An interdisciplinary approach to volcanic risk reduction under conditions of uncertainty: a case study of Tristan da Cunha

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ABSTRACT

This research project adopts an interdisciplinary approach to volcanic risk reduction on the active volcanic island of Tristan da Cunha. Tristan has a relatively poorly defined eruptive record and little effective monitoring capability. Although a young volcano (~200 ka), eruptions have been numerous, with no apparent spatio-temporal correlation, style, volume or compositional relationships. The last eruption in 1961 prompted a temporary (~2 year), evacuation of the island's small population. The paucity of data, uncertainty around future eruptive scenarios, recent volcanic activity and evacuation challenges facing this remote community emphasises the need for increased knowledge about the volcano, and implementation of effective risk reduction measures.

New field observations from Tristan and a precise geochronology of the recent eruptive history are presented. These datasets were administered in an expert elicitation exercise aimed at quantifying uncertainty. Experts provided an objective expression of the existence, extent and significance of the uncertainty surrounding future eruptive scenarios on the island. In order to effectively communicate the science and encourage implementation of risk reduction measures, knowledge of the social context and collaboration with islanders was essential.

Study of the social context established that while the Tristan population are disproportionately vulnerable to the effects of volcanic eruptions and other natural hazards due to location, the community retains inherent coping capacity, held in social capital. Cultural changes manifest from 'system shocks' such as the evacuation, and from slower drivers, such as the recent introduction of modern media and communications, are acknowledged to have both strengthened and eroded resilience.

All data (results from natural, decision and social sciences) were integrated into a participatory communication strategy, focussed around a scenario planning exercise. This encouraged islanders to consider responses to possible future eruptive scenarios and improve mitigation. An evacuation drill was successfully completed with the whole community, and is set to be repeated annually.

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Foremost thanks go to Jenni and Peter for your guidance and support. This research has been challenging in many ways and I am thankful to you both for steering me through the passionate yet testing world of interdisciplinary research. It has been interesting and enjoyable working with you both and I look forward to new opportunities to continue our efforts! This research was predominantly funded by an ESRC/NERC interdisciplinary studentship and I must also acknowledge financial support from UEA. I appreciate the support of the BGS (and financial assistance from the BUFI initiative) and the valuable advice, supervision and encouragement from Sue. My upmost thanks go to other academics that have assisted with this research, especially Willy for his expertise and advice with the expert elicitation process and analysis. Thanks also to the 18 elicitees and the UEA-based experts who sacrificed their time to finesse the elicitation process for this project: Fionnuala, Mel, Katie, Jon, Jenni and Ricky.

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To all Tristanians I feel the deepest gratitude for your kindness, generosity and support during my two field seasons on your island, particularly to Gracie, Catherine, Connie and Sharon – from the bottom of my heart I thank you for your hospitality, friendship and warmth. The minute I set foot on Tristan, I felt so at home, and you all have done your upmost to support me in my work and establish lifelong friendships. Among them are my dear friends Vera and Desiree, and my little buddy Leo. I hold you all very close to my heart and I thank you for precious conversations, advice and memories. To Leon, seven months together and what seems like a lifetime of memories - 1000+ games of knock, winter swimming in the South Atlantic (brrr...), catching 32 five fingers (mine were the biggest, and you know it), cherry fizz biscuits and penguin poking (even the 'really dead' ones). Was your gear box ever the same? To Clive, I feel so thankful to have seen and shared beautiful mountain vistas with such a good friend. Our last day on the hill was a wonderful way to wrap up an incredible journey....even if we did temporarily lose Boxer and miss the Wales rugby match that wasn't even on. So thanks for getting me around the whole island (first woman ever...right?) in one piece, with a smile on my face and happiness in my heart. I'll miss the sarcasm, the laughs and, of course, the dancing. I won't miss the clumsiness....let's hope I can stay on my feet from now on.

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don’t wish to dwell on the rough patches, so I won’t, but please know how thankful I am and that it will never have to happen again….that is until it’s your turn!

Thanks to Dad for your unwavering enthusiasm hearing about my various stories from around the world, and especially for helping me with the latter stages of my thesis write-up. That week really did help to get this turned around in time. To Helen and Rob, Mo and Gary for help, support and for just keeping me going through the tough times – thank you. To Martin, thank you for trusting in my ability to do this project. Knowing that someone else thought I could do it made me believe it too. I look forward to sharing another graduation with you, and adorning a floppy hat this time!

I often reflect on my fortune to have had such an incredible research experience coupled with such superb support, both at home and from UEA, but there is no one else to whom I would want to dedicate this thesis to other my mum. Mum - the last four years (ok, 30!) have been tough in many ways but you have been my constant, my confidant, my support. You have had to combat your own battles and yet your encouragement and assistance is unceasing; unwavering. Thank you. Every word of this has been written for a reason, and hopefully one day it may go some way to helping someone. It is all here because of you.

To mum

Left: The Settlement on Tristan da Cunha in 2009. Viewed from ‘*the volcano’* which erupted in 1961 forcing the temporary evacuation of the whole population. Right: Traditional island home looking towards the steaming dome of the 1961-62 eruption. Photo courtesy of the Tristan da Cunha Photo Portfolio: Jim Flint.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

LIST OF EQUATIONS

LIST OF ACRONYMS

AIF	Argon Isotope Facility
BCS	British Chemical Standards
BGS	British Geological Survey
BUFI	British Universities Funding Initiative
CBDRM	Community Based Disaster Risk Management
CTBTO	Comprehensive Nuclear Test Ban Treaty
CM	Classical Model
CNRS	Centre National de la Recherche Scientifique
CVA	Capacities and Vulnerabilities Analysis
DfID	Department for International Development
DM	Decision Maker
DRR	Disaster Risk Reduction
ERF	Expected Relative Frequency
ESRC	Economic and Social Research Council
EXCALIBUR	Expert Calibration (software)
FCO	Foreign & Commonwealth Office
GLORIA	Geological Long Range Inclined Asdic
GPS	Global Positioning System
IAVCEI	International Association of Volcanology, Chemistry and the Earth's Interior
IDNDR	International Decade of Natural Disaster Reduction
IRIS	Incorporated Research Institutions for Seismology
MAR	Mid Atlantic Ridge
MVO	Montserrat Volcano Observatory
NERC	Natural Environment Research Council
NRC	Natural Resources Canada
OIB	Ocean Island Basalt
PAR	Pressure and Release
PARFUM	Parameter Fitting for Uncertain Models
PRA	Participatory Rural Appraisal
RAND	Research and Development
RIB	Rigid Inflatable Boat
SAC	Scientific Advisory Committee
SABS	South Africa Bureau of Standards
SES	Social-Ecological System
SL	Sustainable Livelihoods
SSHAC	Senior Seismic Hazard Analysis Committee
SSVC	Services Sound and Vision Corporation
SUERC	Scottish Universities Environmental Research Centre
TDC	Tristan da Cunha
UEA	University of East Anglia
UN	United Nations
UNISDR	UN International Strategy for Disaster Risk Reduction
USGS	United States Geological Survey
USNBS	United States National Bureau of Standards
XRF	X-ray Fluorescence

CHAPTER ONE: Introduction

1.1. Introduction and rationale

The frequency and size of losses due to natural disasters are increasing globally (UNISDR, 2011) (Fig. 1.1)**.** This is due to worldwide population increase and concentrated settlement in large conurbations and extremely exposed regions. For example, over half of the world's large cities[1] are located in areas considered highly vulnerable to seismic activity (UNISDR, 2012). All countries are vulnerable to the effects of natural hazards. The interdependent economies of developed countries are, in some ways, as susceptible as poverty-stricken developing nations. Environmental stress, exacerbated by the effects of climate variability will continue to amplify the impact of disaster on global economies, development and ecosystems.

