

Assessing risk from ballistic impacts through aerial hazard mapping, numeric modelling, and laboratory experiments to enhance risk management and risk communication (EQC grant 16/727)

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Summary and results highlights

Rocks and lava thrown from volcanoes (ballistics) produce a severe hazard in areas close to the volcano summit. As volcano tourism continues to grow worldwide, ballistics have become one of the most common cause of incidents involving fatalities at volcanoes with at least 76 recorded deaths at six volcanoes since 1993, including Mt Yasur in Vanuatu. In New Zealand in 2006 one death was reported on Raoul island, and since then a near miss on Ruapehu, a near miss at Tongariro which significantly affected infrastructure used by hikers on the high-use Tongariro Alpine Crossing, and seven near misses from Whakaari (White Island). Here, we pioneer the quantification of ballistic hazard in New Zealand and Vanuatu.

Our adaptive mapping methodology allowed different aerial and ground based techniques to be employed in different scenarios. Mapping from the three volcanoes shows that the ballistic hazard varies considerably between eruptions styles. The distribution of ballistic blocks from the small 2016 phreatic eruption from Whakaari shows a small ballistic hazard zone but with extreme ballistic hazard almost anywhere within the zone (Kilgour et al., in review). At Red Crater on Mt Tongariro, we identified an age constrained eruption deposit (<500yrs) that shows that the hazard from ballistics from phreatic eruptions drops rapidly with distance - from extreme hazard close to the crater to low hazard within a hundred meters (Gates et al., 2017). In contrast, the average individual magmatic eruption pulse at Yasur has a significantly lower hazard with most ballistics landing back into the crater (Fitzgerald et al., in prep). A decrease in hazard intensity with distance was also seen here, though is highly spatially variable ranging over several orders of magnitude with both proximity and azimuth to the vent. However, this assessment covers only a small time window (2 months) and further study is required to assess how ballistic hazard changes over longer periods of time.

The modified Ballista 3D numerical ballistic trajectory model was applied in two different ways at Whakaari and Ngauruhoe to assess ballistic hazard. Multiple model runs were compared to the mapped ballistic distribution and geophysical data at Whakaari to understand in greater detail the ballistic distribution and eruption dynamics. Ballista revealed that multiple low angle ballistic jets were likely coupled with surges which may change the traditional ballistic trajectory and subsequently the expected area of hazard (Kilgour et al., in review). On Ngauruhoe we coupled a single Ballista model with a RAMMs rockfall runout model to show how bouncing and rolling downhill after impact compounds the ballistic hazard, in this case increasing the magnitude of the hazard by over 400% (Kennedy et al., in prep). In addition, we are pioneering a new technique to systematically fit ballistic distributions to model runs (Tsunematsu et al., 2017, 2018).

Vulnerability of different roofing materials to ballistic impact was quantified using the experimental pneumatic ballistic cannon (Williams et al., 2017). Collaboration with the College of Engineering at the University of Canterbury on ballistic impacts to concrete roofs showed fibre reinforced plastics could

eliminate the shrapnel hazard and that a 5 cm layer of ash or lapilli on the concrete could significantly dissipate the impact energy and reduce damage (Williams et al. 2017b; 2018).

Through a publication on ballistic hazard communication (Fitzgerald et al. 2017) and a ballistic hazard workshop we aimed to keep end users informing and directing the science discovery pathways throughout the project. We continue to develop better ways to inform end users. Discussion of this report with Harry Keys has already sparked improved communication methodologies with DOC.

Introduction

Volcano tourism is growing, creating an increasing vulnerable population exposed to ballistic hazards on volcano summits (Erfurt-Cooper, 2011). On September 27th, 2014, Mt Ontake, Japan erupted, ejecting ballistics onto a summit full of lunching hikers, resulting in 55 of the 58 deaths (Oikawa et al., 2016). Only the bad weather and time of eruption (near midnight) prevented casualties being of a similar scale from the August 2012, Upper Te Maari eruption on the Tongariro Crossing (Breard et al., 2014; Fitzgerald et al. 2014; Jolly et al., 2014b). Similar eruptions have occurred frequently over the last 7 years at Whakaari (White Island) volcano (Chardot et al., 2015; Edwards et al. 2017; Jolly et al., 2017). These unheralded eruptions exemplify that the hazard and risks from volcanic ballistics are poorly understood and difficult to manage and plan for (Fitzgerald et al., 2017). There is particular need for a stronger basis for zone shapes and sizes on hazard maps, and improved assessment to calculate risk. Protocols for better understanding and thus managing risk during periods of volcanic crisis and non-crisis are only now being developed and still require rigorous scientific testing (Barclay et al., 2008; Leonard et al. 2014). This project proposes to build upon ground breaking studies of ballistic risk assessment at Te Maari (Fitzgerald et al., 2014; Jolly et al., 2014).

