, iron-stained sands, resulting in a relatively straight basal contact (pointed out by white arrows).
Figure 3.28. Abrupt facies changes from coarse debris-flow deposits (DFD) filling a steep-sided channel to finer-grained overbank facies (OF) are shown in A. These facies changes are more gradational in wide, gently sloping channels observed within the larger river systems (B).

Figure 3.29. Cliff section showing a series of subsequent channels that were established in adjacent locations after previous ones had been filled as pointed out by arrows (A). Other small channels were cut in the same location as previous ones (B) and were subsequently filled with coarse hyperconcentrated-flow deposits, separated by fluvial sediments (Flu).

Figure 3.30. Location map of the Opunake (Op) and Lizzie Bell (LB) river systems and identified fault lines in their vicinity (from Rattenbury et al. 2007) as well as the course of the current Waingongoro River channel (Wai).

Figure 4.1. TAS discrimination diagram (after Le Maitre et al. 1989) of analysed debris-avalanche clasts showing their range in composition from basalt through to andesite.

Figure 4.2. Variations in SiO₂ and lithological proportions for Mt. Taranaki. The oldest debris-avalanche sample suites show the widest range in SiO₂ content (A). They also contain more primitive, basaltic rocks, which are rare in the younger deposits (B). By contrast, the latter comprise a higher proportion of andesite. The total number of analysed samples for each suite is given in Table 4.1.

Figure 4.3. K₂O vs. SiO₂ variation diagrams for Mt. Taranaki (filled diamond) and Pouakai (open circle) debris-avalanche clasts. According to the classification of Gill (1981) the volcanics range from medium-K, low-Si to high-K, high-Si rocks, with Pouakai clasts showing predominantly lower-K contents than Mt. Taranaki.

Figure 4.4. Major element variation as a function of SiO₂ content for Mt. Taranaki (filled diamond) and Pouakai (open circle) debris-avalanche samples.

Figure 4.5. Trace element variation versus SiO₂ abundance for Mt. Taranaki (filled diamond) and Pouakai (open circle) debris-avalanche samples.

Figure 4.6. Chondrite-normalised rare earth element diagrams (normalising values from Sun & McDonough, 1989). A: Mt. Taranaki sample suites show enrichment of LREE over HREE, a feature characteristic of arc magmas. B: In comparison, Pouakai samples have lower REE
contents than Mt. Taranaki rocks (shaded in grey). Three samples are distinct with similar abundances of La-Pr but markedly lower concentrations of Nd, Sm and HREE.

Figure 4.7. Composite normalised extended element diagram of selected trace and rare earth elements normalised to N-MORB for Mt. Taranaki sample suites (normalising values from Sun & McDonough 1989). A: Mt. Taranaki rocks show a typical arc signature, characterised by enrichment of LILE relative to normal MORB, strong depletion in Nb relative to K, Th, U and Pb and enrichment of Pb and Sr over Ce. B: Andesitic and most basaltic samples of the Mt. Taranaki suites show parallel trends of trace and rare earth element with the latter generally having lower concentrations of incompatible trace elements. The normalised trace element distributions of some basalt clasts are distinct from the overall observed pattern. C: One basaltic sample of the Mangati suite (AZ06-73) shows a significantly more subdued arc signature than the average Mt. Taranaki rocks (shaded in grey). Two basaltic rocks of the Okawa series (AZ04-06 and -07) and one clast of the Motunui suite (AZ04-27) show a weak but yet more distinct subduction-related trace and rare earth element pattern.

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Figure 4.9. Variation of $^{87}$Sr/$^{86}$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 $^{87}$Sr/$^{86}$Sr isotopic compositions but three basalts from the oldest Mt. Taranaki suites are distinct with lower $^{87}$Sr/$^{86}$Sr ratios.

Figure 4.10. Taranaki debris-avalanche clasts show a distinct negative correlation between $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd isotopic compositions.

Figure 4.11. Lead isotope composition of selected Mt. Taranaki and Pouakai debris-avalanche clasts. A: Variation of $^{207}$Pb/$^{204}$Pb in relation to $^{206}$Pb/$^{204}$Pb. B: Plot of $^{208}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb.

Figure 4.12. K$_2$O vs. SiO$_2$ variation diagrams for Taranaki eruptives. Each sample suite is distinct (A) and the linear fits of the stratigraphic units show a progressive increase in K$_2$O with decreasing age (B).

Figure 4.13. When plotted versus age, K55 values of the individual sample suites conform closely to an exponential curve of increasing K$_2$O with decreasing age. The unusually high K55 value of the Oeo suite (marked in red) is a result of the limited number of samples and the resulting steep,
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Figure 4.14. Most LILE are coupled with K<sub>2</sub>O. On a plot of Ba versus K<sub>2</sub>O individual stratigraphic suites form distinct clusters due to increasing concentrations in these elements with decreasing age (A). Lead concentrations show a greater spread of data with age but still define a trend of increasing Pb and K<sub>2</sub>O with decreasing age, which allow a clear distinction between the oldest and youngest units (B).

Figure 4.15. Variation of Al<sub>2</sub>O<sub>3</sub> is complex and differences between individual stratigraphic suites seem to mainly reflect differences in SiO<sub>2</sub> content rather than age trends. Only the youngest eruptives are distinct with overall lower concentrations of Al<sub>2</sub>O<sub>3</sub> compared to the other suites.

Figure 4.16. Debris-avalanche samples from Pouakai show lower concentrations in Pb than the Mt. Taranaki suites and a constant trend with increasing SiO<sub>2</sub> (A). Barium contents are lower for low-silica compositions but overlap with the oldest suites from Mt. Taranaki towards higher SiO<sub>2</sub> abundances (B). The Maitahi suite also shows a steeper fractionation trend than the other sample suites.

Figure 4.17. Plots showing the differences in HFSE between Mt. Taranaki and Pouakai samples suites. A: The Maitahi suite has distinctly lower contents of Hf and marks a relatively constant trend with increasing SiO<sub>2</sub>. 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. 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. 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).

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Figure 4.23. 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.

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