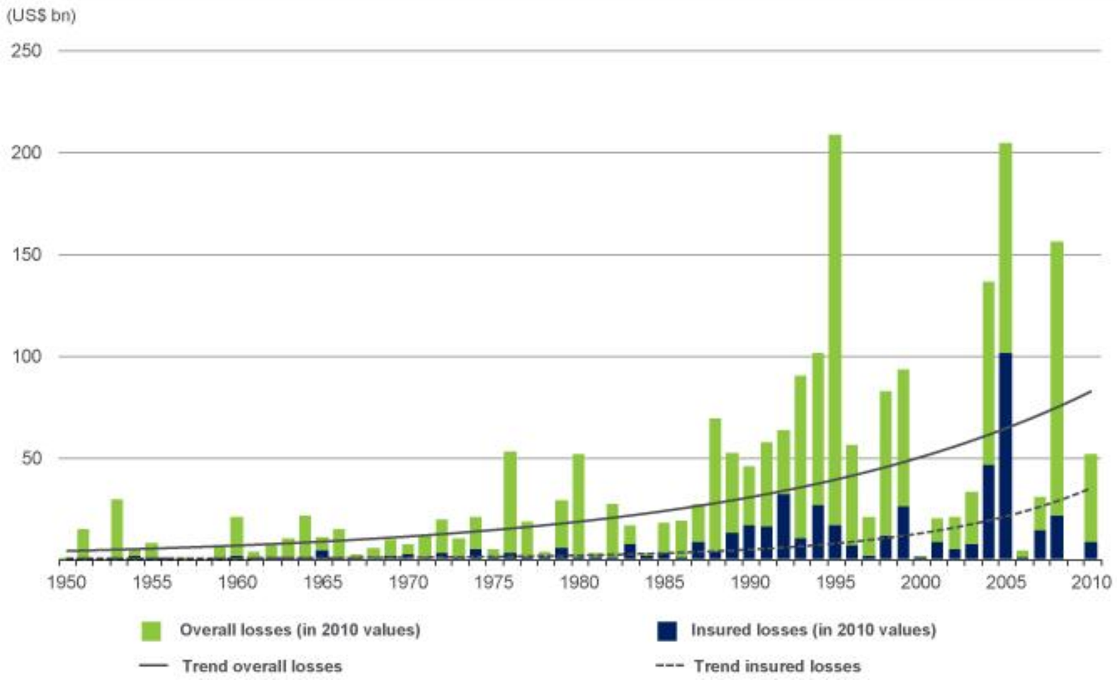


Fig. 1.1. Great natural catastrophes worldwide 1950-2010 - overall and insured losses with trend. Source: Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE, Jan 2011.

[1] Cities are considered to be 'large' if they have populations between 2 and 15 million.

This upward trend in disaster losses has been recognised for some time and has prompted national and international risk reduction programmes. The International Decade for Natural Disaster Reduction (IDNDR), declared in 1990, aimed to reduce losses from disasters by accessing and utilising the wealth of science and engineering expertise through international cooperative programmes. While there were important successes in terms of forging links between political and scientific communities in the past 20 years or more, economic losses stemming from natural disasters continued to increase. The IDNDR successor programme, the UN International Strategy for Disaster Risk Reduction (UNISDR) is building on these networks and, rather than focusing attention on knowledge of the hazard, is directing resources to strengthening resilience of nations and communities, following guidelines of the Hyogo Framework for Action 2005-2015.

Volcanic eruptions are one of several geophysical phenomena which threaten lives and livelihoods. Volcanoes are an integral part of our natural environment with over 1,500 known potentially active volcanoes worldwide, and in excess of 11% of the world's population living within a volcanic risk zone (Simkin and Siebert, 2000; Ewert and Harpel, 2004; Siebert et al., 2010). Volcanic activity is as variable as it is common, with eruptions ranging from low volume passive effusion of lava, to large scale violent explosions that impact global climate. The capricious nature of these systems is one of many inherent uncertainties, and brings a considerable challenge for scientists to understand, and attempt to determine, the natural parameters, relationships and influences at each volcano. Further, when a volcano exhibits signs of unrest, decision makers invariably seek scientific opinion, for example, regarding the pattern of likely activity, how and when this might change during the course of an eruption, and when the eruption may cease altogether. Unfortunately, even with the best possible scientific monitoring, these questions are difficult to answer with a strong degree of certainty.

Uncertainty and accountability pose particular problems for both decision makers and experts providing advice. There is pressure for scientific opinion to be presented to decision makers as a single 'definitive' interpretation, where risk has been measured, unknowns have been reduced, and experts are seen to be in agreement (Stirling, 2008; Stirling, 2010) (see Chapter 4). This approach is seen as scientifically rigorous, accurate and most useful for policy, and might be the best course of action if probabilities and possibilities are well understood. However, if outcomes are poorly defined and/or there is no basis for probabilities, definitive science-based decisions may be misleading and potentially dangerous. Suppressing uncertainty (by concealing ambiguity and ignorance) may fail to take into account alternative interpretations and surprise[2] events. A more appropriate approach may involve applying a plurality of methods in order to illuminate alternative interpretations, and thus render decision makers accountable for decisions (see Chapter 7). While this may not be as desirable to the decision maker, the breadth of scope and attention to information and knowledge diversity is actually more scientifically rigorous, thus procuring better-informed decisions and less risky actions (Stirling and Gee, 2002).

While the absence of certainty is at the heart of the difficulties of framing, quantifying and communicating risk to decision makers, effective risk communication to wider stakeholders groups must also appropriately handle uncertain information. This presents a central challenge, not only to volcanology, but also to those engaged in developing and communicating volcanic risk reduction strategies. Effective communication of volcanic risk and uncertainty is vitally important to encouraging risk-reducing behaviour but, in practice, strategies often fail to have the desired effect (e.g., Paton et al., 1998; Paton et al., 2008). This could be due to, for example, the complexity of translating scientific information from scientist to stakeholder, especially if there are difficulties in comprehension; differences between expert and lay understandings of the problem; or if there is disparity between available information and the needs of the population at risk (Haynes et al., 2007, 2008b). Alternatively, a vulnerable population may understand the hazards yet fail to act appropriately because of other social, cultural or economic factors (Loughlin et al., 2002).

Tackling the communication challenge successfully requires practitioners with an understanding of physical processes; the ability to handle scientific uncertainty, and an aptitude and desire to take an inclusive, collaborative approach to communicating this information in ways adapted to specific hazard and social contexts (e.g., Stirling, 2010; Pidgeon and Fischhoff, 2011).

It is now relatively widely acknowledged that advances in volcanic risk reduction research are contingent on the integration of sociological knowledge and techniques, physical science approaches, and tailored communication methods (Barclay et al., 2008). There have been some innovative multi-disciplinary studies which focus on key challenges of reducing and mitigating volcanic risk, by understanding important components of the problem; for example, risk perception (Gregg et al., 2004; Gaillard, 2008; Haynes et al., 2008b; Paton et

[2] Knowledge leaps in volcanology are often brought about by 'surprise' events, e.g., high SO_2 levels from the eruption of El Chichon (Mexico) in 1982; a landslide triggering the 1980 eruption of Mount St. Helens (USA); and rapid summit subsidence and elevated SO_2 production during the 2000 Miyakejima (Japan) eruption. Unfortunately, these unforeseen events are often associated with increased losses.

al., 2008); traditional beliefs and knowledge, (Cronin et al., 2004a; Mercer et al., 2007); the role of religion (Chester, 2005; Chester et al., 2008a); risk and hazard communication (Haynes et al., 2007, 2008a); community resilience (e.g. Paton et al., 2001); and sustainable livelihoods (Kelman, 2008). However, there are relatively few examples from volcanology which generate a holistic overview of the social *and* physical system. This requires integration of differing strands of research to further knowledge of the hazard, to explore the unique characteristics of communities, and to strive to understand the mechanisms that act to build resilience and reduce vulnerability within them.

1.2. Aim & objectives

This introduction presents a clear rationale for further research into volcanic risk reduction. Advances require interdisciplinary efforts drawing on physical, decision and social science methods in order to: a) advance knowledge of the physical hazard(s) and uncertainties to inform and improve forecasting attempts; b) characterise hazard and community-specific vulnerabilities, capacities, and the spatio-temporal drivers; and, c) improve risk mitigation and preparedness. To be successful, risk reduction measures rely on the integration of these approaches, collaboration and deliberation with stakeholders throughout the research, and effective, tailored communication strategies for those at risk.

The aim of this research, therefore, was to develop and test an interdisciplinary approach to volcanic risk reduction under conditions of severe uncertainty for a case study: the small island population of Tristan da Cunha (Tristan). This primary aim can be subdivided into ten broad goals:

1. To examine the volcanology of Tristan and make relevant field observations to inform a volcanic hazard assessment;
2. To determine high precision $^{40}Ar/^{39}Ar$ ages of rock samples from key locations to test several hypotheses relating to spatio-temporal trends and styles of volcanism;
3. To design and conduct an expert elicitation procedure in order to synthesise expert judgements of possible future eruptive style and location on Tristan;
4. To map local perspectives on volcanic hazards and on their importance relative to other natural hazards;
5. To explore the history of settlement on the island and the present day social, political and economic context;

6. To identify and explore patterns of social organisation, activity and adjustments that have, and may, contribute to resilience and vulnerability;
7. To identify existing communication networks, both formal and informal, particularly in relation to natural hazards and to the communication of uncertainty;
8. To develop and implement risk and uncertainty communication strategies appropriate to the local context;
9. To test and evaluate the contribution of the context-specific communication methods to support an island risk reduction strategy;
10. To support the community in their mitigation endeavours.

1.2.1. Case study research

The structure of this research is based around a case study. This style of research presented an opportunity to not only study phenomena particular to the setting, but also enabled comparisons to be drawn with well studied analogous systems. The study was designed to evolve in an iterative manner with one research component informing another (Fig. 1.2).

