# GEOLOGICAL EVOLUTION AND MAGMATIC MODELS FOR SPATIALLY AND TEMPORALLY VARIABLE MODES OF DISTRIBUTED VOLCANISM, JEJU ISLAND, REPUBLIC OF KOREA

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*When the haze clears,*

*You see the mountain.*

*When you gaze at the mountain,*

*You see within and beyond.*

# Abstract

Dispersed volcanism in intraplate settings produces volcanic fields that may erupt over millions of years to produce hundreds to thousands of scoria and spatter cones, tuff cones and maars, as well as lava flows. Many aspects of this globally ubiquitous process are poorly known, ranging from the tectonic drivers to the mechanisms controlling magma accumulation and ascent. To investigate magma generation processes leading to a variety of individual eruption types at volcanic fields and to understand the spatio-temporal evolution of these whole-systems, knowledge of the geochemical and petrological properties of erupted products must be linked to the geologic and tectonic framework. This study was based on detailed stratigraphic sampling of small- (<0.01 $km^3$) and large-volume (>1 $km^3$) eruptive sequences in the Jeju Island Volcanic Field, Korea at both individual exposed eruption centres and from deep drill cores. This island is the subaerial representation of a volcanic field developed above continental crust over the last 1.8 Ma. Pyroclastic and lava samples were analysed for whole-rock major-, trace-elements and Sr-Nd-Pb isotopes, and for mineral compositions and Sr-Nd-Pb isotopes.

The Jeju magmatic system started with small-volume alkali basaltic eruptions sourced at mantle depths equivalent to c. 2.5 GPa in partially hydrous peridotite. These magmas passed through the crust and erupted rapidly, with minor modification. Intrusions and eruptions accommodated regional tectonic strain, and excess melts became stalled to fractionate toward trachyte compositions in both the lower and upper crust. Trachyte erupted sporadically, with the first episode at c. 750 ka. After this, the system started to erupt with volumetric rates two orders of magnitude higher. This accelerated magma production involved alkali basalt melts derived from greater depths/pressures (3.5 GPa) than earlier, along with subalkali basalts derived from c. 2.5 GPa. Despite prevailing extensional tectonics in the Ryukyu Volcanic Arc and strain accommodation at Jeju, further magmas accumulated and evolved to trachyte compositions at lower crustal depths and erupted in a second episode c. 25 ka ago. Small-volume eruptions of rapidly rising primitive alkali basalt also continued throughout the life of the field, and potentially interacted with shallower reservoirs of subalkali magmas to generate bimodal volcanism. Depending on magma volumes, intrusion and plumbing complexities, these generated a range from simple volcanic

structures to complex multiple-episode and/or multiple vent eruptive centres at the surface.

The geochemical data collected revealed how seemingly simple monogenetic eruptions can be fed by complex and distinct magmatic entities. The same was valid for the entire field, where magma source and evolution conditions vary over time. The variety in volcanic activity is a function of magma types influenced by prior mantle modification events, as well as local and distal tectonic stresses and strain arrangements. This study showed that it is ultimately the site and spatial pattern of melting and melt-production rate that determines the final surface morphology, elevation and spatial distribution of magma types in a volcanic field.

# Acknowledgements

Many people have made valuable contributions to the completion of this work. I will endeavour to name them all, and I apologize in advance to those who will have been left out, not because I don't value their contribution, but because of the rust in my memory.

First and foremost I would like to thank wholeheartedly Shane Cronin and Ian Smith for offering me the Jeju Island project after I had unsuccessfully applied for a spot in its Auckland "younger sister" project. Their effort, as well as that of all those involved in the FRST/IIOF (Foundation for Research Science and Technology/International Investment Opportunity Fund) project provided me with an opportunity to pursue my passion for learning more about volcanic systems, and a Massey University Vice Chancellor's Doctoral Scholarship gave me a steady income.

