NATURAL HAZARDS RESEARCH PLATFORM

Contest 2015

Title: First Steps to a National Volcano Hazard Model

Leader: Professor Mark Bebbington

Organisation: Massey University

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Final Report

Key message

New Zealand has a world class National Seismic Hazard Model, but earthquakes are not the only geological peril that threatens New Zealand. So a team of researchers from Massey, Auckland and Otago universities, and GNS Science, have been working to scope out what the equivalent national-level model for volcanic hazard might look like, and to produce a first-order estimate of the 'when, where and how large' of the next eruption from a New Zealand volcano. By a process of expert elicitation and statistical modelling we have forecasts of the time to the next eruption onset at each volcano and, conditional on that, a forecast of the eruption magnitude. At volcanic fields, complex volcanoes and calderas (e.g. Auckland, Tongariro, Okataina) we also have a forecast of where the next vent location will be.

Abstract:
The aim of this research was to take the first steps towards a national-level volcanic hazard model (NVHM). This is an essential pre-requisite to placing volcanic risk on a platform which will permit comparing the *present* risk from volcanoes to (for example) that from earthquakes. This project sought to develop a common framework for NZ volcanism using two parallel and complementary approaches: (1) through questionnaires and a workshop of local experts in volcanic hazard estimation, distributions were elicited for the time to, and the likely size of, the next eruption at each New Zealand volcano; and (2) new statistical techniques were developed using empirical Bayes analysis of analogue volcanoes to validate and quantify the uncertainty in volcanic hazard estimates derived via expert elicitation. The final (re-)validated results represent the first level of the NVHM.

Keywords: Volcanic, hazard, probabilistic, New Zealand

Introduction / Background:
Volcanology is becoming an increasingly quantitative science, with the result that formal volcanic hazard assessments are now routinely performed in site evaluations for nuclear facilities, and this approach is spreading to other land-use planning activities. The underlying principle of traditional hazard forecasting is that the record of past events provides the best available indicator of possible future events. While deterministic models may be used in 'worst case' analyses to rule out impacts from particular hazards, probabilistic approaches are generally used to cover the expected spectrum of possibilities.

The first step is to quantify volcanic hazard at a national level, for comparison with other hazards such as earthquakes. This requires identifying the potential eruption sources, and for each source the likelihoods of an eruption over time, the duration and size or magnitude of an eruption and, in cases where volcanism is distributed, the location of a future eruption. Subsequent steps require dealing with the distribution, frequency and intensity of particular

hazardous volcanic products, and a consensus framework for combining and visualizing the resulting hazard will need to be created. A scoping exercise on this issue was part of this project.

At many volcanoes, the eruptive record is short, or incomplete, with few known eruptions. Thus a subjective hazard analysis method via expert elicitation could provide a better estimate than statistical analysis of an incomplete or sparse record. To carry an expert elicitation, a survey instrument must be based on the known record to allow elicitation from a common footing. This project carried out such an exercise for New Zealand volcanoes. A number of expert judgements were combined using Cooke's classical method. The aim was to elicit both a probability distribution for the time to the next eruption at a specific volcano, and another (conditional on the repose time until the eruption) for its magnitude. New Zealand has at least 12 volcanoes that pose a credible threat to life and/or infrastructure (including aviation), with variable degrees of knowledge of their eruptive histories, magnitudes of previous eruptions, or other factors such as eruption duration.

Impact Statement

First steps to a national volcano hazard model: Subjective estimation of time varying hazard from New Zealand volcanoes through expert elicitation and Bayesian analogues.

By 2018 New Zealand will have its first National Volcanic Hazard Model and a robust national probabilistic volcanic eruption forecast developed and tested under a common framework. National and regional authorities, lifelines providers and government departments will be using this instrument to effectively prioritise investment into risk management and resilience initiatives.

❖ 1.1 Research Aim

Title: An agreed structure for a National Volcano Hazard Model
Research Aim achieved? Yes / -

The aim was to arrive at a comprehensive outline of what should be included in a New Zealand national volcano hazard model, and the methods by which it could, and should, be populated. The output for this Research Aim was to submit a jointly (and widely) authored manuscript to a suitable journal as an open-access paper.