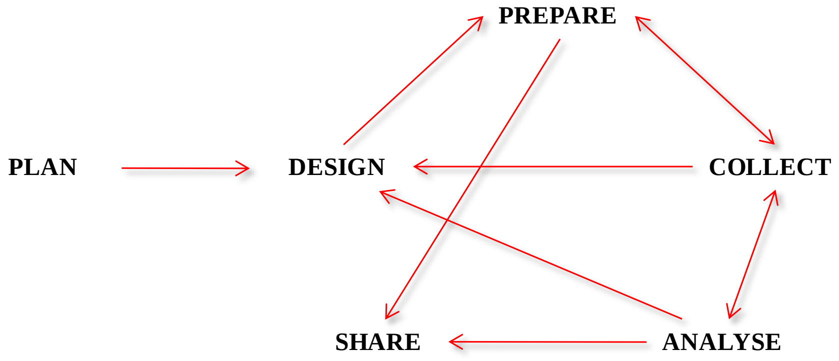


Fig. 1.2. Case study research as a linear yet iterative process.

Case studies are ideal when little is known about a particular location, context, processes or behaviours (Hartley, 1994; Flyvbjerg, 2006). In social science, however, the scientific value of case studies is contested, with sceptics claiming that generalisation from a single case is impossible, and that case studies are subjective, arbitrary and only suitable for generating hypotheses. Others assert that case study research is misunderstood and that context-dependent knowledge can actually be more valuable than theoretical research, that the force of example is underestimated, and that case studies can be used to test hypotheses (e.g., Flyvbjerg, 2006 and references therein). It is true that large samples are essential to gain breadth of knowledge, but thoroughly executed case studies offer greater depth (Kuhn, 1987; Flyvbjerg, 2006).

Case study research is often used in field volcanology due, in practical terms, to the relative paucity of eruptions, challenges of accessibility and lack of resources, but also because each volcano has a unique eruptive history and 'personality'. While all volcanologists are implicitly aware of the dangers of generalisation (i.e. individual eruptions at the *same* volcano are often different), by applying the principle of uniformitarianism, which posits that the present is the key to the past (and thus the future), context-dependent knowledge from case studies can be carefully used to compare with analogous systems. This is particularly true, for example, in comparing pre-eruptive and physical behaviour, and responses of magmas that share chemical and physical properties.

1.2.2. A case study of Tristan da Cunha

Tristan da Cunha (Tristan) is a remote, active volcano in the South Atlantic which last erupted in 1961-62. The island (~120 km^2) is presently home to a small population of 262 people who reside in the north of the island as a single community (see Chapters 2 and 5 for more details). The reasons for selecting Tristan as a case for an interdisciplinary study of this nature are numerous. First, it was particularly relevant to conduct a study of this type on an active volcano. This was partly to enable comparisons to be drawn with analogous volcanic systems and settings, as many active volcanoes are found on small islands. Further, working on Tristan offered access to social memory of the last eruption, providing interesting insights into differing comprehensions of the risk posed by the volcano. Another important motive was the benefit of focussing research on a physically and socially contained case study context and population. This simplified analysis of the various factors relevant to the communication of risk and uncertainty in the natural environment. Beyond this, working on Tristan offered an opportunity to improve knowledge of the volcano, and better define the eruptive history (see objectives 1 and 2), in an attempt to reduce uncertainty about future eruptive scenarios (see objectives 3 and 8). It also presented an opportunity to analyse the specific social context, and examine particular characteristics, which serve to increase vulnerability to natural hazards, as well as those that build resilience (see objectives 4 - 7). While island communities are often disproportionately vulnerable to the effects of natural hazards, they can also develop strong and successful coping mechanisms which can provide lessons in strengthening resilience (e.g., Pelling and Uitto, 2001; Gaillard, 2007; Kelman, 2008). Further, there exists a relatively rich account of Tristan's short, yet eventful, history of settlement (< 200 years) (e.g., Brander, 1940) which permitted analysis of how present day vulnerabilities may reflect historic events, and how current community activities and new policies may affect vulnerability in the future (Lewis, 2009).

1.3. Methodological approach and thesis structure

This section outlines the methodological approaches taken and provides a synopsis of the thesis structure. However, before outlining the methodological approach, it is necessary to set the context of this research in terms of the philosophical framework used, and to present particular challenges pertinent to interdisciplinary research.

1.3.1. Philosophical framework

Every person has a worldview or paradigm; a lens through which they see the world, based on particular ontological and epistemological assumptions (Guba and Lincoln, 1994). Epistemology refers to the necessary and sufficient conditions of knowledge; the theory of knowledge, and how we know what we know (Crotty, 1998). Ontology concerns particular beliefs of the nature of reality, i.e. is the social world an objective entity or inherently subjective and constructed? (Bryman, 2008). There is a wealth of epistemological approaches, with extremes such as positivism and constructivism at either end, and a multitude of positions in between. Positivism rests upon an objectivist ontology and argues that the natural and social world exists 'out there', independent from our knowledge of it, and can be discovered and examined in an objective way. Positivism is usually associated with 'hard science' subjects (natural, physical and computing sciences) which apply quantitative methodologies in a reductionist manner. Positivistic scientists claim to be value-free, and measure and test the world as disinterested, objective observers. In contrast, constructivism rests upon a relativist ontology in which it is argued that the world is socially constructed and does not exist independently from our knowledge of it (Guba and Lincoln, 1994). This epistemology is more common in social sciences, and qualitative methodologies are regularly applied.

These distinct philosophical perspectives pose a central challenge for the interdisciplinary researcher who investigates both natural and social phenomena. Interdisciplinary researchers may opt for a critical realist stance, where a distinction between studies of the natural and social worlds is acknowledged; yet it is believed that the social world can be studied objectively. This stance also realises that social agents are not as highly controlled as objects defined by the natural sciences, in that they are continually modifying their world in light of new stimuli (e.g., Bhaskar, 1989). Pragmatism is another position that straddles the extremes, and is associated with mixed methods research applying both quantitative and qualitative methodologies. Pragmatic research is driven by the problem in hand, and conditioned by the goal of the research question, which is often of greater importance than the method, or the paradigm, that underlies it (e.g., Cherryholmes, 1992; Morgan, 2007). Given the applied nature of this research question, the wider issue-driven goals of volcanic risk reduction and the worldview of the researcher, this study is underpinned by a pragmatic epistemology.

Issue-driven research is now becoming less exceptional, likely due to the more apparent inter-linkages between society and the environment. Traditional problem-solving strategies are seemingly ineffective against the intractable modern challenges of handling and explicating risk and uncertainty and, as a result, have encouraged the development of more inclusive inquiry and knowledge production approaches. Post-normal science, for example, has emerged in response to the challenges of policy issues of risk and the environment. The concept of post-normal science attempts to advance evidence-based decision making in cases where, 'facts are uncertain, values in dispute, stakes high and decisions urgent' (Ravetz, 1986; Funtowicz and Ravetz, 1991). By creating an 'extended peer community', involving policy makers, experts and other stakeholders, important decisions can be made even when all factors are not necessarily known (Funtowicz and Ravetz, 1993). A post-normal science approach is becoming increasingly applied to address 'wicked[3]' issues such as global environmental change.

1.3.2. Interdisciplinarity

Disaster risk reduction is another real-world issue being addressed by problem-driven research. Similarly to post-normal science, interdisciplinary and participatory approaches

[3] Wicked problems are aggressive issues that are incomplete, contradictory, uncertain and indefinable (Rittel and Webber, 1973). They do not lend themselves to traditional, linear problem-solving approaches and require collaboration across disciplines and scales.

also seek to invoke and interweave knowledge and expertise from different disciplines and specialisms in order to solve problems. The rising application of interdisciplinary approaches has also been exacerbated by increased within-discipline specialisation (e.g., Gibbons et al., 1994; Morillo et al., 2003). Applied interdisciplinary research is often creative and innovative, and results can sometimes lead to major shifts in thinking. However, there are strong and abiding barriers including perceived weakness of particular disciplines (especially if there are clear epistemological and methodological differences); preservation of disciplinary integrity; data misinterpretation; power and control conflicts; lack of support structures, and funding problems (e.g., Heberlein, 1988; Petts et al., 2008). These obstacles make designing, conducting and communicating interdisciplinary research a challenge.

In volcanology, there has been a gradual shift in focus to applied, interdisciplinary research which adopts socially sensitive methodologies, and is orientated to the reduction of human vulnerability to volcanic eruptions (Chester et al., 2002). It may seem obvious that volcanological research should be placed within a social context. The broad goal of the discipline is to improve understanding of the natural system to help save lives and livelihoods. However, volcanology, like many other disciplines, has encountered many of the same obstacles to interdisciplinary research mentioned above. At the extreme end, a directed position (particularly on modelling, monitoring and system dynamics) has created some unease at the perceived ‘invasion’ of ‘soft’ sciences reducing the integrity of the field and validity of the research. The reason for this may be that volcanologists tend to have a traditional science grounding, and lack knowledge of a range of science methodologies and epistemological training (Barclay et al., 2008). More commonly, obstacles to interdisciplinary approaches tend to be rooted in lack of time, resources and knowledge of appropriate and effective communication strategies.

