Proposal overview

Proposal information

Investment area: 2019 Endeavour Fund - Research Programmes

Contracting organisation: University of Auckland

New Zealand Business Number (NZBN):
9429041925300

Registration number:

Year 1 funding requested:

$2,735,357.00 GST excl. amount	$410,303.55 GST amount	$3,145,660.55 Total amount

Total funding requested:

$13,676,785.00 GST excl. amount	$2,051,517.75 GST amount	$15,728,302.75 Total amount

Title:
Transitioning Taranaki to a Volcanic Future

Investment mechanism:
Research Programmes

Number of years' funding requested:
5

Fund objective:

- (•) Economic
- ( ) Environmental
- ( ) Social

General signals

High potential impact in areas of future value, growth or critical need for New Zealand

Leverage wider investment and knowledge in New Zealand and overseas

Gives effect to Vision Mātauranga

Take account of broader Government policy and strategy documents

Future growth or critical needs

Creating & growing knowledge-intensive industries

Supporting the transition to a low-emissions economy

Explain this selection (200 words)

The government has a strategic priority to identify risks to NZ's intergenerational wellbeing, with natural disasters indicated as among the most important to financial/physical/human capitals. Our proposed research will build the knowledge and tools to support NZ to adapt and transform to such threats, including an inevitable long-term eruption of Mt. Taranaki (50% chance/next 50 years) presenting wide risks to the central-upper North Island. In line with the draft National Disaster Resilience Strategy, we focus not only on active management for specific risks/assets, but also on generic resilience adaptations. The project also draws heavily on Mātauranga Māori, recognising that in the face of disruption, robust business and community decisions require partnerships and collaboration, and can draw on whakaoranga processes. The government is also committed towards regional development and the draft tourism strategy recognises opportunities afforded by Māori culture and provision of unique visitor experiences. In Taranaki, with recent settlements and investment priorities signalled around mountain tourism, there is now a priority-need to build volcanic/risk capabilities and inform the region's strategic vision. We will lever international knowledge and practice through comparative studies in Italy, Indonesia, Mexico and the USA, where communities are similarly preparing for, or living through long-term volcanic disruption.

Impact category

Protect & Add Value

Explain this alignment (200 words)

New Zealand's risk management and resilience-building practices have been strongly shaped by a paradigm of static hazards and disaster cycles that are sequential and orderly (i.e. planning/risk reduction-event-response-recovery). Our project will force a radical re-think of this approach. We tackle not only a dynamically evolving hazard, where data captured during an unfolding event will trigger new risk conclusions, but also eruption episodes that are potentially decadal or longer, with elements of the disaster cycle becoming disordered and merged. In the Taranaki situation the regional economy, and those downwind in a fallout zone from Auckland to the Central North Island, will face daily-weekly disruptions of transport and energy sectors, poisoning of waterways, drinking water and pasture/crops, along with fatigue and fear. *W*e will protect economic growth by providing the tools and capabilities for sectors (including in agriculture, tourism and infrastructure) and governance practices to transition in this context. This will enable is to make timely decisions and adapt practices to evolving risks and never-before-presented information from volcanic-hazard forecasting tools. The outcomes of this work will help New Zealand to learn to adapt and transform to other rapid or permanent changes, such as those threatening from climate/environmental change or technological events.

Keywords

- Volcanic hazard mitigation
- Economic development
- Disaster risk reduction
- Disaster recovery
- Hazard science
- Economic benefits/cost saving
- Tourism
- Agriculture
- Volcanic risk
- Risk and uncertainty
- probabilistic hazard assessment
- Volcanism
- Taranaki
- transition pathways
- robust decision making

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Proposal summary and Eligibility

Proposal summary

Taranaki is the most likely New Zealand volcano to cause national-scale impacts over our lifetimes. Positioned upwind from our most populous regions of Auckland, Waikato and Bay of Plenty, all Taranaki eruptions will disrupt air and surface transport, tourism, farming, power and water supplies. This volcano has a 50% probability of erupting over the next 50 years. Yet the dormancy since Taranaki's last eruption (~AD1790) is one of its longest. Thus we have no modern experience of its typically very long eruptions. Past research shows that once Mt. Taranaki starts erupting, it continues for years, decades, or centuries. A recent estimate of the net losses in economic activity from a brief Mt. Taranaki eruption (considering only a subset of potential impacts) is crudely estimated at ~NZ$1.7-4.0 billion of GDP per year, or ~NZ$13-26 billion, for a decade of volcanism. Our research will build and test the geological, engineering and socio-economic knowledge essential for the New Zealand economy to transition through such an unprecedented level of on-going disruption. Using a novel integration of volcanic scientific knowledge, experimentation and advanced mathematical and economic simulation, we aim to radically cut down uncertainty that hinders decisive hazard and mitigation planning for transitioning to a new state of ongoing hazard. We will demonstrate how robust decisions can be made across space, through time, for multiple stakeholders. In this way we will also discover how to transform New Zealand in the face of continuous change. This requires developing an integrated quantitative understanding of volcanism in order to confidently forecast the volcanic impacts over timeframes suited to socio-economic decision-making.

Please confirm that your application meets the eligibility criteria

Yes

If you are unsure whether your proposal meets these criteria please explain why:

Executive summary (560 words)

The hazard and risk management paradigm of New Zealand is focussed on isolated and finite events. Even with several events (e.g., Canterbury Earthquake Sequence), our response and recovery all assume that a hazard episode will finish, and all infrastructure, communities and economies can be recovered to "normality". Here we address the problem of: **What if a hazard event started and never stopped?** In this case **we need new adaptive or transformative capacity to address long-term hazard disruption,** specifically under conditions of deep uncertainty. We hypothesise that by researching how to transform New Zealand through a **likely nationally devastating scenario of volcanic reawakening at Mt. Taranaki**, we can fast-track development of new knowledge into adaptation and transformation of our communities and economy through any type of uncertain future disruption case. There is a 50% chance of Mt. Taranaki erupting over the next 50 years and once reawakened, eruptions will continue for decades. Long term Taranaki volcanism will impact all sectors of our economy throughout the entire North Island, with especially devastating consequences for transport, airports (especially Auckland), the oil, gas and electricity sector, along with agriculture and tourism.

Science Excellence and research plan

We will develop new science in five areas: (RA1.1) co-creation of new decision-support processes for adaptation to ongoing disruption under deep uncertainty; (RA1.2) development of an agile new multiscale spatially and temporally socioeconomic modelling toolkit to continually forecast local, regional and national impacts considering ongoing changes in hazard/consequence state and adaptation strategy; (RA1.3) revive and build on to Mātauranga Māori/Mātauranga-ā-iwi knowledge to support Māori business and community adaptation; (RA1.4) construct new probabilistic statistical frameworks that integrate multi-volcanic hazard and apply predictive volcanic potential variables during dynamic, long-term hazard episodes, and (RA1.5) address a fundamental scientific weakness in the globally evaluation of volcanic hazards, by discovering specific geochemical or geophysical indicators that have predictive power of volcanic potential on a time cycle relevant for communities and business.

Team Excellence

We have built an inter-disciplinary team of >40 emerging to seasoned researchers spanning specialities in geology, statistics/mathematics, Mātauranga Māori and economics, under the proven science leadership of the outgoing Director of the Resilience NSC (Resilience to Nature's Challenges National Science Challenge), Prof Shane Cronin and co-leader Dr Garry McDonald, who has led a series of innovations in New Zealand's economic decision support knowledge through many MBIE and commercial research programmes. We have assembled the national front-runners in volcano and hazard science from five universities, GNS Science and commercial research providers, alongside strategic international partners (USA/Italy/Australia) that open doors to vast analogue experience and analytical equipment.

Benefit to New Zealand

Our work will transform volcano hazard forecasting tools for hazard management authorities and communities with new mathematical hazard approaches that can be applied worldwide, and a new agile socio-economic decision framework to support just decision-making during ongoing disruption for local and national government agencies, infrastructure/lifeline agencies, iwi-authorities and iwi-led businesses. The socioeconomic tool will allow the impacts of adaptation/mitigation decisions and changes in hazard state to be forecast and updated through constant challenging operating conditions and deeply uncertain futures of long-term disruption.

Implementation Pathway

We apply iterative, co-creation processes throughout with, with end-user-led research wānanga (workshops) throughout. Involving leaders of the successful Resilience National Science Challenge team, we bring together a core team of proven collaborators and scientists that can readily bring research to real world impact.

Vision Mātauranga

Is Vision Mātauranga relevant to this proposal?

Yes

Provide the rationale that substantiates this position (200 words)

Māori knowledge of volcanic landscapes, hazard and risk is part of an enduring relationship built with land, people and place over many centuries. Maunga Taranaki – a personification of an ancestor - and the waterways flowing from him are deeply entrenched in whakapapa and identity for the 8 iwi of Taranaki. This relationship is critical to recognise and understand in order to create appropriate pathways to adapt for an active volcanic future. Mātauranga-ā-iwi (tribal knowledge) regarding Maunga Taranaki have endured resource and environmental change, and iwi have survived through past eruptions. Furthermore, iwi have major investments in land, marae, schools and business, especially the agriculture, culture and tourism foci of our research. We see Mātauranga-ā-iwi guiding this research programme as a future adaptive store of indigenous innovation for contemporary and new taiao, strategies and practices for adaptation to ongoing disruption. Māori researchers with whakapapa links to the Taranaki and downwind regions are key researchers (Procter, Sciascia, McCallion) and will help co-create appropriate frameworks, methods, tikanga and socio-economic modelling paradigms tailored to iwi communities and businesses. Knowledge and strategies generated from the research will be transformational and be disseminated to iwi and international partners in ways that are functional (wānanga).

Excellence

Science Excellence (1120 words)

Societal Issue

Taranaki is the most likely NZ volcano to cause national-scale impacts over our lifetimes, with a 50% chance of erupting over the next 50 years (Turner et al., 2008c; Damaschke et al., 2018). Due to its location and prevailing westerly winds, any eruption will affect cities, all transport, tourism, farming, power and water supplies across the North Island (Shane, 2005; Bebbington et al., 2008; Torres-Orozsco, 2018). Auckland is particularly vulnerable, with the probability for impact from a Taranaki ash fall 2 to 7 times higher than from any other volcano, including a local eruption (Shane and Hoverd, 2002; Shane, 2005). Taranaki's last eruption was ~AD1780-90 (Platz et al., 2012; Lerner et al., 2019), making its present dormancy one of the longest known (cf., Damaschke et al., 2017). Most Taranaki eruptions occur in clusters, with activity lasting years to decades (Platz et al., 2007; Turner et al., 2008a; Torres-Orozco et al., 2017a, 2017b, 2018). Long lived-eruptions are common around the world at analogue volcanoes: e.g., Merapi (Indonesia) since 1822 (Thouret et al., 2000); Semeru (Indonesia) since 1818 (Thouret et al., 2007; Doyle et al., 2010); and Colima (Mexico) for >200 years (Massaro et al., 2018). No risk reduction, response or recovery plans have any contingency for a decade-long eruption. Only *Tangata Whenua*in the Taranaki area have experienced this (cf., Platz et al., 2007; Lerner et al., in review).

Science Challenge

We must integrate new socio-economic tools, statistical hazard estimation and quantitative volcano-magma systems parameters into holistic and agile decision support tools to steer us through periods of long-term volcanic hazard disruption. This build a national capacity to thrive under any kind of ongoing national-scale disruption under deep uncertainty.

Hypotheses

- Novel socio-economic models of adaptation and long-term transition will best prepare us for the short-and-long term reduction of risk during enduring volcanic eruptions, or other states of long-term disruption.
- New robust statistical emulation of eruption scenarios and an integrated hazard-to-impact typology will greatly reduce uncertainty around assessing socio-economic impacts of complex volcanic events and long-lived volcanic hazard states.

- The consequences of volcanism at Taranaki can be better forecast by creating new volcanic potential indicators for rates and types of magma processes.

Approach, novelty and effectiveness

1. **Effectiveness through co-creation**. We will apply an action research approach that iteratively develops predictive volcanic indicators from concept to constraint and test their predictive power and usefulness during an agile development process that enables rapid-prototyping. This will involve working collaboratively in a co-creation processes with our end-users.
2. **Socio-economic decision support tools for ongoing disruption**. We will extend from the current approach for simulating socio-economic hazard consequence (based on comparative, or counter-factual studies), by developing new dynamic analysis frameworks that that trace adaptive responses. This will reduce uncertainty and support more robust decisions around adaptation of investment/business operation and risk-avoidance strategies throughout NZ. Our extensional science will incorporate event tree approaches, based on Bayesian networks that capture multiple triggers for socio-economic change and adaptation, including looped and interacting consequences. Furthermore, we will track emerging decision-making processes that underpin robust adaptation to disruption under conditions of deep uncertainty.
3. **Mātauranga Māori and volcanism**: Mātauranga-ā-iwi (tribal knowledge) and tikanga (practices) related to volcano, alpine, river, and coastal hazards is identified and recorded. Iwi/hapū and volcanic researchers develop a shared understanding about the permanence or transience of landscape features – such as river catchments/landslides – and potential impacts on values including Te Mana o te Wai. Mātauranga-ā-iwi is leveraged for use in the transition modelling toolkits.
4. **Mathematical hazard-impact typology**: We will integrate volcanic hazards on an all-of-NZ basis by developing new mathematical science through a 'test-bed' of the forecasting power of volcanic potential indicators, iteratively refining these with volcano-process scientists, before integrating into new-generation forecasting tools. This extends from eruption-pattern-recognition (Damaschke et al., 2017) into a unique world-first simulation model of a stratovolcano. We will leverage a range of existing process-based models of volcanic phenomena (ashfall/pyroclastic flow/lahar/debris avalanche/gas) to create mathematical bridging functions to quantify impacts on built infrastructure, and probabilities for socio-economic consequences, including tracking uncertainties
5. **Volcanic potential indicators**: Complex models of stratovolcanoes invoke networks of stores and processing of magmas before eruption (e.g., Turner et al., 2004; Price et al., 1999; Cassidy et al., 2018). Forecasting eruption outcomes remains a grand scientific challenge, as recently expressed by Cassidy et al. (2018) in Nature Communications. To tackle our overarching science challenge, we must provide robust indicators of a magma system state, distilling decades of petrological and geochemical research into a set of quantitative parameters with forecasting power. Targeted investigations for this are reliant on an existing exceptionally high-resolution record of volcanic events (Turner et al., 2008c; 2011a; Damaschke et al., 2017). We have seen time-variant hazard properties of this system, including a cyclic variation in eruption frequency (Turner et al., 2008a; 2008b; 2011) possibly related to magma composition (Turner et al. 2008b; Green et al., 2013). These features must be built into statistical models currently blind to physical and chemical processes. Our research focuses on targeting the most significant processes and timescales, such as detecting magma recharge and gas-content (explosivity).

Benefits

- By creating new volcanic science, experimentation and advanced mathematical and socio-economic simulation, we can radically cut down uncertainty that hinders decisive natural hazard and mitigation planning.
- We will discover how to transform NZ in the face of continuous hazard by integrating our understanding of volcanic disruptions over timeframes suited to socio-economic decision-making.
- *Additional benefits*: We will create an exemplar of how to manage a much broader range of disruptive events (natural or anthropogenic) through time, across space, for multi-stakeholders, reporting multiscale capital and intergenerational well-being impacts (Forgie and McDonald, 2013) – creating a wider benefit than just volcanic hazard mitigation (e.g., Zero Carbon Act, Climate Change adaptation).

