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.
The role of substrate hydrogeology and surface hydrology in the construction of phreatomagmatic volcanoes on an active monogenetic field (Auckland, New Zealand)

A thesis presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Earth Science

At Massey University, Palmerston North, New Zealand

Javier Agustín Flores
2015
Abstract

Phreatomagmatic activity is pervasive in the Auckland Volcanic Field (AVF) with more than two thirds of the erupted volcanoes showing this type of activity at different degrees, dominantly at the onset of their eruptive histories. In general, the volcanoes built in the northern AVF rest on Late Miocene Waitemata Group rocks (turbiditic siltstone and sandstone succession), whereas in the southern AVF the Waitemata rocks are overlain by tens of metres of Plio-Pleistocene, water-saturated sediments (Tauranga Group and Kaawa Formation). Identifying the control exerted by the type of substrate in the eruption dynamics of the phreatomagmatic phases of three volcanoes in the AVF is the objective of this study. The stratigraphic, sedimentary, and pyroclast characteristics of the phreatomagmatic sequences of Maungataketake, Motukorea, and North Head volcanoes, together with supplementary information on the geology and hydrogeology of the area, were investigated to solve the problem. Three phreatomagmatic eruptive scenarios were outlined. Scenario 1 (Maungataketake eruption) and Scenario 2 (Motukorea eruption) depict the formation of maar-diatreme volcanoes in the southern and northern AVF, respectively. The dominant presence of lithics from the upper part of the substrate in their tephra rings suggests the construction of their tephra rings from shallow-seated explosions. Due to the water-saturated sediments filling the diatreme in Scenario 1, the eruption appears to have remained relatively wet throughout. Conversely, the drier Waitemata rocks involved in Scenario 2 promoted a progressive drying of the eruption. Scenario 3 (North Head eruption) represents a Surtseyan eruption scenario in which the rising magma erupted to the shallow sea floor (a few metres-water depth), promoting rapid chilling and explosive fragmentation. This study shows that the characterization of lithics within the tephra ring and the geological and hydrogeological information provide valuable clues to envisage the degree of influence of the substrate in the phreatomagmatic eruption dynamics. Other studies in the AVF appear to confirm this view. It is proposed that any future phreatomagmatic eruption in the AVF will be strongly influenced by the substrate hydrogeology and geology, as well as the surface hydrological conditions.
Acknowledgements

I am grateful to all people working for the departments of Massey University that in one way or another have contributed to the achievement of this thesis. A special recognition goes to my main supervisor, Karoly Németh, for his patience, priceless guidance, support, and encouragement from the beginning to the end. I am very thankful for the continuous and highly valuable support of supervisors Shane Cronin and Jan Lindsay (The University of Auckland). Many thanks to Kate Arentsen for her great support regarding organizational and administrative matters. I acknowledge the people from the Volcanic Risk Solution department (Eric Bread, Gaby Gómez, Gert Lube, Manuela Toast, Maggi Damashke, Marco Brenna, Rafael Torres, Jonathan Procter, Mark Bebbington, Georg Zellmer, Adam Neather) and especially to my friend and colleague Gábor Kereszturi for his willingness and apt help in the field and with academic matters. I acknowledge the motivation and encouragement of my first mentor of volcanology, Claus Siebe (Instituto de Geofísica, UNAM, México), to continue my studies on volcanoes.

This research was supported by the Massey University-led FRST-IIOF project “Facing the challenge of Auckland’s volcanism” (funded by the New Zealand Ministry of Business, Innovation and Employment), the New Zealand Natural Hazards Research Platform project “Living with Volcanic Risks”, and the DEVORA (Determining Volcanic Risk in Auckland) project, co-funded by the NZ Earthquake Commission (EQC) and the Auckland Council, GNS Science, The University of Auckland and Massey University. I was provided a scholarship (university fees, insurance and stipend) by the FRST-IIOF project from Dec 2010 to Dec 2013. CONACYT (Mexican National Council of Science and Technology) awarded a stipend during 2014 (I am grateful to Cindy Agustin-Flores and Oscar Alvarado-Flores for paperwork regarding the application in Mexico). I am very thankful to my friends José Rivera, Marc Adamson, Donald Hsieh, and Andrés Arcila for providing with accommodation in Auckland during field work. I am very grateful to the Instituto de Geofísica at UNAM (México) through Claus Siebe, Carles Canet, Dolors Ferres, Ligia Pérez-Cruz, and Lilia Arana for the valuable support in the latest stage of completion of this thesis.