Nonetheless, there is now growing recognition that to allow research to contribute to the reduction of risk in volcanic settings, more attention needs to be paid to components that contribute to increasing risk, other than the physical threat. This involves understanding the contribution of social processes, changing vulnerability, exposure and capacity, and the development of new interdisciplinary approaches.

1.3.3. Methodological approach

This research takes an interdisciplinary approach to volcanic risk reduction, focused on a case study of Tristan da Cunha. This section will briefly outline the methodologies used in this research as they will be discussed in more depth in each of the following chapters.

This approach integrates qualitative and quantitative methodologies within an analytic-deliberative (A-D) framework. The term analytic-deliberative derives from the risk domain and was a framework initially applied to characterise risks for assessment, though there are now wider applications (e.g., Kerr et al., 1998). A key driver of A-D processes is the failure of experts to 'engage effectively with the knowledge, values and interests of stakeholders, and the wider public' (Burgess et al., 2007). The analytic component refers to 'ways of building understanding by systematically applying specific theories and methods that have been developed within communities of expertise' (Stern and Fineberg, 1996, p.97). Deliberation is defined as, 'a formal or informal process for communication and for raising and collectively considering issues', and 'implies an iterative process that moves towards closure' (Stern and Fineberg, 1996, p.73). By using this framework, the two components ideally develop each other, with each analysis improving deliberation by supplying further facts and information to the discussion. Also, vice versa, deliberation by engendering clarity, improved understanding of the analytical component, and offering new perspectives throughout the process. The A-D process also increases reflexivity and capacity to learn, as well as robustness and legitimacy of policy decisions.

By applying an A-D framework to this research, the approach to, and results from, all these research components informed each other in an iterative manner (see Fig. 1.3). Rather than dividing a description of the research segments into analytic and deliberative components, or qualitative and quantitative approaches, the methodological approach will be briefly outlined in chronological order. An outline of the write-up of this research will follow (see Section 1.3.4).

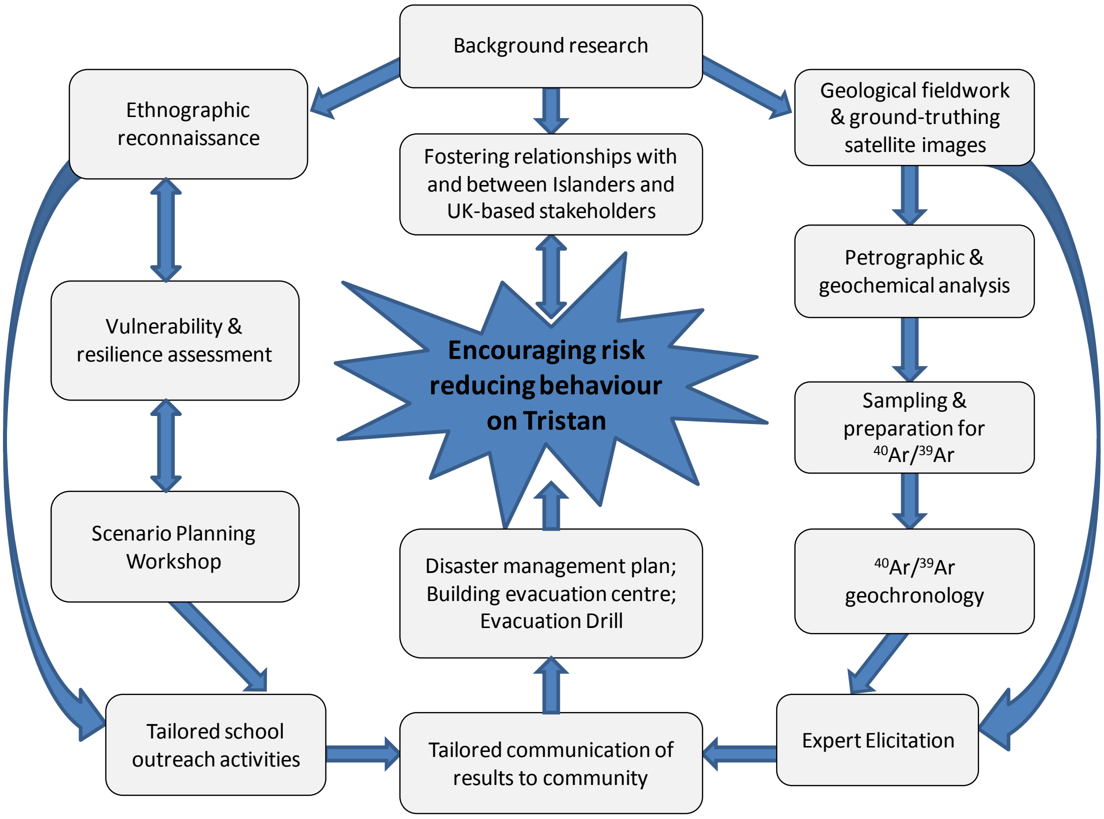


Fig. 1.3. Schematic of methodological approach to research.

At the project outset, much time was spent investigating the magnitude of the problem, both in terms of the wider issues of risk reduction and the particular context of Tristan. To ensure viability of the project, and to help formulate research questions thoroughly, initial contact was made with the Tristan Island Council and Foreign & Commonwealth Office (FCO) officials in the UK. Both were supportive of the research intentions and considered them timely for integration with new strategies for developing the island. Early meetings with FCO officials ensured complete transparency of the project intentions, especially with regard to the limitations of PhD project resources, funding and likely outputs. Crucially, this early contact and openness facilitated access to Tristan. Getting to Tristan is particularly difficult as the only means of transport is by ship, and berth numbers are low (~12). Scientists undertaking non-essential research on Tristan remain relatively low on the passenger priority list for ships; behind all islander 'medevacs' (medical evacuations: emergency and non-urgent), and islanders conducting business trips or training abroad.

Prior to fieldwork, much time was spent creating and fostering networks with individuals and groups who had worked on Tristan, visited the island, or just had a keen interest. This provided a source of information, but also facilitated construction of valuable relationships which provided support and guidance throughout the project.

The goal of the first period of fieldwork (September - December 2009) was to conduct geological fieldwork with an aim to: a) collect rock samples appropriate for petrographical, petrological and geochemical analysis and the $^{40}Ar/^{39}Ar$ dating strategy (see objective 2); b) make new field observations and ground truth information gathered from satellite images and aerial photographs (see objective 1); and c) to obtain local knowledge from mountain guides and other islanders about morphological and volcanological features, as well as information about their understanding of volcanic processes and hazards (see objective 4).

Although much of the work in the first season contributed to the analytical component, considerable time was also spent investing in a trust account with islanders. Rather than staying in self-catering accommodation, it was preferable to be housed with a family, in order to facilitate immersion into the community's way of life. The first month of fieldwork was spent gradually building relationships with islanders, both formally via fieldwork-related activities, and socially by partaking in community-based activities, attending social occasions, and learning local crafts and techniques. This also provided an opportunity to explain project intentions and output limitations, and consider what social science methodological approaches would be most suitable to achieve objectives outlined in Section 1.2. Further, this offered the islanders an opportunity to informally make their views known on the research project. Mixed methodological approaches included participant observation, structured interviews with ex-patriates, FCO officials and the Island Administrator, and purposeful conversations with islanders. Outreach activities with school pupils were initiated.

Between field seasons, research was focussed on sample preparation for $^{40}Ar/^{39}Ar$ analysis, petrological and geochemical analysis of rock samples. During this time, an expert elicitation procedure was conducted (applying the Classical Model and a paired comparison approach) with 18 volcanologists from UK-based institutions (see objective 3).

For the second field season (November 2010 – March 2011), the aim of the fieldwork was to collate and integrate all the results, and to design and implement communication strategies appropriate the local context (see objectives 8 -10). Extended outreach programmes with the school pupils included a film project about the 1961-62 eruption and evacuation. Other communication methods included a scenario planning workshop and community presentations. All communication strategies were informed by a 'needs and knowledge' assessment of the islanders, as well as an assessment of vulnerability and resilience. These data were gathered by taking an ethnographic approach to research (see objectives 5-7).

Ethical considerations were always prioritised, and the potentially sensitive nature of this topic was recognised from the outset. The researcher was bound by UEA Research Ethics Guidelines and procedures. In particular, participant anonymity, voluntary participation and the avoidance of psychological distress were emphasised.

1.3.4. Thesis structure

Following this introduction, subsequent chapters present the approach to, and results from, this interdisciplinary research. However, for clarity, the chapters have been partitioned into particular fields of knowledge (with the exception of Chapter 7):

The geology and physiography of Tristan is outlined in Chapter 2. New observations are integrated with prior data, and key features, knowledge gaps and theories are highlighted, which inform the approaches discussed in Chapters 3, 4 and 7.