Leveraging knowledge and facilities through collaboration

Our team spans geological, economic, Mātauranga-ā-iwiand mathematical researchers from throughout NZ and overseas. We have levered an extremely important connection with Italian researchers that are working on an analogue problem at Vesuvius volcano, located within the massive Neapolitan metropolitan area. To support our work, we have built a team of highly specialised geochemical and geophysical researchers enabling access to world-leading laboratory and experimental facilities in the USA, Australia and Europe.

Opportunities for Māori knowledge

Māori knowledge has ensured their endurance and survival through eruptions in Taranaki's past. While not current knowledge, these inherent resilient relationships will be a key to identifying practices for the future. Furthermore, traditional indicators of environmental and volcanic change will be integrated into volcanic forecast indicators. Adapting to ongoing volcanic system change will involve Taranaki Māori communities and Iwi authorities re-evaluating current modes of investment to protect their assets for future generations.

Team Excellence (560 words)

Prof Cronin and Dr McDonald will co-lead our research. Cronin is the current Director of the Resilience NSC, where he has built a highly successful collaboration with >200 inter-disciplinary end-users/researchers that have produced >80 peer-reviewed research outputs (achieving a field weighted citation factor of >1.5). He previously led Volcanic Risk Solutions (Massey University) receiving MBIE, Marsden and commercial funding >$17m. He has co-authored >200 papers with >5,900 citations. McDonald has extensive corporate experience (as a founding-Director of ME with >1,600 projects, >$70m) and science leadership (>15 MBIE-funded research programmes, >$30m).

Delivery of our research requires the following skills/knowledge:

- **Co-creation processes**. A/Prof Wilson and Mr Fairclough have exemplary skills in the design and implementation of collaborative stakeholder processes. Wilson leads the Resilience NSC' Rural toolbox, and Fairclough (currently chair of the National Lifelines Council) has led numerous government/business/community stakeholder processes.
- **Socio-economic modelling**. Drs Smith/Harvey and A/Prof Wreford bring world-leading skills in development of integrated decision-support tools and robust decision-making processes that enable evidence-based assessment of socio-economic impacts (e.g. MERIT) across space, through time, for multiple stakeholders.
- **Mātauranga Māori.** A/Prof Procter, Dr Sciascia and Mr McCallion all have whakapapa links to the Taranaki region and a wide diversity of leadership experience in Mātauranga Māori research focused on hazards, environment, cultural and social issues. Procter currently leads the Mātauranga Māori workstream of the Resilience NSC, and Sciascia will take over that role in mid-2019.
- **Geo-statistics**. Prof Bebbington and Drs Wang/Mead have specialist statistical skills in hazard estimation and forecasting, stochastic modelling, computational analysis and uncertainty estimation. These skills will integrate predictive indicators of the volcanic-event chain.
- **Volcanology**: We have assembled a world-class team of volcanologists from NZ/Australia/US/Italy/Germany. They include emerging researchers to the most highly cited geoscientists (Turner/Baker/Cronin/Sulpizio). This includes key specialists in diverse fields (geochemistry/magma properties/mantle/crust geology/experimentation). They are coordinated by Dr Brenna and A/Prof Ukstins, providing leadership opportunities and an international best-practice view.

Partnerships

Within team: Cronin/McDonald/Bebbington/Wilson/Proctor/Sciascia are all part of the leadership team of the Resilience NSC. They have also completed aligned MBIE-funded programmes (>10) including: Understanding and Being Resilient to Super-volcanoes, Towards Robust Decision-Making, Living with Volcanic Risk and the Taranaki-focused Better Recovery through MRCGE.

International: Our team has exemplary international partnerships, including in the US (Ukstins), Australia (Turner/Rushmer), who bring in core capabilities not available in NZ – such as high-resolution isotope geochemistry and Secondary Ion Mass Spectrometry. We also have targeted collaboration with three Italian voclanologists (Sulpizio/Lucchi/Giordano) who lead Italy's response to re-awakening volcanism in Vesuvius, Italy. Our colleagues at the University of Munich, Germany (Scheu/Montanaro) also facilitate our access to the most famous experimental volcanology laboratory in the world.

Māori: Our team has enduring collaborative relationships with all the Taranaki-iwi, along with several Māori land trusts, and Māori businesses in the region. Sciascia comes from (and was raised in) Te Ati Awa, Ngāti Ruanui and Ngāruahine Rangi and has worked alongside all 8 iwi in iwi-governance roles.

People risk management

We mix a healthy gender balance along with a diverse group of well-established through to mid-career and emerging researchers in all areas of our research, minimising people risks. Through monthly research meetings we will maintain a risk register and adopt risk-management strategies including broad-scanning of workplans, proactive adaptive management, and agile face-to-face engagement. We have a co-leadership model (ensuring availability), an Advisory Group (sounding-board for strategies), and world-leading international advisors (reducing technical risk).

Impact

Describe how your research will deliver Benefit to New Zealand (1120 words)

The problem

Of all volcanic hazards, Taranaki is the most likely to cause national scale impacts over our lifetimes. Although >200 years since the last eruption, this dormancy is atypical, with the probability of an event in the next 50 years exceedingly high (50%). Formidable disruptions to air-and-surface transport, tourism, farming, power and water supplies will likely extend well beyond the local region, with the populous and economic 'power-house' regions of Auckland, Waikato and Bay of Plenty positioned down-wind. Even more pivotal than its geographic extend is the potential temporal extent. Evidence suggests that once Taranaki starts erupting, it continues for years even decades. A suitable analogy is Mt Merapi, Indonesia – in an active state since c1930, producing thousands of casualties including >380 in 2010. NZ clearly has no modern experience of such episodes, and at no scale of governance has there been practice and conditioning for dealing with long-term ongoing disruptions. The prevailing disaster management paradigm is of static hazards and disaster cycles that are sequential and orderly (planning/risk reduction-event-response-recovery). A radical re-think is required. Our research will build the knowledge, tools and preparedness to support NZ to make timely decisions and adapt practices under an evolving threat, where elements of the disaster cycle are disordered and merged, and new information is periodically presented from novel volcanic-hazard forecasting tools.

Leverage wider investment and knowledge in New Zealand and overseas

The main collaborative benefits we will gain through our international partnership is access to a pool of specialised, state-of-the-art knowledge, practice and experimental/analytical facilities. Specifically, comparative studies on Vesuvius volcano in Italy by our colleagues will help us parallel-test approaches ranging from volcanology through to innovations in evaluating societal impact and adaptation pathways. They are more advanced than us in detailed event response planning and decision-making tools, with also areas of advance in volcano-impact knowledge from more recent eruption events and intense archaeological volcanological studies in the area. Access to an international pool of expertise on magma-isotopic studies brings an intellectual and laboratory capability not possible within NZ. Prof Turner and A/Prof Rushmer lead one of the best-equipped (Thermo-fisher demonstration) laboratories in the world and bring decades of experience in applying a range of isotopic systems to bear on reawakening and active volcanoes. Turner has applied isotopic methods to understanding the gas-state, explosivity potential and timescales of magma movement during ongoing long eruption episodes in Montserrat (Caribbean), Indonesia, and Tonga. Other collaborators bring in wider analytical skill sets and laboratory facilities that we cannot replicate in NZ (Ukstins with Ion-probe and other specialist analytical tools; Sheu/Montanaro with explosion/experimental laboratories).

Leveraging of existing research investment our socio-economic modelling extends cutting-edge work undertaken within the Resilience NSC, QuakeCoRE, NHRP (Faster Rebuilds with MRCGE, Towards Robust Decision Making: Uncertainty Quantification for RiskScape-MERIT Modelling) (McDonald et al., 2017a; 2018) and MBIE Endeavour/Targeted Research (several gold-star rated) Economics of Resilient Infrastructure, Sustainable Aquifer Management, Learning to Live with Volcanic Risk, Living with Volcanic Risk and Facing the Challenge of Auckland's Volcanism programmes.

Scale of potential benefits

To illustrate the scale of potential benefits from this programme, a recent estimate of net losses in economic activity over a year from a brief Taranaki eruption is crudely estimated at ~NZ$1.7-4.0 billion of GDP (McDonald et al., 2017b). Taking an average of $2.6 billion, and assuming conservatively that the next Taranaki event extends over just a decade (with probability of commencement of 1% annually, discount rate 6%) we find that even the expected (i.e. probability-adjusted) gains from reducing losses by just 5% will exceed $150 million over the next 50 years, but could be nearly $1 billion if the eruption occurs imminently. And remarkably these calculations only consider a subset of the potential benefits achievable. For one, the above initial loss estimates were based largely just on key local impacts, omitting ceased operation of industrial plants outside of Taranaki, the implications for aviation, and threats to distant drinking water, pasture, crops. Also not considered were potential losses to machinery and infrastructure (e.g. water supply), of which the financial burden of repair and replacement could last decades. Using a novel integration of volcanic scientific knowledge, experimentation, socio-economic and advanced statistical/mathematical simulation/modelling, we will radically cut down uncertainty so that businesses and infrastructure providers from across the broad economic spectrum can seek more strategic outcomes from operations and investment planning, both in anticipation and during an event. Against all this the research programme clearly presents an opportunity for very high impact in areas of future value/growth and is a critical need for NZ. Furthermore, the outcomes of this work will also help NZ to learn how to adapt and transform to other rapid or permanent changes, such as those threatening from climate/environmental change or technological events.

Government policy and strategy documents

The urgency for this research stems not only from the high risk posed, but also the local governance context, i.e. recent treaty settlements and government/iwi investment priorities signalled around mountain tourism and authentic cultural experiences (MBIE, 2018). Clearly the time to act is now to strategically inform the region's vision. The programme also strongly supports Treasury in its stated intent, which prioritises identification of risks to NZ's intergenerational well-being, with natural disasters indicated as among the most important risks (Treasury, 2018a). Our proposed public decision-support tools will themselves also be structured in line with Treasury's Living Standard's framework (Treasury, 2018b), which recognises the need to monitor changes in wealth across multi-capitals, and that what matters to New Zealanders cannot be measured by standard economic measures alone (Smith, 2018). But also, consistent with the draft National Disaster Resilience Strategy (NDRS), we focus not only on active management for the specific Taranaki risk, but also on generic resilience adaptations (CDEM, 2018). The process of preparing and conditioning for the types of risks posed by Taranaki will be a key benefit of the programme.

Mātauranga Māori benefits

As is also recognised in the NDRS, Māori are natural kaitiaki (guardians) of the environment – this stems from a deep whakapapa connection to the land and waterways that are not only identity markers, but are pillars of cultural significance for Māori communities and iwi within Taranaki. We see this programme supporting the active role of kaitiakitanga by Taranaki iwi to understanding hazards and risk in the context of Maunga Taranaki and developing strategies and practice for adaptation that is culturally meaningful and appropriate.

Describe your Implementation Pathway/s and how they will deliver benefit to New Zealand (1120 words)

Key initiatives, timing and pathway

Over the last 18 months we have **co-designed a research agenda** with our key stakeholders during workshops and one-on-one meetings (Taranaki CDEM Group, Taranaki Regional and District Councils, Department of Conservation, Venture Taranaki, DairyNZ, Dept. Prime Minister and Cabinet – National Risk Unit, Ministry of Civil Defence and Emergency Management, Dept. Internal Affairs – Central Government Local Government Partnerships Group, NZ Treasury, NZ Transport Agency, Ministry of Transport, Civil Aviation Authority, Ministry of Business Innovation and Employment – Petroleum and Minerals and Energy Markets). Our work will sit alongside the Taranaki 2050 Transition Roadmap process and can feed into this outcomes around managing uncertainty and change during long-term economic transition. We also have freedom to operate within Taranaki with full support and aligned resources of our partners (e.g., Taranaki CDEM Group has an aligned application to ours with the Ministry of Civil Defence Resilience Capability fund). Further to this, we have also developed key relationships with other research organisations, including alignment and coordination between the Mātauranga Māori, Rural, Volcanic and Multihazards risk streams of the 2019-2014 Resilience National Science Challenge.

Our implementation process is centred on direct resource into co-creation (RA1.1) where we develop enduring partnerships with end users, initially through a Terms of Reference, we build toward levering delivery partners (stakeholders) and Advisory Group members to achieve additional science impact. Our co-creation processes will involve regular stakeholder/iwi-led face-to-face workshops to ensure our technical workstreams (RAs1.2&1.4) are fit-for-purpose, and also that we are managing risk, thoroughly testing assumptions and removing barriers to long-term uptake. Our programme has at least 14 co-creation workshops (≥10 stakeholder/iwi-led in Yrs2-4) spread evenly (≥4 in Yr1, ≥5 in Yrs2&3, ≥5 in Yr4), and two annual Advisory Group Meetings chaired by our group of research-to-practice interlocuters, including Roger Fairclough (Chair of the National Lifelines Council and Resilience NSC Infrastructure Advisory Board) Brad Scot (GNS Science), Aaron Mckellion (Waka Digital) and locally Teresa Gordon (Taranaki CDEM Group).

Our **implementation pathway specification** is designed so that co-creation workshops are efficient and adaptive. Initial workshops (Yr1) are focused on establishing process, building relationships and shared understandings, as well as developing metrics for evaluation. Subsequent workshops (Yrs2-4) are all stakeholder/iwi-led and aligned with decision-making processes, sharpening the delivery of our high-quality science. Importantly, outputs from our socio-economic, Mātauranga-ā-iwi (tribal knowledge), statistical/simulation modelling and geochemical tool-chest will be available for use from Yr1 onwards; and will be continuously and seamlessly updated with science added progressively. Our stakeholder/iwi delivery partners will thus have the cutting-edge science at their fingertips, in each workshop, enabling stress-testing of our work on-the-fly.

Considering, identifying and responding to the needs, opportunities or contribution from Māori knowledge

Partnerships are established between iwi/hapū, researchers and other stakeholders. Iwi-led co-creation wānanga (workshops) set Mātauranga-ā-iwi (tribal knowledge) practices alongside scientific knowledge. Dialogues on volcanic state and landscape state are held/recorded as appropriate (oral recording/video), and a shared understanding developed about the landscape (e.g., river catchments) and important values such as Te Mana o te Wai. An iwi-volcano PhD researcher and a team of iwi-researchers will help build Mātauranga-ā-iwi.

Strength of current relationships

Our team has strong current relationships with all our key stakeholders. This includes the agencies listed above alongside Auckland/Waikato/Bay of Plenty/Hawkes Bay/Hamilton Councils, the 8 Taranaki iwi, industry organisations, critical infrastructure providers (National Lifelines Council), and financial businesses (AIG/AoN/BNZ). We will enhance and extend these relationships through stakeholder-led workshops in our co-creation processes, our Advisory Group, and aligned networks (National Lifelines Council, Resilience NSC Infrastructure Advisory Group).

