Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

Linking distal volcaniclastic sedimentation and stratigraphy with the growth and development of stratovolcanoes, Ruapehu volcano, New Zealand

A thesis presented in partial fulfilment of the requirements
for the degree of

Doctor of Philosophy
in
Earth Sciences

at Massey University, Palmerston North, New Zealand.

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

Manuela Tost

2015

"Look deep into Nature, and then you will understand everything better"

~ Albert Einstein

ABSTRACT

Large, long-lived stratovolcanoes are inherently unstable, and commonly experience large-scale flank collapse. The resulting debris avalanches permanently alter the edifice and the valleys they impact. New mapping reveals that at least six hitherto unknown debris avalanches occurred from Mt. Ruapehu, New Zealand. They collectively inundated >1,200 km^2 and ranged between 1.3 and >3 km^3 in volume, the latter being the largest debris avalanche known from the volcano. Constriction of the sliding debris avalanches into deep river valleys enhanced basal erosion, incorporation of water-saturated substrate and formation of a basal lubrication zone. This led to runouts of up to 100 km, 2 - 3 times longer than expected for equivalent unconfined dry landslides. Two of the seven river catchments affected by debris avalanches were truncated from the volcano by proximal debris choking. The debris avalanches commonly coincided with warming from glacial into interglacial periods and rapid deglaciation of Mt. Ruapehu. A loss of ice-armouring of the slopes and increased water saturation likely weakened the edifice. At least two of the debris avalanches were triggered by intrusion of new magma into the mountain. The highly resistant debris-avalanche deposits form distinctive plateaus at the highest topographic elevations along present eroding river valleys, in places reflecting earlier drainage pathways. Deposit ages and those from lower climate-controlled (non-volcanic) fluvial aggradational terraces allowed calculation of regional uplift rates, which varied between 1.3 ± 0.5 mm yr^{-1} to 5 ± 1.3 mm yr^{-1} over the last c. 125 ka. Each major flank failure led to decompression of the Mt. Ruapehu magmatic system, triggering pulses of numerous large-scale eruptions and syn-eruptive lahars. Ar-Ar dating of lava clasts within the debris avalanche deposits provided evidence of volcanic episodes that are not exposed on the present edifice. The oldest deposits from Mt. Ruapehu are now identified at ≥340,000 ka and show that a complex multi-stage storage magma system was operating, similar to that of the present day. Hornblende-bearing xenoliths from these lavas show that a magmatic crustal underplate at >40 km depth existed beneath the volcano by ~486.5 ± 37.6 ka. Combined, samples from the mass-flow deposits and the cone lavas show more complex variation over time than previously thought, but generally reflect a progressively increasing heat flux and a shift of the magma-storage system from the lower crust to mid- and upper-crustal levels.

ACKNOWLEDGEMENTS

This research would not have been possible without the assistance of my chief-supervisor Prof Shane Cronin. He suggested my research project and helped me receive a Massey Doctoral scholarship as well as other financial assistance during the course of my PhD. I would also like to thank him for helpful discussions and new ideas during my Doctorate, as well as his thorough reviews of my thesis, manuscripts, and conference abstracts. Most importantly, I'm incredibly grateful that he's always been supportive of me; whether I needed advice and/or someone to talk to in professional as well as private matters.

I also wish to thank my co-supervisors Dr Jonathan Procter and Prof Vince Neall (Massey University), Prof Richard Price (Waikato University) and Assoc Prof Ian Smith (The University of Auckland) for their fruitful discussions over the last four years. I especially want to thank Prof Richard Price for the thorough revision of major parts of my thesis and his helpful criticism. I am grateful to Assoc Prof Ian Smith (University of Auckland) for arranging the use of the XRF-equipment at The University of Auckland. I would also like to thank Dr Alan Palmer (Massey University) for his field assistance, and Dr Bob Stewart, and Dr Georg Zellmer (Massey University) for helpful discussions regarding the Turakina debris flow. Mr. John Wilmshurst (The University of Auckland) is thanked for his helpful assistance in XRF analysis and sample preparation, and Mr Gordon Holms (ANU, Canberra, Australia) for his beautiful thin section preparation. Furthermore, I would like to thank Prof Anthony Koppers and Mr Dan Miggins (Oregon State University, USA) for preparation of suitable samples for ^{40}Ar/^{39}Ar-dating, as well as their determination in getting the best possible results, even though it mend re-analyzing 12 out of 20 samples. Furthermore, I would like to thank Dr Gert Lube (Massey University) and Dr Pilar Villamor (GNS, Wellington) for helpful discussions regarding the physical parameters of debris avalanches, and regional tectonic fault systems. I furthermore want to thank Dr Gert Lube for making me visit the 2012 Tongariro debris avalanche in order to gain insights into the proximal features of confined landslides, but most importantly I thank him for his friendship and for believing in me.

I furthermore want to thank my fellow postgraduate students, Dr Gabor Kereszturi, Dr Natalia Pardo, Dr Marco Brenna, Gaby Gomez, Rafael Torres-Orozco, Szabolcs Kosik, Eric Breard, and Adam Neather for sharing our “PhD experience”, and helping each other during harder times. I furthermore would like to thank Eric Breard for a fun collaboration during the November 2012 eruption of Mt. Tongariro, and for numerous useful late-night scientific discussions.

I would also like to thank Kate Arentsen (Massey University), the true angel of the VRS department. She has always been helpful, thorough, understanding, and supportive in every single matter one can think of, ranging from car bookings down to correcting manuscripts and theses. I am sure without her, and her constant good spirits, I would have had a much harder time during my PhD.