A workshop involving volcanologists, statisticians, and hazards scientists was held in February 2016 to define the goals, challenges and next steps for developing a national probabilistic volcanic hazard model for New Zealand. A draft discussion paper was circulated prior to the workshop, which saw a lively discussion on the second day. The workshop notes were compiled as a draft manuscript, which was returned to the participants for correction and amplification. Reponses were received from approximately half of the author list, and the second iteration of responses incorporated into the final manuscript. This has now

appeared (lead author Mark Stirling) in the open access journal *Frontiers in Volcanology*. A copy is attached as Appendix 1.

The consensus goals of a New Zealand national volcano hazard model center around data, scientific and end-user acceptance, multi-hazard and risk assessment utility. It should be open source, with a GIS front end. The challenges identified include: data quality, quantity and uncertainty; how multiple hazards should be measured and combined; how the results could inform building codes; defining default volcanic source (see Research Aim 1.2 below) and hazard models; validation and updating.

The desirable immediate next scientific steps were seen as developing new models for the emplacement of lavas across low topographies; agreeing on the most suitable model for the emplacement of pyroclastic density currents; and updating probabilistic ashfall models. As part of these objectives it is seen as particularly desirable to compare existing mapped volcanic deposits with hazard models, and to investigate the volume partitioning of volcanic eruptions among the various hazards.

Outputs for Research Aim 1.1

Journal article (published. Open source)

Stirling M, Bebbington M, Brenna M, Cronin S, Christophersen A, Deligne N, Hurst T, Jolly A, Jolly G, Kennedy B, Kereszturi G, Lindsay J, Neall V, Procter J, Rhoades D, Scott B, Shane P, Smith I, Smith R, Wang T, White J, Wilson C, Wilson T (2017) Conceptual development of a national volcanic hazard model for New Zealand. Frontiers in Volcanology 5, 51.

End-users

- Auckland Council
- CDEM Groups
- Central Plateau Advisory Group
- EQC
- Taranaki Regional Council
- Taranaki Seismic and Volcanic Advisory Group.

❖ 1.2 Research Aim

Title: Expert elicitation of present day hazard from New Zealand volcanoes
Research Aim achieved? Yes / -

The aim was, through questionnaires and a workshop, to elicit distributions for the time to, and the likely size of, the next eruption at each New Zealand volcano. The output was to be a report and/or journal manuscript synthesising the expert opinions and the consequent hazard

A total of 28 scientists provided, for 12 volcanoes, estimates of the Volcanic Explosivity Index (VEI, used as a measure of eruption intensity) of the next eruption and, conditional on the VEI, the repose to that eruption and its duration, and in some cases location. The expert

opinions were combined using Cooke's classical method to arrive at a consensus hazard estimate. From this we can calculate the probability that a given volcano will be the next to erupt as a function of elapsed time, the probability of a given eruption size at a particular volcano given the time until it occurs, the duration of an eruption given its size and, in calderas, volcanic fields, and the complex stratovolcano Tongariro, where the next eruptive vent is likely to be.

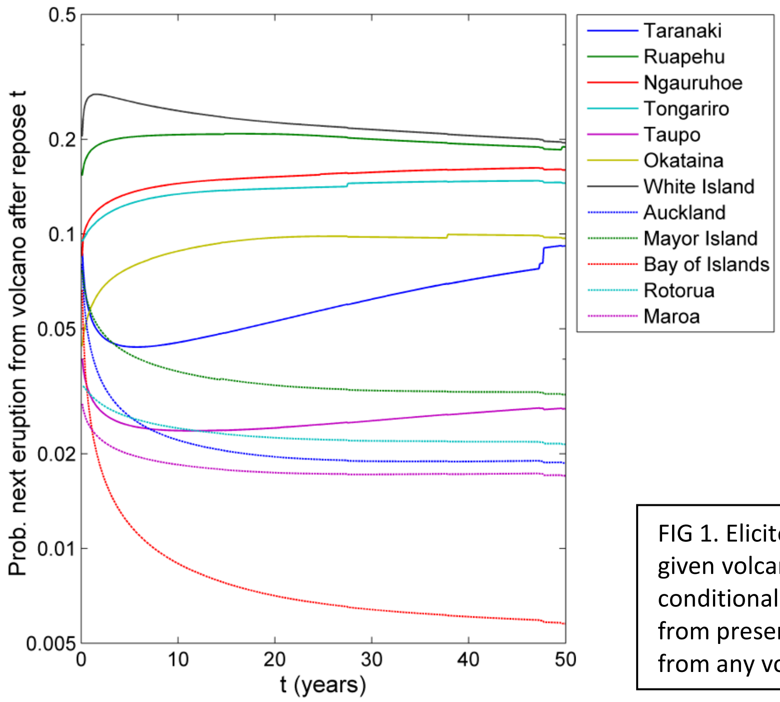

FIG 1. Elicited probability that a given volcano is the next to erupt, conditional on the length of time from present without an eruption from any volcano.