A special acknowledgment goes for Anja Möebis for her valuable technical support at the laboratory. Also many thanks to Doug Hopcroft with Scanning Electron Microscope work, Ritchie Sims for the microprobe analysis at the University of Auckland, and Elizabeth Rangel for the preparation of thin sections. I appreciate the support from the University of Auckland and the Institute of Earth Sciences and Engineering during my staying for one month during 2011 in Auckland. Regarding the published papers (Chapters 5, 6, and 7); I highly appreciate the time and effort of journal reviewers Rafaello Cioni, Claus Siebe, Volker Lorenz, Alexander Belousov, Pierre-Simon Ross, James White, and Gerardo Carrasco for their recommendations to improve the manuscripts.
A highly special recognition goes to the thesis reviewers and examiners Robert Stewart (Massey University, New Zealand), Adrian Pittari (Waikato University, New Zealand), and Pierre-S., Ross (Institute National de la Recherche Scientifique, Canada) for their useful and valuable suggestions and observations.

From my heart I thank Natalia Pardo for being there when I needed help, without her unconditional support the process of adapting to an “exciting” Palmy would have been very difficult. There are many people who made my staying in Palmy a lifetime experience, which made me feel motivated during my studies, through their always great company: Alvaro Wehrle, Agustín Oberti, Ana Mar, Adimar Lujan, Angela Denes, Gábor Kereszturi, Gaby Gómez, Jimena Rodriguez, Jimena Yapura, Junior Perawiti, Luca Panizzi, Majela González, Cote Solovera, Marcela Almirón, Manuela San Roman, Patricia Rubio, Rafael Torres, Roberto Calvelo, Soledad Navarrete, Thiago Alves, and many others. Thanks a lot for your love.

The continuous encouragement and financial support at the beginning and the end of my PhD studies from my parents (Yolanda Flores and Javier Agustín) are priceless and unconditional, an effort for which I am very grateful. Thanks a lot for your love.
# Table of contents

Abstract.......................................................................................................................................................

Acknowledgements.........................................................................................................................................

Table of contents ........................................................................................................................................

List of figures ...............................................................................................................................................

List of tables ................................................................................................................................................

Chapter 1. Introduction ...........................................................................................................................

1.1 Introduction.............................................................................................................................................

1.2 Study site, motives, and objectives .........................................................................................................

Chapter 2. The principles of phreatomagmatism .............................................................................

2.1 Introduction.............................................................................................................................................

2.1.1 Terminology.........................................................................................................................................

2.2 Monogenetic volcanism ..........................................................................................................................

2.3 Generalities on explosive water-magma interaction ........................................................................

2.3.1 Magma fragmentation and resulting juvenile pyroclasts ................................................................

2.3.2 Host rock disruption and resulting lithics ..........................................................................................

2.3.3 Transport and deposition of pyroclasts ............................................................................................

2.3.4 Resulting landforms and deposits ......................................................................................................

2.4 Controls on phreatomagmatic eruptions ............................................................................................

2.4.1 Overview on kimberlite pipes in the substrate context ....................................................................

2.5 Conclusions ..........................................................................................................................................

Chapter 3. Geological and hydrogeological setting .................................................................

3.1 Introduction...........................................................................................................................................

3.2 Geological and tectonic setting of the AVF .........................................................................................

3.3 The AVF hydrogeology ..........................................................................................................................

3.3.1 The Waitemata Group ....................................................................................................................... 

3.3.2 Basin filling Pliocene sediments: The Kaawa formation ....................................................................

3.3.3 Pliocene to Holocene basin filling sediments: The Tauranga Group ............................................... 

3.4 Understanding of the hydrogeological conditions at the time of the eruptions ................................

3.5 Conclusions .......................................................................................................................................... 

Chapter 4. Methodology .......................................................................................................................

