Developing a suite of multi-hazard volcanic eruption scenarios using an interdisciplinary approach

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Abstract

Understanding future eruptions and their potential consequences is an important component of volcanic disaster risk reduction. Suites of scenarios are a useful compromise between fully probabilistic and fully deterministic (single scenario) approaches. In this paper, we present an interdisciplinary approach that combines stakeholder (volcanologists, disaster risk researchers, policy advisors, infrastructure managers, and emergency managers) requirements with fundamental science to produce multi-hazard eruption scenarios for a high-risk volcano. We apply this approach to the Auckland Volcanic Field (AVF) to develop a suite of scenarios ('*DEVORA Scenarios*') that cover the wide spectrum of credible expected eruption activity. Demand was driven by a desire from stakeholders for scenarios that are scientifically credible and relevant for disaster risk management purposes, including evacuation, welfare, recovery, and critical infrastructure disruption planning. Stakeholders were embedded throughout the scenario development process, most importantly at the scoping and design stage, and through multiple formal and informal review cycles. Balancing scientific credibility while ensuring the scenarios are relevant to stakeholders was a challenge that required considerable time by all parties. Importantly, the process of scenario development was just as useful as the final product: it facilitated open discourse on major scientific uncertainties and information gaps on AVF volcanism, hazards, and risk. This served two important ends: 1) it allowed scientists to communicate areas of uncertainty to other stakeholders such as emergency managers, and 2) it identified potential future research avenues with an obvious and tangible societal benefit. It is anticipated that the DEVORA Scenarios will serve as a foundation for studies exploring the societal ramifications of a future AVF eruption. The process we outline here can be followed to develop credible and relevant suites of eruption scenarios for disaster risk management purposes in other environments.

Keywords: Disaster risk reduction; stakeholder engagement; co-production of knowledge; event scenarios

1. Introduction

Preparing for, responding to, and managing the recovery following a volcanic eruption is filled with uncertain and dynamic challenges. Stakeholders must grapple with the inherent technical complexity of volcanism, the potential impacts on society (direct and indirect), the complex responses of society to those risks, the needs of affected communities, and more (Newhall 1982; Fiske 1984; Ronan et al. 2000; Fearnley 2013; Christie et al. 2015; Fearnley and Beaven 2018; Bretton et al. 2018a, b; Donovan 2019). Emergency managers, government officials, community planners, politicians, and community leaders, and other stakeholders rely on volcanic risk information that is salient, credible, and legitimate to inform management of the risks (Peterson 1988; Aspinall et al. 2003; Marzocchi et al. 2012; Donovan et al. 2012; Leonard et al. 2014; Aitsi-Selmi et al. 2016; Beaven et al. 2017; Doyle and Paton 2017; Fearnley and Beaven 2018). Scholarly work on the science-practice boundary defines these concepts: Credibility is whether information is perceived to meet the standards of scientific plausibility and is technically adequate; Salience is whether the information is relevant to end-user needs (i.e. does it answer their questions?); Legitimacy is whether the process that has been followed has produced information where all relevant parties have been included, is unbiased, transparent, and may have required compromise (Cash et al. 2002; Clark et al. 2016; Fearnley and Beaven 2018). Therefore, it is necessary that information be carefully developed and communicated to those that must make policy, organisational, or operational decisions (e.g. when, who, and where to evacuate) before, during, and after volcanic eruptions.

Scenario planning is recognised as one of the key approaches to integrating diverse information requirements for emergency response and recovery planning and preparation (Alexander 2000). Best practice scenario planning requires collaborative and interdisciplinary methods in order to integrate the diverse data types and methodological approaches (Bloom and Menefee 1994; Keough and Shanahan 2008). A collaborative and interdisciplinary approach facilitates dialogue between participants which builds institutional learning, improves decision-making processes, and identifies new or emerging challenges that may arise during a disaster response or recovery by integrating multiple mental models (van der Heijden 1997; Chermack 2004; Keough and Shanahan 2008; Moats et al. 2008; Clark et al. 2016; Sword-Daniels 2016). As a communication and collaborative research tool, scenarios and the scenario planning process help foster openness to different perspectives, and aid in understanding complexity (Chermack 2004; Doyle et al. 2011; Clark et al. 2016; Doyle and Paton 2017). From this perspective, scenario planning reduces the cost of knowledge transfer and allows for more effective and efficient decision-making (Chermack 2004). Thus, scenario planning is an effective device for considering the complex and dynamic risk environments volcanic eruptions present (Barclay et al. 2008; Hicks et al. 2014; Doyle et al. 2015). Eruption scenarios have previously been developed in a range of formats, such as event narratives (Johnston et al. 1997; Galderisi et al. 2011), scenarios of specific eruption phenomena (Macedonio et al. 2008), or integrated multi-hazard scenarios (Zuccaro et al. 2008). However, there are relatively few documented examples of interdisciplinary approaches for scenario development that incorporate diverse stakeholder requirements in volcanic risk environments (Hicks et al. 2014).

In this contribution we describe the interdisciplinary approach undertaken to construct a suite of multi-hazard volcanic eruption scenarios (‘*DEVORA Scenarios*’). We outline a process that focusses on using credible science and user requirements as equally critical and complementary components of the scenario development process. The objective of taking this approach to developing the DEVORA Scenarios was to ensure their utility in a variety of disaster risk reduction activities related to the Auckland Volcanic Field (AVF). The scenario development process was driven by stakeholder requirements (e.g., evacuation planning, economic loss modelling) to ensure the outputs were as useful and useable as possible. In the next section we provide a brief overview of our study area: Auckland, New Zealand. We then discuss the interdisciplinary approach undertaken to construct multi-hazard eruption scenarios, focussing on decisions that were made throughout the process and the rationale for making them, and stressing that this approach is transferable to other volcanic areas. Finally, we discuss the benefits and challenges associated with the approach taken in this study and areas that require further consideration.

2. Background: Auckland, New Zealand

2.1 Volcanology of the Auckland Volcanic Field

The city of Auckland, New Zealand, is built upon the Auckland Volcanic Field (AVF) (Figure 1). The AVF is a 360 km^2 intraplate volcanic field that has been active for approximately 200,000 years (Searle 1964; Kermode 1992; Allen and Smith 1994; Hayward et al. 2011; Runge et al. 2015; Leonard et al. 2017). Most of the 53 identified eruptions within the AVF have dense rock equivalent (DRE) volumes between 0.001 and 0.03 km^3; only two eruptions have eruptive volumes > 0.1 km^3 (Kereszturi et al. 2013; Leonard et al. 2017). The most recent, and largest (0.7 km^3 DRE), eruption within the AVF was ca. 550 yr. BP at Rangitoto Island (Needham et al. 2011; Kereszturi et al. 2013; Leonard et al. 2017). The geologic record indicates that AVF eruptions can be 'wet' (phreatomagmatic), 'dry' (magmatic), or both, and locally variable environmental conditions play an important role in their occurrence (Allen and Smith 1994; Agustín-Flores et al. 2014, 2015a; Kereszturi et al. 2014a). This has implications for the types of volcanic hazards that may occur during a future AVF eruption (Allen and Smith 1994; Németh et al. 2012; Kereszturi et al. 2014a). The location or general vicinity of the next AVF vent is unknown (Searle 1964; Bebbington and Cronin 2011; Leonard et al. 2017). Consequently, anywhere within the 360 km^2 area field is treated as a potential site for the next AVF eruption from a risk management perspective (Lindsay et al. 2010; Leonard et al. 2017). Thus, foreseeing and planning for the potential impacts from a future AVF eruption is complex.

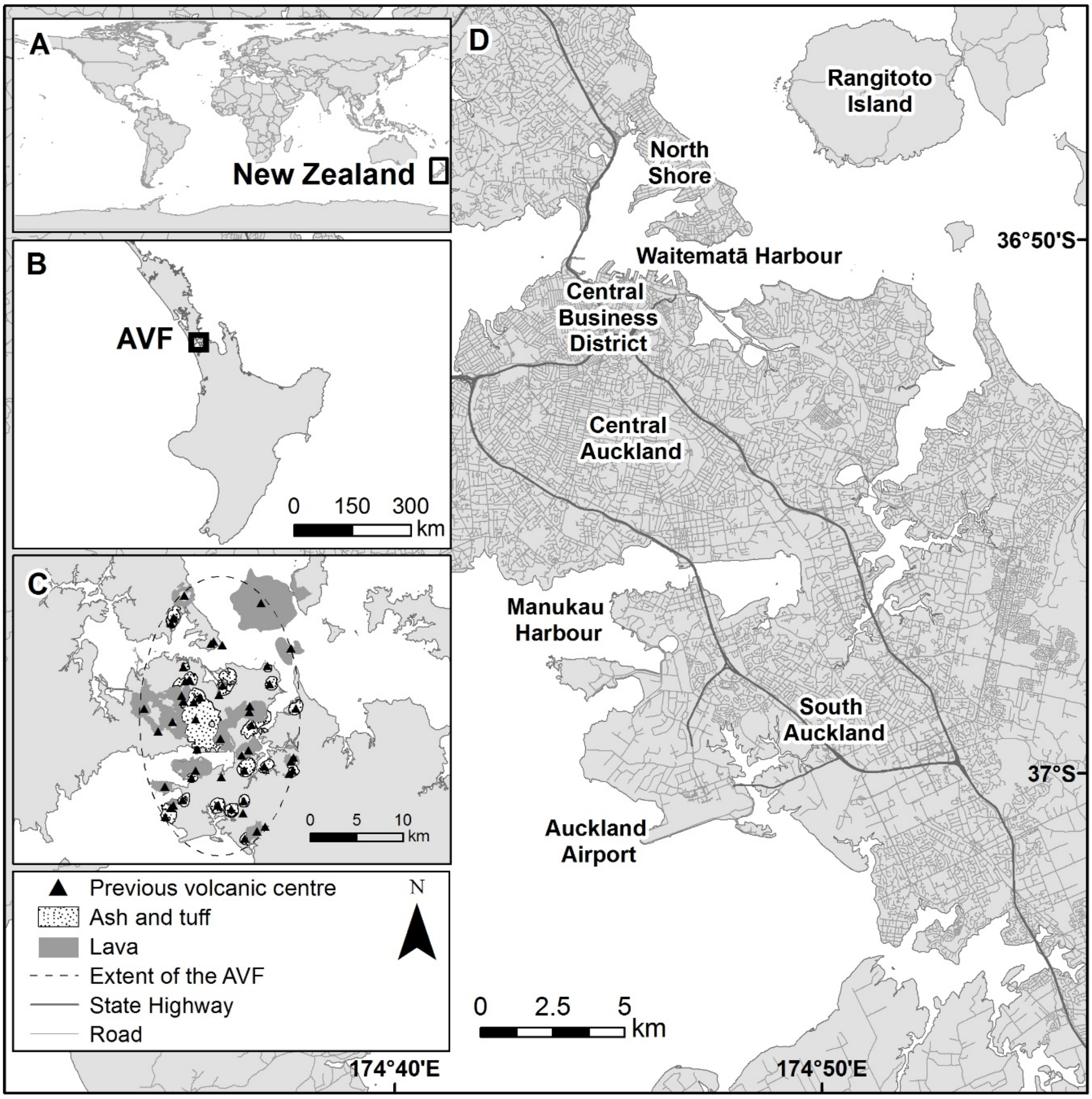

Figure 1: A) Location of New Zealand, B) Location of the Auckland and the AVF, C) Distribution of past volcanic centres, eruptive products, and approximate extent of the AVF (Kermode 1992; Hayward et al. 2011; Kereszturi et al. 2014a; Runge et al. 2015), D) Geographic locations within Auckland. Roads used as a proxy for population density.