The volcano considered most likely to erupt (Figure 1) is White Island, which duly erupted just over 2 months after the elicitation workshop. The volcanic centres in Tongariro National Park are the other likely candidates. Because White Island and the Tongariro National Park volcanoes erupt relatively frequently, a long period without any eruptions makes Taupo and Taranaki more likely to be the next eruption. The median (best estimate) forecasts for the next eruption date are in Table 1, along with the 80% probability intervals. Rotorua and Maroa are not tabulated as they were estimated to be extinct with probabilities of about 0.5, and so the median and upper prediction limit could not be calculated (Manuscript submitted; Data not shown).

TABLE 1. Elicited dates of next eruption from each volcano

Volcano	Date (AD)		
	Median	80% Prediction Interval	
Taranaki	2082	(Feb 2024	2473)
Ruapehu	Nov 2019	(May 2016	2040)
Ngauruhoe	2034	(Aug 2016	2235)
Tongariro	2038	(Dec 2016	2333)
Taupo	2866	(2054	8456)
Okataina	2092	(Feb 2019	8636)
White Island	Nov 2021	(Mar 2016	2060)
Auckland	3256	(2096	27,616)
Mayor Island	4336	(Feb 2026	12,896)

Bay of Islands	53416	(8216 >200,000)

In all cases except Ngauruhoe, the elicited eruption duration increased with VEI, and was correlated with expected repose. There was surprisingly little difference in elicited eruption duration between volcanoes.

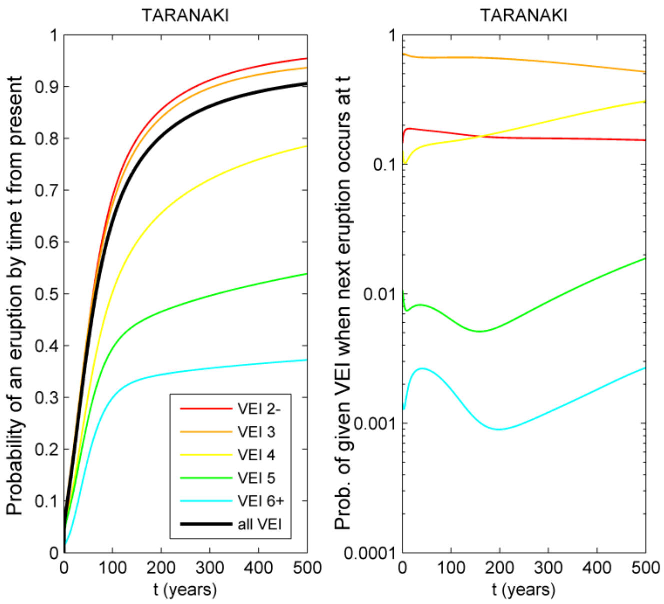

FIG 2. Elicited probability of an eruption occurring by a given time, conditional on it being of a specific VEI (left) to next eruption (left) and probability of the next eruption being of a given VEI, conditional on the time of the eruption (right). Time measured from present.

Excepting Taranaki, which is in an extended repose and expected to resume activity with a larger eruption (Figure 2), the andesitic volcanoes had very similar elicited distributions for the VEI of a future eruption (Table 2). The majority of the volcanoes exhibited time-predictability (larger eruptions become more likely with increasing repose) in the elicited VEI distributions.

TABLE 2. Expert VEI distributions for the next eruption from each volcano

Volcano	VEI					
	≤2	3, ≤3	4	5	≥6, 6	≥7
Taranaki	0.1631	0.6488	0.1707	0.0128	0.0047	
Ruapehu	0.7151	0.2134	0.0478	0.0194	0.0043	
Ngauruhoe	0.7771	0.1484	0.0605	0.0083	0.0058	
Tongariro	0.7826	0.1400	0.0476	0.0256	0.0042	
Okataina	0.5231	0.0618	0.1170	0.1723	0.1258	
White Island	0.7622	0.2070	0.0201	0.0075	0.0032	
Auckland	0.7666	0.2011	0.0275	0.0024	0.0024	
Mayor Island	0.4205	0.2833	0.2042	0.0836	0.0084	
Taupo		0.3643	0.4333	0.1368	0.0522	0.0135
Rotorua		0.5010	0.1895	0.1556	0.0953	0.0586
Maroa		0.5081	0.2244	0.1445	0.0688	0.0542

Elicited future vent locations for Taupo, Tongariro and Okataina reflect strongly the most recent eruptions. In the Bay of Islands volcanic field, the elicited spatial distribution of future vents is centred on the centroid of the vent locations, while in Auckland it has picked out two ‘empty’ regions within the field (Figure 3) which do not contain previous vents. There was no indication of dependence between eruption location and size.