Here we build on the academic momentum achieved from the Te Maari ballistic research. Collaborative ties were established between New Zealand, Japan and Vanuatu with the recent tragic events in Japan and at other volcanoes around the world that resulted in fatalities from ballistic producing eruptions (Fitzgerald et al., 2017). A ballistic producing explosion killed a DOC worker on Raoul Island, New Zealand (Brown et al., 2017) and in the past decade there have been “near miss” ballistic producing eruptions at Ruapehu (Kilgour et al., 2010), White Island and Tongariro (Scott and Potter, 2014; Jolly et al., 2016). It is important to learn from the fatal events worldwide and use these lessons to improve risk communication and management at our New Zealand volcanoes. Ballistic hazards are often ignored in hazard assessments (Fitzgerald et al., 2017). These unheralded events have resulted in government requested initiatives that highlight the need for better ballistic hazard assessments, particularly in areas frequented by tourists, skiers, and mountain climbers. Results from our preliminary trip to Japan have allowed us to focus our methodologies (Everaerts, 2008; Gomez et al., 2010, Tsunematsu et al., 2010) and ballistic research around lessons learned and end user goals to produce a distinct set of new objectives for this second phase of ballistic hazard research at the University of Canterbury.

A key component of this project is the involvement of the Department of Conservation and GNS Science from the onset to ensure usefulness for end users (Leonard et al., 2014). We will use the data collected in New Zealand and Japan to improve ballistic hazard and risk assessments, and build and refine fragility estimates for risk model(s) applicable to all New Zealand volcanoes. Then through systematic studies we will refine methods of communication to the public to reduce risk.



Figure 1. A roof impacted by ballistics during the 2000 eruption of Usu volcano (photo courtesy of Professor Okada).

Objectives

The objectives for this research were to:

1. Develop 3D maps of ballistic energy distributions around a) the recent vents on the Tongariro crossing and b) Yasur volcano, Vanuatu using field and aerial mapping from UAVs. These maps will contribute to time varying hazard and risk assessments.
2. Characterise the ballistic hazard. This involved refining a 3D ballistic trajectory model through integration of a) rock bouncing criteria to model the effects of slope on ballistic deposition, and b) deformable lava bombs, and implementing capability for New Zealand scientists to use the model by running a Ballista workshop.
3. Develop the Ballistic Experimental Laboratory to refine hazard and vulnerability models of an impacting volcanic ballistic including investigating the likelihood of bouncing on different surfaces, the ability to generate shrapnel, and the effectiveness of protective measures.
4. Refine and modify risk communication resources (hazards maps and signage specific to zones proximal to the vent) using the data collected from objectives 1-3. Through existing GNS protocol, public interviews and expert solicitation will refine different versions of these communication resources for different end users, e.g. hikers, skiers, DOC workers, and GNS staff. Together with DOC, GNS and the Vanuatu Geohazards team we will refine signage and protocol for proximal areas in the event of an eruption.

Conclusions and key findings

Findings from this project contribute towards better ballistic hazard and risk assessment, more informed decision making when building and installing protective measures, and better communication products between scientists and end-users. We summarise our key findings and conclusions under each of the four objectives below.

Objective 1

- Using UAVs, we successfully mapped ballistic hazard from deposits around Red Crater and Emerald Lakes on the Tongariro Crossing (Fig. 2a). Our work identified deposits on top of the <500 yr old lava flow, constraining the age of these eruption deposits, and showed a ballistic hazard zone extending approximately 1km from the vent area and impacting approximately 2km of the Tongariro Crossing. The hazard decreases with distance from vent from between 31 and 39 ballistics per m² 50 m from the vent to 1 impact per m² 400 m from vent (Gates et al., 2017: Gates et al., in prep).
- At Mt Yasur, Vanuatu, we compared two high resolution photo draped DEMs made from two drone flights between August and October 2016 (Fitzgerald et al., in prep). Coupled with seismo-acoustic

data and observations (Jolly et al., 2017) (Fig. 2b) on eruption frequency, a S-SE directed ballistic hazard area was identified over a two-month, time constrained period.