The foundation of a sound geological investigation remains the fieldwork. I was fortunate to do this in an island where the majority of people spend their holidays. Therefore, wherever I went, I always met people with a smile on their face and a friendly word of welcome, although I couldn't understand them at the time. Even the soldier with his rifle did not consider me and my geological pick as a threat, when I suddenly stumbled out of the bush upon a military installation at the top of Dangsanbong. During the first field season I was, however, plagued by the unmovable bureaucracy of Korean car rental companies, who needed to see an international driving permit for me to get on four wheels. And I was left at the airport alone, with the prospect of doing fieldwork by bus. To be fair, however, I ought to thank the public transportation system on Jeju for its efficiency and good coverage. Eventually I did receive an international driver permit, thanks to the help of a kind receptionist at the Jeju Grand Hotel and of Dave Smith in Perth. When not alone, field work was done successfully with the logistical support and organization of several Korean colleagues. Special thanks go to Prof. Sohn (for the leadership), Mr. Kwon (for the driving), Dr. Jeon (for getting the necessary permits) and various other Korean students and academics, who enthusiastically joined me and the Massey contingent in a concerted effort to have us make the most of our Korean experience… and that's how we learnt why Korea is the "land of morning calm". Korea is also the land of delicious food, and the best is the one you taste adventurously without the guidance of the locals, and, together with Károly Németh, I will surely forever

remember the delicious, spicy, living-sea-slugs hotpot at Songaksan, or the equally peculiar though not as delicious "scraped up rice boiled in water" after a glorious black pig barbecue. And thanks go to Károly for scrambling up behind me to the summit of Mount Halla to reach the peaceful roof of Jeju, beyond the "hordes of Genghis Kahn".

After the fieldwork comes the analytical part, which, although not as adventurous is nonetheless necessary. As any good geochemist knows, sample preparation mainly consists of cleaning equipment, and all the more so at Massey, where labs are shared with uncooperative soil scientists. Precious assistance was nonetheless provided by Bob Toes, Ian Furkert, Clel Wallace and Damian Jones. Analytical work would have been impossible without the efforts of John Wilmshurst on the XRF and Ritchie Sims on the microprobe at the University of Auckland, Charlotte Allen on the LA-ICP-MS at the Australian National University in Canberra, and Ashlea Wainwright and Roland Maas in the isotope lab at the University of Melbourne.

Once the data are plotted on a chemical diagram, joining the dots and making any "real-world" sense of the images appearing on the screen was much facilitated by critical and constructive discussion with (and I'll name them in alphabetical order) Anja Möbis, Bob Stewart, Gábor Kereszturi, Gert Lube, Greg Valentine, Ian Smith, Javier Augustín-Flores, Károly Hidas, Károly Németh, Lucy McGee, Marc Bebbington, Mary Gee, Matteo Roverato, Natalia Pardo, Nicolas Le Corvec, Richard Price, Shane Cronin and Ting Wang as well as the official and unofficial reviewers of the submitted manuscripts and academics who commented on my posters at various conferences. Special thanks go to Ting Wang, who helped me to make actual mathematical sense of the data.

If one way of disseminating one's knowledge is by publishing in reputable journals, another is by attending conferences and communicating one's ideas in person. During the course of my PhD I was privileged to attend the meeting for the 250$^{th}$ Anniversary of the Birth of Volcán Jorullo in Morelia, Mexico in September 2009, which included the (in)famous horse ride to the feet of Paricutin, the 2009 Geological Society of South Korea annual meeting in Jeju, the 2009 Geological Society of New Zealand conference in Oamaru, and the AGU Fall Meeting 2009 (self supported) in San Francisco, where I met a particularly "gentle people", although it wasn't "summertime", and nobody had "flowers in their hair". In 2010 I attended the explosive basaltic volcanism course at Etna, Sicily organized by the AIV and the

INGV, and again the annual meeting of the Geological Society of South Korea, followed by a spectacular few days (extended by the raging waves of the East Sea hindering the ferry service) of fieldwork on Ulleung Island. 2011 was the year of the rabbit, as well as that of the IUGG General Assembly in Melbourne (self supported) and of Goldschmidt in Prague, followed by a "Central European" experience organized by Károly and his indefatigable Hungarian and Slovak friends. Finally in 2012, just before submitting this work, I attended the 4th International Maar Conference in Auckland. For all these experiences (even the self financed) I would like to thank Shane Cronin and Kate Arentsen for financial and organizational support. Finally, my thanks go to my parents, who brought me up appreciating the beauty and complexity of nature and especially of the geological world of the Swiss-Italian Alps, and later supported me in my quest for knowledge. More recently, Ting motivated and inspired me when I failed to see a higher scope in my work, and patiently supported me every other day.

I would like to dedicate this thesis to the memory of Katia and Maurice Krafft, whose effort to educate the general public on volcanic hazards fascinated me when I was a little boy, and later inspired me to pursue a career in geology and volcanology.

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