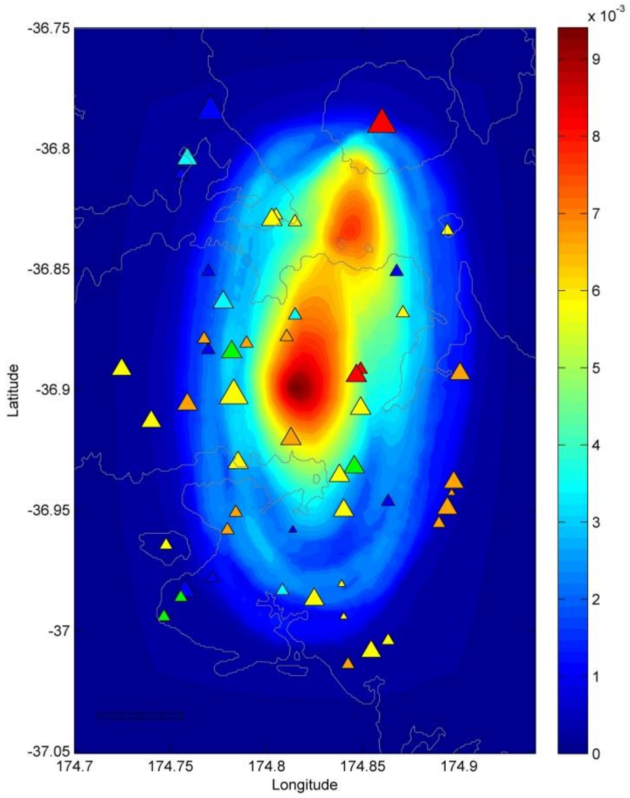

FIG 3. Elicited probability (per km^2) for location of next eruptive vent from the Auckland Volcanic Field. Triangles denote previous vents, with age on the heat scale (blue = oldest to red = youngest), and symbol size scaling with the eruption volume.

Outputs for Research Aim 1.2

Journal article (submitted)

Bebbington, M., Stirling, M., Cronin, S., Wang, T., Jolly, G., 2016: National-level long-term eruption forecasts by expert elicitation. Submitted to Bulletin of Volcanology. (See Appendix 2)

Conference abstract in published proceedings

Bebbington, M., Stirling, M., Cronin, S., Wang, T., Jolly, G., 2016: Expert elicitation for a national-level volcano hazard model. Geophysical Research Abstracts 18: EGU2016-3591. Retrieved from: http://meetingorganizer.copernicus.org/EGU2016/EGU2016-3591.pdf [poster presented at the EGU General Assembly 2016, Vienna, Austria, 17-22 April]

Conference presentation

Bebbington, M., Stirling, M., Cronin, S., Wang, T., Jolly, G., 2016: National-level long-term eruption forecasts by expert elicitation. IAVCEI 2017 Scientific Assembly, Portland, 14-18 August 2017.

Report

Bebbington, M. Stirling, M., Cronin, S., Wang, T., 2016: First steps to a national volcano hazard model: Estimation of time varying hazard from New Zealand volcanoes through expert elicitation and Bayesian analogues - Expert Elicitation Exercise Preliminary Report.

End-users

- Auckland Council
- CDEM Groups
- Central Plateau Advisory Group
- EQC
- Taranaki Regional Council
- Taranaki Seismic and Volcanic Advisory Group.

❖ 1.3 Research Aim

Title: Validating expert opinion on time-varying hazard estimates
Research Aim achieved? Yes / -

The aim was to develop new statistical techniques using empirical Bayes analysis of analogue volcanoes to validate and quantify the uncertainty in volcanic hazard estimates derived via expert elicitation.

During a project team meeting at GNS Science on 11 August 2015, a preliminary list of analogue volcanoes was proposed. The data for these were assembled (see Appendix to the June 2016 project report).