Track record

Our team has an excellent track record in the delivery of integrated decision support tools for forecasting and assessing the socio-economic impacts associated with disruption events, through time and space for multiple stakeholders. Under the Wellington Resilience Project (Smith et al., 2018), senior executives of 18 infrastructure providers (covering transport, electricity, telecommunications, water, gas and petrochemical sectors) applied RiskScape-MERIT (McDonald et al., 2018) modelling to create an integrated all-of-infrastructure value case for resilience building in Wellington. The Auckland, Waikato, Bay of Plenty, Wellington and Canterbury Regional Councils have all adopted our socio-economic toolkit as one of their key strategic planning tools. The ability of our team to deliver user-friendly tools is evidenced by the strong uptake of their work within NZ, and adoption for assessing disruption in Australia (Infrastructure Australia) and Indonesia (Bappenas). Benefits delivered from our past volcanic hazard work include the implementation of successful response plans to the 2007 eruptions and the 2007 lake-breakout lahar from Mt. Ruapehu, as well as the 2012 eruption of Te Maari, Tongariro. This work included evaluating infrastructure risk mitigation strategies and protection structures, designing monitoring/warning systems and providing scientific advice throughout readiness, response and recovery phases of these events, with industry, community and government partners.

Uptake by other end or next users

We have exemplary relationships to all likely next-users including all CDEM organisations, critical infrastructure lifeline providers, Regional Councils, Territorial Authorities, central government ministries, departments and agencies as evidenced by our role in provision of strategic research and commercial services under the Resilience NSC (Rural co-creation laboratory, Hazard/Economics toolboxes and Infrastructure Advisory Group), QuakeCoRE, National Policy Statements (>25 studies) along with pivotal information provisioning for asset management planning purposes (e.g. Waikato Local Authority Shared-Services Agreement covering *all* 14 Waikato local authorities where our MBIE-funded W/ISE (Rutledge et al., 2008), and NPS-UDC work underpins *all* Council-related infrastructure investments). Our proposed socio-economic work will have significant spill-over benefits for these processes, enabling them to consider multiple future baselines, assess a full range of multi-capital and well-being impacts under conditions of uncertainty for alternative transition pathways.

Our proposed research will also **deliver wider benefits** to NZ by meeting requirements under the Local Government Act 2002 (e.g. infrastructure asset management and investment planning and information provision for the NPS-UDC), Resource Management Act 1991 (under S.6, adding strategic tools for risk-based management of hazards), Civil Defence Emergency Management Act 2002 and the proposed NDRS (managing risk and enabling/empowering/supporting community resilience). This research however goes significantly further, recognising that disruptive events are increasingly becoming the norm, rather than the exception. Our research is applicable to any form of on-going disruption (geo-political/environmental/hazard) providing us with decision-support tools that enable us to better navigate through complex transitions. Through our commercial partners, we will seek opportunities to leverage our research for wider benefit both within NZ and elsewhere.

Partnering arrangements

An Advisory Group will be established at the onset of the programme consisting of representatives from councils (Taranaki RC, Taranaki CDEM, New Plymouth, Stratford and South Taranaki), business (Venture Taranaki/AIG/Aon/BNZ), Taranaki-iwi, industry organisations (DairyNZ/PEPANZ), and government (MCDEM/DPMC/Treasury/ MBIE Petroleum and Minerals-Energy Markets/DIA/NZTA/CAA). The group will meet at least annually to review existing workplans, comment on future workplans, and aid in risk management.

Describe the impact track record of your team (560 words)

Our research is **distinguished by collaboration** across university researchers, Crown Research Institutes, independent research providers, international research leaders, stakeholders and iwi. We have assembled a world-class team of scientists with the right mix of skills and track records to be effective and impactful. In particular our team is experienced in transdisciplinary and applied research that is used in processes and commercial outcomes by our end-users. Our team builds on core partnerships formed over the last decade through the National Hazards Research Platform, the Resilience NSC, and many other joint research initiatives. We have added a raft of new collaborators, particularly early and mid-career researchers, eight PhD students and three Post-Doc fellows to further build NZ research capability.

Our team includes researchers across **Auckland, Massey, Canterbury and Lincoln universities, along with GNS Science, Market Economics**, Macquarie University (Australia), University of Iowa (USA), University of Bari, Bologna and Roma Tre (Italy). Our researchers include those who have successfully **delivered the largest-scale science research programmes offered globally**, including the Resilience NSC (Cronin, Proctor, McDonald, T. Wilson), >11 Marsden fund projects (Cronin, Baker, White, C. Wilson, Kennedy, Wang, Jolly), >20 MBIE (or ministry-equivalent) programmes (McDonald, Cronin, Proctor), an Earthquake Commission/Auckland Council project on Auckland Volcanic hazard (Lindsay, DEVORA), major NASA and US National Science Foundation grants (Ukstins) and large Australian Research Council grants (Turner, Rushmer). Furthermore, our team includes many high-performing emerging and early to mid-career researchers for whom we are providing leadership mentorship opportunities (Smith, Brenna, Wang, Sciascia, Harvey), and key roles within critical steps of the programme (Wreford, Scott, Rowe, Kilgour, Shane, Werner). We include key national leaders in Mātauranga Māori research and Māori engagement (Sciascia, Procter, McCallion).

Our past research in this area includes excellent/gold-star rated stakeholder engagement (e.g., Economics of Resilient Infrastructure, Learning to Live with Volcanic Risk, Living with Volcanic Risk, Facing the Challenge of Auckland's Volcanism). We have also conducted significant commercial research, with McDonald/Smith/Harvey and colleagues having undertaken >$70m of **research-based consultancy work** covering >1,600 projects. Working closely with end-users, they have co-developed several extensively applied integrated socio-economic decision-support tools (ISE/MERIT) that embed science directly into policy, decision-making (including **>200 successful expert witness appearances** on strategic regional/national investment issues in the Environment/High/Appeal/Supreme Courts. The MERIT model is an exemplar **spin-off commercial** product that is jointly administered under a MoU by GNS Science, ME and Resilient Organisations. Core team members have also worked collaboratively with MCDEM/NZTA/MoT/Treasury and local authorities, contributing to the National Disaster Resilience Strategy, **post-event decision-support** (1995-96 and 2007 Ruapehu eruptions; 2012 Tongariro eruption; 2016 Kaikoura earthquakes, 2010-11 Canterbury earthquakes), civil defence training exercises (2018 Alpine Fault Magnitude 8; Volcanic Exercises Pahu (2013), Ruaumoko and Billow (2008)), as well as **developing business investment cases** for resilience (2018 Wellington Resilience Project (18 public/private infrastructure providers)/2018-19 MBIE Fuel Security).

Our implementation strategy will draw on **high-calibre engagement skills** of Mr Fairclough (National Lifelines Chair, strategic government advisor), Māori business leader Mr McCallion (Waka Digital, for Iwi and Māori land/investment trusts), volcano-science communicator Mr Scott (GNS Science), as well as our community partners at Taranaki CDEM, Taranaki RC, and an Advisory Group of key parties. We have held numerous workshops with stakeholders over the last 18-months to build the framework for this research with our whole team.

Post-contract outcomes for New Zealand (280 words)

2 Years: NZ local and national government agencies and key industry sectors (agriculture/energy/tourism) are aware of the planning needs of long-term volcanic eruption scenarios from Mt. Taranaki and have considered planning options to reduce risk and adapt practice. In particular, the paradigm of evacuation and closedown of businesses/services has been reconsidered, with ongoing operation through long-term events considered as the most likely viable option for reduced economic impact. New hazard scenarios and probabilities of occurrence are available to inform planning and there are a series of new volcanic state indicators that reduce the uncertainty in volcanic hazard forecasts.

5 Years: NZ agencies (government and industry) have innovative socio-economic planning tools to manage adaptation to any future volcanic crises from Mt. Taranaki. The socio-economic tools are underpinned by a new generation of robust probabilistic models that reflect underlying volcanic process and state information. New probabilistic approaches to hazard evaluation at Mt. Taranaki are being applied in adapted forms to other volcano hazard evaluations in NZ and worldwide. A robust series of volcanic hazard state/potential indicators are tested and applied to inform more reliable probabilistic forecasts and manage long-term complex volcanic crises.

10 Years: NZ agencies (government and industry) regularly apply adaptive socio-economic planning tools to plan, track and evaluate adaptation strategies for a range of natural and technological hazards/issues facing the country. For volcanic scenarios at most NZ volcanoes, magmatic system indicators are well-established and feed robust hazard forecasting. Volcanic response and recovery planning, as well as long-term adaptation planning for permanent volcanic change, are fully integrated into the National Disaster Resilience Strategy and promulgated through the investment strategies of regional and national government, communities and businesses throughout NZ.

Project plan

Work programme/Impact Statements

Sequence	Short title	Type	Start date	End date	Realisation date
1	Multiscale decision support tools that enable communities, farming/industry/business, iwi and government to create robust socio-economic transition pathways through ongoing disruption.	Impact statement	01/10/2019	30/09/2024	
1.1	Co-creation processes deep uncertainty	Research aim	01/10/2019	30/09/2024	
1.1.1	Affirm stakeholder and advisory groups	Critical step	01/10/2019	31/12/2019	
1.1.2	Agreed multiscale metrics and baselines	Critical step	01/01/2020	31/10/2020	
1.1.3	Review and refine prototype modelling	Critical step	01/11/2020	31/07/2022	
1.1.4	Stress-test robust decision-making	Critical step	01/08/2022	31/01/2024	
1.1.5	Co-creation processes, findings, and reflections	Critical step	01/02/2024	30/09/2024	
1.2	Decision support for dynamic transition	Research aim	01/10/2019	31/07/2024	
1.2.1	Creation of hazard-to-impact systems map	Critical step	01/10/2019	31/07/2021	
1.2.2	Hotspot identification	Critical step	01/01/2020	31/07/2021	
1.2.3	Bespoke sector modelling	Critical step	01/10/2020	31/10/2022	
1.2.4	Whole-of-economy modelling	Critical step	01/02/2022	31/10/2023	
1.2.5	Model simplification and distillation	Critical step	01/02/2022	31/07/2024	
1.3	Leveraging Mātauranga-ā-iwi	Research aim	01/10/2019	31/07/2024	
1.3.1	Building partnerships	Critical step	01/10/2019	31/10/2020	

1.3.2	Building Mātauranga-ā-iwi	Critical step	01/11/2020	31/07/2021	
1.3.3	Building dialogue on volcanic state/landscape	Critical step	01/08/2021	30/04/2022	
1.3.4	Traditional indicators and sites of unrest	Critical step	01/05/2022	31/01/2023	
1.3.5	Mātauranga-ā-iwi knowledge and practices	Critical step	01/02/2023	31/10/2023	
1.3.6	Mātauranga-ā-iwi alongside modelling	Critical step	01/11/2023	31/07/2024	
1.4	Simulating on-going and disruptive volcanism	Research aim	01/10/2019	31/07/2024	
1.4.1	Multiscale modelling of volcano dynamics	Critical step	01/10/2019	31/10/2022	
1.4.2	Statistical modelling of pre-/syn-eruptives	Critical step	01/10/2019	31/10/2023	
1.4.3	Statistical model of volcanic products	Critical step	01/10/2019	31/10/2023	
1.4.4	Weather-modulated susceptibility	Critical step	01/10/2019	31/10/2023	
1.4.5	Statistical emulators	Critical step	01/10/2019	31/10/2023	
1.4.6	Ash impacts modelling	Critical step	01/10/2019	31/10/2023	
1.4.7	Physical impacts for significant infrastructure	Critical step	01/05/2021	31/10/2023	
1.4.8	Visualisation tools	Critical step	01/11/2023	31/07/2024	
1.5	Geochemical tool chest for hazard forecasting	Research aim	01/10/2019	31/07/2024	
1.5.1	Pre-eruption diagnostic indicators	Critical step	01/10/2019	31/10/2022	
1.5.2	Magma pathways	Critical step	01/10/2019	31/10/2022	
1.5.3	Eruption pathways	Critical step	01/10/2019	31/10/2023	
1.5.4	Explosive potential	Critical step	01/10/2019	31/10/2023	
1.5.5	Realtime assessment	Critical step	01/05/2021	31/07/2024	

Impact statement 1

Impact statement 1

Impact statement title
Multiscale decision support tools that enable communities, farming/industry/business, iwi and government to create robust socio-economic transition pathways through ongoing disruption.

Impact statement (140 words)
Communities, businesses, Māori organisations and iwi/hapū, along with local and national government agencies of New Zealand are applying co-created, multiscale (spatially and temporally) socio-economic toolkits to adapt to severe ongoing disruption of daily life in response to long-term hazard events involving deep uncertainty. In particular, New Zealand is prepared to thrive alongside the high probability case of long-term future volcanic unrest at Mt. Taranaki alongside other similar national-scale environmental or technological hazards (such as climate change impacts and resource limitations). Agile adaptation and proactive planning are supported by quantitative testing and recasting of future socio-economic strategies under constantly-changing threats. This capability is underpinned by an integrated mathematical hazard engine, which translates fundamental system properties (in this case, volcano-magmatic systems) through a federated suite of specific hazard-simulations (e.g., ashfall, mass flow), incorporating a range of stress-tested volcanic 'potential' indicators.

Start date:
01/10/2019

End date:
30/09/2024

Impact statement leader:
Joel Baker
The University of Auckland
Mark Bebbington
Nicola Smith
Thomas Wilson
Ting Wang
The University of Otago

Impact statement 1 > Research aim 1.1

Research aim title
Co-creation processes deep uncertainty

Research aim statement (140 words)
Co-creation laboratories will assess transition pathways for multiple stakeholders at local-to-national scales. Using a collaborative and iterative approach our stakeholders will help design, refine and stress-test our decision-support tools to create robust socio-economic transition pathways through *ex-ante* simulations of ongoing disruption volcanic activity at Mt. Taranaki. These pathways will be evaluated through the use of multi-capital and intergenerational wellbeing metrics through space (community/district/region/nation) and across time (quarterly time-steps) over a 30-year horizon.

Start date:
01/10/2019

End date:
30/09/2024

Impact statement 1 > Research aim 1.1 > Critical step 1.1.1

Critical step title
Affirm stakeholder and advisory groups

Critical step statement (140 words)
The final set of stakeholders for our co-creation processes is affirmed. Over the last 18-months we have co-designed our proposal with many stakeholders (through workshops hosted by Taranaki CDEM, strategic central government meetings, and ongoing discussions with key industry/business/iwi groups). Within this step we will bring together representatives of these organisations, reflect on whether additional organisations are necessary, and contact any new additions.

Similarly, the Advisory Group for this programme is affirmed. The preliminary group is a leverage of the Infrastructure Advisory Group established under the Resilience National Science Challenge. Roger Fairclough, current chair of the National Lifelines Council, will chair this group.

Start date:
01/10/2019

End date:
31/12/2019

Impact statement 1 > Research aim 1.1 > Critical step 1.1.2

Critical step title
Agreed multiscale metrics and baselines

Critical step statement (140 words)
Co-designed multiscale metrics and baselines are produced. Through at least 4 stakeholder co-creation wānanga (workshops) we will have co-designed: a) multiscale socio-economic metrics, capturing various societal values, for assessing our transitions pathways against. They will cover multiple scales (community, district, region, nation), multiple capitals (natural, human, social, physical/financial), and intergenerational wellbeing (including distributional breakdowns). Where possible, they will be aligned with Treasury's Living Standards Framework and prototype Living Standards Analysis Model; and b) a set of baseline/counterfactual scenarios of social and economic growth to measure transition against. These growth scenarios will go beyond 'business-as-usual', acknowledging that a range of plausible futures exist for Taranaki and New Zealand.