2.2 Socio-economic background of Auckland, New Zealand

Auckland currently has a permanent population of 1.7 million (most within central Auckland: Figure 1d), approximately one third of the total New Zealand population. Population growth for 2017 was 2.6%, making it one of New Zealand's fastest growing population centres (Stats NZ Tatauranga Aotearoa 2017a). Auckland is a key economic centre, contributing 37.5% to New Zealand's Gross Domestic Product (GDP) (Stats NZ Tatauranga Aotearoa 2017b) and is the base for several facilities of national significance. For example, Auckland Airport, located in

South Auckland, has approximately 500,000 international passenger arrivals during each peak month (December and January), and 75% of the total international passenger arrivals into New Zealand enter the country through Auckland Airport (Auckland Airport 2018a, b). In 2017 alone, approximately 20.5 million passengers (international and domestic), NZ$6.8 billion of exports (~12% of total New Zealand exports), and NZ$11.8 billion of imports (~21% of total New Zealand imports) passed through the airport (Auckland Airport 2018a, b; Stats NZ Tatauranga Aotearoa 2018). Auckland seaport located in Waitematā Harbour had NZ$6 billion of exports (~11% of total New Zealand exports) and NZ$22.8 billion imports (~40% of total New Zealand imports) passed through it in 2017 (Stats NZ Tatauranga Aotearoa 2018). The national electricity grid goes through Auckland with limited redundancy. If electricity transmission is disrupted in Auckland, no electricity with be transmitted north of Auckland (Deligne et al. 2017a). Thus, disruption to Auckland's urban functionality can be nationally significant.

2.3 Managing and assessing volcanic risk in Auckland

Strong science-practitioner-policy relationships are critical for effective disaster risk governance (Paton et al. 1998), which is a key priority area of the Sendai Framework (UNISDR 2015; Aitsi-Selmi et al. 2016). There has been a strong emphasis from the entire New Zealand civil defence and emergency management sector to facilitate strong linkages between science, practice, and policy, and this has been acknowledged as one of New Zealand's strengths in its strategy towards disaster resilience (Ministry of Civil Defence and Emergency Management 2019). In part, this has been achieved through strategically developed research platforms and programmes, such as Determining Volcanic Risk in Auckland (DEVORA), that embed scientists, practitioners, and policy makers within the research and knowledge development process. As a result, these research programmes have fostered close stakeholder engagement and co-production as a key feature of attempting to ensure natural hazards and risk research in New Zealand is as relevant and legitimate as possible, as well as credible (Beaven et al. 2017; Thompson et al. 2017).

Given the high degree of risk associated with future AVF volcanism, there is demand from local and national emergency management officials for information products that can inform disaster risk reduction planning (Deligne et al. 2015a, b). Research studies, policy and practice documents and engagement activities have identified a range of information that stakeholders have requested, generally within the following categories: potential direct impacts (e.g., number of damaged buildings or evacuated people, infrastructure loss of service: Blake et al. 2017; Deligne et al. 2017b), potential indirect eruption impacts (e.g., national implications on the flow of imports and exports: McDonald et al. 2017), potential warning time (e.g., evacuation decision-making: Tomsen et al. 2014) and potential post-eruption environment (e.g., clean-up and recovery requirements: Johnston et al. 1997; Brunsdon and Park 2009; Lindsay et al. 2010; Blake et al. 2017; Deligne et al. 2017a; Hayes et al. 2017). This information provides useful awareness around the potential scale of disaster and context within which decisions will need to be made.

Scenarios are a proven method for deriving disaster risk information for AVF-specific disaster risk management planning (Brunsdon and Park 2009; Lindsay et al. 2010; Daly and Johnston 2015). In 1997, Johnston et al. (1997) developed a suite of mostly narrative scenarios of expected AVF volcanism for the Auckland Regional Council (ARC). This facilitated exploration of impacts, culminating in a risk assessment for Auckland critical infrastructure (Daly and Johnston 2015). The utilisation of scenarios has been a useful communication tool to envision the potential impacts from a future AVF eruption. In 2008, the transdisciplinary Determining Volcanic Risk in Auckland (DEVORA) research programme was established as a collective effort by Auckland Council (local/regional government body), the Earthquake Commission (national government insurance agency), GNS Science (national geological survey), numerous New Zealand-based universities, and other partner agencies to improve the understanding and assessment of volcanic hazard and risk in the Auckland metropolitan area from AVF and distal eruptions, and to provide a strategy and rationale for appropriate risk mitigation (Deligne et al. 2015a). This applied research programme has since promoted integrated multidisciplinary research from geological studies through to volcanic hazards, vulnerability, risk assessments, and development of risk reduction and resilience planning and practices. The close relationship between the science and practitioner communities has led to enhanced understanding of the information requirements of each group. There has been considerable demand from stakeholders for scenarios that can provide insights into issues such as potential infrastructure outages, expected economic losses, and evacuation decision-making (Deligne et al. 2017a; Blake et al. 2017). The Johnston et al. (1997) scenarios provided a useful starting point, but they do not contain the necessary spatio-temporal hazard footprint and hazard intensity information required by contemporary stakeholders. Further, there has been considerable knowledge gained from the DEVORA research programme allowing enhanced insights into the hazards and impacts of a future AVF eruption. Therefore, it was necessary to develop a new suite of scenarios that could meet stakeholder needs and incorporate new knowledge.

Following the Johnston et al. (1997) ARC AVF scenario suite, a scenario was developed for an all-of-government emergency management exercise called ‘Exercise Ruaumoko’, which was designed to test capacity responding to AVF unrest in the lead up to an eruption (Brunsdon and Park 2009; Lindsay et al. 2010). ‘Exercise Ruaumoko’ was subsequently used as a basis for an educational simulation and role-play tool to teach postgraduate students scientific and emergency management concepts (Dohaney et al. 2015; Fitzgerald et al. 2016). This scenario was further developed to explore the impacts of AVF volcanism on Auckland’s infrastructure (Deligne et al. 2015b). The Māngere Bridge has been used to explore impacts on critical infrastructure, mitigation and response requirements, and potential physical and economic losses in the AVF (Blake et al. 2017; Deligne et al. 2017a, b; Hayes et al. 2017; McDonald et al. 2017). However, a noted limitation from these works was the availability, and thus use, of only one eruption scenario. The geological record indicates that collectively, previous AVF eruptions exhibit a wide range of potential eruption dynamics (e.g., style, hazards, vent location, volume). Therefore, there was a need for the development of a more comprehensive suite of eruption scenarios representative of AVF volcanism.

3. Scenario planning and development

Due to different contextual environments (e.g. cultural norms, project objectives) there are a variety of models and variations on the scenario planning process (e.g. Schoemaker 1995; Schwartz 1996; Wilson and Ralston 2006; Avin 2007), but most have common elements (Keough and Shanahan 2008; Moats et al. 2008; Amer et al. 2013). Broadly, these elements include: 1) developing an environment conducive for scenario planning, 2) conducting analysis to build a picture of the scenario planning requirements, 3) creating scenarios, and 4) using the scenarios.

Developing an environment conducive for scenario planning includes consideration of issues such recognising the need for scenario planning, outlining project objectives and scope, and identifying relevant stakeholders (Keough and Shanahan 2008; Moats et al. 2008). Recognising the need for scenario planning requires an organisational culture that is conducive to the participatory requirements of scenario planning, but some organisations may not be well equipped to make use of scenario planning (Keough and Shanahan 2008). Determining project scope/objectives and identifying relevant stakeholders that must be included is critical to ensure that scenarios are useful for their intended purpose. Best practice suggests that teams should be made up of a wide variety of participants with differing intellectual and cultural backgrounds to ensure that the scenarios cover necessary breadth and detail (Schwartz 1996; Davies et al. 2005; Keough and Shanahan 2008).

A coherent picture of the scenario planning requirements must then be built. This requires: 1) collecting necessary data, 2) identifying and conducting detailed research on critical drivers and key issues, 3) analysing issues of uncertainty/variability and 4) obtaining an envelope of uncertainty that the scenarios must cover, which will inform how many scenarios must be developed. Once this information is obtained, creation of the scenarios can commence by the scenario building team (Keough and Shanahan 2008). The specific approach and tools used to develop the scenarios will depend on the context of the work being conducted (Bloom and Menefee 1994). Finally, the scenarios are then used to evaluate necessary planning requirements. This conceptual approach to scenario planning is used in this work to develop the DEVORA Scenarios.

3.1 Developing volcanic eruption scenarios for the AVF

Two basic principles underpinned our scenario development process: 1) using robust scientific evidence, and 2) ensuring streamlined compatibility with current and future applications (e.g., impact assessment). To adhere to these principles, we conducted an in-depth literature review of AVF research, and we sought regular input through formal consultation and informal meetings from diverse stakeholders throughout the scenario development process to help structure and inform key aspects of the scenarios (described in Section 3.1.4; Figure 2). Here, stakeholders were anyone involved with the scenario development process including: physical volcanologists, geophysicists, geochemists, disaster risk researchers, policy advisors, geotechnical engineers, infrastructure managers, and emergency management officials. Stakeholders were all actively involved with the DEVORA research programme, which allowed us to draw upon existing relationships to facilitate engagement during the scenario development process. During the meetings it became clear that emergency management stakeholders were primarily concerned with likely societal impacts and potential management requirements rather than the intricacies of the volcanic activity. Practitioner and policy experts' specific interests were diverse but focused much on ensuring information was relevant, including: how long it would take to evacuate different sectors of the city, how to manage re-entry into evacuated areas, and what the post-eruption environment would look like (e.g., damage, economic losses). In contrast, the volcanologists were concerned that scenarios be scientifically credible, accurately reflecting the future potential eruptive behaviour of the AVF, and that they managed uncertainty through use of appropriate analogues, geological information, and expert judgement. This classic risk assessment stakeholder tension led us to conclude that undertaking the collaborative process would be important to facilitate understanding between each group.

In the following sections we outline the approach taken to develop the DEVORA Scenarios.