Of the Soil and Earth Sciences Group I would further especially like to thank Matthew Irvin, Bob Toes, Ian Furkert, David Feek, and Dr Anja Möbis. All of them introduced me to the labs (and 4WD driving) at the start of my PhD and helped me out whenever I had difficulties during sample preparation processes, or GIS-data processing. But most of all, they always made me laugh, and knew when there was nothing else needed but a big supportive hug. I especially would like to thank Dr Anja Möbis for all the time we shared: the coffee breaks, the lunch breaks, the

dinners at her or my home; for her friendship and her constant support. I am not sure I would have made it through the four years without her by my side.
I also want to thank the examiners of my thesis: Assoc Prof Ian Fuller, Prof Timothy Davies, and Prof Claus Siebe for their thorough and constructive review of this study. I highly appreciated the discussion with them during my oral, especially regarding potential future research collaborations. They made me feel like I'm already part of the scientific community rather than a student nervous about the outcome of her examination. Overall, they made this final hurdle a very pleasant and fun experience.

I am also grateful to all the farmers on the Ruapehu ring plain who allowed me access to their land. I especially thank Jeff Williams at Mataroa who invited me to stay with him, prepared homemade sandwiches and coffee to share for lunch, and became a true and close friend.

My PhD was funded by a scholarship granted by the Institute of Natural Resources and a Massey Doctoral Scholarship. Furthermore this work was supported by the New Zealand Natural Hazard Research Platform. I would also like to thank the IAVCEI committee for their travel grant, which allowed me to attend the 1st International Conference on Volcano Geology in Madeira, Portugal.

My life would definitely not have been the same without all the amazing people I met in Palmerston North who became friends and made my time spend here truly memorable. Of these I would especially like to thank Chris Prentice, Callum Gibbins, Julie Morris, Kristi Tungatt, Ruthie Henchman, Angela Denes, Daniel Farley, Friederike von Schlippe, Andrew Penwarden, Ana Maria Ramirez, Dylan Ball, Gaby Gomez, Omar Cristobal, Zsuzsa Smolinka, Diana Cabrera, Sophie Staniforth, Jonathan Parsons, Cormac Chalmers, and Claire Black who were my Kiwi-family, far away from my original one. Feeling their support, encouragement, and love was all I ever needed after a hard day to lift me up again. I further would like to thank them for having shown me an amazing life outside of work, filled with exploring the most beautiful places all over New Zealand.

I am extremely grateful to my family and friends in Germany who have supported and encouraged me before and during my entire PhD study, even from the other side of the globe. They gave me the courage to move to New Zealand in the first place, and always made me believe that I can achieve anything for as long as they are part of my life. Of all those beautiful overseas people, I would especially like to thank Anne Deremetz, Arndt Morgenroth, Maximilian Hansen, Swantje and Wendelin Teschemacher, Katrina Weber, Bastian Schwarz, Martin Laudel, Benedikt Lerch, Steffen and Jens Moser, Alexander and Claudia Karaula, Peter and Birgit Niedner, and Brigit, Renate, Friedel, Annette, and Wilhelm Sander for their constant support, their friendship, and for always being there when really needed, even if it involved last-minute 32-hour flights.
I'm incredibly thankful to my parents and my brother without whom I would have never made it here, who always tried their hardest to find solutions to “overseas”-problems and always had time to listen to all those stories I told, whether they were good or low-spirited.

Last but most importantly, I would like to thank Stefanie van Büren, who had been my first true friend and family member here in New Zealand. She was one of the most admirable people I

had ever met. Seeing the way she faced her life, always impressed me and made me feel so much braver than I truly was. She was my climbing, surfing, horse-back riding, and tramping buddy during weekends and public holidays, and my coffee drinking buddy during times of hard work at the department. She always had an open ear for my struggles, and I am incredible grateful for the support, understanding, loyalty and friendship I had received from her over the years. This thesis is dedicated to her.

TABLE OF CONTENTS

ABSTRACT i

ACKNOWLEDGEMENTS iii

TABLE OF CONTENTS vi

LIST OF TABLES xi

LIST OF FIGURES xiii

CHAPTER 1: INTRODUCTION 1

1.1 INTRODUCTION 1
1.2 OBJECTIVES OF THIS STUDY 2
1.3 GEOLOGICAL SETTING 3
1.3.1 TAUPO VOLCANIC ZONE 3
1.3.2 TONGARIRO VOLCANIC CENTRE 4
1.3.3 MOUNT RUAPEHU 4
1.4 AGE CONTROL - COVER BED STRATIGRAPHY, AGGRADATIONAL TERRACE FORMATION, AND RHYOLITIC TEPHRA MARKER BEDS 7
1.5 GEOGRAPHY OF THE STUDY AREA 9
1.5.1 THE HAUTAPU RIVER 10
1.5.2 THE TURAKINA RIVER 10
1.5.3 THE WHANGAEHU RIVER 10
1.5.4 THE MANGAWHERO RIVER 12
1.5.5 THE MANGANUIOTEAO RIVER 12
1.5.6 THE WHAKAPAPA RIVER 13
1.5.7 THE WHANGANUI RIVER 13
1.6 CLIMATE AND LAND USE 14
1.7 NOMENCLATURE 16
1.7.1 DEBRIS AVALANCHES 17
1.7.2 DEBRIS FLOWS 17
1.7.3 HYPERCONCENTRATED FLOWS 18
1.7.4 “NORMAL” STREAM FLOW DEPOSITS 18