Start date:
01/01/2020

End date:
31/10/2020

Impact statement 1 > Research aim 1.1 > Critical step 1.1.3

Critical step title
Review and refine prototype modelling

Critical step statement (140 words)
At least 4 stakeholder co-creation wānanga (workshops) are completed. These wānanga have reviewed and refined the prototype outputs from the socio-economic, probabilistic event-tree modelling, and volcanic streams to ensure that they are appropriate for inclusion in decision-making processes. The form of the outputs from the prototype modelling is finalised, and preliminary sets of outputs are produced to aid stakeholder/iwi leading the next set of wānanga for CS1.1.4. A dynamic typology of the direct geophysical and socio-economic impacts (as developed in collaboration with RAs1.2-4) has been produced.

Start date:
01/11/2020

End date:
31/07/2022

Impact statement 1 > Research aim 1.1 > Critical step 1.1.4

Critical step title
Stress-test robust decision-making

Critical step statement (140 words)
At least 6 co-creation wānanga (workshops) have been completed to stress-test and develop transition pathways through ex ante simulation of ongoing disruption at Mt. Taranaki. These wānanga were stakeholder/iwi-led.

Start date:
01/08/2022

End date:
31/01/2024

Impact statement 1 > Research aim 1.1 > Critical step 1.1.5

Critical step title
Co-creation processes, findings, and reflections

Critical step statement (140 words)
Collaboratively developed joint guidelines for policy, planning and decision-making purposes have been produced. These will be an exemplar for aiding stakeholder groups in transition through on-going volcanic disruption. A final 'reflective learning' wananga was held and documentation of our co-creation process, findings and reflections has been developed.

Start date:
01/02/2024

End date:
30/09/2024

Impact statement 1 > Research aim 1.2

Research aim title
Decision support for dynamic transition

Research aim statement (140 words)
Develops decision support tools for just economic transition pathways through ongoing disruption, under deep uncertainty.

Start date:
01/10/2019

End date:
31/07/2024

Impact statement 1 > Research aim 1.2 > Critical step 1.2.1

Critical step title
Creation of hazard-to-impact systems map

Critical step statement (140 words)
A full hazard-to-impact systems map is produced. Created out of literature reviews, historic event analysis and expert elicitation, this map systematically describes the cause-effect sequences from an initial triggering (volcanic) event through to impacts across a broad range of potential wellbeing categories (i.e. as informed by Living Standards Framework). The mapping (influence diagrams/Bayesian-network approach) is sufficiently broad and generic to cover wide spatial, temporal, and intensity variations in triggering events, but also is adaptive enough to enable the incorporation of new knowledge as it emerges.

Start date:
01/10/2019

End date:
31/07/2021

Impact statement 1 > Research aim 1.2 > Critical step 1.2.2

Critical step title
Hotspot identification

Critical step statement (140 words)
Using the relationships defined in the systems map, along with a set of test scenarios capturing variation in the triggering event, network topology measures and indicators have been developed. These enable the identification of system components that are most important in amplifying disruption impacts through a socioeconomic system. Insights from this analysis have provided key insights to stakeholders on important ‘hotspots’ and ‘leverage points’.

Start date:
01/01/2020

End date:
31/07/2021

Impact statement 1 > Research aim 1.2 > Critical step 1.2.3

Critical step title
Bespoke sector modelling

Critical step statement (140 words)
Bespoke sectoral decision-support tools are completed for selected sectors. These tools were co-created with sectoral stakeholders (food, transport, energy and tourism) utilising, as appropriate, the most advanced frameworks and methods for decision-making under uncertainty (i.e. real options analysis, dynamic adaptive pathways, robust decision-making). Within the development process these tools were stress-tested across multiple events, providing stakeholders with practise in: agile decision-making under long-term and unfolding disruptions; early identification of key decision points for each sector; and identification of strategies that are robust for alternative contexts.

Start date:
01/10/2020

End date:
31/10/2022

Impact statement 1 > Research aim 1.2 > Critical step 1.2.4

Critical step title
Whole-of-economy modelling

Critical step statement (140 words)
The sectoral models developed in CS1.2.3 are integrated into the dynamic whole-of-economy model i.e. a top-down stock-and-flow model, incorporating an open economy general-equilibrium structure. The outcomes of implementing a set of resilience and 'just transitioning' strategies, co-designed with stakeholders, have been evaluated using this whole-of-economy model. Reporting capabilities have been extended, so that rather than just reporting aggregate measures of economic performance (e.g. GDP, employment), they provide a more nuanced lens to interpret impact, consistent with Treasury's National Living Standards Framework.

Start date:
01/02/2022

End date:
31/10/2023

Impact statement 1 > Research aim 1.2 > Critical step 1.2.5

Critical step title
Model simplification and distillation

Critical step statement (140 words)
The socio-economic models have been distilled and simplified. This enables them to now be run very quickly without the need for high performance computing. This distillation and simplification included replacing existing complex linkages with emulators (such as neural networks trained on model dynamics) where possible, sensitivity analysis to identify unnecessary or redundant elements. Using machine learning techniques to elucidate emergent relationships, enabled gains in performance through bypassing complex model coupling or chaining.

Start date:
01/02/2022

End date:
31/07/2024

Impact statement 1 > Research aim 1.3

Research aim title
Leveraging Mātauranga-ā-iwi

Research aim statement (140 words)
Creates transition pathways for Iwi/hapū and Māori land trusts under on-going volcanic disruption, by applying new knowledge of volcanic behaviour and novel robust probabilistic forecasts and integrating Mātauranga-ā-iwi traditional knowledge of volcanic warning and hazard response. Using co-creating processes alongside iwi to ensure that their māturanga is interwoven into key decision making processes.

Start date:
01/10/2019

End date:
31/07/2024

Impact statement 1 > Research aim 1.3 > Critical step 1.3.1

Critical step title
Building partnerships

Critical step statement (140 words)
Partnerships have been established between iwi/hapū and volcano researchers, building a shared sense of involvement and investment in the research programme's aims and values. These partnerships are fundamental to enable both traditional and western science knowledge to be developed and communicated when considering impacts and decisions for responses to volcanic disruptions. An iwi-volcano researcher and communication network now exists in the Taranaki region.

Start date:
01/10/2019

End date:
31/10/2020

Impact statement 1 > Research aim 1.3 > Critical step 1.3.2

Critical step title
Building Mātauranga-ā-iwi

Critical step statement (140 words)
Ongoing dialogue through a series of hui and wānanga (more than 4) has contributed to iwi/hapū understanding on Mātauranga-ā-iwi of the volcano and natural resources. This knowledge has been recorded as appropriate (e.g. oral recording, video, report). Collaboratively, through the partnerships built in CS1.3.1, researchers and local iwi/hapū have determined where it would be appropriate (and possible) to leverage Mātauranga-ā-iwi for use in the programme's modelling toolkits.

Start date:
01/11/2020

End date:
31/07/2021

Impact statement 1 > Research aim 1.3 > Critical step 1.3.3

Critical step title
Building dialogue on volcanic state/landscape

Critical step statement (140 words)
Brokered dialogues between iwi/hapū and volcanic researchers on volcanic state and landscape state have been held, and recorded as appropriate (e.g. oral recording, video, report). These dialogues were focused on the permanence or transience of landscape features – such as river catchments/landslides – and the potential impact on important values including Te Mana o te Wai.

Start date:
01/08/2021

End date:
30/04/2022

Impact statement 1 > Research aim 1.3 > Critical step 1.3.4

Critical step title
Traditional indicators and sites of unrest

Critical step statement (140 words)
Traditional indicators and sites of volcanic unrest (kokowai, springs, vents, warm ground) have been identified. This knowledge is stored in text, GIS (spatial), audio recordings, or other data formats, as appropriate.

Start date:
01/05/2022

End date:
31/01/2023

Impact statement 1 > Research aim 1.3 > Critical step 1.3.5

Critical step title
Mātauranga-ā-iwi knowledge and practices

Critical step statement (140 words)
Traditional Mātauranga-ā-iwi knowledge and practices (tikanga) specifically relating to volcano, alpine, river, and coastal hazards are identified and documented as appropriate (e.g. oral recording, video, report).

Start date:
01/02/2023

End date:
31/10/2023

Impact statement 1 > Research aim 1.3 > Critical step 1.3.6

Critical step title
Mātauranga-ā-iwi alongside modelling

Critical step statement (140 words)
Iwi-led wānanga have been completed that interweave Mātauranga-ā-iwi and practices alongside new scientific knowledge. Dissemination of our work, via our project website, is in Te Reo Māori along with English.

Start date:
01/11/2023
End date:
31/07/2024

Impact statement 1 > Research aim 1.4

Research aim title
Simulating on-going and disruptive volcanism

Research aim statement (140 words)
Develops a novel mathematical typology for integrating volcanic hazard on an all-of-NZ basis by a) developing new mathematical science through a 'test-bed' of the forecasting power of geochemical indicators; b) integrating these indicators into a novel probabilistic forecast tool for Taranaki. This will extend existing eruption history/pattern recognition approaches enabling a unique mechanical model of Taranaki to be created; c) taking a range of process-based models of volcanic phenomena (ashfall, pyroclastic flow, lahar, debris avalanche, gas) and creating mathematical relationships that describe geo-physical impacts on built (horizontal/vertical) infrastructure; and d) collates this information for estimation of hazard probabilities for societal consequences, including tracking uncertainties.

Start date:
01/10/2019
End date:
31/07/2024

Impact statement 1 > Research aim 1.4 > Critical step 1.4.1

Critical step title
Multiscale modelling of volcano dynamics

Critical step statement (140 words)
Bayesian hierarchical models (with uncertainty) have been used to quantify the timescales of magma ascent, magma and gas flux. A multiscale hierarchical model of internal volcano dynamics (geochemistry/petrology) has been developed.

Start date:
01/10/2019
End date:
31/10/2022

Impact statement 1 > Research aim 1.4 > Critical step 1.4.2

Critical step title
Statistical modelling of pre-/syn-eruptives

Critical step statement (140 words)
Links between geochemistry/petrology and the long-term eruption record (recurrence and style) have been thoroughly investigated to determine the forecasting power of different indicators. Findings from this investigation led to the formulation and testing of a simulation procedure based on geochemical observations from past events at Taranaki and/or analogue volcanoes.

Start date:
01/10/2019

End date:
31/10/2023

Impact statement 1 > Research aim 1.4 > Critical step 1.4.3

Critical step title
Statistical model of volcanic products

Critical step statement (140 words)
An efficient statistical model for generating estimates of different volcanic products (what ends up where) at a daily scale has been created. This model simulates eruptions using a mixture of tephra fall and collapses and daily weather conditions. The model has been tested and documented.

Start date:
01/10/2019

End date:
31/10/2023

Impact statement 1 > Research aim 1.4 > Critical step 1.4.4

Critical step title
Weather-modulated susceptibility

Critical step statement (140 words)
The model from CS1.4.3 has been extended by incorporating a synthetic synoptic weather stream along with a stochastic triggering condition, so that lahar initiation can be simulated. This extension has been added to the model documentation.

Start date:
01/10/2019

End date:
31/10/2023

Impact statement 1 > Research aim 1.4 > Critical step 1.4.5

Critical step title
Statistical emulators

Critical step statement (140 words)
Statistical emulators of geo-physical impacts have been constructed by running existing numerical flow models, under a statistical experimental design in parameter space. These statistical emulators simulate flows (ashfall, pyroclastic flow, lahar, debris avalanche, gas) incredibly fast and efficiently.

Start date:
01/10/2019

End date:
31/10/2023

Impact statement 1 > Research aim 1.4 > Critical step 1.4.6

Critical step title
Ash impacts modelling

Critical step statement (140 words)
An ash impacts model is completed and documented. This model uses a fast, efficient procedure to simulate both atmospheric densities (for air travel impacts) and deposition of ash across the North Island and beyond (for infrastructure impacts), on a day-to-day schedule incorporating the synthetic synoptic weather stream.

Start date:
01/10/2019

End date:
31/10/2023

Impact statement 1 > Research aim 1.4 > Critical step 1.4.7

Critical step title
Physical impacts for significant infrastructure

Critical step statement (140 words)
The dynamic volcano (CS1.4.2/1.4.3), flow susceptibility (CS1.4.4), emulators (CS1.4.5), and the ash impact (CS1.4.6) models have been combined to produce spatio-temporal estimates of geo-physical impacts, including uncertainties. To simulate the hazard impacts on the built environment, these geo-physical impacts have been linked to nationally significant infrastructure using mathematical vulnerability and susceptibility relationships.

Start date:
01/05/2021

End date:
31/10/2023

Impact statement 1 > Research aim 1.4 > Critical step 1.4.8

Critical step title
Visualisation tools

Critical step statement (140 words)
A suite of visualisation tools has been assembled and published on the website, where appropriate. These tools link volcano behaviour right through to monitoring/ impact observation and have been developed and adapted through engagement with stakeholders including local iwi/hapū.

Start date:
01/11/2023

End date:
31/07/2024

Impact statement 1 > Research aim 1.5

Research aim title
Geochemical tool chest for hazard forecasting

Research aim statement (140 words)
Develops new volcanic science to discover parameters that reliably indicate volcanic state and hazard potential, and apply these in relation to magma processes that govern specific eruption outcomes for Taranaki. This includes developing new chemical and physical approaches and experimental targets to parametrise settings for deep to surface processes.

Start date:
01/10/2019

End date:
31/07/2024

Impact statement 1 > Research aim 1.5 > Critical step 1.5.1

Critical step title
Pre-eruption diagnostic indicators

Critical step statement (140 words)
Geochemical and geophysical indicators have been developed from the record of past volcanism that: a) more robustly indicate the time to the next eruption; b) link chemical and geophysical properties to eruption volume/magnitude; and c) reliably forecast the likely duration of an eruption.

Start date:
01/10/2019

End date:
31/10/2022

Impact statement 1 > Research aim 1.5 > Critical step 1.5.2

Critical step title
Magma pathways

Critical step statement (140 words)
A model of crustal structure and magma source/processing is completed. This informs new scenarios of magma assembly and rise, including timescales and warning periods from geophysical detection of unrest to eruption. Environmental, chemical, and physical indicators of unrest are identified and codified, including traditional Māori knowledge (from RA1.3). Critical thresholds are established to indicate a shift to a new episode of activity.

Start date:
01/10/2019

End date:
31/10/2022

Impact statement 1 > Research aim 1.5 > Critical step 1.5.3

Critical step title
Eruption pathways

Critical step statement (140 words)
A quantitative framework of the environmental and conduit factors that lead to diverse eruption outcomes is complete, based on detailed textural and experimental studies on Taranaki eruption products. A suite of paleo-eruption scenarios for Taranaki are complete, informed and expanded by targeted knowledge of analogue volcanic systems at Vesuvius, Merapi and Colima. A library of indicators for the starting phases of specific eruption scenarios has been compiled from the first erupted products of scenarios built.

Start date:
01/10/2019

End date:
31/10/2023

Impact statement 1 > Research aim 1.5 > Critical step 1.5.4

Critical step title
Explosive potential

Critical step statement (140 words)
Short-lived isotopes (uranium decay series) have been used to quantify the partitioning of magma and gas and the transport of magmatic gas to eruption, based on Taranaki and analogue volcanoes. A framework of gas-pathways and eruption outcomes at Taranaki has been constructed from studies of melt inclusions and chemical diffusion in erupted minerals. The chemical and isotopic study results are integrated into a series of indicators that predict eruption explosivity.