In Chapter 3, the $^{40}Ar/^{39}Ar$ geochronology technique is introduced, and the application of this method to fifteen carefully selected rock samples from Tristan is described. The $^{40}Ar/^{39}Ar$ approach offers greater dating precision and methodological advantages than the K-Ar method, and can be particularly useful for constraining ages of relatively young samples. Implications of the findings for timing, location and styles of future volcanism on Tristan are discussed.

Expert elicitation literature is reviewed in Chapter 4, and the suitability and applicability of the 'Classical Model' of expert elicitation to the Tristan problem is examined. This approach was adopted and customised in view of the unique set of challenges posed by this very data-impoverished setting. Results of the elicitation, conducted with 18 UK-based volcanologists are presented, and implications for decision making on-island are considered. An appraisal of the methodology is offered, highlighting the challenges of the technique and suggestions for future application of the approach to extremely uncertain situations.

In Chapter 5, the Tristan community is examined from a sociological perspective. The history of settlement on the island, and the present day social context of the community, is described. Particularly, this chapter draws attention to characteristics that may serve to increase vulnerability to natural hazards, which are developed further in Chapter 6.

In Chapter 6, a comprehensive discussion of the islanders' social characteristics is presented. Qualitative data were gathered by applying an ethnographic approach, and framed around components of models used in disasters and socio-ecological studies. Participant observation was sensitized to social, political and economic features that increase vulnerability, as well as capacities of the islanders that may serve to strengthen resilience. This chapter acknowledges the dynamic nature of vulnerability and resilience, and reflects on possible causes of these fluctuations through Tristan's history. Recent cultural changes are discussed and possible consequences to social defences are proposed.

The challenges of communicating risk and uncertainty are discussed in Chapter 7, and some tailored approaches to effective risk discourse are presented. By drawing on a trust account that had developed throughout the project, and by employing a variety of channels, results described in Chapters 3 and 4 were discussed with the community. Communication strategies were centred on a scenario planning workshop with Island Council members. This was designed as a way of engaging members of the community to consider plausible future eruptive scenarios, and the responsibilities, attitudes and assumptions of individuals during an imagined crisis. Data from Chapters 5 and 6 informed this exercise.

A synthesis and conclusions to the research are provided in Chapter 8. Important areas to focus future volcanic risk communication research are highlighted.

1.4. Summary

This introductory chapter highlights the challenge of reducing losses from natural disasters. Despite substantial knowledge advances about natural system dynamics and effects, losses continue to rise. This challenge points to the need for alternative approaches to reducing risk in hazardous environments.

Priorities for volcanic risk reduction are now not solely focussed around improved knowledge of the volcano. Approaches need to integrate methods designed to identify, quantify and communicate uncertainties, with methods from social science disciplines which seek to better understand communities at risk.

This thesis attempts to integrate these interdisciplinary research components in a single study, with an aim to reduce the risk of volcanic hazards on the small volcanic island of Tristan da Cunha.

CHAPTER TWO: The geology and physiography of Tristan da Cunha

2.1. Introduction

The island of Tristan da Cunha, (Tristan) (Fig. 1; see inside front cover), is the emergent top of an active volcano situated at 37°06'S, 12°17'W, in the South Atlantic Ocean (Fig. 2.1a). Tristan has a roughly conical edifice, with a maximum diameter of 1,200 m and rises ~5,500 m from the sea floor. The uppermost 2,060 m is exposed sub-aerially (Plate 2.1; see end of chapter). Volcanic activity is usually attributed to a deep seated mantle plume, rather than partial melting from the Mid Atlantic Ridge (MAR), approximately 350 km eastward (Sleep, 1990). Tristan is the largest of a small group of islands, that includes Nightingale, Inaccessible, Middle (or Alex), and Stoltenhoff (Fig. 2.1b); all eroded remnants of once larger volcanic cones. Subaerial eruptive deposits are almost all silica under-saturated volcanic rocks, spanning a compositional sequence from basanite to phonolite, and probably emplaced within the last ~200 ka (see Chapter 3).

The last subaerial eruption on Tristan occurred in 1961, following two months of escalating seismic activity. A small tephri-phonolitic dome and blocky a'a flows was constructed in the north of the island, destroying the fishing factory and damaging some island homes. Although the flows did not eradicate the whole village, the population self-evacuated shortly after the onset of the eruption and spent two years in the UK before returning to Tristan to resume their way of life (see Chapters 5 and 6).

Following felt seismic activity (largest: M = 4.8) in July 2004 and the presence of fresh phonolitic pumice (Reagan et al., 2008) found floating nearby in the sea and washed up on beaches, a volcanic hazard assessment was conducted to examine the island for signs of volcanic unrest (Hards, 2004). Hards determined that a volcanic crisis was not imminent and that the seismic activity was probably linked to a submarine eruption somewhere offshore of Nightingale Island (O'Mongain et al., 2007). However, due to a very sparse data set and the difficulties presented by using only two seismometers (which are also close to each other, ~ 1 km), the associated errors were very large and a precise location of events could not be determined (O'Mongain et al., 2005).

This chapter provides a review of the state of knowledge and relevant aspects of the physical and volcanological characteristics of Tristan and the localised setting. Field observations and new data relevant to sample collection will be presented - alongside work by other authors - providing insights into eruptive behaviour.

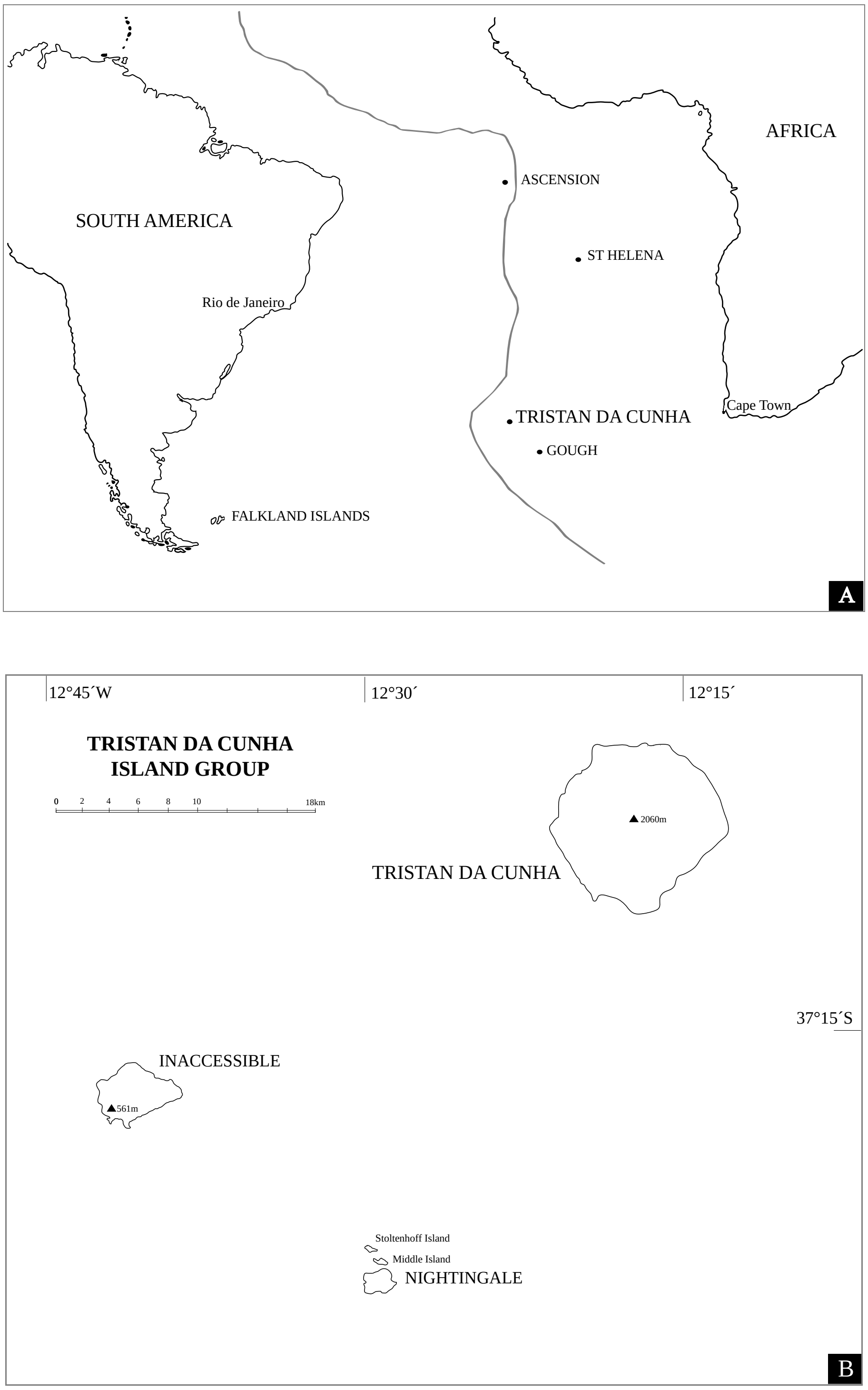


Fig. 2.1. Location sketches of Tristan da Cunha. A: position within the South Atlantic Ocean with relative locations of some other British Overseas Territories. B: position relative to Inaccessible and Nightingale Islands.