CHAPTER 2: METHODS 19

2.1 FIELD STUDIES 19
2.2 PETROGRAPHY 19
2.3 X-RAY FLUORESCENCE SPECTROSCOPY 19
2.4 LASER ABLATION INDUCTIVELY COUPLED PLASMA MASS SPECTROMETRY (LA-ICP-MS) 20

2.5 ELECTRON MICROPROBE ANALYSIS 20
2.6 ^{40}Ar/^{39}Ar-DATING 20

CHAPTER 3: THE HAUTAPU RIVER – POTENTIAL IMPLICATIONS OF MASS WASTING INTO RIVER CATCHMENTS SOURCED FROM ACTIVE VOLCANOES 22

3.1 INTRODUCTION 22
3.2 CONTRIBUTIONS OF CO-AUTHORS 23
3.3 IMPACTS OF CATASTROPHIC VOLCANIC COLLAPSE ON THE EROSION AND MORPHOLOGY OF A DISTAL FLUVIAL LANDSCAPE: HAUTAPU RIVER, MOUNT RUAPEHU, NEW ZEALAND 24
ABSTRACT 24
3.3.1 INTRODUCTION 24
3.3.1.1 Geological Setting 26
3.3.1.2 Southeastern Ruapehu drainage system 27
3.3.1.3 Nomenclature 28
3.3.1.4 Methods 30
3.3.2 RESULTS 30
3.3.2.1 The Mataroa Formation – stratigraphy and sedimentology 30
Facies 1 – Debris Avalanche Deposit 30
Facies 2 – Lahar Deposits 31
3.3.2.2 Age Control 31
Cover-bed stratigraphy 31
Correlation using petrology and geochemistry 34
Geomorphic evidence from Fluvial Aggradational Terraces 34
3.3.3 DISCUSSION 36
3.3.3.1 Mataroa Debris Avalanche Triggering 36
3.3.3.2 Emplacement Mechanisms of the Mataroa Formation volcaniclastic deposits 36
3.3.3.3 Relationship to the Whangaehu Formation 40
3.3.3.4 Landscape and sedimentological response to a catastrophic debris avalanche 40
3.3.4 CONCLUSIONS 44
3.3.5 ACKNOWLEDGEMENTS 44

CHAPTER 4: GEOMORPHOLOGICAL CONTROLLED RUNOUT OF LARGE-SCALED MASS WASTING EVENTS AT MOUNT RUAPEHU, NEW ZEALAND 46

4.1 INTRODUCTION 46
4.2 CONTRIBUTIONS OF CO-AUTHORS 47
4.3 TRANSPORT AND EMPLACEMENT MECHANISMS OF CHANNELIZED LONG-RUNOUT DEBRIS AVALANCHES, RUAPEHU VOLCANO, NEW ZEALAND 48
ABSTRACT 48
4.3.1 INTRODUCTION 48