Start date:
01/10/2019

End date:
31/10/2023

Impact statement 1 > Research aim 1.5 > Critical step 1.5.5

Critical step title
Realtime assessment

Critical step statement (140 words)
A quantitative assessment framework has been developed that enables the rapid updating of forecasts of the next events during an eruption sequence. Forecasts are updated based on rapid analysis of new eruption products, chemical and geophysical signals, and a library of highly detailed paleo-eruption scenarios.

Start date:
01/05/2021

End date:
31/07/2024

Research plan, methods & specialist resources

Research plan (560 words)
We seek to build much-needed capacity for New Zealand to adapt/transform under ***long duration and evolving natural hazard disruptions***, by focusing on a high-probability volcanic-disruption case posing great national-scale consequences. During such events, the nature of impacts and risks shift rapidly. To achieve this objective, we will: (1) build the science to better predict 'what-comes-next' during a disruption, including advancing our ability to capitalise on new information as it emerges (RAs1.3-1.5); and (2) create the tools, processes and experience that enables decision-makers to select robust strategies for transformation (RAs1.1-1.3). We demonstrate this approach through a major Taranaki volcanic scenario, anticipated by geological knowledge, but not yet experienced during European history.

Our research comprises five research aims (Fig. 1), with interconnected critical steps (see Gantt Chart). **RA1.1 (Co-creation processes; Wilson/Fairclough)** forms our foundation. For the Taranaki context, co-creation involves successive workshops/wānanga where stakeholders stress-test the utility of new decision-support tools (from RA1.2), define criteria to select robust strategies, and practice formulating and selecting strategies, all in a collaborative process that favours learning across multiple worldviews. **RA1.2 (Decision-support for dynamic transition; Smith/Wreford)** delivers the tools that enable stakeholders to *ex ante* identification of key risks, decision points and robust strategies. Defining features will be system-wide consideration of impacts, multi-scale applicability, adaptation to new information (from RA1.4), rapid deployment, and stakeholder-led co-design (from RA1.1). **RA1.3 (Leveraging Mātauranga Māori; Procter/Sciascia)** creates transition pathways for Iwi/hapū communities and businesses impact-based investment cases, by applying new robust probabilistic forecasts and knowledge of volcano behaviour (from RAs1.4-1.5) and leveraging decision-support tools (from RA1.2). It also establishes Mātauranga-ā-iwi knowledge of volcanic warning and hazard response. Under **RA1.4 (Simulating on-going & disruptive volcanism; Bebbington/Wang),** the forecasting power of quantitative indicators of volcanic potential (from RA1.5) are tested and refined, then incorporated into novel probabilistic forecasting models for Taranaki volcano. These will encompass a time-varying long-term view, alongside short-term changes during event sequences. By leveraging a range of process-based models of volcanic phenomena, forecasts are also extended to full simulations of geophysical impacts on society/economy, while continually tracking uncertainties. In **RA1.5 (Geochemical tool-chest for hazard forecasting; Brenna/Ukstins),** new volcanic science discovers parameters that reliably indicate volcanic state and hazard potential, based on magma processes that govern specific eruption outcomes at Taranaki. This includes developing new chemical and physical approaches and experiments to parametrise processes from deep-to-surface settings.

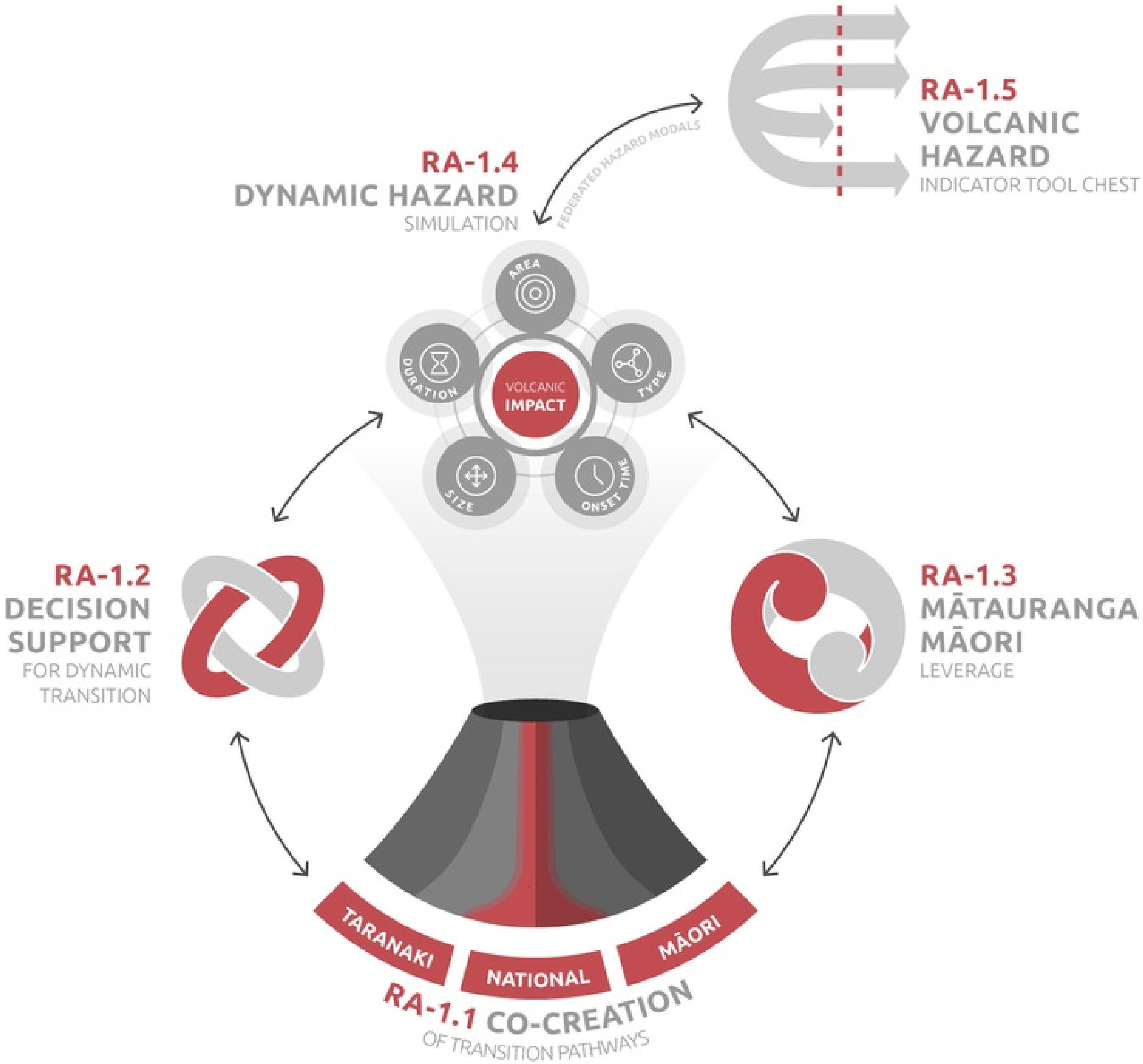
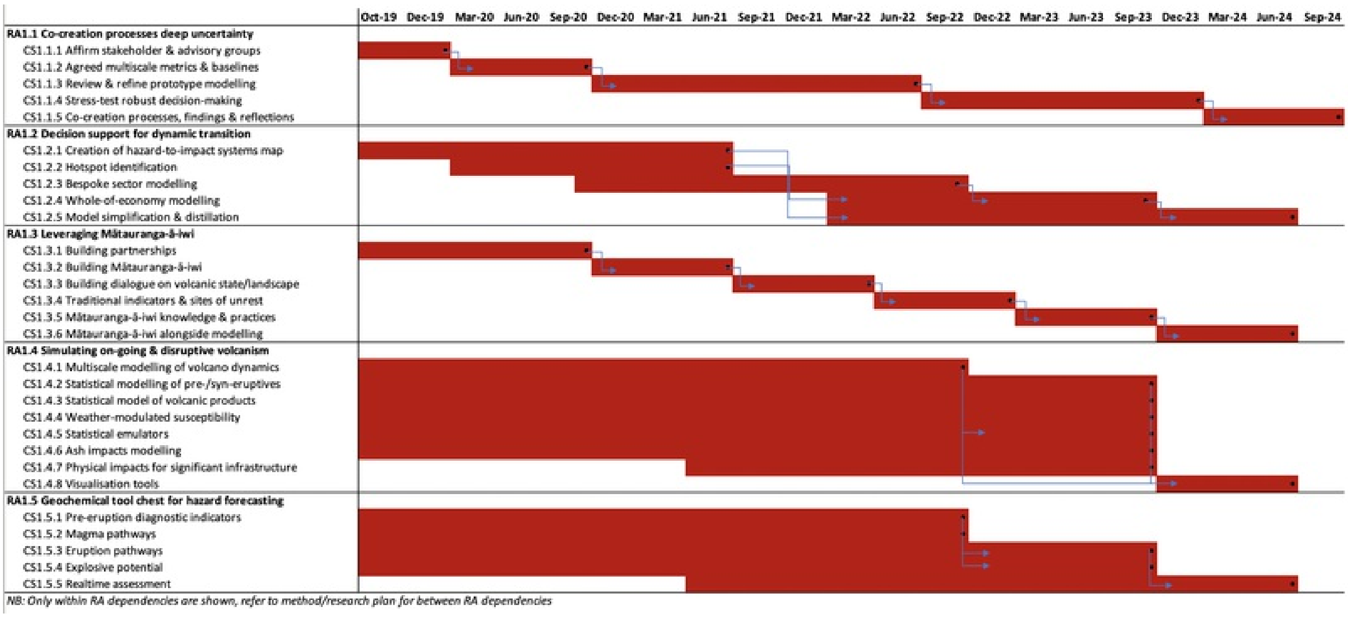


Figure 1: Project design and Research Aims (RA).

Regular monthly **project management** meetings between the science/RA co-leads will track progress and ensure ongoing iteration between all workstreams. An annual full-team meeting will be held in June/July of each year to highlight findings, track performance, and refine research directions for the following year.

To **manage technical risk**, our team (particularly RA1.2/RA1.4) will adopt best practice in software engineering. Specifically, we will apply agile processes that: a) continually deliver working prototypes using an incremental and modular design that adds science progressively; b) use collaborative co-design with stakeholders (leveraging Mātauranga-ā-iwi) to refine and stress-test working prototypes through regular face-to-face workshops (as per RA1.1); c) uniquely test volcanism indicators for predictive suitability, replacing/updating/adapting them on-the-fly as the research progresses; d) pay constant attention to technical excellence and good design through agile continuous iterative feedback between RAs (e.g. RA1.1 to/from RA1.2, RA1.2 to/from RA1.4, and RA1.4 to/from RA1.5); and e) use cloud-based services for **managing data and model** version (Git/GitHub) control.

Gantt Chart



Methods (1680 words)

Programme rationale and key research question: NZ is faced with several socio-economic risks including geo-political changes, environmental challenges (climate change, biodiversity loss, exposure to natural hazards) and technological disruption. We urgently require decision-making frameworks (tools/processes/practices) that answer: "*How best can communities, businesses, iwi and government transition through socio-economic disruption that is on-going and continuous*?" We address this dilemma through an *ex-ante*, but highly plausible, exemplar of volcanic unrest at Mt. Taranaki. **Our choice of Mt. Taranaki as a case study** is because it is the most likely NZ volcano to cause national-scale impacts over our lifetimes, with a 50% chance of erupting over the next 50 years (Damaschke et al., 2015). Moreover, once erupting Taranaki's activity is likely to continue for decades disrupting almost every aspect of society and economy.

How we will perform our research: We use an iterative co-creation process, that significantly leverages existing investments in the Resilience NSC, and progressively adds cutting-edge science in a global-first end-to-end assessment framework that significantly reduces uncertainty for decision-making as we transition through long-term volcanic unrest. Our research has five inter-linked Research Aims (NB: RA=Research Aim, CS=Critical Step (in **bold**), connections between RAs are made explicit (in *italics*), **rationale** for each is RA is provided following its title, and all **data/models are managed** by agile processes using cloud-computing services (Git for version control, GitHub for data/model storage).

RA1.1 Co-creation processes under uncertainty (Wilson and Fairclough)

Co-creation design will assess transition pathways for multiple stakeholders at local-to-national scales. Using an iterative approach, our stakeholders will help design, refine and stress-test our decision-support tools to create robust socio-economic transition pathways via *ex-ante* simulations under ongoing volcanic unrest. These pathways will be evaluated using multi-capital and intergenerational well-being metrics through space (community/district/region/nation) and across time (quarterly time-steps) over a 30-year horizon.

Key steps: a) Affirm stakeholder and advisory groups (**CS1.1.1**) – involves establishing a Terms of Reference for the groups and review group membership (current TaranakiCDEM/Taranaki RC/National Lifelines Council/DairyNZ/DoC/iwi/ResilienceNSC Infrastructure Advisory Group) and addition of new members as deemed necessary; b) Agreed multiscale metrics and baselines – involves co-designing with RA1.2 multiscale socio-economic metrics to measure transition, aligned with Treasury's National Living Standards Framework (Treasury, 2018b) (**CS1.1.2**), c) Review and refine prototype impact modelling (**CS1.1.3**) – involves collaboration with RA1.2 and RA1.4; d) Stress-test robust decision-making with RA1.2 (**CS1.1.4**) – requires **stakeholder/iwi-led** wānanga/workshops that create and record transitions pathways through the on-going volcanic disruption; and e) Co-creation processes, findings and reflections – wider dissemination of research findings/processes/modelling and record 'reflective learning' for future researchers (**CS1.1.5**).

RA1.2 Decision support for dynamic transition (Smith and Wreford)

To best protect the functioning of NZ's socio-economic system, we require science to support decision-making for the sectors that are most likely to be critically disrupted. Additionally, we require science to understand how the wider community may change, including enabling, incentivising or restricting behaviours, and the collection and distribution of resources to support those in need. Robust decision-support tools require a 'whole-of-system' understanding of the pathways through which physical impacts of an unfolding volcanic event, and resulting human responses, will instigate changes in well-being. For decision-support tools to be useful they must be deployed in a timely fashion, which will be aided here by pre-crisis testing, development and implementation.

Key steps: a) Creation of hazard-to-impact systems diagram (**CS1.2.1**) – easily updated cause-effect sequences (multiscale influence diagrams/Bayesian-network approaches/fault-tree analysis) propagating from trigger event through consequential hazard chain, to impact across multiple well-beings (aligned to Treasury's Living Standards Framework (King et al., 2018)); b) Hotspot identification (**CS1.2.2**) – network topology identifying key system components whose compromise amplifies (or whose addition dampens) disruption impacts; c) Sectoral modelling (**CS1.2.3**) – we co-design with our delivery partners (food/transport/energy/tourism) (contributes to *RA1.1, CS1.1.2&3*) **novel bespoke decision-support tools** (real options analysis/dynamic adaptive pathways/robust decision making), stress-test these tools under dynamically unfolding volcanic events, and develop robust adaptive strategies for action; d) Whole-of-economy modelling (**CS1.2.4**) – integrates the sectoral (**CS1.2.3**) with cutting-edge top-down stock-flow socio-economic (computable general equilibrium) models and, in turn, evaluates a set of resilience 'just transition' strategies reporting across multiple well-beings **under deep uncertainty** (contributes to *RA1.1, CS1.1.2-4*); e) Model simplification/distillation (**CS1.2.5**) – of our integrated complex socio-economic systems model using emulators (trained neural networks by-passing complex model coupling/chaining) enabling rapid deployment, including **for other types of disruptive events**.