- Collection of field data at Whakaari by GNS Science scientist Geoff Kilgour following a small phreatic eruption in 2016 allowed analysis of the ballistic hazard from this eruption to be completed by Geoff and Stephanie Gates the following year. Mapping revealed hundreds of ballistics per m² around the tourist track at Whakaari (White Island) (Fig. 2c) (Kilgour et al., in review).

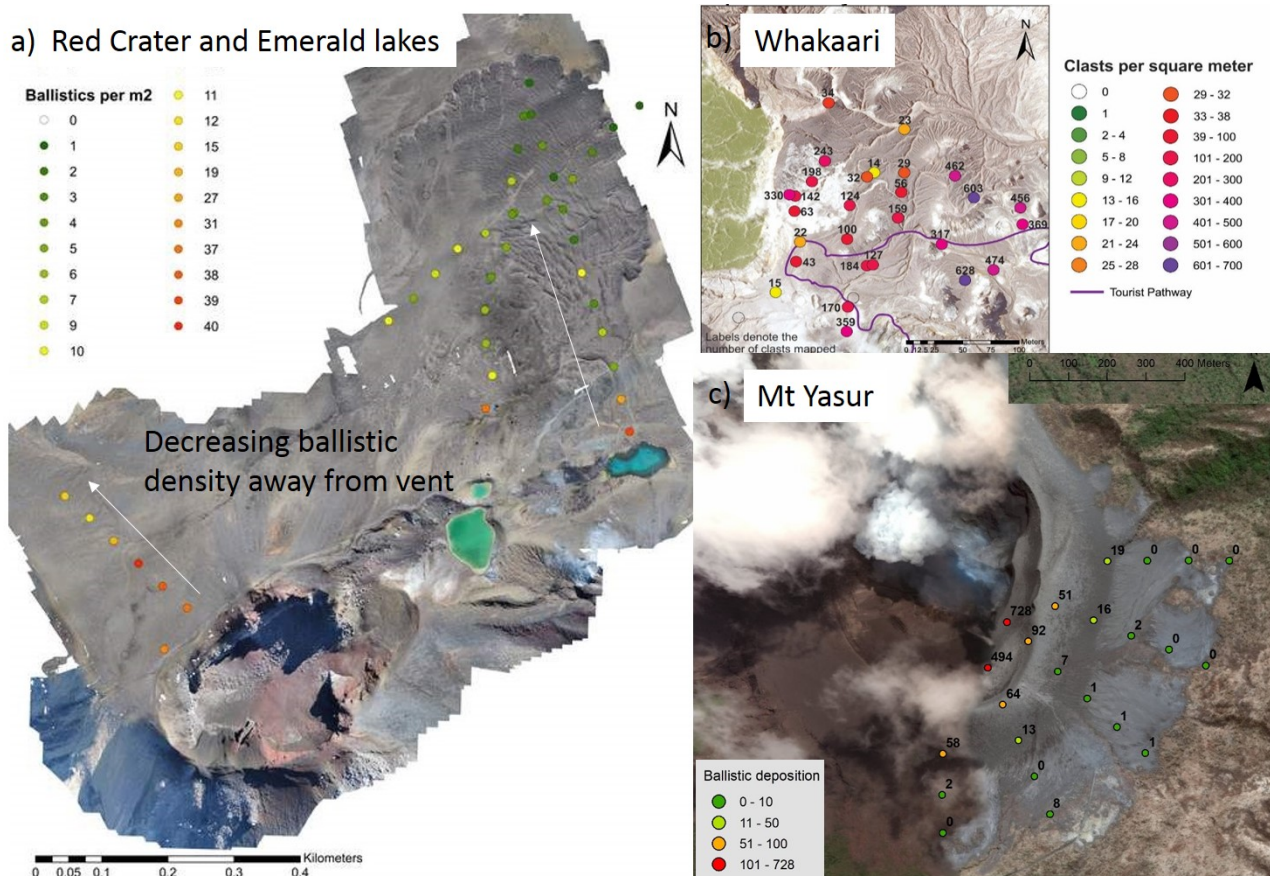


Figure 2. The distribution of ballistics around a) Red crater, b) Whakaari, and c) Mt Yasur (number of ballistics per 400m²).