4.3.1.1 Geological Setting 50

4.3.2 RESULTS 50

4.3.2.1 Deposits of long-runout Ruapehu debris avalanches 50

Mataroa Formation 51

Lower Whangaehu Formation 53

Oreore Formation 53

Pukekaha Formation 54

Piriaka Formation 54

4.3.2.2 Debris-avalanche runout and mobility 58

4.3.3 DISCUSSION 60

4.3.3.1 Long runouts of the Mount Ruapehu debris avalanches 63

4.3.4 CONCLUSION 63

4.3.5 ACKNOWLEDGEMENTS 64

CHAPTER 5: LINKING DISTAL VOLCANICLASTIC SEDIMENTATION AND STRATIGRAPHY WITH THE DEVELOPMENT OF RUAPEHU, NEW ZEALAND 65

5.1 INTRODUCTION 65

5.1.1 GEOLOGICAL SETTING 65

5.2 METHODS 66

5.3 STRATIGRAPHY AND SEDIMENTOLOGY OF THE MASS-FLOW DEPOSITS 68

5.3.1 THE TURAKINA DEBRIS FLOW 68

5.3.2 THE MATAROA (AND WHANGAEHU) FORMATION 68

5.3.3 THE OREORE FORMATION 69

5.3.4 THE PIRIAKA FORMATION 71

5.3.5 THE PUKEKAHA FORMATION 75

5.4 RECONSTRUCTION OF CONE-BUILDING AND COLLAPSE WITH NEW VOLCANICLASTIC STRATIGRAPHY 77

5.4.1 THE TURAKINA ERUPTIVE INTERVAL (340 - 280 KA) 77

5.4.2 THE TE HERENGA CONE-BUILDING EPISODE (250 - 180 KA) 77

5.4.3 THE OREORE ERUPTIVE INTERVAL (180 - 160 KA) 79

5.4.4 THE WAHIANOA CONE-BUILDING EPISODE (160 - 119 KA) 80

5.4.5 THE WAIMARINO ERUPTIVE INTERVAL (100 - 55 KA) 80

5.4.6 POST-50 KA RING-PLAIN STRATIGRAPHY 83

5.5 CONCLUSIONS 84

CHAPTER 6: NEW INSIGHTS INTO THE EVOLUTION OF THE MOUNT RUAPEHU MAGMATIC SYSTEM REVEALED BY DISTAL MASS-FLOW DEPOSITS 86

6.1 INTRODUCTION 86

6.1.2 GEOLOGICAL SETTING 86

6.1.3 DISTAL MASS-FLOW DEPOSITS 88

6.2 ANALYTICAL METHODS 88
6.2 PETROLOGY 90
6.2.1 PHENOCRYST CHARACTERISTICS 90
6.2.2 GROUNDMASS CHARACTERISTICS 93
6.2.3 AUTOLITH CHARACTERISTICS 93
6.2.4 XENOLITH AND XENOCRYST CHARACTERISTICS 94
6.3 GEOCHEMISTRY 94
6.3.1 MAJOR ELEMENT COMPOSITION 94
6.3.2 TRACE ELEMENT COMPOSITIONS 96
6.3.3 AMPHIBOLE COMPOSITION 97
6.4 DISCUSSION 98
6.4.1 THE TURAKINA ERUPTIVE EPOCH (340 - 280 KA) 99
6.4.2 THE TE HERENGA ERUPTIVE EPOCH (250 - 180 KA) 103
6.4.3 THE OREORE ERUPTIVE EPOCH (180 - 160 KA) 105
6.4.4 THE WAIMARINO ERUPTIVE EPOCH (100 - 55 KA) 105
6.5 CONCLUSIONS 105

CHAPTER 7: LANDSCAPE DEVELOPMENT AND CLIMATE INFLUENCE ON EDIFICE STABILITY AT MOUNT RUAPEHU, NEW ZEALAND 107

7.1 INTRODUCTION 107
7.1.1 GEOLOGICAL SETTING 108
7.2 METHODS 110
7.3 RESULTS 110
7.3.1 GENERALISED GEOLOGY OF THE RUAPEHU RING-PLAIN DRAINAGE SYSTEMS 110
7.3.2 NON-VOLCANIC AGGRADATIONAL TERRACE SEQUENCES 111
7.3.3 VOLCANIC AGGRADATIONAL TERRACE SEQUENCES 112
7.3.4 APPROXIMATE RATES OF UPLIFT, AND MASS-WASTING SEDIMENT FLUXES 115
7.4 DISCUSSION 115
7.4.1 CATCHMENT CHANGE IN RUAPEHU RIVER SYSTEMS FOLLOWING LARGE-SCALE DEBRIS-AVALANCHE DEPOSITION 116
7.4.1.1 The Turakina River 116
7.4.1.2 The Hautapu River 116
7.4.1.3 The Mangawhero River 118
7.4.1.4 The Whakapapa and Whanganui River systems 118
7.4.1.5 The Manganuioteao River 120
7.4.2 CLIMATE CHANGE AND MAJOR CALDERA UNREST AS POTENTIAL TRIGGER FOR MOUNT RUAPEHU FLANK FAILURES AND LONG-RUNOUT MASS FLOWS 120
7.5 CONCLUSIONS 122

CHAPTER 8: SYNOPSIS AND FUTURE OUTLOOK 124

8.1 APPROACH AND FINDINGS OF THIS STUDY 124
8.2 RECONSTRUCTION OF THE ERUPTIVE HISTORY OF MT. RUAPEHU 125
8.3 PETROLOGICAL AND GEOCHEMICAL IMPLICATIONS OF THIS STUDY 127
8.4 DEBRIS AVALANCHE HAZARDS 128
8.5 POST-COLLAPSE GEOMORPHIC IMPACTS OF VOLCANIC DEBRIS AVALANCHES 128

CHAPTER 9: CONCLUSIONS 130

9.2 FULFILMENT OF STUDY OBJECTIVES 130
9.3 UNANTICIPATED FINDINGS 131
9.3.1 IGNEOUS BASEMENT IDENTIFICATION 131
9.3.2 TRANSPORT AND EMPLACEMENT MECHANISMS OF CHANNELIZED DEBRIS AVALANCHES 132
9.3.3 CLIMATE INTERACTION AS POTENTIAL TRIGGER FOR FLANK COLLAPSES AT MT. RUAPEHU 132
9.4 POTENTIAL FUTURE WORK 132

CHAPTER 10: REFERENCES 134

APPENDIX A

APPENDIX I. PHYSICAL PARAMETERS OF LANDSLIDES, PUMICE FLOWS, AND BLOCK-AND-ASH FLOWS A

APPENDIX II. XRF- AND ICP-MS WHOLE-ROCK DATA OF THE RUAPEHU MASS FLOWS T
APPENDIX III. STATEMENT OF CONTRIBUTION TO PUBLICATION CHAPTER 3 AC

APPENDIX IV. STATEMENT OF CONTRIBUTION TO PUBLICATION CHAPTER 4 AE

LIST OF TABLES

Table 1. 27

Volume, age, and magma flux of the four cone-building formations exposed on Mt. Ruapehu. Table after Gamble et al., 2003.

Table 2. 39

Representative whole rock composition of the Mataroa Formation. Th, La, and Ce concentrations are measured for overlap corrections.

Table 3. 42

Representative whole rock composition of the Lower Whangaehu Formation. Th, La, and Ce concentrations are measured for overlap corrections.

Table 4. 52

Major depositional characteristics of unconfined and channelized volcanic debris avalanches

Table 5. 54

Approximate depositional ages of the Ruapehu debris avalanches in relation to the four cone-building formations identified and mapped on the edifice by Hackett and Houghton (1989).

Table 6. 61

Approximate runout and apparent coefficient of friction of the confined Ruapehu debris avalanches considering spreading of the mass within a v-shaped valley, calculated after Legros (2002). Assuming linear thickness decrease, the author suggests that the center of mass (L*) travels about one quarter of the total runout distance (L_{max}) of the flow, resulting in significantly higher apparent coefficients of friction (H/L*) than calculated using total runout distance (L_{max}) and total drop height (H).