RA1.3 Leveraging Mātauranga Māori (Procter and Sciascia)

It is imperative that we understand how people culturally-locked to locations of intense and continual disruption, make a transition through it. By leveraging Mātauranga-ā-iwi we will understand how people have previously adapted under volcanic unrest, identifying traditional indicators and sites of volcanic state through co-creating processes alongside iwi to ensure that their māturanga is interwoven into key decision-making processes. The latter includes stress-testing robust decision-support tools for 'stay and defend' approaches to Maori business (Tourism/Agriculture) during ongoing (semi-permanent) disruption conditions with rapid change and evolving risks. Dissemination of our work, via our project website, will be in Te Reo Māori along with English and we are committed to returning this knowledge to the communities and iwi through a series of wānanga.

Key steps: a) Build partnerships and an iwi-volcano researcher and communication network in the Taranaki region (**CS1.3.1**), b) Build dialogue and understanding on Mātauranga-ā-iwi of the volcano, its natural resources, and how we may leverage that knowledge in development of our decision-support toolkits (**CS1.3.2**) – contributes to *RAs 1.1 (CS1.1.2)* and *1.2 (CS1.2.3&4)*; c) Build engagement and dialogue on volcanic state and landscape, brokering dialogues about the permanence or transience of landscape features including landslides/river catchments (including Te Mana o te Wai) (**CS1.3.3**) – contributes to *RA1.4 (CS1.4.4)*; d) identify traditional indicators and sites of volcanic unrest (kokowai/springs/vents/warm ground) (**CS1.3.4**) – contributes to *RA1.4 (CS1.4.2)*; e) identify traditional Mātauranga-ā-iwi and tikanga (protocols/practices) of volcano/alpine/river/coastal hazards in the Taranaki region (**CS1.3.5**); and f) integrates scientific knowledge alongside new Mātauranga-ā-iwi practices (**CS1.3.6**) – contributes to *RA1.1 (CS1.1.4)*, creating transition pathways for iwi/hapū and Māori land trusts by applying Mātauranga-ā-iwi traditional and new knowledge into our decision support tools, including for impact-based investing.

RA1.4 Simulating on-going & disruptive volcanism (Bebbington and Wang)

Develops a novel statistical/mathematical methodology for integrating volcanic hazards on an all-of-NZ basis by a) developing new statistical science through a 'test-bed' of the forecasting power of volcanic potential indicators (derived from *RA.15, CS1.5-5*); b) integrating these indicators into a novel probabilistic forecast tool for Taranaki that includes precursory behaviour and dynamically updates through activity cycles. This extends the static eruption history/pattern recognition approaches creating a unique computational/mechanical model of Taranaki; c) leveraging a range of existing process-based models of volcanic phenomena, including ashfall (Turner et al., 2014); pyroclastic flow (Procter et al., 2010; Lube et al., 2015); lahar (Procter et al., 2012); debris avalanche (Roverato et al., 2104; Tost et al., 2014)); acid gas/leachates (Cronin et al., 2003; 2014), and creating statistical relationships that describe physical impacts on built infrastructure; and d) collates this information for estimation of impact hazard probabilities for the socio-economic consequences modelling (*RA1.2, CS1.2.3&4*), including tracking uncertainties. Overall, this RA develops a **world-first test-bed** for rapidly evaluating and selecting indicators, from empirical geochemistry/petrology studies based on their predictive power in determining key characteristics of volcanism (magnitude/onset time/eruption style/duration). Indicator selection is an iterative process involving selection/statistical testing/adoption/discarding – thus, an indicator may initially be adopted, but later replaced supplemented as better indicators become available.

Key steps: a) Multiscale hierarchical model of internal volcano dynamics developed (**CS1.4.1**) – quantifies the evolution of geochemical and petrological states using Bayesian hierarchical models (with uncertainty); b) Statistical model of pre- and syn-eruptive indicators are developed – links geochemistry foundations to existing long-term record, using point-process models with geochemical data as co-variants, and analogues to calibrate geochemistry/geophysics linkages. False alarms/stalled eruptions are included (**CS1.4.2**); c) simulates eruptions using mixture of tephra fall and collapses, establishing an efficient model for predicting distribution (**CS1.4.3**); d) weather-modulated susceptibility for post-eruptive flow-events/lahars determined (**CS1.4.4**); e) Statistical emulators constructed, permitting fast efficient simulation of flows – this represents a significant advance over existing numerical flow models, which run slowly, making their use in nimble syn-event simulations difficult (**CS1.4.5**); f) Ash impacts model (incorporating weather) created – simulates atmospheric densities (for air travel) and deposition of ash across North Island and beyond (**CS1.4.6**); g) regional impacts determined for national significant infrastructure – combines **CS1.4.2-6** to determine physical infrastructure damage spatio-temporally (contributes to *RA1.2, CS1.2.3&4*) (**CS1.4.7**); and h) Suite of visualization tools assembled (**CS1.4.8**).

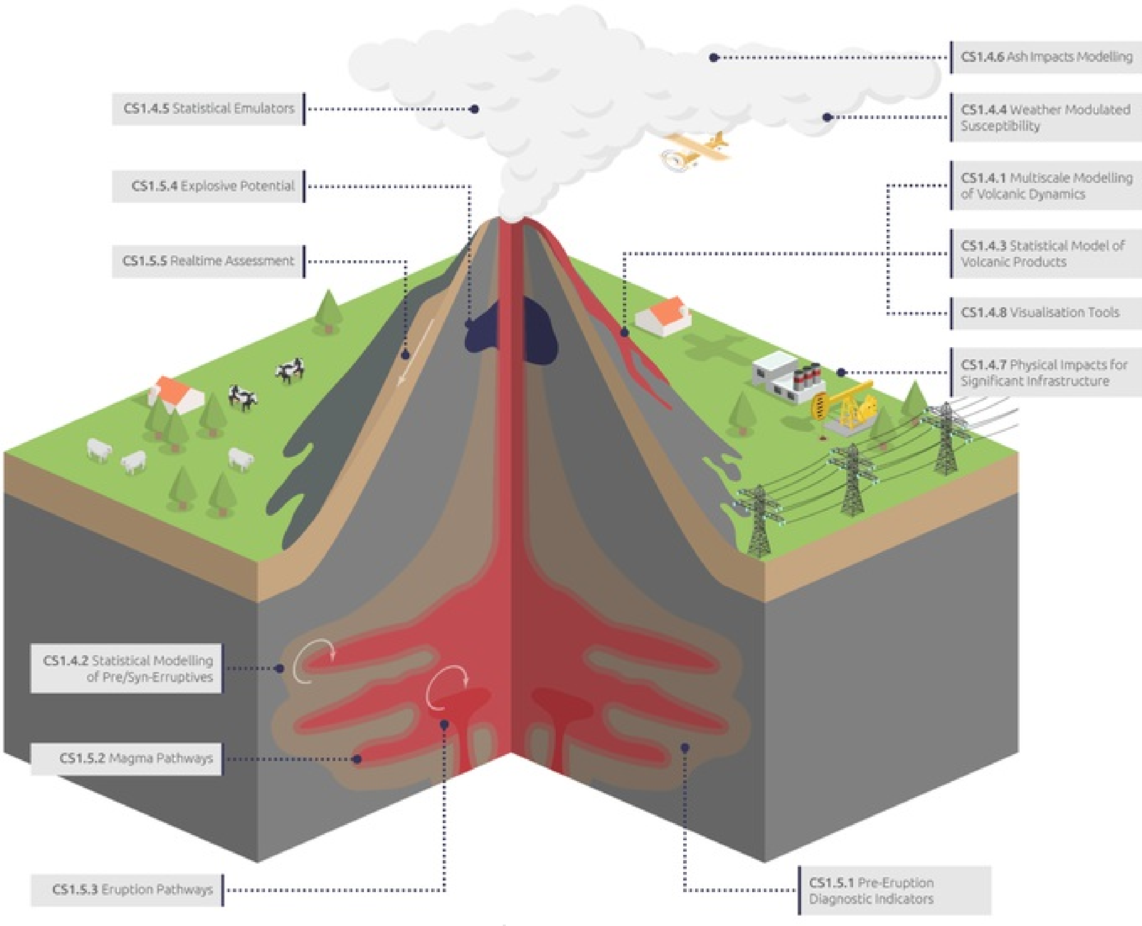


Figure 2 Volcanic potential indicators, from RA1.4 and RA1.5

RA1.5 Geochemical tool chest for hazard forecasting (Brenna and Ukstins)

Developing new volcanic science to discover parameters that reliably indicate volcanic state, hazard potential, as well as specific eruption outcomes. This includes developing new chemical and physical approaches and experimental targets to parametrise settings for deep-to-surface volcanic processes (Fig. 2). Output indicators from this research streams are continuously tested through *RA1.4*'s statistical test-bed.

Key steps: a) Pre-eruption diagnostic indicators geochemical and geo-physical indicators are created from records of past volcanism that more robustly indicate time to the next eruption and better link chemical and geophysical properties to eruption volume/magnitude (**CS1.5.1**); b) New scenarios of magma assembly and rise are generated that provide timescales and warning periods from geophysical detection-of-unrest to eruption, identification and coding of chemical and physical indicators of unrest (including from Māori observation and knowledge), and critical thresholds are established of 'shifts' to new episodes of activity (**CS1.5.2**); c) A quantitative framework of environment and conduit factors leading to diverse eruption outcomes is generated along with a library of paleo-eruption scenarios, based on detailed textual and experimental studies of Taranaki (also analogue volcanic systems e.g. Vesuvius/Merapi/Colima) eruption products (**CS1.5.3**); d) Short-lived isotopes (Uranium decay series) are used to quantify the partitioning of magma/gas, the transport of magmatic gas to eruption based on Taranaki (and analogue systems), and to predict eruption explosivity (**CS1.5.4**); and e) a quantitative framework is established that enables rapid update (real-time assessment) of forecasts of the next events during an eruptive sequence, based on the rapid analysis of new eruptive productions, chemical and geophysical signals and the library of paleo-eruption scenarios as per *CS1.5.3* (**CS1.5.5**).

Specialist resources (560 words)

Analytical equipment

We have arranged reciprocal access for critical instrumentation with our key international collaborators. There are other alternative back-up laboratories for the main instruments. The resources we need include:

1. Electron Microprobe Analysis – for analysing crystal histories and compositional zonation, and compositions of melt-inclusions. We can access a standard instrument at Victoria University ($500/day), a more-sensitive instrument for mapping and trace element analysis at the University of Iowa through A.Prof. Ukstins ($US600/day), and an ultra-high resolution (Field-emission Electron Microprobe) instrument currently being purchased/installed at University of Auckland ($800/day)
2. Laser-Ablation Inductively-Coupled Mass-Spectrometry Analysis (LA-ICP-MS), or solution ICP-MS. Trace-elemental analysis of single-crystals and zonation of crystals will be carried out at University of Auckland (standard LA-ICP-MS $600/day), with a higher resolution multi-collector mass-spectrometer for in-crystal strontium isotopic analysis at University of Otago ($1500/day).
3. Secondary Ion Mass Spectrometry (SIMS or Ion microprobe) – to analyse light elemental diffusion (e.g., Li in feldspar), and water/volatile content of melt inclusions within minerals. This is available via collaborative arrangements with A.Prof. Ukstins at the Arizona State University ($US1000/day)
4. Fourier Transform Infrared Analysis (FTIR), to analyse carbon dioxide and water content within glasses and melt inclusions. Standard instruments are at Massey, Canterbury and Auckland universities ($250/day), with higher resolution and mapping capabilities at the Australian Synchrotron (Schipper, Cronin, Ukstins, Brenna and Kennedy are expert users and our international collaborator Prof. Rushmer sits on the Australian Synchrotron steering committee).
5. Isotopic clean laboratories, U-Series isotopic processing lines and high-resolution multi-collector mass spectrometers for U-series, Pb, Sr, Nd, Re-Os isotopic systems as well as U-Series dating. These facilities are available via a new Thermo-Analytical demonstration lab at Macquarie University managed by our international collaborator Prof. Turner ($AU1000-3000/day depending on analytical methods).
6. Micro-Computed Tomography – for analysis of magma-vesiculation/bubble textures and the determination of explosivity of eruptions. This is available at University of Auckland and via the Imaging and Medical Beamline of the Australian Synchrotron (Schipper, Cronin and Kennedy are expert users). In addition, via collaborators of Cronin, specialised high-resolution microtomography systems can be accessed at other synchrotrons around the world (e.g., UK and Berkeley)
7. High-precision Argon-Argon radiometric dating – for age analysis of key deposits. Can be obtained via a long-term collaborator at Oregon State University ($US700/determination).

Experimental equipment

1. Physical explosion experimental equipment and laboratory at Ludwigs Maximillian University, Munich, Germany, which enables the pressurisation and explosion of Taranaki samples to simulate conduit and ejection conditions. This facility is available to expert users Cronin and Kennedy via our international partners Dr Scheu and Prof. Dingwell ($NZ20-30k per experimental season – 2-3 months' work).
2. High-temperature, high-pressure experimental melt/crystallisation laboratory at University of Rome – for calibration of crystallisation histories and rise conditions for Taranaki magmas. This facility is available for expert user Brenna for nominal costs ($NZ5k per series of experiments).
3. High-temperature magma viscosity experimental laboratory at University of Canterbury. This is available via Kennedy (~$300/day).

Computing/modelling equipment

All computing, modelling and virtual-reality simulation resources are available within Massey University, Market Economics, and especially via pre-arranged time on the NeSI high performance computing system in New Zealand, for which Procter, Mead and McDonald are expert users. In addition, Procter has long-standing collaborative arrangements with the supercomputer centre of the State University of New York in Buffalo, USA and Mead with CSIRO, Australia.

Funding requested

Impact statement funding

Multiscale decision support tools that enable communities, farming/industry/business, iwi and government to create robust socio-economic transition pathways through ongoing disruption.