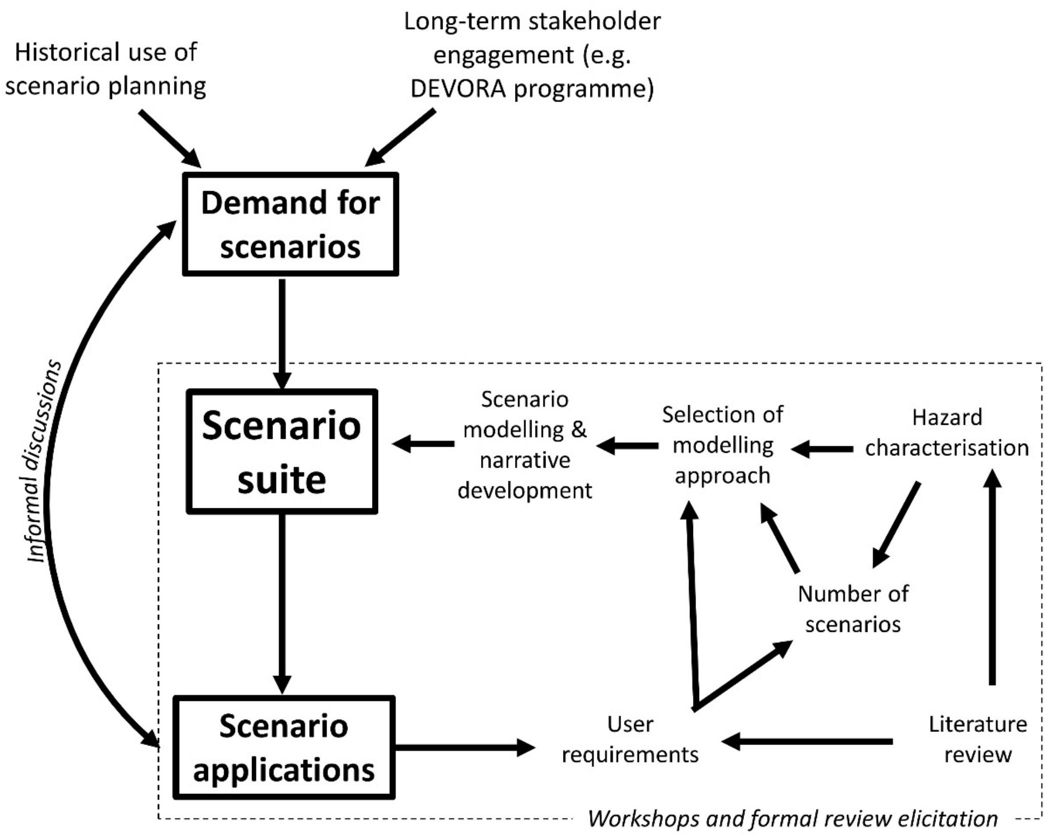

Figure 2: The DEVORA Scenarios development process.

3.1.1 Format of the scenarios

Volcanic impacts are rarely static in space and time. Volcanic processes can produce a variety of hazardous phenomena at different times before, during, and after an eruption. Responding organisations and communities can undertake measures before, during, or after an eruption that reduce or exacerbate the resulting impacts (Tilling 1989; Horwell and Baxter 2006; Wilson et al. 2012; Pierson et al. 2014; Hayes et al. 2015). For eruption scenarios to be able to convey realistic impacts, it is necessary to consider the time and space variations in the hazardous phenomena (Zuccaro and De Gregorio 2013). To do so, eruption scenarios must be time-sequenced with evolving activity as the scenario unfolds, as opposed to a cumulative snapshot of the final distribution of volcanic hazards. Therefore, the DEVORA Scenarios were produced to be time-sequenced as this allows for future analysis of evolving impacts through each scenario.

Due to the importance of spatio-temporal sequencing, and in consultation with stakeholders, we decided that the most flexible approach would be to develop a collection of shapefiles of each hazard that occurs through the eruption sequence, as this would allow future researchers to assess the cascading impacts that would occur from the eruption scenarios. Qualitative narratives that broadly describe the major events of the eruption scenario would accompany the shapefiles. The qualitative narrative was for communication purposes to allow those utilising the scenarios to understand the major events that were occurring in the eruption scenarios.

3.1.2 Number of scenarios

Agreeing on the number of scenarios to develop is an important part of the scenario development process as it contributes to the balance between credibility, salience, and legitimacy. A single scenario is simpler to communicate, but it will come at the expense of legitimacy: It may present a biased indication of volcanism, due to not incorporating potential uncertainty, and/or if some viewpoints are not incorporated into the scenarios (e.g., Girod et al. 2009). However, it is impractical to consider every different combination of events that could occur in the future. A large number of scenarios is also likely to come at the expense of relevance to stakeholders as they will take a substantial amount of time to develop and too much choice can be overwhelming (Girod et al. 2009). Thus, it is necessary to strike a balance between incorporating variety into the scenario suite (to serve the needs of end-users) and not developing too many scenarios.

Our intention was to cover a number of scenarios that would present the most representative variety of potential societal impacts from AVF volcanism, rather than fully categorise all potential dynamics of future AVF eruptions. We considered that focussing on the potential variety of societal impacts would provide scenarios that were relevant and legitimate to stakeholders, whilst still being flexible enough to include the necessary complexity to maintain credibility. The AVF can produce phreatomagmatic, magmatic explosive, and magmatic effusive styles of eruption (Allen and Smith 1994), and the eruption style is greatly influenced by local environmental conditions (Kereszturi et al. 2014a). Each style produces multiple hazardous phenomena, which in turn produce different societal impacts. For example, a fine coating of volcanic tephra or lava on the same road necessitates different mitigation and management requirements. In addition, eruptions within the AVF span several orders of magnitude in erupted volume, which likely affects the duration and intensity of resultant volcanic hazards (Searle 1964; Kermode 1992; Allen and Smith 1994; Kereszturi et al. 2013, 2014a). Therefore, to produce a credible representation of AVF volcanism it was necessary to develop a suite of different multi-hazard eruption scenarios in a variety of locations throughout the AVF.

To manage the balance required, we held a brainstorming meeting in 2014 involving volcanology and volcanic impact researchers. This initial brainstorming meeting was attended by only researchers to allow for a consistent project to be presented to additional stakeholders for their consideration and feedback. At this meeting it was concluded that vent location would likely be a major influence on the type of volcanism and the resulting societal consequences, particularly at locations where strategically important infrastructure nodes were located. Scenario vent location, therefore, was an important consideration when deciding on the number of scenarios. For practical purposes, vent opening location probability is considered uniform across the AVF (Sandri et al. 2012; Le Corvec et al. 2013). Given that there was no evidence to suggest a precise location of the next AVF eruption, geological considerations and locations thought to be of strategic importance for Auckland's urban functionality were used to justify scenario locations. The criteria we used to determine locations for the DEVORA Scenarios were:

- each location must fall within the Runge et al. (2015) "tight" elliptical AVF boundary;
- the locations must be geographical spread across Auckland;
- the locations collectively must allow for the exploration of different eruption styles and hazards likely in a future AVF eruption;
- the locations collectively must allow for the exploration of impacts to different exposed assets; and
- scenario vents are not at the site of a known existing AVF vent.

To facilitate legitimacy in the selection of vent locations, the precise location of each scenario was determined by the group of researchers through discussion and consensus. Through the ensuing discussion we settled on the location of eight scenarios[1] that would cover the requirements listed above (Figure 3; Table 1). Although an argument could be made for additional scenarios with vents occurring in alternative locations, we felt that these eight locations would provide sufficient diversity and indication of the spectrum of impacts whilst minimising overlap between scenarios and the potential to overwhelm stakeholders.

[1] Note: Scenario C: Māngere Bridge was developed earlier than the other seven scenarios, and as a result its vent location was chosen following a slightly different approach (see Fitzgerald et al. 2016; Deligne et al. 2017a; Table 1).

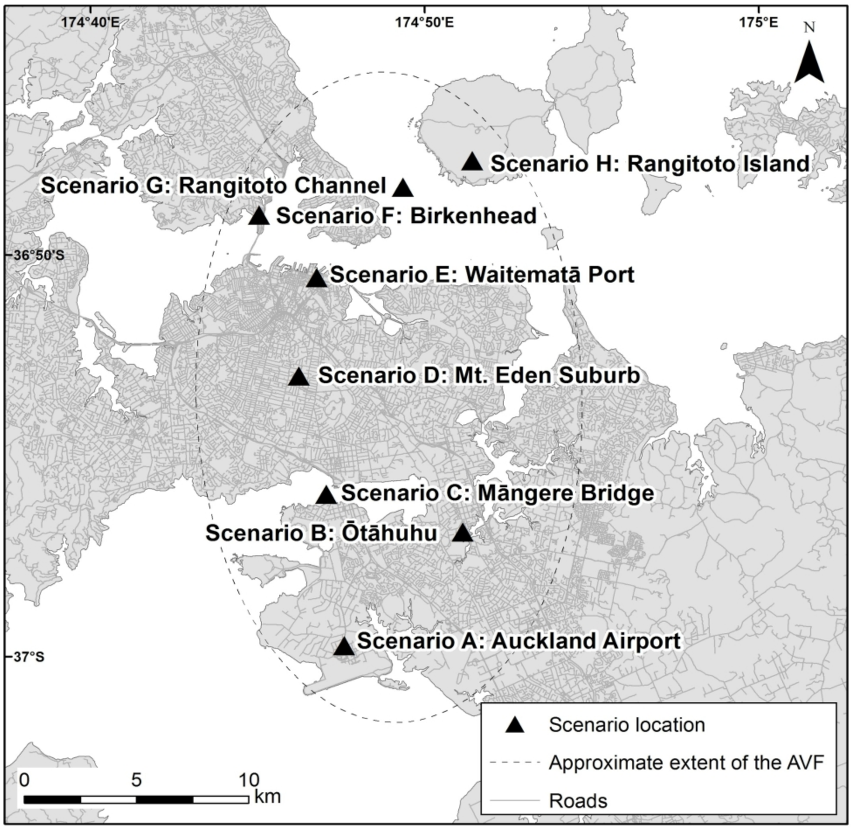

Figure 3: Locations and names of the DEVORA Scenarios. Roads included as a proxy for population density. AVF extent from Runge et al. (2015).

Table 1: The DEVORA Scenarios and reasons for selecting them.

Scenario name	Reasoning
Scenario A: Auckland Airport	● Proximity to Auckland Airport (nationally significant infrastructure) ● Environmental conditions conducive to phreatomagmatic eruptive activity (Kereszturi et al. 2014a, 2017).
Scenario B: Ōtāhuhu	● Proximity to an area with a high density of critical infrastructure ● Environmental conditions conducive to phreatomagmatic activity but could also allow for transition to magmatic eruptive activity (Kereszturi et al. 2014a, 2017).
Scenario C: Māngere Bridge	● Exercise Ruaumoko eruption location. This was a highly socialised scenario location because it was used for an all-of-nation civil defence exercise (Lindsay et al. 2010). Criteria given to 'the volcano' in 2008 (Deligne et al. 2015b): ● Eruption should start in shallow water to consider range of possible eruption types. ● Eruption site should be in an area of mixed socioeconomic groups; ● Eruption site could not force closure of State Highway 1 nor Northwestern Motorway given expected response actions.
Scenario D: Mt. Eden Suburb	● Eruption site likely to result in largest evacuation population. ● Eruption site located in a residential area. ● Environmental conditions conducive to magmatic eruption styles (Kereszturi et al. 2014a, 2017).
Scenario E: Waitematā Port	● Proximity to Waitematā Port operations. ● Environmental conditions conducive to phreatomagmatic eruptive activity (Kereszturi et al. 2014a, 2017).
Scenario F: Birkenhead	● Proximity to Auckland Harbour Bridge. ● On the North Shore. ● Environmental conditions conducive to hybrid eruption style (Kereszturi et al. 2014a, 2017).
Scenario G: Rangitoto Channel	● Proximity to shipping channel. ● Environmental conditions most likely to allow for Surtseyan style eruptive activity (Agustín-Flores et al. 2015b).
Scenario H: Rangitoto Island	● Proximity to most recent site of an AVF eruption, potentially important to consider event clustering. ● Environmental conditions conducive to hybrid eruption style (Kereszturi et al. 2014a, 2017).

In addition to varying the vent location, we also varied other components in the scenarios that would likely exert a substantial control on the societal impacts:

- Volcanic eruption styles and hazards.
- Duration of volcanic unrest activity.
- Duration of volcanic eruption sequence.
- Volume of erupted deposits.
- Hazard modelling parameters.