4.1 Introduction...........................................................................................................................................

4.2 Field work .............................................................................................................................................

4.3 Sample preparation and analysis ...........................................................................................................
Chapter 5. Reconstruction of the Maungataketake phreatomagmatic eruption and implications of the substrate

5.0 Preface ............................................................................................................................................. 33
5.1 Introduction ...................................................................................................................................... 34
5.1.1 Maungataketake age .................................................................................................................. 36
5.2 Geological and hydrogeological setting .......................................................................................... 37
5.3 General architecture of Maungataketake volcano ........................................................................ 38
5.4 Methods and terminology ............................................................................................................... 39
5.5 Results ............................................................................................................................................. 44
5.5.1 Stratigraphy and sedimentary characteristics of the maar ejecta ring deposits ....................... 44
5.6 Eruption reconstruction .................................................................................................................. 49
5.6.1 Phase 1. Vent opening and shallow explosions ........................................................................... 49
5.6.2 Phase 2. Excavation into the Waitemata Group rocks .................................................................. 51
5.6.3 Phase 3. Shallow-seated explosions ............................................................................................ 51
5.6.4 Phase 4. Vent stabilization and waning of eruption ...................................................................... 54
5.7 Maungataketake whole rock and glass chemistry ........................................................................ 54
5.8 Discussion ........................................................................................................................................ 56
5.8.1 Magma fragmentation and host rock disruption ........................................................................... 56
5.8.2 Water availability within the host material .................................................................................... 57
5.8.3 Unconsolidated water-saturated sediments and FCI .................................................................... 57
5.8.4 Duration and waning of the phreatomagmatic eruption .............................................................. 59
5.9 Conclusions .................................................................................................................................... 59
Statement of contribution to doctoral thesis containing publications ................................................. 61

Chapter 6. Reconstruction of the Motukorea phreatomagmatic eruption and implications of the substrate

6.0 Preface ............................................................................................................................................. 63
6.1 Introduction ...................................................................................................................................... 64
6.2 The Auckland Volcanic Field and the Waitemata Group rocks ..................................................... 65
6.3 General architecture of Motukorea volcano and local substrate setting ....................................... 66
6.4 General terminology ....................................................................................................................... 67
6.5 Methodology .................................................................................................................................. 68
6.5.1 Field work and deposit characterization ....................................................................................... 68
6.5.2 Sample preparation and analysis ................................................................................................ 72
6.6 Results: Pyroclast characteristics .................................................................................................. 74
6.7 Sedimentary characteristics of maar ejecta ring formation ............................................................ 75
6.7.1 Lower Tuff Sequence (LTS) ......................................................................................................... 76
6.7.2 Mid Scoria Unit (MSU) ............................................................................................................... 78
6.7.3 Upper Tuff Sequence (UTS) ........................................................................................................ 78
6.8 Discussion ....................................................................................................................................... 79
6.8.1 Depth of explosions associated with the opening of vent and magma fragmentation ................. 79
6.8.1.1 Magma fragmentation ................................................................................................................ 80
6.8.2 Assumptions of substrate disruption based on volumes and nature of lithics: evidence for shallow-seated explosions ........................................................................................................ 80
6.8.3 The reconstruction of Motukorea maar ....................................................................................... 83
6.8.3.1 The first phreatomagmatic stage (LTS) ...................................................................................... 83
6.8.3.2 A change in eruptive style (MSU) ............................................................................................ 83
# Table of Contents

**Chapter 7. Reconstruction of the North Head (Maungauika) Surtseyan eruption and implications of the hydrological conditions**