Analogue volcanoes are assumed to have similar, although not necessarily exactly the same, behaviour as the 'target' volcano. In statistical terms, analogue volcanoes can be modelled as having the same class of hazard rate functions. The variation between the hazard rate of different volcanoes can be expressed as a random variable. To test if the class of analogue volcanoes identified empirically have similar behaviour, we can allow all the volcanoes in the analogue set to have the same form of hazard rate function, but different shape or scale parameters. Bayesian inference can then be performed to assess if the shapes and scales of the hazard rate functions of these volcanoes are statistically significantly different. If only the scale differs, then the volcanoes can be considered suitable analogues, as the difference can be considered due only to a faster or slower 'clock'.

Two volcanoes, Puyehue—Cordón Caulle in Chile and Three Sisters in Oregon, have excellent eruption histories, along with compositions, tectonic settings and eruption styles that match closely those of Tongariro. We therefore considered volcanic eruption records from the two volcanoes as analogues for the Tongariro eruption record. The results using the method described above suggest that the shapes of the hazard rate functions of the three volcanoes are statistically not different. There may be some difference in the time-scaling of the three volcanoes.

We therefore modelled the activity of the three volcanoes using a hazard rate function with the same shape parameter, and a random variable multiplying the hazard rate function to allow for possible scale variations between volcanoes. This provides forecasts for the next onset time from Tongariro at different VEIs. (Table 3). These numbers, while more representative of the record, are considerably in excess of the elicited opinions. This partially reflects the observation that the expert opinions tended to be highly over-dispersed (i.e.,

had a relatively high estimate of an eruption in the short-term). Future work will investigate how to account for incompleteness in the volcanic records, which will depend on an expert assessment and augmentation of the eruptive records.

TABLE 3. Analogue modelling forecasts for Tongariro

VEI	Empirical Bayes Estimate of Next Onset Date	
	Posterior Mean	95% Bootstrap Interval
2+	2460	(2087 3602)
3+	5350	(2253 8087)
4+	7026	(3417 9352)

Outputs of Research Aim 1.3

Journal article (in preparation)

Draft manuscript "Volcanic analogue analysis", attached as Appendix 3, summarises the results and gives details of the new methods. This will be worked up for journal submission.

Data resource

The data of the analogue volcanoes have been tabulated in a series of spreadsheets (attached to June 2016 report).

End-users

- Auckland Council
- CDEM Groups
- Central Plateau Advisory Group
- EQC
- Taranaki Regional Council
- Taranaki Seismic and Volcanic Advisory Group.

Conclusions & Recommendations:

This research project has successfully made the first steps towards developing a New Zealand National Volcanic Hazard Model. We have developed time-varying forecasts for timing, location, size and duration of future eruptions from each of New Zealand's active volcanoes. We have also stimulated agreement by the New Zealand hazards research community on how a National Volcanic Hazard Model should be structured and implemented.

The next step is to bring these together. As suggested by the research community (see Appendix 1), a possible first step would be to revise the national ashfall hazard model (Hurst and Smith 2010) using the new forecasts, within a time-varying paradigm. This would provide a test bed for the proposed NVHM, enabling the devil-containing details to be addressed.

Acknowledgements:
First and foremost we would like to thank the many scientists who unselfishly gave of their time and expertise, and without whom this work would not have been possible. Valuable contributions were received from Tony Hurst, Art Jolly, Vince Neall and James White.

References:
Hurst T, Smith W (2010) Volcanic ashfall in New Zealand - probabilistic hazard modelling for multiple sources. NZ J Geol Geophys 53, 1-14.

Appendices:
Appendix 1
Stirling M, Bebbington M, Brenna M, Cronin S, Christophersen A, Deligne N, Hurst T, Jolly A, Jolly G, Kennedy B, Kereszturi G, Lindsay J, Neall V, Procter J, Rhoades D, Scott B, Shane P, Smith I, Smith R, Wang T, White J, Wilson C, Wilson T (2017) Conceptual development of a national volcanic hazard model for New Zealand. Frontiers in Volcanology 5, 51.

Appendix 2
Bebbington, M., Stirling, M., Cronin, S., Wang, T., Jolly, G., 2016: National-level long-term eruption forecasts by expert elicitation. Submitted to Bulletin of Volcanology.

Appendix 3
Draft manuscript “Volcanic analogue analysis”