3.1.3 Scenario modelling

Scenario modelling (i.e. natural process, hazard and impact) is a fundamental aspect of scenario development as it facilitates transparency. Scenario modelling requires identification of appropriate modelling approaches and their respective information requirements, data gathering, and application. We present the steps undertaken for modelling the DEVORA Scenarios in the subsections below.

3.1.3.1 Step 1: Reviewing data availability

There is no historical or instrumental information on unrest or eruption in the AVF. The most recent AVF eruption predates the written historical record and instrumental measurements in New Zealand (Needham et al. 2011). Although Māori (indigenous people of New Zealand) would likely have witnessed the eruption, no known oral histories have been shared that refer to this event (Lowe et al. 2002). Therefore, we were reliant upon local geological information and international analogues to develop the DEVORA Scenarios.

3.1.3.2 Step 2: Reviewing the expected range of volcanic activity

In addition to vent location, there are four aspects of volcanism we considered important to characterise to ensure that diverse impacts would manifest in the scenario suite: 1) eruption styles and hazards, 2) precursory activity, 3) eruption duration, and 4) bulk erupted volume. Each of these aspects were reviewed for the AVF and relevant analogous eruptions from around the world. An overview of our analysis and how this information informed the scenario development is presented below.

3.1.3.2.1 Eruption styles and hazards

We used geological studies to inform the eruption styles and hazards and analogue eruptions for modelling parameters and unobservable aspects of the scenarios (e.g., unrest activity). The conceptual framework for how volcanic hazards were considered in scenario development is presented in Figure 4. The following criteria was used to define the eruption styles and hazards for the DEVORA Scenarios:

- Since >80 % of AVF eruptions have evidence of phreatomagmatic phases, six of the eight DEVORA scenarios include a phreatomagmatic phase.
- One scenario has no phreatomagmatic phase and is located in an area of low phreatomagmatic susceptibility based on Figure 10 of Kereszturi et al. (2014a).
- At least one scenario only displays phreatomagmatic activity and is located in an area of relatively high phreatomagmatic susceptibility based on Figure 10 of Kereszturi et al. (2014a).
- At least one scenario begins magmatic before transitioning to phreatomagmatic.
- For completeness, there is one Surtseyan eruption and this is located in an area of similar environmental conditions as the Surtseyan North Head eruption, as described by Agustín-Flores et al. (2015b).

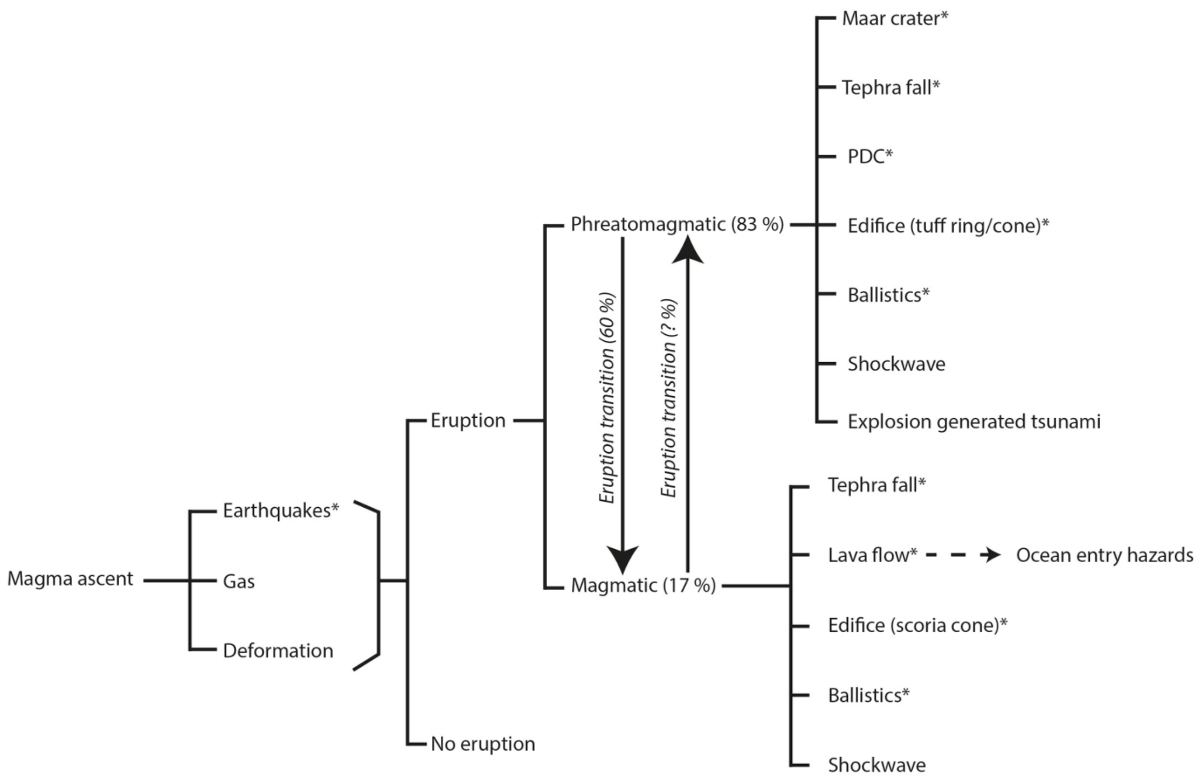

Figure 4: Conceptual diagram of the AVF eruption hazardscape (Allen and Smith 1994; De Lange and Healy 2001; Magill and Blong 2005; Hayward et al. 2011). Note: * indicates hazards that have been considered in the DEVORA Scenarios.

3.1.3.2.2 Detection of volcanic unrest

Knowing when a volcano may erupt and characterising volcanic unrest is a key part of volcanic hazard mitigation, as that information can give authorities time to implement contingency plans (Tilling 1989; Newhall and Punongbayan 1996). In areas of distributed volcanism there is an additional component to this as it is also necessary to know where an eruption may occur, which means identifying unrest is even more critical to managing risk. Magma ascent at volcanoes can be detected by changes in three indicator types of precursory activity: seismicity, deformation, and volcanic gas emissions (Sparks et al. 2012). There is very little record of these phenomena within the geologic record, and so there is a heavy reliance on the instrumental record or analogues. Thus, identifying the potential characteristics of each, and local capacity to monitor each, is an important element to consider in scenario development.

Seismology is one of the most useful tools for monitoring volcanoes because of the high incidence of seismic activity associated with volcanic eruptions (Pallister and McNutt 2015). It is expected that seismic precursory activity currently provides the best basis for detecting magma ascent in the AVF (Sherburn et al. 2007; Lindsay et al. 2010). GeoNet's seismic network automatically locates seismic activity that triggers at least 10 seismic stations, whilst gas and deformation detection require human oversight (Ashenden et al. 2011; Miller and Jolly 2014; Deligne et al. 2019). However, we acknowledge that interpretation of earthquake locations in a volcanological sense also requires considerable human oversight. Thus, for the purposes of the DEVORA Scenarios effort was focussed on developing credible and detectable seismic unrest sequences. The DEVORA Scenarios did not feature tectonic swarms unrelated to volcanic processes (these have not happened in Auckland in the instrumental record). They also do not include unrest sequences that do not result in an eruption, although any of the scenario unrest phases could be used for this purpose.

Ascent of magma (from ~80-100 km depth: Horspool et al. 2006) to the surface in the AVF is likely to be relatively quick (0.01–6 m s^{-1}), suggesting possible ascent durations from source to surface of four hours to 116 days (Blake et al. 2006; Sherburn et al. 2007; Brenna et al.

2018). Assuming a constant ascent rate and first detection at 30 ±10 km depth (assumed point where earthquakes become detectable: Sherburn et al. 2007) gives potential warning times of one hour to 46 days. Ascent rate from the source to the surface is unlikely to be constant, and so the lead time is likely to lie between these values.

The following criteria were used to develop unrest sequences:

- Detected earthquakes occur at ≤ 30 ±10 km depth that become shallower over time.
- At least one scenario includes multiple intrusions that fail to reach the surface, resulting in a long-lasting but sporadic period of unrest. The purpose of this is to reflect the limited knowledge regarding precursory activity within the AVF.
- Unrest scenarios should fit within the maximum/minimum bounds established in the literature for similar volcanoes.

3.1.3.2.3 Eruption duration

The duration of a volcanic eruption is important to consider as it can affect the duration of evacuation/exclusion zones that are in effect, infrastructure outages, and response and recovery decision-making. However, the duration of volcanic eruptions can vary considerably (Siebert et al. 2015). As the exploration of temporal components of AVF volcanic eruptions was a key requirement of the scenarios, a range of potential eruption durations for AVF volcanism were considered. We wanted scenarios occurring at different times of the year so that different wind fields would occur and so that different seasonal impacts could be explored in the future. It is difficult to predict the duration of eruptions, and a global review of all types of volcanism found that the duration can vary from less than one day to centuries (Siebert et al. 2015). To maintain transparency in the scenario development process, we used estimated volumes of previous AVF eruptions and approximate eruption rates from analogue eruptions to estimate potential eruption durations. Durations of eruptions comparable to those likely in the AVF yields average eruption rates across the entire eruption of 1 - 20 $m^3 s^{-1}$ (Machado et al. 1962; Thorarinsson et al. 1973; Scandone 1979; Self et al. 1980; Luhr et al. 1993; Blake et al. 2006; Kereszturi et al. 2013; Schipper et al. 2015). As our intention was for variety, we selected eruption rates within this range would produce a variety of eruption durations from a few days up to one year. The exception to this eruption rate is Scenario C: Māngere Bridge, which included an exceptionally fast outpouring of lava towards the end of the scenario.

3.1.3.2.4 Bulk erupted volume

Eruption volumes allow for the quantification of different hazardous eruptive processes (e.g., lava flows and tephra fall). Bulk eruption volume directly represents the volume of material at Earth's surface, including pore space, meaning that it is a more useful measure of volume for our scenario development than dense rock equivalent (DRE).

Kereszturi et al. (2013)'s comprehensive estimate of minimum volumes of preserved AVF eruption products (excluding medial to distal tephra) was used to constrain the bulk erupted volumes used in the DEVORA Scenarios. Kereszturi et al. (2013) reported bulk eruptive volumes of between $3x10^{-4}$ km^3 (Ash Hill) and 1.1 km^3 (Rangitoto), with a median of $1x10^{-2}$ km^3. However, eruption dynamics are important to consider, as eruptions with a single phreatomagmatic phase have smaller bulk erupted volumes than those with both phreatomagmatic and magmatic phases (Kereszturi et al. 2014a). The omission of medial to distal tephra in the Kereszturi et al. (2013) volume estimates may lead to considerable underestimation of eruptive volumes, as more recent studies indicate medial to distal tephra could be a sizable contribution (Hopkins et al. 2017; Slabbert 2017).

To constrain the bulk erupted volumes for the DEVORA Scenarios, the following criteria were used:

- Bulk eruptive volume should allow for a variety of eruptive hazards and hazard intensities to be produced across the entire scenario suite.
- One eruption with a bulk erupted volume at the lower end of the range estimated for the AVF should be included.

- An eruption with >1 km^3 bulk erupted volume should not be included because this is likely to be a relatively long-lived eruption (e.g., Rangitoto), which we deliberately exclude from this iteration of the scenarios.