Start date	Months	Funding			Total annual funding
01/10/2019	12	$2,735,357.00 GST excl. amount	$410,303.55 GST amount	$3,145,660.55 Total amount	$3,145,660.55
01/10/2020	12	$2,735,357.00 GST excl. amount	$410,303.55 GST amount	$3,145,660.55 Total amount	$3,145,660.55
01/10/2021	12	$2,735,357.00 GST excl. amount	$410,303.55 GST amount	$3,145,660.55 Total amount	$3,145,660.55
01/10/2022	12	$2,735,357.00 GST excl. amount	$410,303.55 GST amount	$3,145,660.55 Total amount	$3,145,660.55
01/10/2023	12	$2,735,357.00 GST excl. amount	$410,303.55 GST amount	$3,145,660.55 Total amount	$3,145,660.55
	Total:	$13,676,785.00 GST excl. amount	$2,051,517.75 GST amount	$15,728,302.75 Total amount	**$15,728,302.75**

Project budget

Personnel:	292,608.00
General operating expenses:	649,081.00
Building depreciation/rental:	0.00
Equipment depreciation/rental:	0.00
Overheads:	314,001.00
Subcontracting:	1,479,668.00
Other expenditure:	0.00
Average annual budget:	**2,735,358.00**

Additional budget information

Project team

Year 1 FTE figures

Name	Organisation	Role	Include CV in print	ORCID
Shane Cronin	The University of Auckland	Key researcher, Science leader	✔	https://orcid.org/0000-0001-7499-603X
Thomas Wilson	University of Canterbury	Key researcher, Leader	✔	https://orcid.org/0000-0002-8816-0708
Marco Brenna	University of Otago	Key researcher	✔	https://orcid.org/0000-0001-6096-6999
James Scott	University of Otago	Other		https://orcid.org/0000-0001-5185-6261
James White	University of Otago	Other		Not invited
Tracy Rushmer	Macquarie University	Key researcher	✔	https://orcid.org/0000-0003-0192-2384
Postdoctoral (TBN)	The University of Auckland	Post-doctoral researcher		Not invited
Postdoctoral TBN	Market Economics Ltd	Post-doctoral researcher		Not invited
Mark Bebbington	Massey University	Key researcher, Leader	✔	https://orcid.org/0000-0003-3504-7418
Garry McDonald	Market Economics Ltd/Director	Key researcher, Science leader	✔	Invitation sent

Nicola Smith	Market Economics	Key researcher, Leader	✔	Invitation sent
Emily Harvey	Market Economics	Key researcher	✔	https://orcid.org/0000-0002-8134-3843
Simon Turner	Macquarie University	Key researcher	✔	https://orcid.org/0000-0002-6426-6495
Michael Rowe	The University of Auckland	Other		https://orcid.org/0000-0002-8052-2882
Ben Kennedy	The University of Canterbury	Key researcher	✔	https://orcid.org/0000-0001-7235-6493
Rita Bento-Allpress	The University of Auckland	Contract manager		Not invited
Aaron McCallion	Waka Digital Ltd	Key researcher	✔	Invitation sent
Ting Wang	The University of Otago	Key researcher, Leader	✔	https://orcid.org/0000-0002-4767-3777
Colin Wilson	Victoria University of Wellington	Other		Not invited
Joel Baker	The University of Auckland	Key researcher, Leader	✔	Invitation sent
Jonathon Procter	Massey University	Key researcher	✔	Invitation sent
Jan Lindsay	The University of Auckland	Other		Not invited
Gert Lube	Massey University	Other		Invitation sent
George Perry	The University of Auckland	Other		Not invited

Phil Shane	University of Auckland	Other		https://orcid.org/0000-0002-7824-1184
Arthur Jolly	GNS Science	Key researcher	✔	https://orcid.org/0000-0003-1020-9062
Sigrun Hreinsdottir	GNS Science	Other		https://orcid.org/0000-0003-0143-1251
Brad Scott	GNS Science	Other		https://orcid.org/0000-0003-3560-0287
Geoff Kilgour	GNS	Key researcher	✔	https://orcid.org/0000-0003-0361-1555
Dave Rogers	Department of Conservation	Other		Invitation sent
Teresa Gordon	Taranaki Regional Council	Other		https://orcid.org/0000-0002-9499-1188
Anita Wreford	Lincoln University	Key researcher	✔	https://orcid.org/0000-0002-9546-4080
Roger Fairclough	Neo Leaf Global Ltd	Other		https://orcid.org/0000-0003-0387-1859
Stuart Mead	Massey University	Key researcher	✔	Invitation sent
Kirsty Lee Thomas	GNS Science	Other		Not invited
Ingrid Ukstins	Iowa State University	Key researcher	✔	https://orcid.org/0000-0002-2315-9626
Christina Magill	Macquarie University	Key researcher	✔	https://orcid.org/0000-0001-8872-1678

GUIDO GIORDANO	Università Roma Tre	Other		https://orcid.org/0000-0002-5819-443X
Mary Jo Vergara	Market Economics Ltd	Other		Not invited
Acushla Sciascia	Massey University	Key researcher	✔	Invitation sent
Ian Schipper	Victoria University Wellington	Key researcher	✔	Invitation sent
Natalia Pardo	University de Las Andes	Key researcher	✔	https://orcid.org/0000-0002-8247-4116
Roberto Sulpizio		Key researcher	✔	https://orcid.org/0000-0002-3930-5421
Postdoctoral (TBN)	The University of Canterbury	Post-doctoral researcher		Not invited
Postdoctoral University	Massey University	Post-doctoral researcher		Not invited
Cynthia Werner		Key researcher	✔	Invitation sent
Federico Lucchi		Other		Invitation sent

Key relationships

End users

Impact statements in your application

Number	Title
IS 1	Multiscale decision support tools that enable communities, farming/industry/business, iwi and government to create robust socio-economic transition pathways through ongoing disruption.

Organisation	IS 1
Civil Aviation Authority	✔
Earthquake Commission (EQC)	✔
New Zealand Airports Association	✔
AIG	✔
MBIE - Energy Markets	✔
Ministry for the Environment	✔
New Zealand Treasury - National Infrastructure Unit	✔
New Plymouth District Council	✔
Local Government New Zealand	✔
Ministry of Business Innovation & Employment	✔
Aon	✔
Petroleum Exploration and Production Association of New Zealand	✔
MPI	✔
Taranaki Regional Council	✔
DoC	✔
DairyNZ	✔
Taranaki CDEM	✔
New Zealand Transport Agency	✔
New Zealand Lifelines Council	✔
Department of Prime Minister & Cabinet - Ministry of Civil Defence & Emergency Management	✔
Ministry of Transport	✔
Department of Prime Minister & Cabinet - National Risk Unit	✔
Ministry of Civil Defence and Emergency Management (MCDEM)	✔
Department of Internal Affairs - Central Government Local Government Partnerships Group	✔
MBIE - Petroleum and Minerals	✔

International collaborations/partnerships

Organisation	Organisation country:	Researcher/project name:
Università degli studi di Bari Aldo Moro	Italy	Prof. Roberto Sulpizio
Università di Bologna	Italy	A.Prof. Federico Lucchi
Università Roma Tre	Italy	Prof. Guido Giordano
Macquarie University	Australia	Prof. Simon Turner
Macquarie University	Australia	A.Prof. Tracy Rushmer
The University of Iowa	United States of America (the)	A.Prof. Ingrid Ukstins
Ludwig-Maximillan Universitat	Germany	Dr Bettina Scheu
Ludwig-Maximillan Universitat	Germany	Dr Cristian Montanaro
Universidad de Las Andes	Colombia	A.Prof Natalia Pardo

International collaboration

Our project will be assisted by world-renowned scientists with compelling international track-records. Based in Europe, Australia and the USA, our collaborators bring internationally-recognised mentorship to the programme, a sounding-board for managing technical risks, and strong established collaborative relationships with the research team, including joint research.

Italian volcanologists, Prof. Roberto Sulpizio, A.Prof. Federico Lucchi, Prof. Guido Giordano

Our three Italian colleagues are existing collaborators of Cronin and all are specialists on re-awakening stratovolcanoes, with experience around the world. The leverage that they bring lies in decades of experience on managing the risks of stratovolcanoes at Etna, Stromboli, Vulcano and Vesuvius. Vesuvius poses an equivalent problem to Mt. Taranaki, with its last eruption occurring during 1944, but there is an expectation of enduring activity that will force a major transformation of the mega-city of Naples. Vulcano is a major touristic centre, with its last eruption in 1888. Both Stromboli and Etna have been in a semi-permanent eruptive state for centuries, with large explosive eruptions on a semi-regular basis, posing ongoing adaptation and economic transformation challenges. Sulpizio is a specialist in understanding hazard processes and eruptive scenarios from deposit sequences and will form part of the teams working on CS1.5.3 and CS1.5.5. Lucchi is a specialist in volcanic collapse, mass-flow deposits and complex volcanic transitions. His expertise will help translate the steps from eruption events into the multi-hazards that follow them, including lahars, enduring changes to catchments, and major periods of erosion. Flank-collapse and major volcanic landslides are the greatest hazards anticipated at Mt. Taranaki and will induce fundamental changes to the landscape, including changes to river/water supply catchments and the possible complete abandonment of land buried by tens of metres of volcanic debris. Lucchi will be a key resource to help us interpret the pre-conditions for volcanic collapse in CS1.5.1. Giordano specialises in chemical-volcanic processes, pre-explosive magmatic conditions and also the temperature properties of volcanic flows, especially pyroclastic flows. His work will contribute to the aims of CS1.5.4.

Australian geochemists, Prof. Simon Turner, A.Prof. Tracy Rushmer

Our work on the rise rates of magmas, the detection of gas-state and explosive potential of magmas, and the understanding of the overall structure of the magma system beneath Mt. Taranaki, is contingent upon a range of detailed trace elemental and especially isotopic analyses. Turner is the leader of a major new geochemical laboratory facility, the southern Hemisphere demonstration laboratory for Thermo Scientific at Macquarie University. He is also the world leader in application of U-Series isotopic techniques to understand the timescales of magma assembly and rise and to thereby understand the gas content that magmas bring to the surface. He will apply these techniques to Taranaki and analogue systems in order to better achieve CS1.5.4 and build rapid assessment tools to track ongoing changes in eruptions for CS1.5.5. Rushmer is a specialist on the application of synchrotron x-ray methods to understand magmatic processes, as well as experimental magma-studies. Her experimental approaches will form a major support to CS1.5.1 and CS1.5.2. Both Turner and Rushmer facilitate access to unique geochemical facilities that are not available in New Zealand.

US volcanologist/geochemist, A.Prof. Ingrid Ukstins

Ukstins is a specialist in the micro-scale analysis of crystals and volatiles in magmas, with an emphasis on evaluating explosive vs. effusive volcanism and understanding from petrological techniques the rise rates of magmas to eruption. She also runs a high-precision electron microprobe laboratory at the University of Iowa and is an expert of other microanalytical techniques such as Secondary Ion Mass Spectrometry. Her access to these resources will make her a key participant in achievement of RA1.5. She, along with Dr Marco Brenna are ideally placed to lead the RA1.5, with both having a complementary range of background skills. Ukstins has worked in large igneous provinces of China and Arabia, as well as in ongoing erupting areas in Iceland and Chile. Her wide experience in a range of analytical techniques means that she provides a broad overview needed to co-manage RA1.5.

German experimental laboratories collaborators: Dr Bettina Scheu and Dr Cristian Montanaro

The experimental volcanology laboratory at Ludwigs Maximillian University of Munich is world renowned and unique. Here we can carry out a range of high-pressure explosion experiments to understand magma fragmentation, conduit flow and eruption column steadiness. The latter is crucial for determining if eruption columns will produce stable tephra falls or collapse to produce deadly pyroclastic flows. They also enable us to understand the stability of lava domes rapidly during a crisis, as well as to simulate a range of magma-hydrothermal interactions and explosive eruptions. Scheu and Montanaro will contribute most strongly to CS1.5.3 and CS1.5.5.

Subcontracting

Impact statement

Multiscale decision support tools that enable communities, farming/industry/business, iwi and government to create robust socio-economic transition pathways through ongoing disruption.

Subcontracting organisation:	Subcontracting status:	Year 1	Year 2	Year 3	Year 4	Year 5
Market Economics Ltd	Letter of Intent	$424,925.00	$424,925.00	$424,925.00	$424,925.00	$424,925.00
Cynthia Werner	Letter of Intent	$57,779.45	$57,779.45	$57,779.45	$57,779.45	$57,779.45
Waka Digital Ltd	Letter of Intent	$54,050.00	$54,050.00	$54,050.00	$54,050.00	$54,050.00
Neoleaf Global Ltd	Letter of Intent	$65,952.50	$65,952.50	$65,952.50	$65,952.50	$65,952.50
Massey University	Letter of Intent	$370,116.00	$370,116.00	$370,116.00	$370,116.00	$370,116.00
The University of Otago	Letter of Intent	$125,314.35	$125,314.35	$125,314.35	$125,314.35	$125,314.35
The University of Canterbury	Letter of Intent	$387,046.30	$387,046.30	$387,046.30	$387,046.30	$387,046.30
Victoria University of Wellington	Letter of Intent	$37,660.20	$37,660.20	$37,660.20	$37,660.20	$37,660.20
Lincoln University	Letter of Intent	$45,634.30	$45,634.30	$45,634.30	$45,634.30	$45,634.30
GNS Science	Letter of Intent	$133,137.80	$133,137.80	$133,137.80	$133,137.80	$133,137.80
	Total	**$1,701,615.90**	**$1,701,615.90**	**$1,701,615.90**	**$1,701,615.90**	**$1,701,615.90**

Supporting information

Intellectual property management

Intellectual property management (560 words)
Intellectual Property (IP) Management Team

An IP Management Team will be established to deal with IP. We will have one representative from each participating organisation including partnership end-user/iwi if they desire. The IP management team will be responsible for all IP generated during our programme. The IP management team representatives (and/or their appointed specialist IP support representatives) will meet at least once a year.

Guidelines for IP Management

All IP arrangements will be recorded through subcontracts and in Terms of Reference for co-creation processes in alignment with the following broad-level guidelines:

1. *Existing IP*: The existing IP owned by a party will remain with that party, but each party will make their existing IP available, for the purpose of this research programme.
2. *Indigenous IP:* Mātauranga Māori is a living taonga and is subject to the rights in the Treaty of Waitangi. In recognition of this, processes around indigenous IP and data will be thoroughly discussed with all iwi end-users at the beginning of the programme, in conjunction with the Te Mana Raraunga (Māori Data Sovereignty Network), and we will be reviewed at our annual (or as required) IP Management Team meetings.
3. *Freedom to operate*: We will have access to all existing IP made available for the programme. We will continually check our freedom to operate with all end-users including iwi.
4. *New IP availability*: A key principle of our IP management is that any IP generated be made available in order to achieve the goals of our research programme, including potentially development of freely available CDEM guidelines for transitioning under the ongoing disruption of a Taranaki/NZ volcanic event. In this regard, there is no need to protect the vast majority of IP within NZ, but due management of the process of information release will be required.
5. *New IP protection*: It is possible that the programme may result in new commercial products or services requiring legal protection. The IP Management Team through their annual review process (or as required) will work with all participating organisations to ensure that new commercial products or services are identified to all participating organisations. Ownership of any such IP will rest with the contributing organisation/s to the programme undertaking that area of research.

Protection of IP

If key participating organisations/end-users require certain data to be held confidentially, this will be dealt with by ‘ring fencing’ activity associated with that data and agreeing that outputs that are available to the wider team to ensure the programme may operate.

Special ethical and regulatory requirements

Special ethical and regulatory requirements (280 words)

There are no specialist ethical or regulatory approvals required to undertake the proposed research.