Table 7. 67

Criteria for estimating the Volcanic Explosivity Index (VEI) of historic eruptions after Newhall and Self (1982).

Table 8. 69

^{40}Ar/^{39}Ar-plateau ages of 15 groundmass separates from the studied mass-flow formations exposed along six major river valleys on the distal Ruapehu ring plain.

Table 9. 83

Stratigraphic column of mass-flow deposits emplaced on the proximal and distal Ruapehu ring plain between 340 - 55 ka.

Table 10. 87

The eruptive episodes of Mt. Ruapehu in correlation to the depositional ages of the mass-flow deposits sampled.

Table 11. 91
Representative major and trace element concentrations of lava and fresh pumice samples from the Ruapehu mass-flow deposits sampled here. A complete database is included in Appendix II.

Table 12. 100
Representative hornblende composition and thermobarometric calculations for the meta-igneous xenoliths within the samples of the Turakina mass-flow deposit.

Table 13. 113
Overview of climate related marine- and fluvial aggradational terrace formation in relation to the periods of Ruapehu mass-flow emplacement (Chapter 5), and major caldera unrest in the TVZ.

Table 14. 117
Surface altitudes and approximate uplift rates of the aggradational fluvial terraces mapped and identified on the medial to distal Ruapehu ring plain.

LIST OF FIGURES

Figure 1. 3

Geological Setting. (A) Locality of Mt. Ruapehu and the Taupo Volcanic Zone (TVZ) on the North Island of New Zealand with respect to the Kermadec Trench and Ridge, and the Havre Trough. Modified after Gamble et al. (1993). (B) Northwest to southeast trending cross-section (red line Fig. 1A) showing the present-day crustal geometry of the TVZ as presented by Smith et al. (1989). Modified after Wilson et al. (1995).

Figure 2. 5

Digital elevation model of the Tongariro Volcanic Centre (TgVC) outlining the major andesite massifs Kakaramea, Pihanga, Tongariro and Ruapehu, as well as the minor volcanic centres Maungakatote and Hauhungatahi.

Figure 3. 7

The individual cone-building formations exposed on the Mt. Ruapehu edifice, mapped and identified by Hackett and Houghton (1989).

Figure 4. 8

SiO_2-variation diagrams for selected major components and trace elements showing variation in whole rock compositions for individual Ruapehu cone-building formations. Labels are colour-matched to Fig. 3 and fields are drawn for the bulk composition of each formation. Data from Price et al. (2012) and ages after Gamble et al. (2003). Potassium fields are after LeMaitre (1989).

Figure 5. 11

Digital elevation model of the proximal and distal Ruapehu ring plain showing the study area and the key settlements along the seven major river systems focussed on in this research.

Figure 6. 15

Major land use within the study area.

Figure 7. 17

The dominant volcaniclastic deposit types exposed within the individual river catchments on the distal Ruapehu ring plain. (A) Debris-avalanche deposits, (B) debris-flow deposits, (C) yperconcentrated-flow deposits, and (D) “normal” stream-flow deposits.

Figure 8. 26

Geological setting. (A) Mt. Ruapehu is located in the centre of New Zealand’s North Island at the southern terminus of the subduction-related Taupo Volcanic Zone (modified after Wilson et al., 1995; Smith et al., 1999). (B) The Whangaehu River currently incises into the southeastern Ruapehu ring plain, whereas the Hautapu River arises from wetlands southeast of Waiouru. Debris-avalanche deposits are exposed along these river catchments (red fields) up to 60 km from source, and reworked andesitic boulders >1.5 m in diameter, related to the diamictons, outline their approximate inundation area (yellow fields). The landscape in this region is dominated by constant uplift associated with subduction-zone related strike-slip faulting. Five major fault systems (Villamor et al., 2006a) strongly influence the present route of the two river systems.

Figure 9. 29

Site of study. (A) The site of study is located c. 40 km southeast of Mt. Ruapehu (rectangle). (B) Volcaniclastic diamictons sourced from the composite cone are exposed along the Hautapu River with major outcrops located between Hihitahi and Mataroa, c. 40 km southeast of the volcano (rectangle in A). The Mataroa Formation (red) is exposed at the highest topographic elevation in the area and forms a distinct plateau. (C) Present-day landscape in the Mataroa area (section line in B), where colours of loess layers are consistent with the timing of their source gravels, as represented by the aggradational terraces in Fig. 9B. The Mataroa Formation forms a distinct plateau that armours the softer Taihape Mudstone from erosion. Ongoing uplift and river incision, overprinted by climate-induced erosion cycles formed four aggradational river terraces. Andesitic boulders of the Mataroa Formation are redeposited on top of these and reflect the course of the proto-Hautapu River during the time of volcaniclastic emplacement.

Figure 10. 32

Lithological characteristics of the Mataroa Formation. (A) Preferred incision of the Hautapu River into the soft Taihape Mudstone resulted in reworking and redeposition of andesitic boulders related to the Mataroa Formation on top of aggradational river terraces and the valley floor. (B) Subrounded andesitic boulders up to 4 m in diameter are reworked from Facies 1 of the Mataroa Formation and remain scattered around the countryside. (C) Facies 1 of the Mataroa Formation is heterolithologic, poorly sorted and massive. The light-coloured clasts are Taihape Mudstone rip-up clasts (Scale: 2 m). (D) The Mataroa Formation overlies Taihape Mudstone, reflecting the onset of volcaniclastic deposition within the Hautapu River catchment (Scale: 1 m). (E-F) The sequence of hyperconcentrated-flow and debris-flow deposits (Facies 2) differs between locations, and reflects the formation of a braided river system after deposition of Facies 1 (Scale: 2 m).