3.1.3.3 Step 3: Scenario storyboard narratives

One of the considerations for the scenarios developed in this work was to include time-sequenced events throughout each scenario (scenario narratives), as they are a common requirement of emergency managers (Alexander 2000; Moats et al. 2008; Doyle et al. 2015). This is because narratives are considered an effective communication device as they increase comprehension, interest, and engagement in science from non-experts (Dahlstrom 2014). We used bullet pointed descriptions of events through each eruption scenario to construct scenario narratives. We first focussed on describing major events in the scenarios, such as the start and end of major eruptive phases, and used this to guide detailed mapping of eruptive phenomena using analytical, empirical, or conceptual models.

3.1.3.4 Step 4: Spatio-temporal hazard modelling

To appropriately characterise and model volcanic hazards for use in impact and risk assessments, it is necessary to have a sound understanding of appropriate hazard intensity metrics that are likely to be used. This was done by reviewing existing vulnerability/fragility functions and impact models to identify the required outputs from the hazard assessment. To ensure scenarios could be developed in a reasonable timeframe we used existing information, rather than develop new analytical models. Thus, we decided to characterise eruption hazards into three categories based on existing capabilities to model each hazard and obtain useful hazard intensity metrics:

1. Hazards for which the spatial variation of hazard intensity is an important variable in determining impact
2. Hazards that will potentially exhibit mostly a binary relationship between hazard and impact (i.e. hazard exposure = complete destruction).

3. Hazards that we acknowledge have the potential to occur during a future AVF eruption, but there is a lack of resources to accurately model and/or there is very little information of how impacts relate to the hazard.

For hazards that fall within category one (Table 2), available impact models and fragility functions were reviewed to determine the most appropriate hazard intensity metrics to use (Jenkins et al. 2014; Wilson et al. 2014). The required hazard intensity metrics were then an important consideration when deciding on the analytical or empirical model(s) that would be used to model the hazard. Hazard models were excluded if they did not provide outputs in the form of the required hazard intensity metrics. When selecting models, we opted for those that were simple to implement computationally and did not require considerable customisation for them to work in the AVF. For category two hazards, the spatial extent would be a sufficient measure of hazard for our purposes, meaning that we focussed on characterising only the footprint of these hazards. For these hazards we focussed on hazard characterisation of AVF phenomena (e.g. spatial footprint of cones). For category three hazards, it was not possible to model the hazard. In these instances, qualitative descriptions were made, but we endeavoured to keep descriptions broad, such that if capacity to model the hazard becomes available in the future, they can seamlessly be added into the DEVORA Scenarios.

Table 2: Expected AVF hazards, the approach taken to characterise the hazards, and the scenarios each hazard appears in

Expected AVF hazards	Hazard characterisation used in DEVORA Scenarios	Approach used to model	Information used for modelling	Scenarios hazard appears in
Tephra fall	Category 1: Deposit loading (kN m^{-2}) and thickness (mm).	Tephra2 (Bonadonna et al. 2014).	Eruption parameters and climatological information.	A, B, C, D, E, F, G, H.
PDC	Category 1: Deposit thickness (mm) and PDC dynamic pressure (kPa).	Energy cone (Palma 2013) and empirical relationships based on Brand et al. (2014).	Eruption parameters, Digital Elevation Model (DEM).	A, B, C, E, F, G, H.
Ballistics	Category 1: Impact energy (Joules).	Ballista (Tsunematsu et al. 2016).	Eruption parameters.	A, B, D, E, F, G, H.
Earthquakes	Category 1: Magnitude, depth, and horizontal location	Expert judgement.	Likely earthquake magnitudes, ascent rates, and detection depth.	A, B, C, D, E, F, G, H.
Tuff ring	Category 2: Binary impact.	Empirical relationships.	Systematic collection of tuff ring morphometry in study area (Allen and Smith 1994; Kereszturi et al. 2013).	A, B, C, E, F, H.
Maar crater	Category 2: Binary impact.	Empirical relationships.	Systematic collection of maar crater morphometry in study area (Allen and Smith 1994; Kereszturi et al. 2013).	A, B, C, E, F, H.
Volcanic cone (scoria, tuff)	Category 2: Binary impact.	Empirical relationships.	Systematic collection of cone morphometry in study area (Allen and Smith 1994; Kereszturi et al. 2013).	B, C, D, F, G, H.
Lava flow	Category 2: Binary impact.	Expert judgement.	Systematic collection of lava volume (Kereszturi et al. 2013), DEM.	B, C, D, F, G.
Volcanic gas	Category 3: Not	Not modelled -	N/A.	Qualitative

emission	modelled - expected future development.	expected future development.		description only in scenarios.
Lava ocean entry hazards (e.g., vaze, littoral explosions, lava front collapse causing large waves)	Category 3: Not modelled - potential future development.	Not modelled - potential future development.	N/A.	Qualitative description only H. Small tsunami described in C.
Shockwave	Category 3: not modelled - potential future development.	Not modelled - potential future development.	N/A.	Does not feature in any scenario.
Explosion-initiated tsunami	Category 3: Not modelled - potential future development.	Not modelled - potential future development.	N/A.	Not included in the scenario suite.

As it was our objective to produce multi-hazard scenarios, it was necessary to consider the effects each hazard might have on other hazardous processes. However, existing 'out of the box' hazard models often only represent a single eruption hazard (e.g., just tephra fall). Thus, it can be difficult to integrate a variety of volcanic hazard models to ensure the collective outputs make logical sense. Thus, throughout the modelling process the implications that each model output would have on other elements of the scenario had to be considered. For example, our approach to lava flow modelling relied upon topography, which could potentially change during an eruption through the construction of an edifice and/or development of a maar crater. To overcome this, time-sequenced maps were constructed that displayed the eruptive products and features of the eruption scenario to inform where lava would possibly flow. Therefore, lava flow modelling had to be undertaken following modelling of all other processes at each time step.

One particularly unique feature of the AVF is the existence of a major urban development built upon it. This yields the question of whether the built environment could influence the spatial variability of hazards and their intensities (e.g., PDC, lava flow: Kereszturi et al. 2014b; Charbonnier et al. 2018; Tsang et al. in review). Some authors have highlighted this possibility for PDC (Gurioli et al. 2007; Zanella et al. 2007; Doronzo and Dellino 2011, 2014; Jenkins et al. 2013; Charbonnier et al. 2018). However, as yet, there is no known tool calibrated for the AVF, and very little practical advice available on how such modelling could be conducted. Therefore, we chose to ignore such effects, acknowledging it as a limitation to the approach taken.

3.1.3.5 Step 5: Development of scenario narratives

Scenario narratives in many disciplines are useful for analysing impact, vulnerability, and risk, and communicating complex processes that are representative of potential hazardous events (Ghanadan and Koomey 2005; Hallegatte 2009; Rounsevell and Metzger 2010; Kriegler et al. 2012; Birkmann et al. 2015). From this perspective, the scenario narratives were written to be representative of the eruption scenario. The intention here was not for high precision and detailed rationale for each event that happens in a given scenario, but rather a written qualitative description of relevant physical processes that were occurring. Scenario narratives were presented in conjunction with cumulative eruptive product maps that provided a visual aid as to where different eruptive products were spatially located at specific moments throughout the scenario timeline. Cumulative eruptive product maps were produced by spatial modelling of different volcanic processes.

3.1.4 Scenario review process

Our two main criteria for the DEVORA Scenarios were that the scenarios be scientifically credible and usable. Therefore, to ensure that both of these criteria were met, we undertook regular review throughout the scenario development process, outlined in the subsections below.

3.1.4.1 Workshop of draft scenarios

A workshop in November 2016 guided the development of an early draft of the eruption scenarios. This workshop included 23 participates made up of volcanologists, disaster risk researchers, policy advisors, geotechnical engineers, and emergency management hazard, risk, and resilience advisors. The workshop helped refine scenario requirements to ensure they would meet stakeholder needs and to maintain scientific credibility of the scenarios. Workshop participants were placed into seven groups that included at least one volcanologist, one risk specialist, and one emergency management official. Each group were given material related to one of the scenarios, excluding Scenario C: Māngere Bridge as this scenario was already complete by this point (Deligne et al. 2017a). Participants worked together to answer a variety of questions on their assigned scenario. Questions related to the types of eruptive phenomena that occurred during the scenario and whether the scenario would likely yield useful insights for volcanic impact assessments. Next, a discussion involving all workshop participants facilitated by JLH explored ways the scenarios could be improved. The discussion considered likelihood of eruption type and hazards for each scenario, incorporation of uncertainty associated with seismic unrest (e.g., credible detection depth and magnitude), credible worst-case eruption durations for the AVF and potential lulls in activity, increased transparency on selection of eruption parameters, and the potential for eruption style transitions and how they would manifest. The final stage of the workshop allowed all participants to add any additional comments to any of the other scenarios using post-it notes. A major point that emerged from the workshop included a desire from workshop attendees for more variability between scenarios, particularly for precursory seismic unrest so that the scenarios could be used to test evacuation decision-making. There was also considerable discussion around future research requirements to be able to build on the scenarios in the future. For example, there was discussion of the available hazard models for different volcanic hazards, their limitations for use in the AVF, and the need to further develop modelling capabilities for some volcanic hazards, particularly PDC and lava flow.

3.1.4.2 Informal meetings

Throughout the scenario development process there were meetings with stakeholders likely to utilise the scenarios. These included Auckland Emergency Management officials and researchers from disciplines such as transport engineering, land use planning, and economic loss modelling. The purpose of these meetings was to expedite collaboration and to ensure that the scenarios being developed would be useful for a variety of applications. Specific feedback on the scenarios during these meetings was not actively sought, but conversations covered limitations of the science behind the scenarios and the intended timeframes of work. Despite the informal nature of these meetings, they were integral to socialising the scenarios beyond the volcanic hazard community and ensuring wide stakeholder buy-in.

3.1.4.3 Formal review elicitation

Due to the many components in a credible multi-hazard volcanic eruption scenario, no single individual had expertise spanning the full range of the DEVORA eruption scenarios. Thus, all researchers affiliated with DEVORA (past and present) were invited to review the scenarios or the parts of the scenarios that fell within their area of expertise. To ensure that reasonable assumptions and appropriate past work were considered in the development of the DEVORA Scenarios, we particularly sought out those that had expertise across the following key areas:

- Monogenetic volcanic processes
- AVF geophysics
- AVF volcanic hazards
- AVF geochemistry

We undertook two rounds of the review. The first round was open to all members of the DEVORA community, and the second round was open to those who had provided reviews in the first round. The scenarios were then revised for a final time to reflect feedback received from the detailed review process and published in a scientific report (Hayes et al. 2018).

4. The DEVORA Scenarios

The DEVORA Scenarios have been comprehensively outlined in a technical report (Hayes et al. 2018), which included rationale, modelling, assumptions, scenario narratives at a daily to monthly breakdown, and eruptive products maps for each scenario. Scenario C: Māngere Bridge was developed at an earlier stage relative to the other seven scenarios and is discussed elsewhere (Deligne et al. 2015b, 2017a; Fitzgerald et al. 2016). The DEVORA Scenarios have associated shapefiles for each hazardous process that was modelled and are time-sequenced. An overview of the eruptive products produced during each scenario is presented in Figure 5 (proximal eruptive products) and Figure 6 (extent of tephra distribution in Auckland). The DEVORA Scenarios also involved a variety of different eruptive styles and occur over different periods of the year (Figure 7).