Objective 2

- A crucial part of this project was to improve the usability of the modelling program Ballista. We created a user interface that allows a user without coding experience to run Ballista (Fig. 3a) (Tsunematsu et al., in prep). Additionally, we created code to enable 3D oblique view outputs to better illustrate ballistic distribution/hazard and show interaction with topography and infrastructure such as hiking trails (Fig. 3b) (Kilgour et al., in review). These modifications now allow the model to be run from New Zealand without reliance on the creator Kae Tsunematsu, giving NZ added ballistic modelling capability that is resilient beyond the length of this project.

A Ballista model scenario was created for a Vulcanian block-producing eruption from Mt Ngauruhoe (based on the case study by Nairn and Self, 1978). The impact position, size, direction and velocity outputs of the Ballista model were then coupled with the rockfall model RAMMS (used for rockfall in Borella et al., 2016) to investigate the effects of slope on ballistic deposition and how this can change the magnitude of hazard (Fig.3c). The RAMMS model results show that the coupled hazard can be over 400% greater than the ballistic hazard alone, and is sensitive to the mass/size, velocity and the slope angle of the impacting

ballistic. The irregular shape of the three-dimensional blocks used in RAMMS, and their interaction with a three-dimensional topography based on a detailed digital elevation model, shows a range of potential rockfall pathways for each impact (Fig.3c). The coupled hazard model supports historic videos showing that bouncing ballistics have occurred on Ngauruhoe and are likely in future eruptions, and that bouncing impacts on the upper flanks can become hazards for anyone on the Tongariro Alpine Crossing trail below (Kennedy et al. in prep). Early quantification of this hazard shows that while the modelled Vulcanian eruption resulted in 6 direct ballistic impacts in a 1 km portion of the trail, the runout of ballistics landing uphill of the trail and rolling or bouncing down the mountain resulted in an additional 18 interactions with the same portion of the trail. In many cases the modelled blocks crossed the trail multiple times because of a switchback in the trail.

- We additionally collaborated with GNS Science to use infrasound to look at eruption frequency and directionality to inform ballistic hazard (Fig. 4b) (Jolly et al., 2017). Acoustic analysis was coupled with stationary camera observations of eruptions to identify the source and directionality. Additionally, drone photography and structure from motion analysis created a high resolution digital surface model of the crater and for the first time created an ash cloud volume in 3D (Fig 3e) (Gomez and Kennedy, 2018).

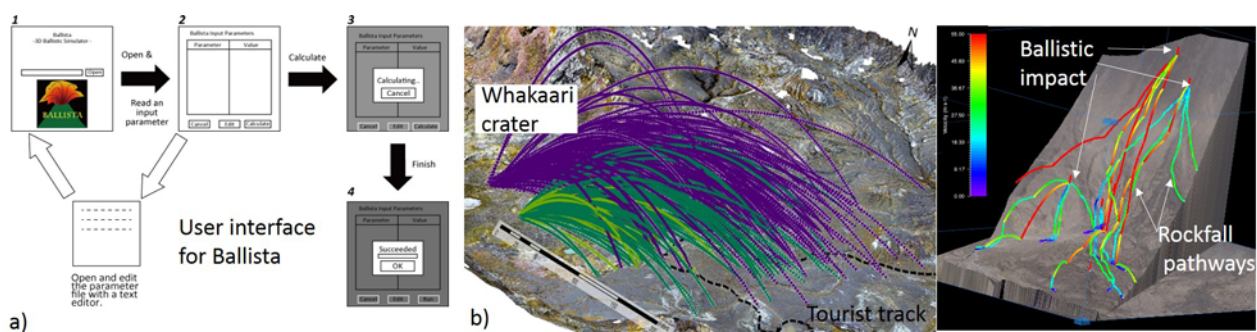


Figure 3. a) the step by step ballista interface, b) 3D ballistic model on photo draped digital surface model of Whakaari, c) coupled ballistic and RAMMS modelling outputs, showing 5 impacts on the flank of Ngauruhoe and 5 potential bouncing pathways for each impact.