Figure 11. 33

Stratigraphic correlation of the Mataroa Formation. Facies 1 is best exposed at two localities and overlain by sequences of hyperconcentrated-flow and debris-flow deposits that comprise various amounts of pumice (Inset map: locality of exposures). (A) The rhyolitic Kawakawa Tephra (27.1 ka cal. B.P.; Lowe et al., 2008) is exposed within the top loess unit of Section (S) 1 and S4. (B) The lowermost hyperconcentrated-flow deposit at S2 contains c. 10 vol.% pumice clasts and indicates eruptive activity of Mt. Ruapehu after Facies 1 emplacement. (C) Several flow units can be distinguished at S2 in part eroding into, and incorporating the underlying flow unit (Scale: 2 m). (D) The uppermost lahar deposit comprises c. 30 vol.% angular pumice clasts. It is overlain by coverbeds at S1 and S4, and marks the end of volcaniclastic deposition within the Hautapu River catchment.

Figure 12. 35

Profile of Facies 1 at Section 1. The deposit contains domains of a boulder-rich, matrix-supported facies, comprising jig-saw fractured clasts up to 2 m in diameter. Volcaniclastic clasts of brecciated material and hyperconcentrated-flow deposits were either derived from the collapsing flanks or incorporated during runout. "Pockets" of exotic material comprise river gravel and Taihape Mudstone, most likely ripped-up from the river bed during runout. (A) Subrounded andesitic boulders within a consolidated matrix-supported framework (Scale: 1 m). (B) Taihape Mudstone rip-up clast within Facies 1 (Scale: 50 cm). (C) Facies 1 is emplaced on top of Taihape Mudstone. In areas of decreasing thickness clasts are generally well-rounded. (D) The dominant lithology of Facies 1 comprises angular to subrounded andesitic clasts within a firmly consolidated inter-block matrix of dominantly silt to fine sand (Scale: 70 cm).

Figure 13. 38

Representative whole-rock composition of the Mataroa and Whangaehu Formations in relation to the lavas exposed on the Mt. Ruapehu cone (Price et al., 2012). Ages from Gamble et al. (2003) and Price et al. (2005). (A) The four major cone-building formations as mapped by Hackett and Houghton (1989). (B) Total-alkali compositions of the Mataroa and Lower Whangaehu Formations reflect basaltic andesites and andesites. Nomenclature after LeBas et al. (1986), IUGS – International Union of Geosciences. (C) In comparison to the Ruapehu lavas (Price et al., 2012), whole-rock compositions of the Mataroa and Whangaehu Formations are similar to those of the Wahianoa cone-building formation. Cone-building formation colours are the same as in (A).

Figure 14. 41

Depositional model of the Mataroa Formation. (A) Prior to emplacement of the Mataroa and Lower Whangaehu Formations (>150 ka), the proto-Hautapu River very likely arose either from the flanks of the Mt. Ruapehu edifice, or the proximal ring plain. A braided river system developed between Turangarere and Taihape. The origin of the proto-Hautapu River on the volcanic edifice implies the source of a proto-Whangaehu River to be located further southwest than at present. Exposures of volcaniclastic deposits along the Whangaehu River, as well as regional strike-slip faulting indicate that the majority of its course has been consistent over time. (B) Substrate-weakening and hydrothermal alteration on the cone resulted in partial collapse of the southeastern Wahianoa flank 125 - 150 ka ago, which produced a debris-avalanche deposit that spilled into the Hautapu (and Whangaehu) River catchment. Sub-plinian to plinian eruptions produced vast amounts of pyroclastic material, which was reworked into lahars that descended the volcanic flanks and were emplaced on top of the debris-avalanche deposit. (C) The Whangaehu River emerged at the eastern flank of the volcanic edifice <125 ka ago. Its course is dictated by regional strike-slip faulting, especially the Rangipo and Karioi Fault, which results in it running southwards and incising into the mass-flow deposits of the Mataroa and Lower Whangaehu Formations. At the same time, the proto-Hautapu River was cut off from the proximal Ruapehu ring plain and presently arises from wetlands south of Waiouru.

Figure 15. 49

(A) Outline of New Zealand's North Island with Mt. Ruapehu located near its centre.

(B) Digital elevation model of the proximal and distal Ruapehu ring plain. Note the difference in geomorphology where an aggradation-dominated landscape changes into an erosive one (dashed line). Six debris-avalanche deposits crop out along five major river catchments that drain the stratovolcano. Basal outcrops of debris-avalanche deposits are limited to the landscape adjacent to the drainage systems and distances >30 km. Scattered andesitic boulders >1.5 m in diameter scattered around the countryside indicate the extent of flow inundation.

Figure 16. 51

The Ruapehu debris avalanches form a distinctive high terrace in valleys of each river catchment due to uplift and river incision. Glacial and interglacial periods have resulted in the formation of river terraces on which reworked andesitic boulders related to the collapse events were emplaced. Modified after Tost et al. (2015).

Figure 17. 55

Six individual debris-avalanche deposits were identified on the distal Ruapehu ring plain and show strikingly similar sedimentological characteristics. (A) The Piriaka-B debris avalanche is inversely graded and unconformably overlies Quaternary river gravel. (B) The basal facies of the Oreore Formation is made up of a debris avalanche deposit unconformably overlying late-Pliocene mudstone. (C) The basal facies of the Mataroa Formation (Scale: 2 m), (D) the Lower Whangaehu Formation (Scale: 2 m), (E) the debris-avalanche deposit exposed within the Pukekaha Formation, and (F) the Piriaka-A debris-avalanche deposit.