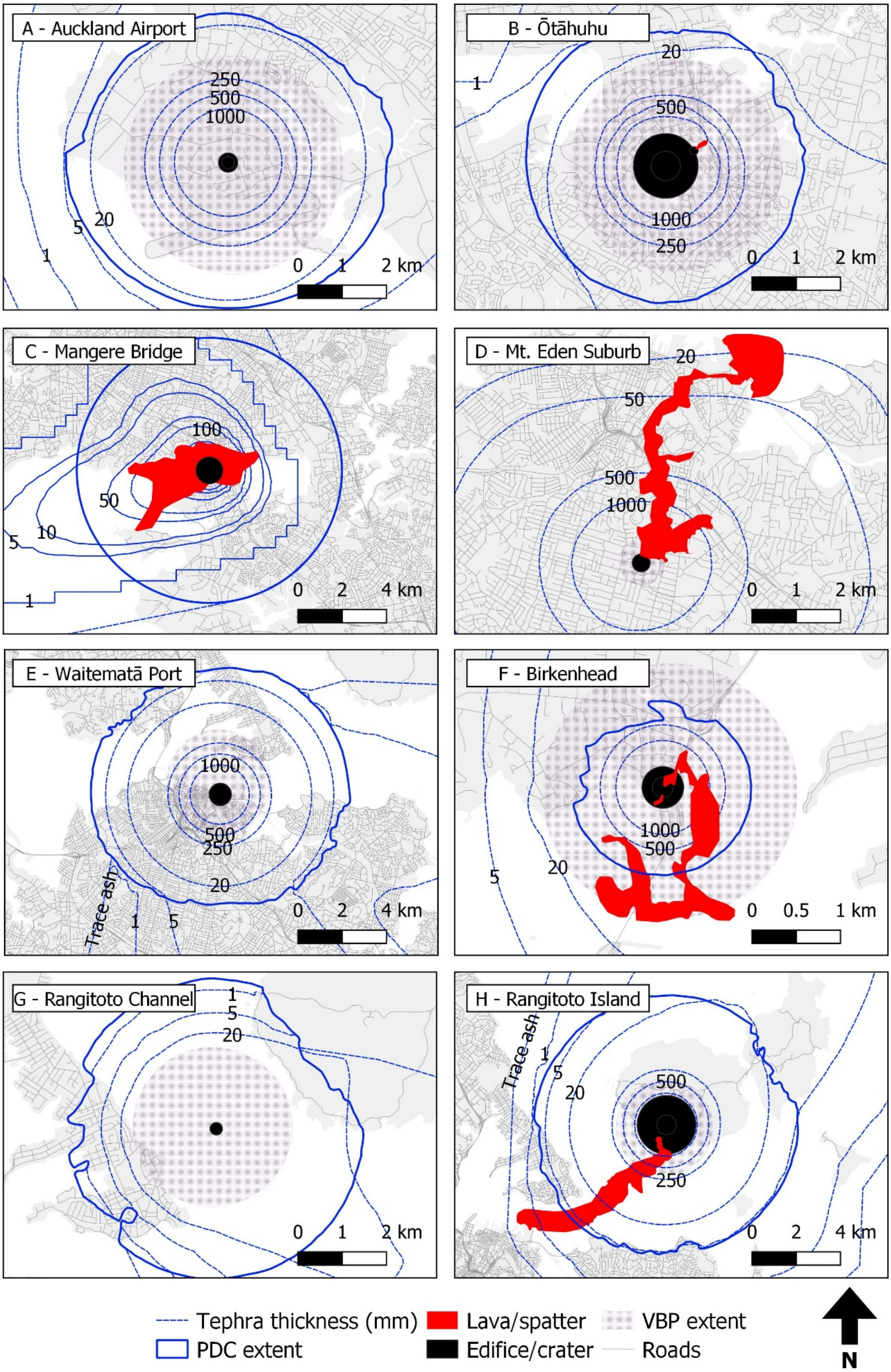

Figure 5: Cumulative proximal deposits of each scenario at the end of the eruption. Note: Scenario C is based on different modelling parameters from the rest of the scenarios (Deligne et al. 2015b, 2017a).

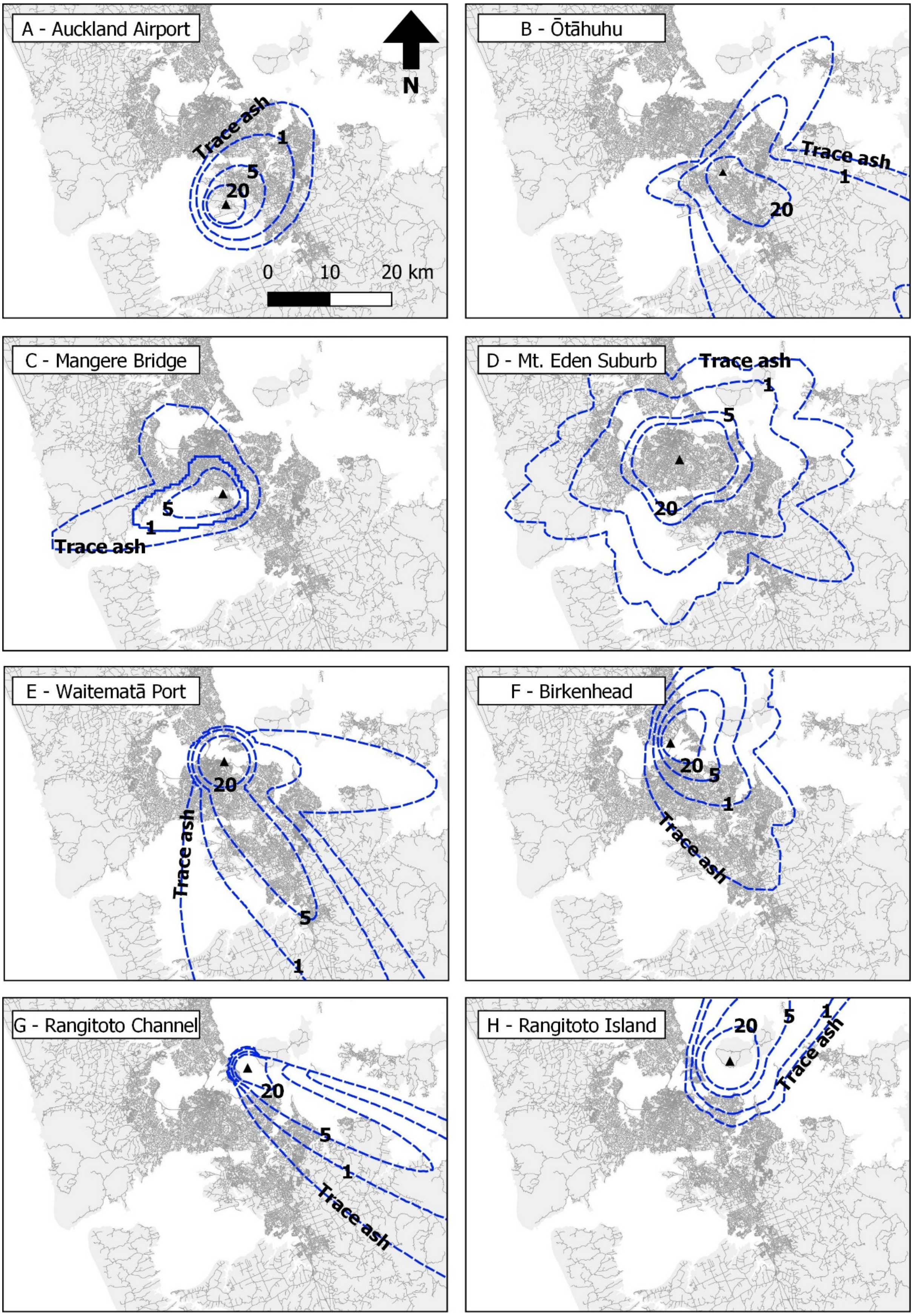

Figure 6: Cumulative distal tephra fall of each scenario at the end of the eruption. Black triangle indicates location of vent.

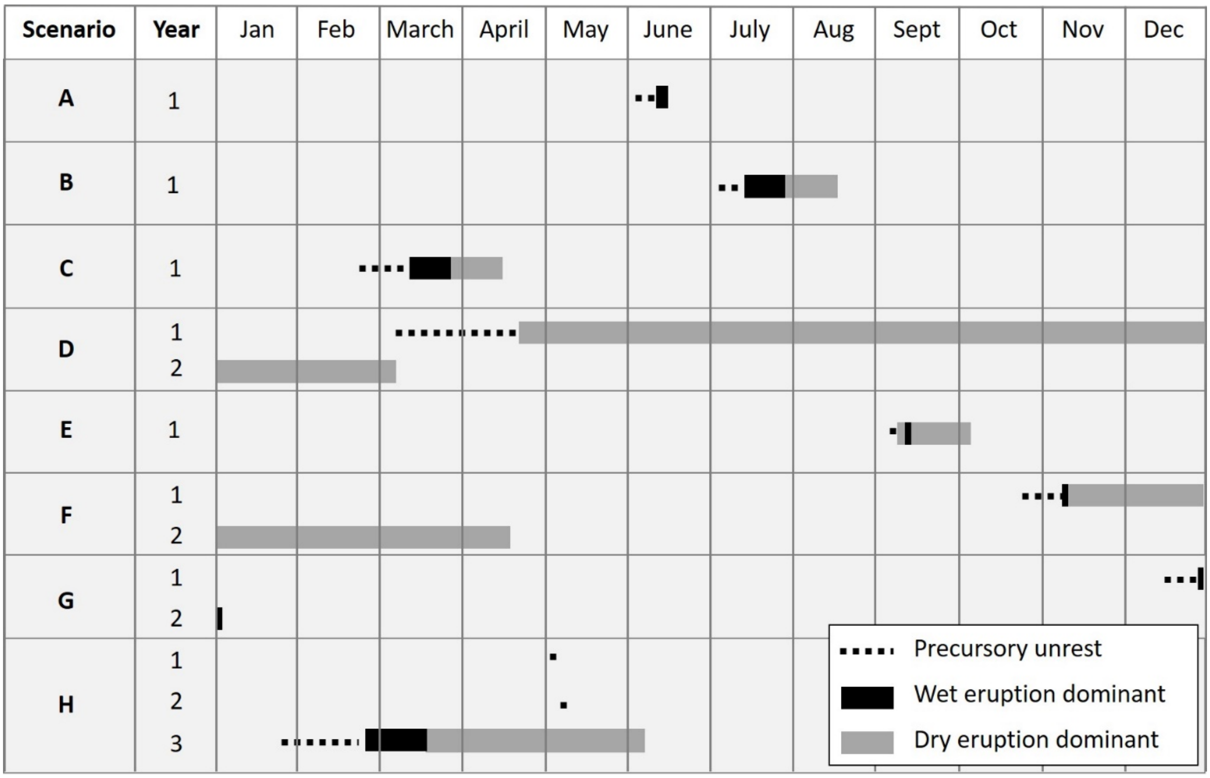

Figure 7: Timeline of each DEVORA scenario.