7.0 Preface ................................................................................................................................. 87
7.1 Introduction ........................................................................................................................... 88
7.2 Surtseyan volcanism............................................................................................................. 89
7.3 The AVF and the North Head (Maungauika) tuff cone ........................................................... 90
7.3.1 The Auckland Volcanic Field ............................................................................................ 90
7.3.2 North Head (Maungauika) tuff cone ................................................................................ 91
7.4 General terminology and methodology ................................................................................ 91
7.4.1 Field work ......................................................................................................................... 91
7.4.2 Laboratory work ............................................................................................................... 92
7.5 Results: North Head eruptive products ................................................................................ 93
7.5.1 Pyroclast characteristics ................................................................................................. 97
7.5.2 Lithofacies ....................................................................................................................... 98
7.6 Tuff cone construction and eruption dynamics ................................................................. 101
7.6.1 Phreatomagmatic subunit 1 (PH1) .................................................................................... 101
7.6.2 Phreatomagmatic subunit 2 (PH2) .................................................................................... 102
7.6.3 Phreatomagmatic subunit 3 (PH3) .................................................................................... 102
7.6.4 Phreatomagmatic subunit 4 (PH4) .................................................................................... 102
7.7 Water influence on magma fragmentation .......................................................................... 103
7.8 North Head volcano and Surtseyan activity in the AVF context and hazard implications ...... 103
7.9 Conclusions ......................................................................................................................... 105

**Chapter 8. Discussion and conclusions** ............................................................................. 109
8.1 Introduction .......................................................................................................................... 109
8.2 Highlights of the studied cases (Chapters 5, 6, and 7) ....................................................... 111
8.2.1 Eruption scenarios ......................................................................................................... 111
8.2.1.1 Scenario 1: the formation of Maungataketake maar-diatreme volcano ......................... 111
8.2.1.2 Scenario 2: the formation of Motukorea maar-diatreme volcano .................................... 111
8.2.1.3 Scenario 3: the formation of North Head tuff cone volcano ...................................... 112
8.2.2 Integration of results ..................................................................................................... 112
8.2.2.1 Eruptive centres and types of deposits ....................................................................... 112
8.2.2.2 Characteristics, percentage and distribution of pyroclasts .......................................... 114
8.2.2.3 Local eruptive settings and environmental conditions ................................................ 114
8.2.2.4 The inferences on eruptive styles and the waning of the phreatomagmatic phase .......... 115
8.3 Discussion .......................................................................................................................... 116
8.3.1 What do pyroclasts reveal? ............................................................................................ 116
8.3.1.1 Juvenile fragments: witnesses of magma fragmentation? ........................................... 116
8.3.1.2 Lithics: a window to the substrate ............................................................................. 117
8.3.2 Deep versus. shallow excavation (Valentine and White model, and Lorenz model) ....... 118
8.3.3 The relevance of the substrate and surface hydrological conditions ......................... 120
8.3.4 Hazard implications ....................................................................................................... 122
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 2.1</td>
<td>Schematic cross-section of erupting maar-diatreme and tuff cone volcanoes, and of the volcanoes after eruption when the craters have been partially filled with sediments</td>