Figure 18. 56

Textural features of the Ruapehu debris avalanches. The deposits are hetero-lithologic and comprise various amounts of incorporated path material, such as (A) Tertiary marine sediments; (B), (D) river gravel; and (B), (C), (D) hyperconcentrated-flow deposits. Fractures, probably due to increased shear stresses, are common within the exposures, especially at interfaces of differing lithofacies. Highlighted clasts within the sketches serve as orientation-points.

Figure 19. 57

Lithological features of the Ruapehu debris-avalanche deposits. (A) The flows overran and incorporated various amounts of path material including river gravel and late-Pliocene mudstones and muddy sandstones. (B) Fractured clasts are generally not common but present within all grain sizes. (C) Larger boulders within the Ruapehu debris-avalanche deposits are generally subrounded. (D), (E) The intra-block matrix is consolidated and generally consists of the fine-sand to silt. (F) Dish-like structures (arrows) exposed within the basal facies of the Oreore Formation.

Figure 20. 61

Parameters of the Ruapehu debris avalanches in relation to non-volcanic landslides, subaerial volcanic landslides (confined and unconfined), submarine landslides, block-and-ash flows, and pumice flows (see Appendix I for data).

Figure 21. 63

Transport and emplacement-model for the Ruapehu debris avalanches. (A) Gravitational collapse of a volcanic flank and movement of the mass downslope. Erosion is dominant at the base and the front of the flow especially in areas of strongly decreasing slope. (B) The bulk of the mass laterally spreads on the low-topography terrain of the proximal ring plain, whereas minor parts are likely confined to steep river channels. Basal and frontal erosion is dominant, and loose volcaniclastics are easily eroded and loaded into the flow. Interstitial fluids increase the basal pore pressure towards the base of the debris avalanche. The overlying mass facilitates downwards-directed progressive granular stress. (C) The initial topography of the distal ring plain channelizes the flow into major river catchments. Granular stress is overall reduced though erosion continues with path material entrained at the base, the front, and the margins. Stream water as well as saturated river sediments augment the volume of interstitial fluids, and strongly increase shearing and pore pressures towards the base of the flow.

Figure 22. 70

Digital elevation model of the proximal and distal Ruapehu ring plain including tectonic faults (red lines) after Villamor and Berryman (2006a; 2006b). Exposures of the mass-flow deposits studied are limited to the proximal ring plain (red field and rectangles). Reconstruction of the approximate inundation area (yellow fields) of the flows is based on reworked andesitic boulders (≥1 m in diameter) associated with the initial event and scattered around the landscape adjacent to the river valleys.

Figure 23. 72

Field observations. (A) The Turakina debris-flow deposit is massive to cross bedded and dominantly contains well-rounded pebble-sized clasts. (B) A sequence of hyperconcentrated-flow deposits overlies the Lower Whangaehu Formation along the Whangaehu River valley. (C) The conglomerate exposed within the Oreore Formation (Scale: 1 m). (D) The lowermost consolidated pumiceous hyperconcentrated-flow deposit of the Oreore Formation (Scale: 2 m). (E) The uppermost sequence of the Oreore Formation is made up of numerous fine-grained pumiceous hyperconcentrated-flow deposits (Scale: 1 m). (F) The basal debris-avalanche deposit of the Piriaka Formation is unconformably overlain by two hyperconcentrated-flow deposits (Scale: 1 m). (G) The c. 10 m thick sequence of hyperconcentrated-flow deposits of the Piriaka Formation exposed in a road cut along State Highway 4 at Raurimu. (H) The debris-flow deposit overlying the previous sequence of hyperconcentrated-flow deposits along the Main Trunk Railway Line at Raurimu. (I) Heat-fractured boulder within a strongly weathered diamicton deposit exposed in a road cut along the Manganuioteao River valley. (J) Hyperconcentrated-flow deposits and overlying coverbeds of the Pukekaha Formation exposed in a quarry along the river valley. (K) Basal hyperconcentrated-flow deposit and overlying coverbed sequence exposed in a road cut along State Highway 4 c. 4 km south of Raetihi. (L) Pumiceous sequence of seven hyperconcentrated-flow deposits exposed in a road cut along State Highway 1 at Hihitahi (Scale: 2 m).

Figure 24. 74

Stratigraphy of the Mataroa Formation modified after Tost et al. (2015). The base of the sequence holds a debris-avalanche deposit with its undulating topography being subsequently infilled and smoothed by at least 15 lahar deposits (hyperconcentrated flows and debris flows).

Figure 25. 75
Stratigraphy of the Oreore Formation. The type locality for the syn-eruptive mass-flow sequence is exposed on farmland c. 2 km northeast of Oreore. The basal debris-avalanche deposit forms an undulating topography in the area which is infilled and smoothed by the overlying lahar deposits, forming a distinctive plateau between Ohorea and Oreore (see Fig. 22 for localities).

Figure 26. 76
Stratigraphy of the Piriaka Formation. The c. 40 m thick sequence forms a distinctive plateau between Piriaka and Te Whakarae. The lithology of the individual units reflects several large-scale sub-plinian to plinian eruptions of Mt. Ruapehu, which were followed by periods of subdued volcanic activity.