The detected unrest durations for the DEVORA eruption scenarios fall within 4–660 days (Figure 7). All unrest durations fit within the estimated range for detected magma ascent estimated for in the AVF, except for Scenario H: Rangitoto Island, which was developed to include multiple intrusions and thus a long, but sporadic, lead-in time. Eruption durations used in the DEVORA Scenarios suite are 4-320 days (Figure 8); these exclude the time required for lava to cool down, a potentially important consideration for physical land recovery. The range of bulk erupted volumes across the DEVORA Scenarios is $1.2x10^{-2}$ (Scenario E: Waitematā Port) to $1.9x10^{-1}$ km^3 (Scenario H: Rangitoto Island) (Figure 8A). Different eruption products also have different bulk erupted volumes, indicative of the influence of different eruptive products through the scenario suite (Figure 8B).

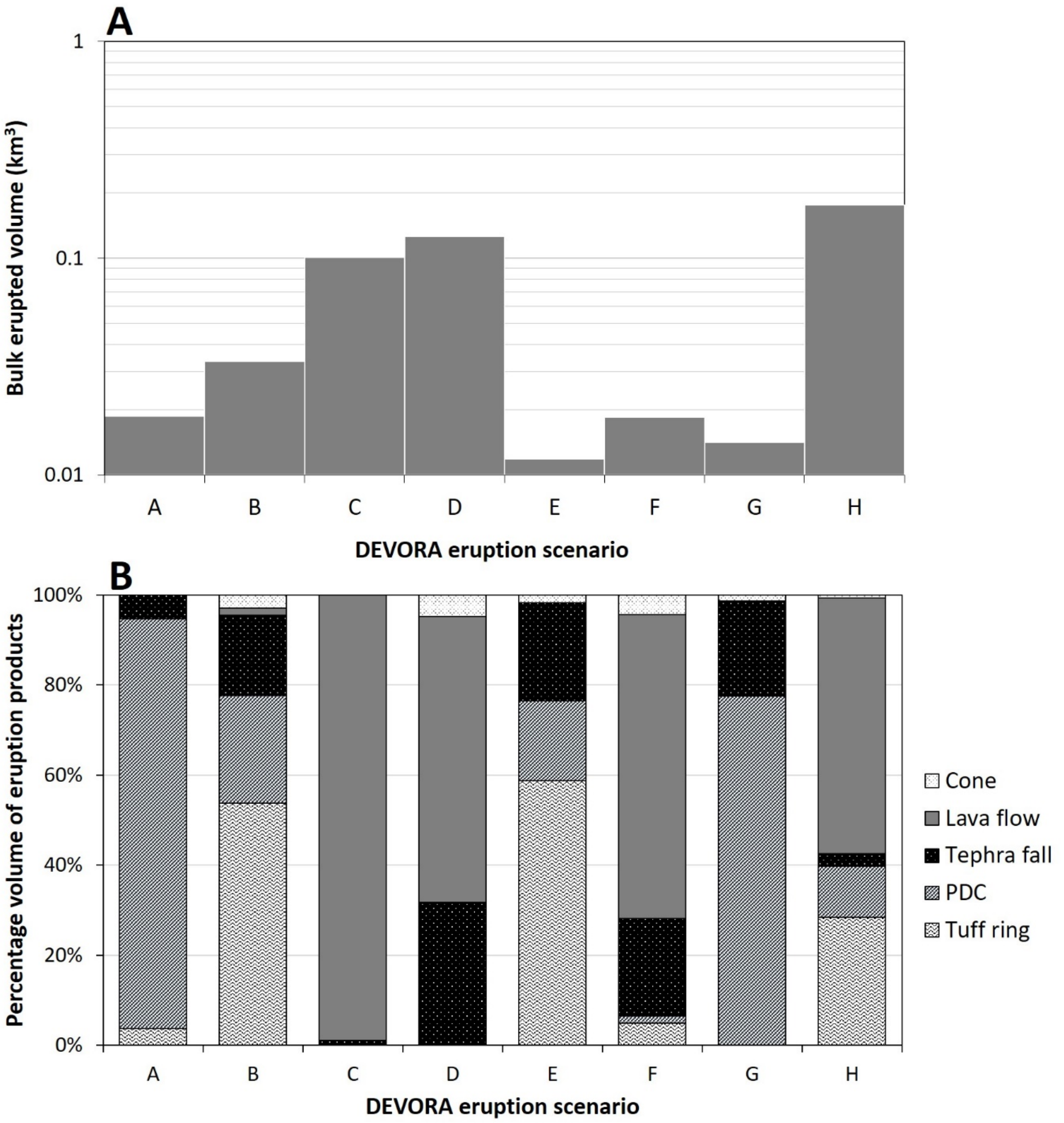

Figure 8: A) Bulk erupted volume and B) relative proportion of different eruptive products of each of the DEVORA Scenarios

5. Discussion

5.1 Benefits of including stakeholder engagement in volcanic eruption scenario development

A key objective of this work was to develop a suite of multi-hazard eruption scenarios that integrates multiple stakeholder requirements to meet a variety of disaster risk reduction applications (e.g. impact/risk analysis, emergency management training, and public communication). Knowledge transfer literature indicates that there are three primary requirements that must be balanced for information to be useful for stakeholders: credibility, salience, and legitimacy (Cash and Clark 2001; Guston 2001; Cash et al. 2002, 2003; Cash and Buizer 2005; McNie 2007; Sarkki et al. 2014). Here, credibility means that the information meets accepted standards and uses appropriate methodological approaches (Cash and Clark 2001). The approach used in this work was successful at establishing credibility of the scenarios by working with and consulting people with expertise across all elements of AVF volcanism, including actively seeking out thought leaders across key domains (e.g. physical volcanology, geochemistry, geophysics). This was effective at ensuring that appropriate literature was consulted, methodologies were sound, and assumptions were reasonable, which was important due to the inherent complexity involved in integrating information from different volcanology domains.

Salience means that the information developed can help answer the questions and needs of stakeholders. For information to be relevant to stakeholder needs it must accomplish two objectives: 1) the content must be appropriate for its intended use, and 2) the information must be provided in a timely manner so that it can be acted upon. Critical to both of these objectives is creating an environment that is conducive for developing shared understanding between different stakeholder groups. This is because what might appear to be relevant information to one group (e.g. scientists), may not appear to be relevant to another group (e.g. decision-makers) and vice versa (Cash et al. 2002). We hope our approach was successful at obtaining relevance by embedding end-users into the scenario development process to ensure they were useful and useable. Also, they were produced as part of DEVORA, a long-standing transdisciplinary research programme that strongly integrates stakeholder perspectives into the strategic research direction of the programme (Deligne et al. 2015a). At the time of writing, the scenarios are being actively used by emergency management, infrastructure managers and other hazard and risk researchers. We also acknowledge the long history of the use of scenario planning for assessing volcanic risk in Auckland (Daly and Johnston 2015). This legacy and the long-standing relationships were able to be leveraged both formally and informally. Through engagement at workshops, stakeholders such as risk scientists, policy advisors, and emergency management officials were able to discuss their wants and needs directly with those with expertise in volcanology and volcanic impacts. This was important for three reasons: 1) it allowed for pragmatic solutions to be identified for complex scientific problems, 2) it provided scientists with information about the desires of stakeholders, which provides a pathway for scientists to identify strategic future research directions, and 3) it gave stakeholders an appreciation for the technical limitations of existing research and knowledge regarding the AVF, which was important for their understanding of likely scientific limitations during a future volcanic crisis.

Legitimacy is the perception that: 1) those that produce the work are perceived to be free of bias and inclusive, 2) transparent processes have been undertaken to produce the information and 3) mutual trust and respect exists between the producer(s) and user(s) of the information (Cash et al. 2003; McNie 2007). Legitimacy can be challenged if key stakeholders are excluded from contributing to the process (Cash et al. 2002). We hope were able to achieve at least some legitimacy by taking an open and collaborative approach, which has created useful, useable, and used scenarios.

Each component of information usability (credibility, salience, and legitimacy) requires careful balancing. While tempting to continually push for greater and greater credibility, this can also come at the expense of salience and/or legitimacy. For example, the creation of new modelling approaches that are highly customised to the AVF may increase the credibility of some of the scenario outputs. Unfortunately, this may take considerable time and money to complete, which may mean that planning cycles that other stakeholders and end-users must adhere to are surpassed and the information is no longer remains actionable. It is important to note this is not to downplay the importance of credibility, but rather that pragmatism and compromise may be necessary to ensure that information is actionable within a reasonable timeframe.

Similarly, including non-traditional stakeholders within the knowledge development process may lead to some viewing this as reducing the credibility of a research output (Thompson et al. 2017). However, excluding them from the process entirely can mean the work loses legitimacy from the perspective of non-traditional stakeholders. Balancing each of these considerations is challenging and is often a source of tension in interdisciplinary projects (Linnerooth-Bayer et al. 2016; Scolobig et al. 2016).

5.2 Limitations and future research

5.2.1 Testing sensitivity of scenario choices

The objective of this work was to develop scenarios that could be used to identify important planning issues, but not to predict or forecast the next eruption within the AVF. In fact, it is almost certain that the next eruption within the AVF will not be in the location and/or follow the narrative of one of the scenarios produced within this work. Thus, there is a question of how sensitive the resulting scenarios, their impacts, and the necessary contingency planning considerations are to choices made in this work (e.g. vent location, hazard model choice, eruption parameters). When constructing the DEVORA Scenarios we emphasised elements that would likely considerably influence the resulting impacts that will occur from a future AVF eruption (vent location, eruption volume, eruption duration, seismic unrest, eruption style) in an effort to capture both a variety of eruptive phenomena and likely major impacts to urban Auckland under the assumption that these would cover most of the necessary contingency planning requirements. However, for a more comprehensive analysis of volcanic hazard and risk, it will be useful to explore how these choices influence variability in societal impacts from an AVF eruption. The next step, which aims to consider some of these issues, will be to develop scenario ensembles, which will simulate the scenarios on a grid across Auckland and assign a conditional and relative probability to each scenario (supplementary material 1). The vision is to have a ready to use rapid impact assessment tool with a pre-run library of impact scenarios that could be utilised during a future eruption crisis as well as to explore long-term pre-event policy decisions (e.g., how long-term changes in land use will influence expected losses).

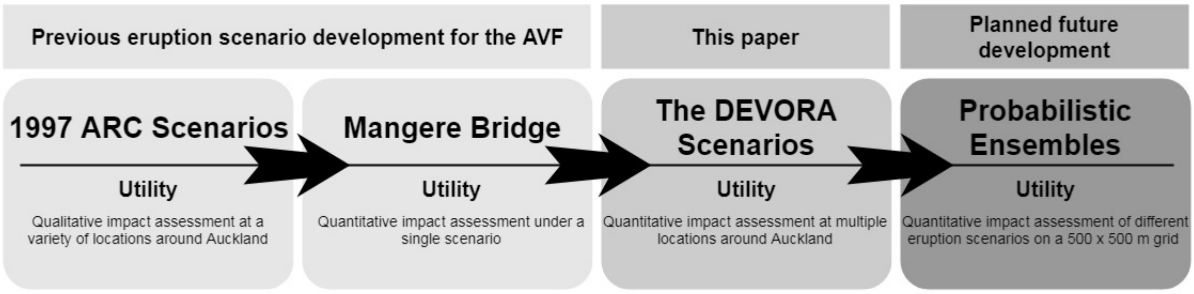

Figure 9: Past, present, and future DEVORA AVF scenario development.