2.2. Geological background

The first official survey of Tristan was conducted by Captain Denham aboard the H.M.S Herald in 1852, although it was not until 1939 that the first accurate map was created (Crawford, 1939). This map (Fig. 2.2) was also the earliest to record, in detail, the names of most of the island's geomorphological features, which are either descriptive e.g., Green Hill, or record an incident at a certain place in local history e.g., the "Ridge Where The Goat Jump Off" (Crawford, 1939).

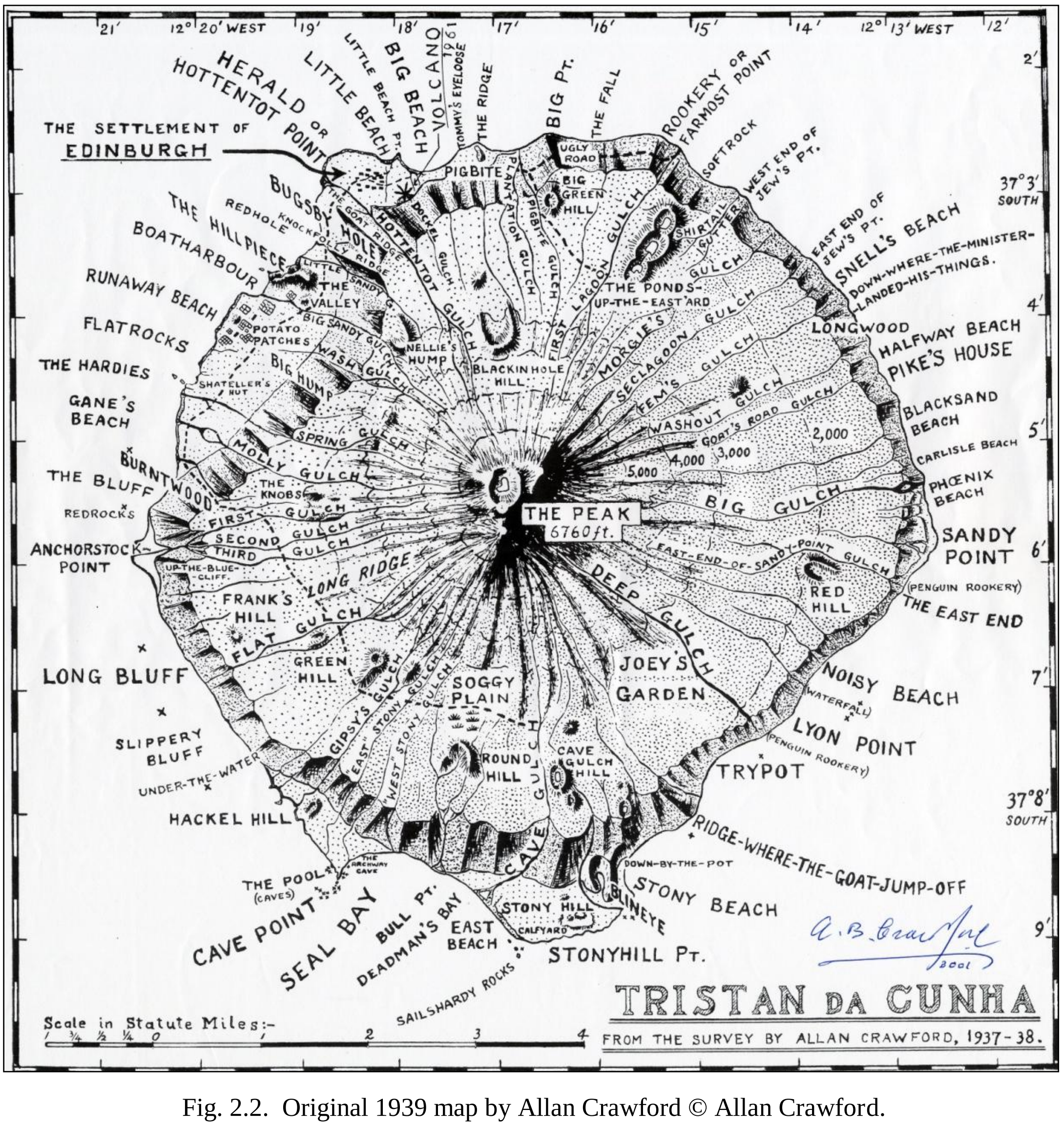


Fig. 2.2. Original 1939 map by Allan Crawford © Allan Crawford.

The geology of Tristan was first described by Douglas (1923) during the Voyage of the "Quest", an expedition to explore the little-known islands of the South Atlantic, Indian and

South Pacific Oceans (Douglas, 1923; Wild, 1923). This publication was shortly followed by a report on the expedition (Campbell Smith, 1930) and a petrological study conducted during the Norwegian Scientific Expedition to the island in 1937-38 (Dunne, 1941).

Several manuscripts were published during the early 1960's by members of the Royal Society Expedition that went to Tristan in 1962 during the waning phase of the 1961-62 eruption (e.g., Gass et al., 1962; Harris and Le Maitre, 1962; Gass, 1963; Harris, 1964). These publications were succeeded by a comprehensive account of the volcanology and physical morphology of Tristan (Baker et al., 1964). The seven-week expedition was approved by the Royal Society in response to the relatively sudden eruption of the volcano. It provided opportunities to survey the geology and to investigate the effects of ash and gases on the island's flora and fauna. The expedition team consisted of four geologists, a botanist, zoologist, meteorologist (Crawford) and an agriculturalist, two British Army members and two Tristanians. The expedition and subsequent report provided a detailed synthesis of all geological and volcanological work to date, including the first geological map (1:30 000; Fig. 2.3), new petrolographic and geochemical analyses, palaeomagnetic measurements and an early attempt at geochronology. The expedition established that Tristan was a relatively young (see Chapter 3 for geochronological data), composite cone with eruptive material of varied composition. Most of the island (including intrusives and parasitic centres) was mapped, although some structures were inferred from aerial photographs. The report still remains the most comprehensive volcanological account of the island, although some data have been reinterpreted in light of new volcanological knowledge, the development of geochronological techniques offering better precision and accuracy, and contemporary rock classification (e.g., Le Roex et al., 1990; Dunkley, 2002). The report will be frequently referred to throughout this chapter.