Figure 27. 78
Stratigraphy of the Pukekaha Formation. Several exposures of volcaniclastics along the Manganuioteao River valley reveal that syn- as well as post-eruptive mass-flow deposits have been spilled into the river catchment between 160 ka ago and the present.

Figure 28. 81
Digital elevation model of the Ruapehu ring plain outlining the mass-flow inundation areas during individual eruptive episodes. (A) Mass flows spilled into the Turakina and Hautapu River valleys during the Turakina eruptive interval 280 - 340 ka ago. (B) Mass-wasting events during the Te Herenga cone-building formation (250 - 180 ka; Gamble et al., 2003) were confined to the Hautapu, Whangaehu, Mangawhero, Whakapapa and Whanganui River valleys. (C) During the Oreore eruptive interval (180 - 160 ka) diamictons were emplaced in the Mangawhero, Whakapapa and Whanganui River catchments. (D) Mass-wasting deposits related to the Wahianoa cone-building formation are exposed along the Hautapu, Manganuioteao, Whakapapa and Whanganui River valleys. (E) Rapid ring-plain aggradation occurred in the southwestern to northeastern sector of the Ruapehu ring plain during the Waimarino eruptive interval (100 - 55 ka ago). (F) Post-50 ka mass-wasting events are generally limited to the proximal Ruapehu ring plain.

Figure 29. 89
Photomicrographs of clasts from the Ruapehu mass flows. (A) Samples with two different groundmasses are exposed within the Turakina eruptive episode, the Oreore Formation, and the Pukekaha Formation. Pyroclasts contain up to 40% subrounded, and in part elongated vesicles. (B) Typically, phenocrysts are subhedral and the groundmass microcrystalline. (C) A hyaline groundmass is limited to samples taken from initial pyroclasts. (D) Clasts from lava flow sequences are generally porphyritic and comprise sieve-textured plagioclase and pyroxene phenocrysts. (E) Glomerocrysts are made up of plagioclase + orthopyroxene + clinopyroxene + olivine. (F) Fine-grained meta-sedimentary xenolith. (G) Meta-igneous hornblende-bearing xenolith. (H) Ruptured phenocrysts within initial pyroclasts testify to explosive eruptions.

Figure 30. 93
Total alkali vs. silica classification for the Ruapehu mass flows. Nomenclature after LeBas et al. (1986).

Figure 31. 95
Selected representative major and trace element variation diagrams for the Ruapehu mass flows. Fields drawn for lava flow formations correspond to those shown in Fig. 4 and are colour-matched to Fig. 3. Potassium fields after LeMaitre (1989).

Figure 32. 96
N-MORB normalized (Sun & McDonough, 1989) multi-element plots for the Ruapehu mass-flow deposits in relation to the lavas of the Te Herenga and Wahianoa cone-building formations exposed on the edifice.

Figure 33. 97
N-MORB normalized (Sun & McDonough, 1989) REE plots for the Ruapehu mass-flow deposits in relation to the lavas of the Te Herenga and Wahianoa cone-building formations exposed on the edifice.

Figure 34. 98
Trace element composition of the Turakina eruptive episode in comparison to the lavas exposed on the volcanic edifices of Mt. Ruapehu (Price et al., 2012), Tongariro (Hobden, 1997) and Hauhungatahi (Cameron et al., 2010).

Figure 35. 104
Model of the dominant magma modification processes affecting the Mt. Ruapehu melt. FC-AFC-FCA and mixing modeler after Ersoy and Helvaci (2010). The relative ratio of assimilated material to crystallized material (r) and the “increments”-value reflect the Ruapehu melts to be derived from primitive mantle-derived melts subjected to 30% crystal fractionation and 6% crustal assimilation (Graham & Hackett, 1987).

Figure 36. 109
Digital elevation model of the Ruapehu ring plain outlining the river systems studied, as well as the areas of volcanic and non-volcanic aggradational fluvial terrace identification (red rectangles). On the proximal and medial Ruapehu ring plain numerous strike-slip faults were mapped and identified by Villamor and Berryman (2006a; 2006b).

Figure 37. 111
The coverbed sequences identified to overly the individual mass-flow formations within each river valley. P=Paleosol; Loess stratigraphy corresponds to the nomenclature from Milne, 1973a.

Figure 38. 114
Digital elevation model of the aggradational fluvial terraces identified along four major river systems of the Ruapehu ring plain. Along all river valleys, sequences of mass-flow deposits,

sourced from the stratovolcano, form a distinct aggradational terrace at the highest elevation of the valley margins. The extremely high sediment flux generally resulted in blockage of the original river path. Subsequently, up to four non-volcanic fluvial aggradational terraces are exposed on lower altitudes.

Figure 39. 119
Rhyolitic caldera formation in the TVZ. (A) The TVZ (yellow field) is a c. northeast-trending magmatic system divided into three individual magmatic zones, based on the chemical composition of the volcaniclastics. Rhyolitic volcanism is limited to the central part of the TVZ (red rectangle). (B) Localities of the major rhyolitic calderas in the central TVZ that erupted large amounts of volcaniclastic material over the last 340 ± 10 ka (Table), which was likely associated with enhanced regional tectonic activity.

Figure 40. 121
Development of New Zealand's climate over the last 400 ka, modified after Beau and Edwards (1983). The red-shaded areas represent the approximate timing of flank failures at Mt Ruapehu. Syn-eruptive events are marked (*). Most of the post-eruptive large-scale (>1 km^3) flank failures of Mt. Ruapehu (Tost et al., 2014) occurred during transitions between cold stages and interstadial climates.