5.2.2 Multi-hazard scenario planning and development

Volcanic eruptions can affect society through multiple interacting hazards (Neri et al. 2013; Hutchison et al. 2016; Zuccaro et al. 2018). This can occur where different volcanic hazards affect different parts of a volcanic region, multiple hazards affect the same part of a community, and/or multiple hazards affect a community through time. Therefore, it is important to consider the implications of these interactions as they may result in a greater severity to society than their individual parts might suggest (Kappes et al. 2012). For example, earthquakes associated with precursory volcanic activity may damage buildings, consequently increasing their vulnerability of collapse when tephra is deposited on their roofs later during an eruption (Zuccaro and De Gregorio 2013). This presents a challenge regarding robustly modelling these interactions. In the AVF, there are several different volcanic hazards that can occur throughout an eruption sequence. It was difficult to model such phenomena in the AVF, particularly because hazard models often do not have capacity to consider potential interactions between all of these different volcanic hazards and it was not within our scope to develop such models. Thus, we were reliant upon expert judgement to consider hazard interactions and cascades. Event trees have been used to develop structured and probabilistic hazard assessments (Newhall and Hoblitt 2001; Neri et al. 2008; Lindsay et al. 2010), but each volcanic hazard is still often treated separately from one another, which limits capacity to explore complex evolution of volcanism through an eruptive sequence. This may not cause too many practical problems in some volcanic environments (e.g. where risk is dominated by a single volcanic hazard) or for some volcanic risk applications (e.g. maximum extent of PDC runout for evacuation purposes). However, in the AVF such considerations are likely to be important to consider as their interactions may considerably influence the resulting impacts to society. Thus, to build upon this work, we suggest development of more formalised assessment frameworks for considering multi-volcanic hazard environments (ideally incorporating probabilistic methods) to produce scenarios like this would be advantageous to enhance transparency within the approach.

5.2.3 Issues for consideration when adapting this approach for other volcanic settings

Applying this approach in other volcanic settings may call for some adjustments to the approach presented here. The DEVORA Scenarios were produced in a setting that has a relatively high degree of geological information to draw from, but no historical or instrumental records. This meant we also had to rely heavily on analogue eruptions. If we had written records or indigenous knowledge of a past eruption, we would very likely have looked to develop this as a scenario. Although it is extremely unlikely a future eruption would repeat the events of a previous eruption, using a highly socialised eruption scenario would serve as a useful communication device to explain expected phenomena. After all, the utility of a scenario is to envision, anticipate, communicate, and train for potential issues that may arise in a disaster and not a rigid prediction (Alexander 2015). Utilising oral tradition and indigenous knowledge would also serve as a valuable co-design and engagement process that would allow two-way knowledge transfer (King et al. 2007; Becker et al. 2008; Cronin and Cashman 2008; Mercer et al. 2012; Hiwasaki et al. 2014).

Our scenario development process reinforced the following lessons:

- It is important to identify key stakeholders early in the scenario development process. This can be achieved by exploring links within existing volcano scientific advisory groups.
- It is important to first establish the key issues that need to be addressed. Naturally, this requires bringing together key stakeholders to identify major issues. We utilised a brainstorming session with key researchers, and then we confirmed the decisions with additional stakeholders through a formalised workshop and informal meetings. It is necessary that the issues are broad and challenge existing assumptions to ensure that important aspects are not being overlooked.
- Terminology is a commonly cited challenge associated with conducting interdisciplinary research and it can be easy to become distracted debating terminology, which presents a risk to the project outcomes (Golde and Gallagher 1999; Jakobsen et al. 2004; Davidson 2015; Thompson et al. 2017; Hardy 2018). An example from our experience is that “geophysical” had different meanings to different disciplines and individuals. We opted to utilise a shared meanings approach (Doyle et al. 2017; Hardy 2018). The shared meanings approach advocates for acceptance of different disciplinary approaches. In a practical sense, this required co-writing of the written report on the scenarios, where stakeholders could have input into the writing and state areas that were confusing or highlight terminology that they did not understand. We also developed a glossary of technical terms to provide clarity regarding how we were using each term.
- Establishing ‘buy-in’ from stakeholders (including scientistis) to the process is important to ensure that stakeholders have confidence in the work, and that their time and expertise will be appropriately utilised (Davies et al. 2015; Johnson 2019). This can be facilitated by utilising existing and long-term relationships built through regular engagement. Regular events (e.g., annual forums and workshops) and collaboration with researchers in other research programmes was a beneficial element to ensuring

engagement amongst stakeholders. A second useful factor was leveraging and adapting an already well socialised piece of work. In our situation, we built upon the existing national disaster simulation scenario ‘Exercise Ruaumoko’, with which many stakeholders were familiar and could see the potential benefits of additional scenarios for disaster risk reduction purposes. In other words, the development of the Scenario C: Māngere Bridge provided insights to the utility of such scenarios and drove demand for an entire suite of scenarios. Thus, where possible, leverage existing institutions, entities, and/or previous work.

- An important consideration is that the scenario development process can represent an ‘end’ of the knowledge development process for some stakeholders (e.g., physical scientists) and the ‘beginning’ for others (e.g., impact researchers, emergency managers). Incorrect interpretations, misunderstandings, and intellectual property issues are abundant when conducting interdisciplinary research (Golde and Gallagher 1999; Davidson 2015; Hardy 2018). Thus, a delicate balancing act was required that promoted the timely completion of the DEVORA Scenarios for user uptake (ensuring relevance) and paying due respect to the substantial knowledge development that had been conducted by previous researchers (ensuring credibility and legitimacy). By opening up the scenario review process to all DEVORA-affiliated researchers (past and present), we gave scientific researchers the opportunity to showcase how their research was being utilised, and to confirm suitable application (ensuring legitimacy). This helped clarify misunderstandings and incorrect interpretations and enhanced the legitimacy of the scenarios amongst stakeholders.

6. Conclusions

We have presented an overview of our interdisciplinary approach to developing a suite of eruption scenarios for the AVF. The DEVORA Scenarios cover a credible range of erupted volumes, durations, detected unrest durations, hazards, and potential volcanic centre locations. We anticipate they will serve as the basis for future studies assessing a range of impacts to Auckland's urban functionality, and will facilitate discussions about the potential disaster risk reduction requirements in the event of a reactivation of eruptive activity within the AVF. It is highly unlikely that one of the scenarios developed in this work will be the next eruption within the AVF. However, forecasting the next event is not the intention of a scenario planning process. It is instead to use the scenario planning process as a unifying link between the typical domain of scientists and decision-makers. Our approach required utilising a variety of scientific disciplines to underpin evidence used throughout the scenario development process. The DEVORA Scenarios development process was driven by a strong interest from stakeholders on the potential variety of impacts from future volcanism in the AVF, and engagement with stakeholders was an important part of the scenario development process along with underpinning scientific evidence. The interdisciplinary approach ensured the scenarios were scientifically credible, relevant to all stakeholders, and legitimised within the DEVORA research community of practice. The end product was a suite of eruption scenarios that will serve the community for years to come, but equally important as the final product was undertaking the process, and learning the needs and limitations of all stakeholders. Although the approach undertaken in this work involved development of an interdisciplinary framework for producing a suite of eruption scenarios in areas where future volcanism is widely distributed and highly uncertain (e.g., volcanic fields and calderas), much of the interdisciplinary approach is transferrable to any volcanic setting.

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Supplementary Material 1

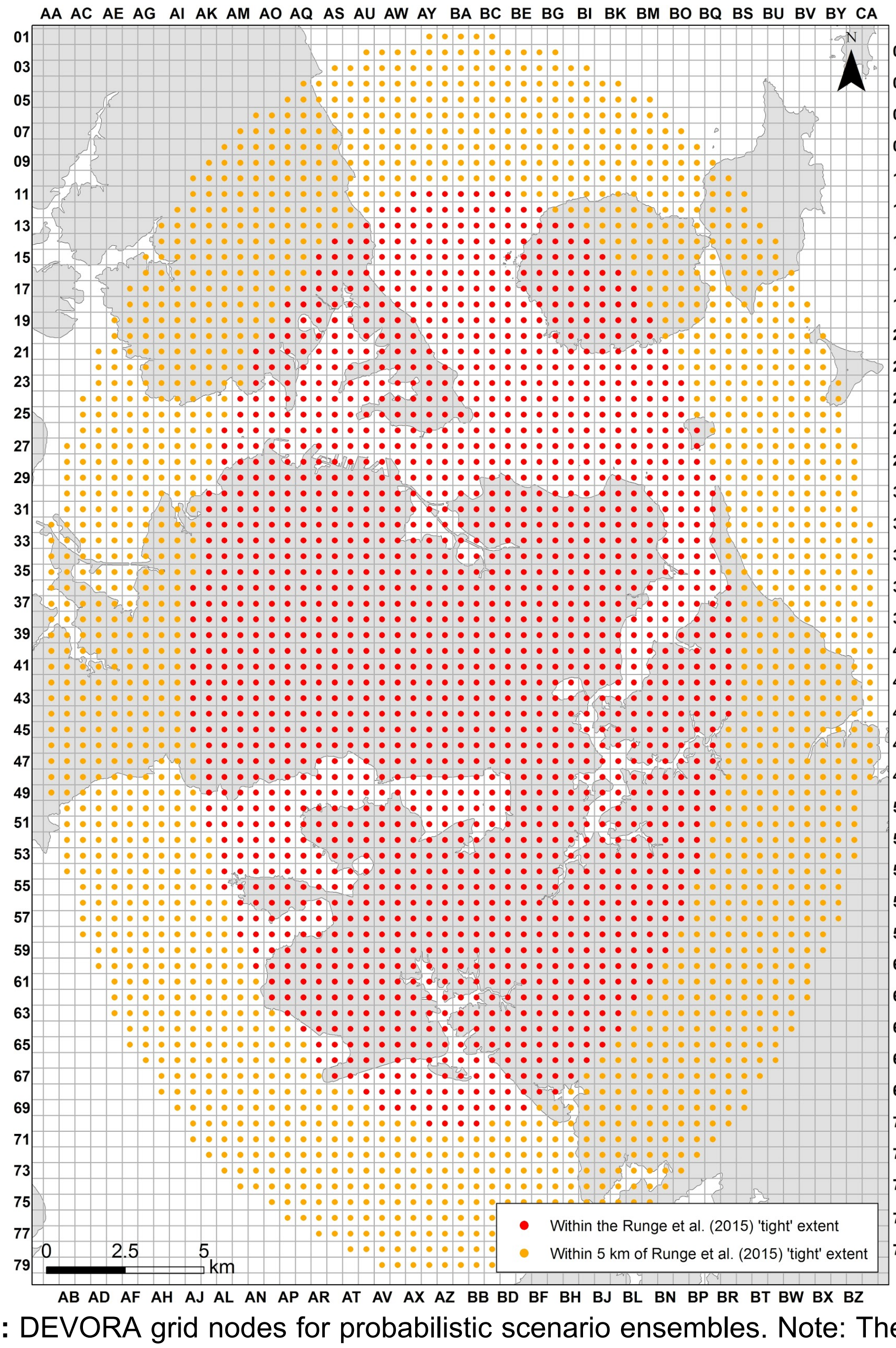

Figure S1: DEVORA grid nodes for probabilistic scenario ensembles. Note: The area within 5 km beyond the Runge et al. (2015) extent indicates a qualitatively less likely area of future vent emergence that cannot be ruled out.

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