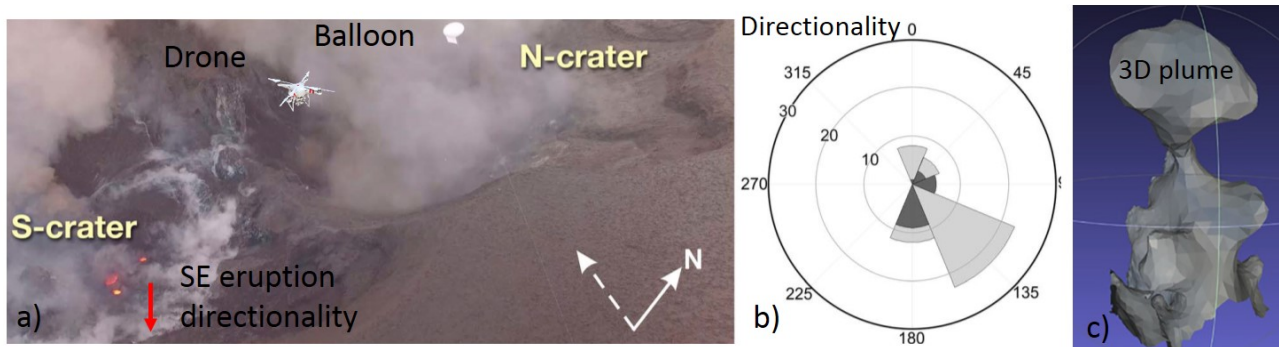


Figure 4 a) drone view from above the craters at Mt Yasur showing the stationary tethered balloon, b) number of eruptions and their associated directionality, from Jolly et al. (2017), c) a small stationary plume isolated as a 3D volume from Gomez and Kennedy, (2017).

Objective 3

- A full suite of variable ballistic energy experiments were performed on a range of different roofing materials to create fragility functions (Williams et al., 2017). The experimental results were compared to field data (e.g. Fig. 1) collected during our fieldwork in Japan with Kae Tsunematsu and Professor Okada.

The fragility functions were designed to be compatible with RISKSCAPE allowing the results to be applied to the different roofing in Auckland and used to investigate eruption scenarios as part of a new collaboration with DeVoRA (Fig. 5b).

- Experiments were also completed investigating the interaction between a layer of ash (Fig. 5a) or scoria over a roof and ballistic impact. A 5 cm thick layer of ash can triple the energy required for ballistic penetration in roofing materials. Additionally, we bonded two layers of Fibreglass reinforced polymers to the underside of concrete slabs. This quadrupled the concrete's energy threshold for generating deadly concrete shrapnel i.e. it took four times the impact energy to produce shrapnel from Fibreglass backed concrete slabs than slabs without the Fibreglass. These experiments have allowed us to create life safety advice for sheltering in or around buildings (Fig. 5c) (Williams et al., 2017).