Proposal Glossary

Word/acronym/ abbreviation/te reo Māori	Full description/translation
CAA	Civil Aviation Authority
CDEM	Civil Defence and Emergency Management
Co-creation	Research conducted jointly between practitioners or the community and academics, with equal relationships, to empower people to become agents of change
CS	Critical Step
DIA	Department of Internal Affairs
DPMC	Department of the Prime Minister and Cabinet
Hapū	*Te Reo Māori*: primary governance unit. Clusters of whanau (extended families) that form a social grouping with a shared territory. The word is often interpreted as 'sub-tribe'.
Hui	*Te Reo Māori*: gathering or meeting
Iwi	*Te Reo Māori:* largest social/economic/political units in Māori society, linked by descent from a common ancestor or ancestors (shared whakapapa). The word is often interpreted as 'tribe'.
Kaitiaki	*Te Reo Māori:* guardians, custodians, caregivers
Kaitiakitanga	*Te Reo Māori:* guardianship, stewardship, trusteeship
Lahar	A violent mudflow or debris flow composed of a slurry of pyroclastic material, rocky debris and water, formed on volcanoes
Magma	Molten rock beneath the Earth's surface, consisting of a mixture of melt and crystals in any relative proportion
Mātauranga-ā-iwi	*Te Reo Māori:* Iwi knowledge - defined as the relationship between the tribe and its land base. Mātauranga-a-iwi is knowledge specific to an iwi and its rohe (tribal area).
Mātauranga Māori	*Te Reo Māori:* Māori knowledge - the body of knowledge originating from Māori ancestors, including the Māori world view and perspectives, Māori creativity and cultural practices.
ME	Market Economics
MED	Ministry of Economic Development
MERIT	Measuring the Economic Resilience of Infrastructure Tool (McDonald et al., 2018; Smith et al., 2017; 2018)
MBIE	Ministry for Business Innovation and Employment
MCDEM	Ministry of Civil Defence and Emergency Management
NDRS	Proposed *National Disaster Resilience Strategy* currently under consideration in the House.
NHRP	National Hazard Resilience Platform
NPS-UDC	National Policy Statement on Urban Development Capacity
NZTA	New Zealand Transport Authority
PEPANZ	Petroleum Exploration & Production New Zealand
Pre- and syn-eruptive	Before and at the time of an eruption
Pyroclastic flow	A ground-hugging, high-velocity and superheated gas-particle flow that travels at high speeds outwards from volcanoes to destroy everything in their path.
RA	Research Aim
RAID	Risk, Assumptions, Issues, Dependencies: a common analysis used in risk assessment.
RC	Regional Council
Resilience NSC	Resilience to Nature's Challenges National Science Challenge
RiskScape	Joint venture with NIWA and GNS Science to provide a modular framework to estimate impacts and losses for assets exposed to natural hazards.
SAM	Smart models for Aquifer Management: MBIE funded-research programme, 2014-2018.
Stratovolcano	A conical volcano built up by many layers (strata) of hardened lava, tephra, pumice and ash. These volcanoes are characterised by a steep profile and periodic, explosive eruptions.
Taiao	*Te Reo Māori:* the natural world or environment
Taonga	*Te Reo Māori:* property possession, treasure, anything prized - applied to anything considered to be of value including socially or culturally valuable objects, resources, phenomenon, ideas and techniques.

Tangata Whenua	*Te Reo Māori:* the people of the land, i.e. the iwi or hapū which have mana whenua (customary authority) over a particular area.
Te Mauri o Te Wai	*Te Reo Māori:* The life supporting capacity, life force of water
Tikanga	*Te Reo Māori:* correct procedure, custom, lore, method, meaning, protocol. The customary system of values and practices that have developed over time and are deeply embedded in a cultural context.
Wānanga	*Te Reo Māori:* conference, forum, meeting of ideas, seminar.
Whakaoranga	*Te Reo Māori: r*esilience - the capacity of whānau to overcome adversity, flourish and enjoy better health and wellbeing.
Whakapapa	*Te Reo Māori:* genealogy, ancestral lineage– including not just human ancestors but all living things, the earth and sky, and the creation of the universe.
Whānau	*Te Reo Māori:* extended family grouping. Basic social unit of Māori society.
W/ISE	Waikato Integrated Scenario Explorer/(Auckland) Integrated Scenario Explorer (Rutledge et al., 2008)

References

Bebbington, M., Cronin, S.J., Chapman, I., Turner, M.B. 2008. Quantifying volcanic ashfall hazard to electricity infrastructure. Journal of Volcanology and Geothermal Research 177: 1055-1062.

Cassidy, M., Manga, M., Cashman, K., Bachmann, O., 2018. Controls on explosive-effusive volcanic eruption styles. Nature Communications DOI: 10.1038/s41467-018-05293-3

CDEM, 2018. National Disaster Resilience Strategy (Draft Consultation Document) https://www.civildefence.govt.nz/assets/Uploads/publications/National-Disaster-Resilience-Strategy/National-Disaster-Resilience-Strategy-FOR-PUBLIC-CONSULTATON-11-October-2018.pdf

Cronin, S.J., Neall, V.E., Lecointre, J.A., Hedley, M.J., Loganathan, P., 2003. Environmental hazards of fluoride in volcanic ash: a case study from Ruapehu volcano, New Zealand. Journal of Volcanology and Geothermal Research 121: 271-291.

Cronin, S.J., Stewart, C., Zernack, A.V., Brenna, M., Procter, J.N., Pardo, N., Christenson, B., Wilson, T., Stewart, R.B., Irwin, M., 2014. Volcanic ash leachate compositions and assessment of health and agricultural hazards from 2012 hydrothermal eruptions, Tongariro, New Zealand. Journal of Volcanology and Geothermal Research 286: 233-247.

Damaschke, M., Cronin, S.J., Holt, K.A., Bebbington, M.S., Hogg, A., 2017. A new 30,000-year high-precision eruption history for the andesitic Mt Taranaki, North Island, New Zealand. Quaternary Research 87(1): 1-23.

Damaschke, M., Cronin, S.J., Bebbington, M.S., 2018. A volcanic event forecasting model for multiple tephra records, demonstrated on Mt. Taranaki, New Zealand. Bulletin of Volcanology 80 (1), 9.

Dittrich, R., Wreford, A., Moran, D. 2016. A survey of decision-making approaches for climate change adaptation: are robust methods the way forward? Ecological Economics 122 pp 79 – 89

Doyle, E.E., Cronin, S.J., Cole, S.E., Thouret, J-C., 2010. The coalescence and organisation of lahars at Semeru volcano, Indonesia. Bulletin of Volcanology 72: 961–970. DOI 10.1007/s00445-010-0381-8

Forgie, V. & McDonald, G., 2013. Towards a Genuine Progress Indicator for New Zealand. In Dymond, J. (Ed) Ecosystem Services in New Zealand: Conditions and Trends. Manaaki Whenua Press, Lincoln.

Green, R.M., Bebbington, M.S., Cronin, S.J., Jones G., 2013. Geochemical precursors for eruption repose length. Geophysical Journal International 193: 855-873. DOI 10.1093/gji/ggt044.

King, A., Huseynli, G., & MacGibbon, N., 2018. Wellbeing frameworks for the Treasury. New Zealand Treasury discussion paper. Wellington: The Treasury.

Lerner, G., Cronin S.J., Turner, G.M., Rowe, M.C., 2019: Paleomagnetic determination of the age and properties of the 1780-1800 AD dome effusion/collapse episode of Mt. Taranaki, New Zealand. Bulletin of Volcanology. DOI : 10.1007/s00445-019-1275-z

Lerner, G., Cronin, S.J., Platz, T., in review: The <1000 yr B.P., Maero eruptive period of Mt. Taranaki (New Zealand). Bulletin of Volcanology

Lube, G., Breard, E.C.P., Cronin, S.J., Jones, J., 2015. Synthesizing large-scale pyroclastic flows: Experimental design, scaling, and first results from PELE, Journal of Geophysical Research, Solid Earth 120 (3): 1487-1502. DOI:10.1002/2014JB011666.

Massaro, S., Sulpizio, R., Costa, A., Capra, L., Lucchi, F., 2018: Understanding eruptive style variations at calc-alkaline volcanoes: the 1913 eruption of Fuego de Colima volcano (Mexico). Bulletin of Volcanology 80: 62. https://doi.org/10.1007/s00445-018-1235-z

MBIE, 2018. Aotearoa New Zealand Government Tourism Strategy (Draft Consultation Document) https://www.mbie.govt.nz/have-your-say/tourism-strategy-consultation/

McDonald, G., Smith, N., Ayers, M., Kim, J-H. & Harvey, E. 2017a. Economic Impact of the 2016 Kaikoura Earthquake: A report prepared for the Ministry of Transport, Market Economics, Takapuna.

McDonald, G.W., Cronin, S.J., Kim, J.-H., Smith, J.J., Murray, C.A., Procter, J.N. 2017b. Computable general equilibrium modelling of economic impacts from volcanic event scenarios at regional and national scale, Mt. Taranaki, New Zealand.

McDonald G, Smith N, Kim J.-H, Brown C, Buxton R, Seville E. 2018. Economic Systems Modelling of Infrastructure Interdependencies for an Alpine Fault Earthquake in New Zealand. Civil Engineering and Environmental Systems, DOI:10.1080/10286603.1018.

Platz, T., Cronin, S.J., Cashman, K.V., Stewart, R.B., Smith, I.E.M., 2007. Transitions from effusive to explosive phases in andesite eruptions – a case-study from the AD1655 eruption of Mt. Taranaki, New Zealand. Journal of Volcanology and Geothermal Research 161: 15-34.

Platz, T., Cronin, S.J., Procter, J.N., Neall, V.E., Foley, S. 2012:. Non-explosive, dome-

forming eruptions at Mt. Taranaki, New Zealand. Geomorphology 136: 15-30. DOI 10.1016/j.geomorph.2011.06.016.
Price, R. C., Stewart, R. B., Woodhead, J. D. & Smith, I. E. 1999. Petrogenesis of High-K Arc Magmas, Evidence from Egmont Volcano, North Island, New Zealand. Journal of Petrology 40, 167-197
Procter, J.N., Cronin, S.J., Platz, T., Patra, A., Dalbey, K., Sheridan, M., Neall, V., 2010. Mapping Block-and-ash flow hazards based on Titan2D simulations; a case study from Mt Taranaki, NZ. Natural Hazards 53: 483–501. DOI 10.1007/s11069-009-9440-x
Procter, J.N., Cronin, S.J., Sheridan, M.F., 2012: Evaluation of Titan2D modelling Forecasts for the 2007 Crater Lake break-out Lahar, Mt. Ruapehu, New Zealand. Geomorphology 136: 95-105. DOI 10.1016/j.geomorph.2011.05.001.
Roverarto, M., Cronin, S.J., Procter, J.N., Capra, L., 2014. Textural features indicate the transport and emplacement of the >7 km3 Pungarehu debris avalanche deposit, Mt. Taranaki, New Zealand. Bulletin of the Geological Society of America 127: 3-18. DOI: 10.1130/B30946.1
Rutledge, D., Cameron, M., Elliott, S., Fenton, T., Huser, B., McBride, G., McDonald, G., O'Connor, M., Phyn, D., Poot, J., Price, R., Scrimgeour, F., Small, B., Tait, A., van Delden, H., Wedderburn, E. & Woods, R. 2008. Choosing Regional Futures: Challenges and choices in building integrated models to support long term regional planning in NZ. Regional Science, Policy and Practice, 1:185-207.
Shane P., Hoverd, J., 2002. Distal record of multi-sourced tephra in Onepoto Basin, Auckland, New Zealand: implications for volcanic chronology, frequency and hazards. Bulletin of Volcanology 64: 441-454.
Shane, P., 2005. Towards a comprehensive distal andesitic tephrostratigraphic framework for New Zealand based on eruptions from Egmont volcano. Journal of Quaternary Science 20: 45-57.
Smith N, McDonald G, Harvey, E. 2017. Dynamic Economic Model: Economics of Resilient Infrastructure Programme Research Report 2017/02. GNS Science
Smith, N., McDonald, G., Brown, C., Seville, E., Buxton, R., Uma, S., Horspool, N., Grace, E., Harvey, E., Ayers, M. & Kim, J-H. 2018. The Wellington Lifelines Regional Resilience Project, Wellington Lifelines, Wellington.
Smith, C. 2018. Treasury Living Standards Dashboard: Monitoring Intergenerational Wellbeing. Kōtātā Insight, Wellington
Thouret, J-C., Lavigne, F., Kelfoun, K., Bronto, S., 2000. Toward a revised hazard assessment at Merapi volcano, Central Java. Journal of Volcanology and Geothermal Research 100: 479-502.
Thouret, J-C., Lavigne, F., Suwa, H., Sukatja B., Surono 2007. Volcanic hazards at Mount Semeru, East Java (Indonesia), with emphasis on lahars. Bulletin of Volcanology 70: 221-244.
Torres-Orozco, R., Cronin, S.J., Damaschke, M., Pardo, N., 2017a. Diverse dynamics of Holocene mafic-intermediate Plinian eruptions at Mt. Taranaki (Egmont), New Zealand. Bulletin of Volcanology 79 (11), 76
Torres-Orozco, R., Cronin S.J., Pardo, N., Palmer, A.S., 2017b. New insights into Holocene eruption episodes from proximal deposit sequences at Mt. Taranaki (Egmont), New Zealand. Bulletin of Volcanology 79-3. DOI 10.1007/s00445-016-1085-5.
Torres-Orozco, R., Cronin, S.J., Pardo, N., Palmer, A.S. 2018. Volcanic hazard scenarios for multiphase andesitic Plinian eruptions from lithostratigraphy: Insights into pyroclastic density current diversity at Mount Taranaki, New Zealand. Geological Society of America Bulletin https://doi-org.ezproxy.auckland.ac.nz/10.1130/B31850.1
Tost, M., Cronin, S.J., Procter, J.N., 2014. Transport and emplacement mechanisms of channelized long-runout debris avalanches, Ruapehu volcano, New Zealand. Bulletin of Volcanology 76: 881. DOI 10.1007/s00445-014-0881-z
The Treasury 2018a. Statement of Intent 2017-2021. The Treasury, Wellington. https://treasury.govt.nz/publications/soi/statement-intent-2017-2021
The Treasury, 2018b. The Treasury Approach to the Living Standards Framework. The Treasury, Wellington. https://treasury.govt.nz/publications/tp/treasury-approach-living-standards-framework
Turner, S., Black, S. Berlo, K. 2004. 210Pb–226Ra and 228Ra–232Th systematics in young arc lavas: implications for magma degassing and ascent rates. Earth and Planetary Science Letters 227: 1-16.
Turner, M.B., Cronin, S.J., Smith, I.E., Stewart, R.B., Neall, V.E., 2008a. Eruption episodes and magma recharge events in andesitic systems; Mt Taranaki, New Zealand, Journal of Volcanology and Geothermal Research 177: 1063-1076.
Turner, M.B., Cronin, S.J., Smith, I.E.M., Bebbington, M., Stewart, R.B., 2008b. Using titanomagnetite textures to elucidate volcanic eruption histories. Geology 36: 31-34.
Turner, M.B., Cronin, S.J., Bebbington, M.S., Platz, T., 2008c. Developing a probabilistic

eruption forecast for dormant volcanoes; a case study from Mt Taranaki, New Zealand. Bulletin of Volcanology 70: 507-515. DOI 10.1007/s00445-007-0151-4.
Turner, M.B., Cronin, S.J., Bebbington, M.S., Smith, I.E.M., Stewart, R.B., 2011. Integrating records of explosive and effusive activity from proximal and distal sequences: Mt. Taranaki, New Zealand. Quaternary International 246: 364-373. DOI 10.1016/j.quaint.2011.07.006
Turner, R., Moore, S., Pardo, N., Kereszturi, G., Uddstrom M., Hurst T., Cronin, S., 2014. The use of a numerical weather prediction and a Lagrangian transport (NAME-III) and dispersion (ASFALL) models to explain patterns of observed ash deposition and dispersion following the August 2012 Te Maari, New Zealand eruption. Journal of Volcanology and Geothermal Research 286: 437-451

Classifications

ANZSRC

Impact statements in your application

Number	Title
IS 1	Transitioning Taranaki to a Volcanic Future

Research Classification - ANZSRC FOR

Anzsrc For	**IS 1%**	
There are no matching results		

Research Classification - ANZSRC SEO

Anzsrc Seo	**IS 1%**	
There are no matching results		