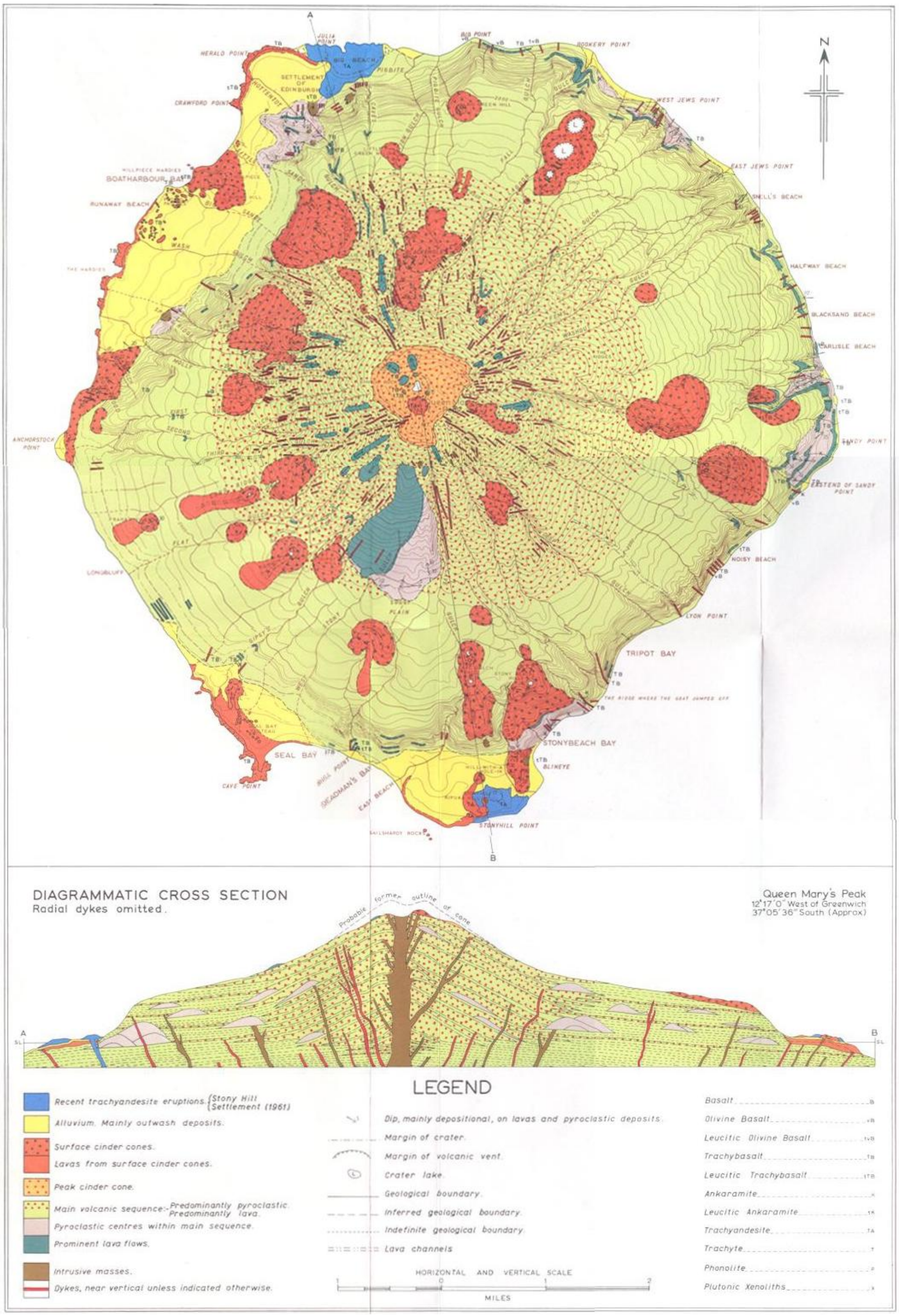


Fig. 2.3. Geological map of Tristan da Cunha, produced following the Royal Society Expedition to the Island in 1961-62 (1:30 000). Taken from Baker et al., (1964).

2.2.1. Regional tectonics and magmatism

Tristan's volcanic edifice is superimposed on young oceanic lithosphere (magnetic anomaly 5, i.e. 15 Ma) and, at its shortest distance, lies approximately 350 km east of the axial rift of the Mid Atlantic Ridge (MAR). South of this point, the MAR is markedly offset by a large transform fault with dextral displacement. Tristan is located at the western end of the aseismic Walvis Ridge (Fig. 2.4); a distinct volcanic lineament generally considered to be the surface expression of a deep rooted plume, possibly sourced from the core-mantle boundary (e.g., Courtillot et al., 2003). Likewise, volcanism on Tristan and adjacent islands (Nightingale and Inaccessible) is not considered to be related to partial melting at the MAR, rather is attributed to a hotspot (i.e. melting anomaly).

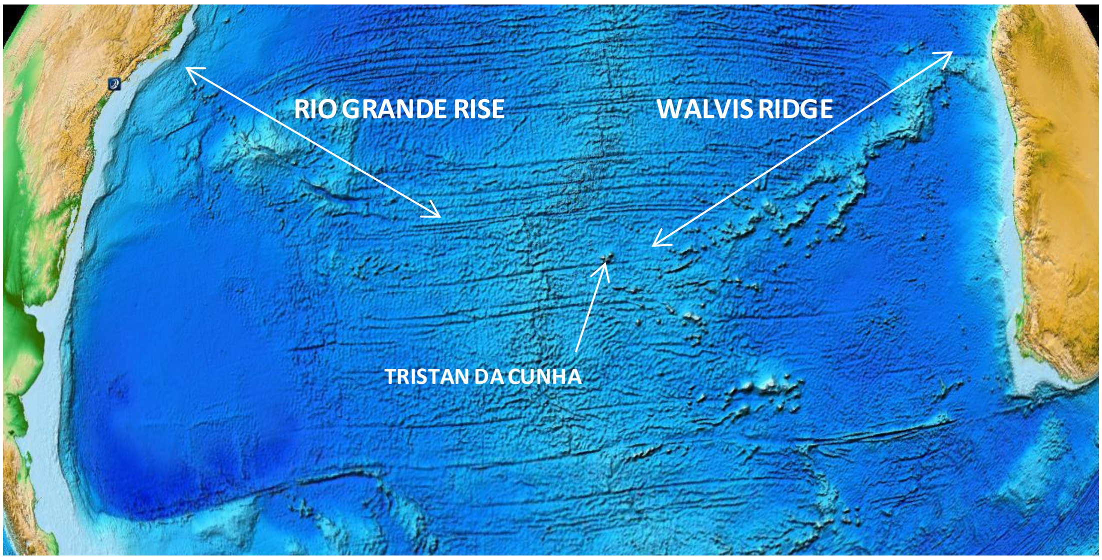


Fig. 2.4. Global relief model of the Walvis Ridge and Rio Grande Rise (Amante and Eakins, 2009).

Although the origin of intraplate melting anomalies is the subject of an ongoing debate (e.g., Anderson, 2000; Courtillot et al., 2003; DePaulo and Manga, 2003; Ritsema and Allen, 2003; Foulger, 2010; Conrad et al., 2011), there is compelling evidence for a deep source feeding the Tristan hotspot. Courtillot et al., (2003) outline five characteristics of a primary hotspot, or deep mantle plume: the occurrence of a linear chain of volcanoes progressing in age with distance from the hotspot; the presence of flood basalts at the origin of the track; a large buoyancy flux; consistently high $^{3}He/^{4}He$ ratios, and a low shear wave velocity in the underlying mantle. Of 49 known hotspots, only seven are regarded as primary, meeting at least three of the five 'criteria': Afar, Easter, Hawaii, Iceland, Louisville, Reunion and Tristan.

Volcanism from the Tristan hotspot is inferred to have commenced, prior to the onset of rifting in the South Atlantic Ocean, 134.7 ± 1 Ma ago (Renne et al., 1992), erupting the Paraná continental flood basalts in Brazil (e.g., Theide and Vasconcelos, 2010) and the Etendeka basalts in Namibia. The Walvis Ridge and Rio Grande Rise are interpreted as representing the relic trace of the Tristan hotspot between these two exposures as the South Atlantic spread apart.

Buoyancy flux[4] of mantle material is computed using swell morphology and/or mantle flow estimations (Davies, 1988; Sleep, 1990). If a hotspot is to be regarded as primary, the buoyancy flux of the plume must be greater than 1 Mg s^{-1} in order to melt mantle material beneath old lithosphere. Further, 'strong' plumes would also be able to avoid shearing by mantle flow before reaching the lithosphere (Steinberger and O'Connell, 1998). The buoyancy flux of the Tristan plume is calculated at 1.7 Mg s^{-1} (Sleep, 1990) - comparable to Iceland and Reunion. Although meeting three out of five criteria earns Tristan primary plume status (according to Courtillot et al., 2003), the buoyancy flux is still relatively weak and is regarded as both unreliable (in terms of measurement) by Courtillot et al., 2003 and 'fairly reliable' by Sleep, 1990. An earlier buoyancy flux calculation of 0.5 Mg s^{-1} indicates the uncertainty of this value (Davies, 1988).

Tristan is also the only primary plume candidate to have consistently low $^{3}He/^{4}He$ values (Farley and Neroda, 1998). High $^{3}He/^{4}He$ values (ten times the atmospheric ratio R_A) of hotspot lavas are attributed to upwellings from isolated, primitive sources, probably deep in the mantle (Farley and Neroda, 1998).

There are alternative mechanisms for intraplate volcanism. These include localised cracking of the lithosphere (Forsyth et al., 2006), asthenospheric shear due to mantle convection (Conrad et al., 2011), and small-scale convection triggered at the edges of cratons or continents (King and Ritsema, 2000; King, 2007). The Tristan hotspot cannot be explained by edge driven convection as it is not located within 1000 km (the distance based on the horizontal extent of a convective cell) of a continent-ocean or craton boundary. However, it is possible that eruptions sourced from the Tristan hotspot are caused by localised mantle shear. Conrad et al., (2011) identify a spatial correlation between seamount volcanism and rapidly shearing asthenosphere, reporting average shear speeds about 1.45 times greater

[4] The buoyancy flux of mantle plumes is a measure of plume strength. This is given by the difference in density between plume mantle and surrounding mantle, multiplied by the buoyancy-driven volume flux of the plume. Buoyancy flux, in terms of mantle plumes, applies the units Mg s^{-1} rather than units of buoyancy flux in atmospheric dispersion models, for example, where units m^4 s^{-3} are employed.

beneath submarine volcanism than volcanically inactive areas of young (< 10 Ma) seafloor. Melt genesis is a consequence of differences in mantle flow interacting with variations in mantle strength or composition. This interaction creates an obstacle which drives a component of the sheared flow upwards towards lower pressure and suitable melting conditions. Initial variations in mantle flow are created by movement of the plate and underlying mantle relative to each other. Asthenospheric shear around the Tristan hotspot is calculated to be faster (4-6 cm yr^{-1}) than at any other location beneath the Atlantic basin (Conrad et al., 2011).