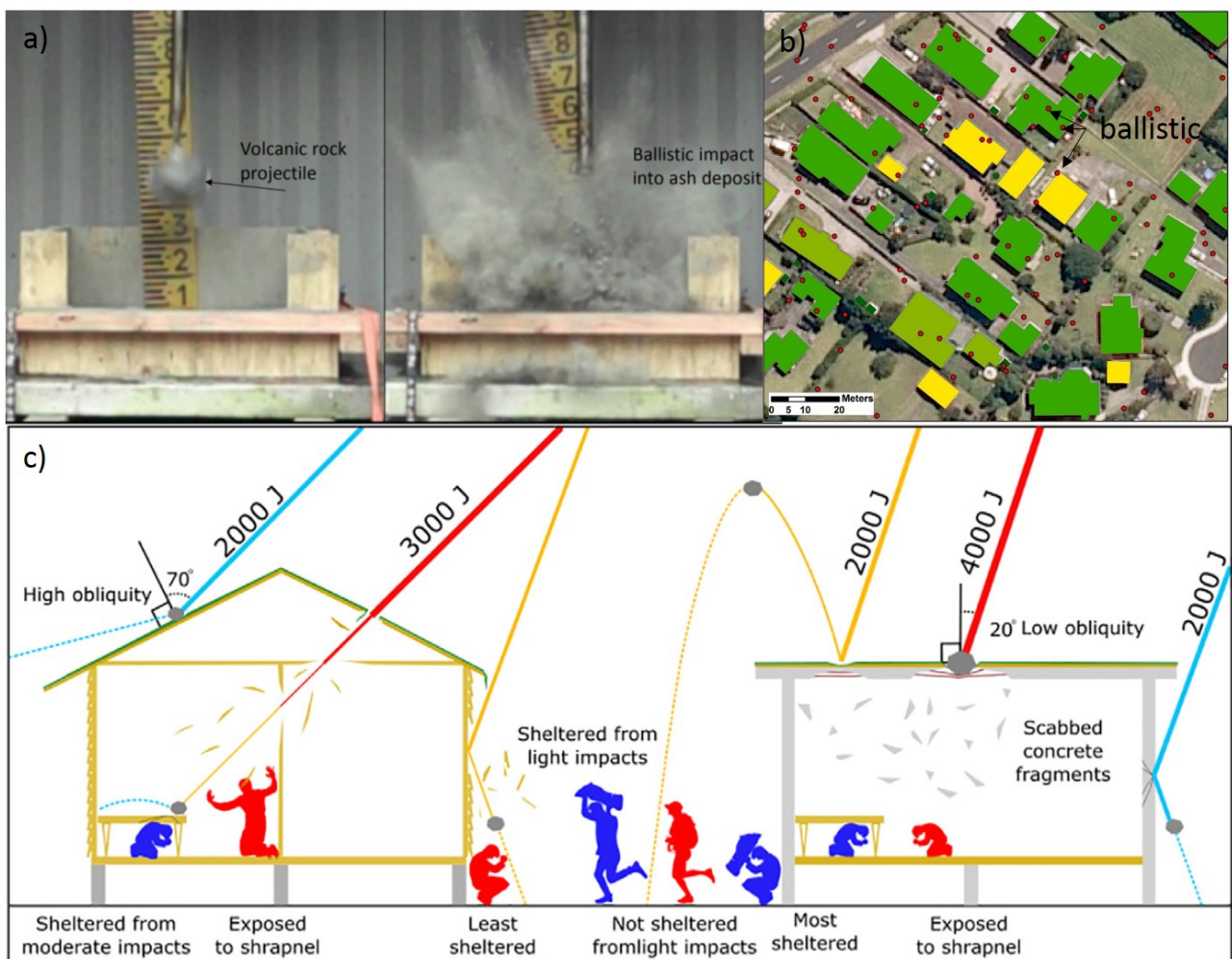


Figure 5. a) Two video frames show the before and after of a ballistic block impacting a 5cm layer of ash cushioning a concrete slab, b) Auckland houses colour coded for different roof types with red dots representing impact outputs from a Ballista simulation from Williams (2016), c) Life safety advice for sheltering in and around buildings from Williams et al., (2017).

Objective 4

- Together with Mt Fuji Research Institute, GNS Science and DOC, , we developed a ballistic hazard communication and risk management publication (Fitzgerald et al. 2017). The publication summarized ballistic hazard communication and risk management processes and products and how they are used to reduce risk on volcanoes worldwide. We highlighted the diverse range of communication methodologies that could be employed before during and after a volcanic crisis (Fig. 6a). Complementary to this publication we ran a workshop at GNS Science Wairakei (Fig. 6b)

with attendees from all New Zealand Universities, GNS Science, Mt Fuji Research Institute and the Vanuatu Geohazards team. The workshop focused on both the usability of the Ballista model (mentioned earlier) but also ballistic risk reduction. The workshop was highlighted in the International Association of Volcanology and the Earths’ Interior newsletter in 2016. The workshop spawned additional projects and collaborations across New Zealand and abroad and has additionally resulted in the addition of two ballistic related questions to the annual questionnaire at Ruapehu ski fields (e.g. Leonard et al., 2008).