<td>8</td>
</tr>
<tr>
<td>Fig. 2.2</td>
<td>Main morphological types of juvenile fragments found by experimental results of explosive interaction of magma with water</td>
<td>10</td>
</tr>
<tr>
<td>Fig. 2.3</td>
<td>Generalized schematic cross-section of a dilute pyroclastic density current (base surge)</td>
<td>11</td>
</tr>
<tr>
<td>Fig. 3.1</td>
<td>The AVF with the location of Maungataketake, Motukorea, and North Head volcanoes, along with other volcanoes</td>
<td>20</td>
</tr>
<tr>
<td>Fig. 3.2</td>
<td>Generalized regional stratigraphic column of the lithologies found beneath the AVF</td>
<td>22</td>
</tr>
<tr>
<td>Fig. 3.3</td>
<td>Simplified geology map from the area surrounding the Auckland region</td>
<td>23</td>
</tr>
<tr>
<td>Fig. 5.1.</td>
<td>Plan view of Maungataketake volcano showing five key sites (M1 to M5)</td>
<td>35</td>
</tr>
<tr>
<td>Fig. 5.2.</td>
<td>Schematic correlation of logs and identified units</td>
<td>41</td>
</tr>
<tr>
<td>Fig. 5.3</td>
<td>Modal analysis and long axis of vesicles graphs</td>
<td>42</td>
</tr>
<tr>
<td>Fig. 5.4</td>
<td>Stereo light microscope, plane-polarised, and scanning electron microscope images</td>
<td>46</td>
</tr>
<tr>
<td>Fig. 5.5</td>
<td>Photographs and corresponding logs for key sites M1 to M5</td>
<td>50</td>
</tr>
<tr>
<td>Fig. 5.6</td>
<td>Photographs showing the lithofacies and boundaries between units in detail</td>
<td>52</td>
</tr>
<tr>
<td>Fig. 5.7</td>
<td>Cartoons that represent a simplified model of the Maungataketake eruption history</td>
<td>53</td>
</tr>
<tr>
<td>Fig. 5.8</td>
<td>Major element (wt.%) variation diagrams</td>
<td>55</td>
</tr>
<tr>
<td>Fig. 6.1</td>
<td>Aerial photograph of Motukorea volcano</td>
<td>66</td>
</tr>
<tr>
<td>Fig. 6.2</td>
<td>Stratigraphic sequence at S1</td>
<td>69</td>
</tr>
<tr>
<td>Fig. 6.3</td>
<td>Stratigraphic sequence at S2a/S2b</td>
<td>71</td>
</tr>
<tr>
<td>Fig. 6.4</td>
<td>Stratigraphic sequence at S3</td>
<td>72</td>
</tr>
<tr>
<td>Fig. 6.5</td>
<td>Stratigraphic correlation between S1, S2a/S2b, and S3</td>
<td>73</td>
</tr>
<tr>
<td>Fig. 6.6</td>
<td>Stereo light microscope, plane-polarised, and scanning electron microscope images</td>
<td>74</td>
</tr>
<tr>
<td>Fig. 6.7</td>
<td>Close-up view of lithofacies</td>
<td>76</td>
</tr>
<tr>
<td>Fig. 6.8</td>
<td>Cartoons representing a simplified model of the Motukorea eruption history</td>
<td>82</td>
</tr>
<tr>
<td>Fig. 7.1</td>
<td>Elevation and depth map and plan view of North Head volcano</td>
<td>89</td>
</tr>
<tr>
<td>Fig. 7.2</td>
<td>Segment of the phreatomagmatic subunit PH1 and stratigraphic log</td>
<td>93</td>
</tr>
<tr>
<td>Fig. 7.3</td>
<td>Stratigraphic sequence and log that contains the phreatomagmatic subunit PH2</td>
<td>94</td>
</tr>
<tr>
<td>Fig. 7.4</td>
<td>Stratigraphic sequence and log that contains the phreatomagmatic subunit PH3</td>
<td>95</td>
</tr>
<tr>
<td>Fig. 7.5</td>
<td>Segment of the phreatomagmatic subunit PH4 and stratigraphic log</td>
<td>96</td>
</tr>
<tr>
<td>Fig. 7.6</td>
<td>Close-up view of the six lithofacies identified within the North Head sequence</td>
<td>96</td>
</tr>
<tr>
<td>Fig. 7.7</td>
<td>Stereo light microscope, plane-polarised, and scanning electron microscope images</td>
<td>98</td>
</tr>
</tbody>
</table>
Fig. 7.8 Cartoons representing a simplified model of the North Head eruption history and construction...

Fig. 8.1 Schematic and simplified representation of the models of the three phreatomagmatic eruptive scenarios for similar settings in the Auckland Volcanic Field ................................................................. 110

Fig. 8.2 Schematic and simplified representation of Lorenz model (1986) and its revised version proposed by Valentine and White (2012)........................................................................................................................................... 119
List of Tables

Table 5.1 Nomenclature of Maungataketake deposit types and grain size ................................................ 43
Table 5.2 Lithofacies of Maungataketake deposits .................................................................................... 47
Table 5.3 Lithostratigraphic units of Maungataketake deposits ................................................................. 48
Table 6.1 Nomenclature of Motukorea deposit types and grain size .......................................................... 70
Table 6.2 Lithofacies of Motukorea deposits .............................................................................................. 77
Table 7.1 Nomenclature of North Head deposit types and grain size ........................................................... 92
Table 7.2 Lithofacies of North Head ............................................................................................................ 99
Table 8.1 Summary of the general morphometric, stratigraphic, sedimentary, and pyroclast characteristics of the studied volcanoes ........................................................................................................ 113