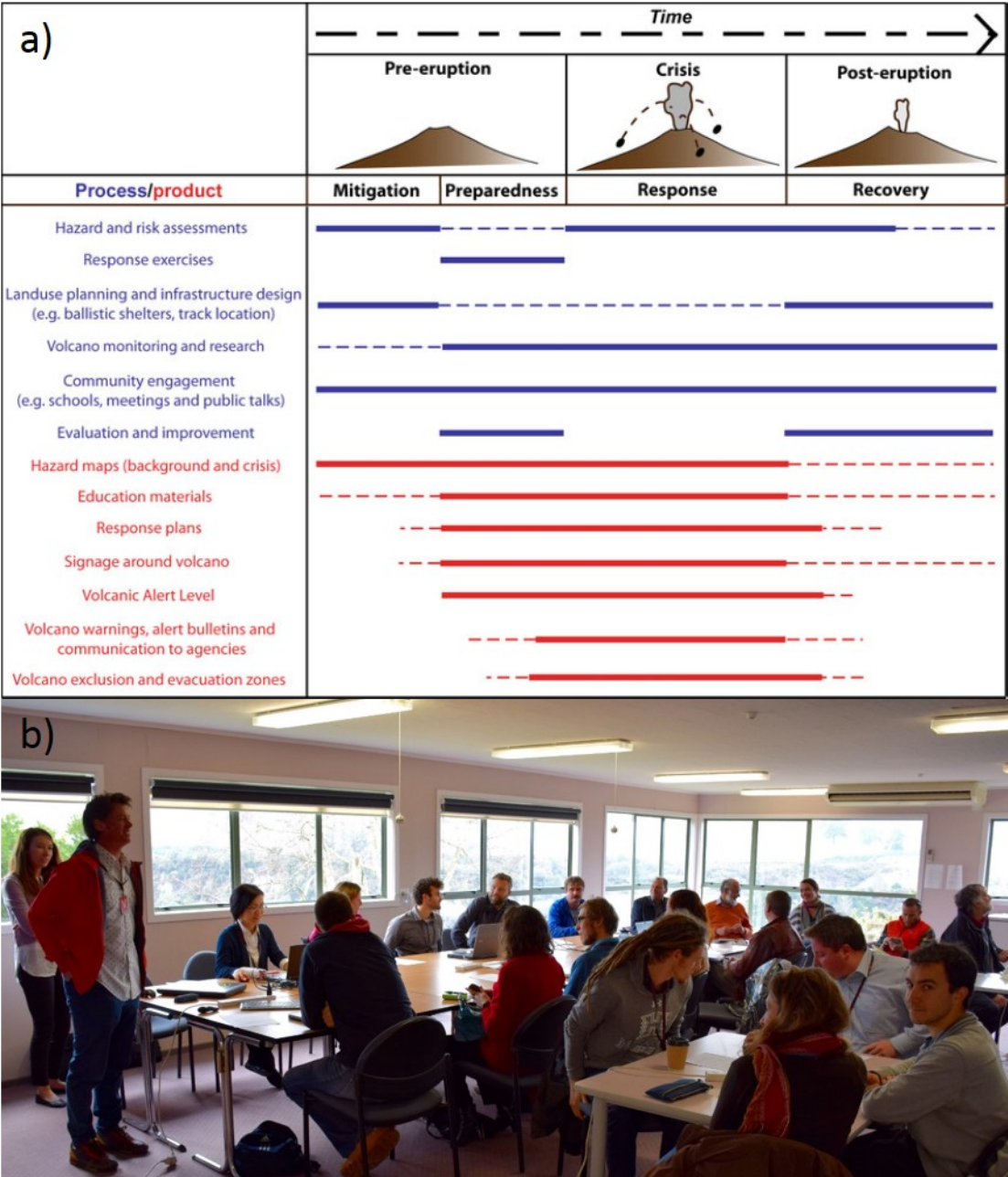


Figure 6. a) Ballistic hazard and risk communication processes and products and their use before during and after volcanic crisis from Fitzgerald et al. (2017), b) the Ballistic Hazard and Modelling workshop at Wairakei, New Zealand.

Impact (i.e. how this research reduces the impact of natural disaster on people and property)

Until now, agencies recommending and enforcing volcano summit hazard zones have had little ballistic hazard data to back up their decisions. Here, we have provided some of the first quantifiable data to these agencies. We have raised the awareness of ballistics to key end users and the public as a distinct and

quantifiable hazard. Our data influenced decisions on an equipment bunker, and locations of some toilet facilities in Tongariro National Park. Our questions on ballistic hazards have now been incorporated into the Ruapehu ski field volcanic hazard exercise to measure and reinforce ballistic hazard and life safety actions. Similarly, our ballistic modelling is now used in ballistic eruption scenarios for the Auckland Volcanic Field, and outputs are provided in a manner for easy inclusion in Riskscape to assess potential damage for Auckland buildings and infrastructure. It is also planned to be taken up on a new interagency framework for hazard maps under development lead by GNS Science, allowing for modelling of ballistic zones to match a chosen risk tolerance. This is a stepwise change in way we make hazard maps for ballistics internationally – to date these have been mostly based off of expert judgment estimates from small numbers of local past events and some judged calibration to comparative eruptions around the world.

Future work

The success of this team has produced lasting collaborative relationships that will facilitate continued volcanic hazard research.

- (1) Through DeVoRA we have initiated a multi hazard PhD project for Nicole Allen combining ballistic, airfall, and pyroclastic flow hazards in multi hazard framework for Auckland Volcanic Field.
- (2) The success of this collaboration in Vanuatu has also facilitated a sub contract with GNS to support geophysical experiments at active volcanoes and plans are currently underway to support the ongoing crisis on Ambae volcano, Vanuatu.
- (3) This project has been an important cornerstone in the negotiations around the future of end user focussed natural hazards in New Zealand and has helped direct future ballistic hazard research and its interaction with other hazards planned in the Natural Hazard Research Platform.

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Outputs and Dissemination

Media

- Ben Kennedy: Story collider, Science media centre event, Wellington Meow Club, May, 2018.
- Ben Kennedy, Rebecca Fitzgerald, and George Williams: Prime's "Beneath New Zealand" episode on Volcanoes. Aired in 2016.
- Ben Kennedy, Graham Leonard, Rebecca Fitzgerald and George Williams: RNZ's "Our Changing World" podcast interviewed by Alison Ballance. Aired 15 June 2017.
<http://www.radionz.co.nz/national/programmes/ourchangingworld/audio/201847343/will-your-roof-withstand-flying-volcanic-rocks>
- Thomas Wilson, Ben Kennedy and George Williams: TV1 News. Aired 30 July 2017 <https://www.tvnz.co.nz/one-news/new-zealand/watch-safe-your-house-if-volcano-erupts-nearby>

The ballistic workshop was reported in the IAVCEI newsletter 2016 No.3.

http://www.iavceivolcano.org/downloads/news/2016/2016_IAVCEI_news_3.pdf

Peer reviewed publications

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Presentations

1. Gomez CA and Tsunematsu K (2018). The role of DEM resolution on ballistic distribution using the BALLISTA model at Merapi Volcano. *Japan Geoscience Union Meeting 2018, Chiba, Japan*
2. Matoza RS, Jolly A, Chouet B, Dawson P, Fee D, Iezzi A, Kennedy B, Fitzgerald R, Johnson R, Kilgour G, Christenson B, Garaebiti E, Key N (2018). Seismo-acoustic wavefield of strombolian explosions at Yasur volcano, Vanuatu using a broadband seismo-acoustic network and infrasonic sensors on a tethered aerostat. *Cities on Volcanoes 10, Naples, Italy*.
3. Tsunematsu K, Kennedy BM, Gomez CA, Fitzgerald RH, Chopard B (2018). Statistical Analysis of the Distribution of Ballistic Deposits using the BALLISTA Model. *Japan Geoscience Union Meeting 2018, Chiba, Japan*
4. Williams GT, Frewen C, Morgan S, Kennedy BM, Wilson TM, Scott A, Lalllemant D and Jenkins SF (2018) How to increase the strength of your roof against volcanic projectiles: Insights from ballistic cannon experiments. *AOGS-EGU, Tagaytay, Philippines*.
5. Austin A, Matoza R, Fee D, Jolly A, Iezzi A, Johnson R, Kilgour G, Christenson B, Garaebiti E, Kennedy B, Fitzgerald R, Key N, Teissier A (2017). Flashing arcs at Yasur Volcano, Vanuatu and their relationship to strombolian eruption mechanics. *IAVCEI 2017 Scientific Assembly, Portland, Oregon, USA*.
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11. Gomez CA and Tsunematsu K (2017). *Finite Element Modeling of Volcanic Ballistic Impacts in Soft Ash and on Buildings - a Hazard Approach.* Japan Geoscience Union Meeting 2017, Chiba, Japan.
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13. Matoza R, Jolly A, Fee D, Johnson R, Chouet B, Dawson P, Kilgour G, Christenson B, Garaebiti E, Iezzi A, Austin A, Kennedy B, Fitzgerald R, Key N (2017). *Seismo-acoustic wavefield of strombolian explosions at Yasur Volcano, Vanuatu using a broadband seismo-acoustic network, infrasound arrays, and infrasonic sensors on tethered balloons.* IAVCEI 2017 Scientific Assembly, Portland, Oregon, USA.
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List of key end users

GNS Science, Department of Conservation, Ruapehu Ski fields, Vanuatu Geohazards, Ngāti Tūwharetoa, Ngāti Rangi, Ngāti Hikairo, Auckland City council, DeVORA, White Island Tours, Ngāti Awa