Whether volcanism at Tristan is the result of one (or more) of the processes mentioned above or another, as yet unidentified, mechanism, the origin and processes leading to melting are still poorly understood.

2.2.2. Island structure and physiography

Tristan is a large oceanic stratovolcano, of which almost 40% of the 5,550 m high edifice is exposed subaerially. The island has an almost perfect conical form and is relatively circular in plan, with a maximum diameter of 12 km and an area of 120 km^2. The estimated volume of the subaerial portion is 78 km^3; therefore, the overall estimated volume of the entire edifice is 2,500 km^3, given an average gradient of 15°. The base of the volcano covers approximately 1,350 km^2 of the ocean floor, ~3.5 km below sea level.

The island can be divided into three main physiographic units: the Main Cliffs, the Base & Peak, and the Coastal Strips (Fig. 2.5). These units will be referred to throughout the thesis and are briefly described in the following three sub-sections. One of Tristan's most striking features is the extent of erosion by water action, both at the shoreline and by surface runoff, carving numerous deep ravines known locally as gulches which radially transect the island (Plate 2.2 and Fig. 1). Gulches range between 10 – 50 m in depth and up to 100 m wide. Tristan is heavily vegetated with low-lying flora which conceals the surface extent of the lavas and the abundant parasitic centres which punctuate the flanks. Owing to this dense vegetation growth, rock exposures are only evident in gulches or on the slopes of parasitic centres. Individual exposures are therefore difficult to trace for any considerable distance.

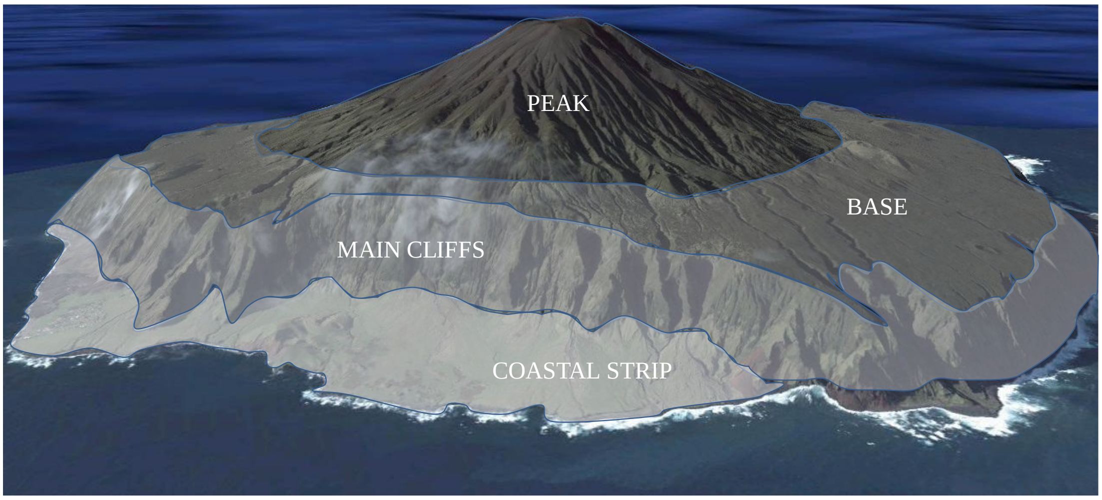


Fig. 2.5. Main physiographic units of Tristan. Map adapted from Google Earth.

Waterfalls around the island are ephemeral and only flow following heavy rain. The southern coastal strip has many more active waterfalls than the northern strip; probably due to topographical controls. There are several examples of large, dried up waterfalls, now vegetated, that do not re-mobilise even after a prolonged period of intense rainfall. Several of these can be seen along the northern coastal strip, especially in the cliffs at Little Sandy Gulch where evidence of a previous dynamic fall with a large plunge pool is now merely a trickle. This implies that the hydrological system has been modified in the past.

The volcanic edifice is composed of an alternation of permeable layers (rubbly, fragmental horizons and scoria) and impermeable layers (massive lava flows). The relatively low surface flow rate compared with the high levels of rainfall and steeply dipping topography (8-30°) suggest a high infiltration rate. It is possible that water is held as perched aquifers within the permeable layers of the edifice, overlying a basal aquifer. Alternatively, the inland aquifers may be dyke-confined. Radial dykes from the Peak outcrop at the Main Cliffs where, in at least three locations (Pigbite, Settlement & Bull Point), natural springs are associated with such features. It is possible that the underlying basal aquifer is marked by these freshwater outlets.

2.2.2.1. Main Cliffs

The Main Cliffs are the most visually arresting part of the island, framing the Base and the Peak. Although never quite vertical, the cliffs extend up to 900 m in places (Plate 2.3). Contrary to work published prior to the Royal Society Expedition, it is now held that cliff formation is attributable to marine erosion (Baker et al., 1964; Dunkley, 2002), rather than to fault activity (Dunne, 1941) which is apparently absent all over the island.

The cliffs are inferred to be the oldest succession of deposits, with the bottom-most flows likely a record of the earliest sub-aerial volcanism. The strata dip gently (~5-8˚) outwards and their radial nature suggests that lavas are most likely to have derived from a summit vent (Baker et al., 1964). The sequence of interbedded lavas (with rubbly horizons, or autobreccias) and pyroclastics is occasionally interspersed with localised parasitic centres which occur within the sequence (Plate 2.4). Flows range in thickness from 30 cm to 10 m, with thicker, massive flows displaying pronounced columnar jointing. Occasionally, flows can be traced for up to a kilometre but, due to extensive vegetation growth, usually can only be followed for a few hundred metres. Compositions range from ankaramitic basanites through to aphyric tephrites. Intrusions are commonplace and 'en echelon' dykes, usually with left-trending segmentation, are frequently exposed in the succession.

2.2.2.2. Base and Peak

The 'Base' and the 'Peak' represent the lower and upper flanks of the volcano, beyond the cliff boundary. Although the titles imply two distinct areas, there is a relatively smooth transition between the shallow dipping lower slopes of the Base (~8°) and the steeply dipping upper slopes of the Peak (~30°). Both 'zones' are composed of lavas with intercalated pyroclastics which dip radially seaward. Lavas on the Base and Peak are compositionally similar to the Main Cliff succession (dominantly tephritic), although more evolved compositions have erupted on the upper slopes of the Peak and from parasitic centres on the Base.

The Base lies approximately between 700-1000 m and is heavily vegetated with grasses, shrubs and ferns (Plate 2.5). Numerous (< 30) parasitic centres, considered to be post-shield volcanism, have punctuated the surface and exhibit varying erosional states (see Appendix 1), although there appears to be no relationship between degree of degradation, location, age, volume and composition (see Chapter 3). Many centres have breached on the seaward side, either from the crater itself, or from the base of the cone. A summary of the main characteristics are presented in Appendix 1. Despite the dense vegetation, distinct morphological features can still be identified, including prominent levees, flow fronts and, occasionally, pressure ridges. Lavas issuing from breached centres are more pronounced on younger parasitic cones such as Green Hill (Fig. 1 and Plate 2.6). Small maars are evident on the Base, including three NNE trending centres (the Ponds) on the north-eastern edge and the Cave Gulch centres on the southern edge (Fig. 1 and Plate 2.7). Each crater has steeply dipping walls surrounded by a low-lying ring of fragmental debris which is almost continuous with the surrounding flanks. Both the Ponds and the Cave Gulch centres lie on a radial line from the summit and were likely formed by a radial dyke intersecting the water table. Evidence of phreatic eruptions in a volcanic system of relatively low-explosivity illustrates the need to understand the hydrological situation on Tristan (Clarke et al., 2009).

The Peak denotes the area above 1000 m, although the highest point of the summit region is also locally referred to by the same name. One key distinction between the Base and Peak is the apparent increase in pyroclastic material relative to lavas. This is partly an illusion from the lack of vegetation on the upper slopes of the Peak, but also due to the intense erosion of lavas that cap the ridges on either side of the gulches at this height (Plate 2.8). Mafic lavas tend to be thinner on the Peak and thicken as the inclination diminishes, and evolved lavas are less widespread, but thicker (< 10 m).

At the summit is a large, well-preserved scoria cone partially filled by a natural lake (Plate 2.9). The crater is roughly circular and about 500 m in diameter. Narrow crater ramparts are composed of well-preserved agglutinated scoria and cap the slopes which dip radially at a shallow angle (relative to the Peak slopes). The crater walls are very steep and contain agglutinates and bombs. In agreement with Dunkley (2002), the incision of the crater into surrounding lavas is likely to be a maar created by phreatic or phreatomagmatic activity. On the eastern flanks of the Peak, there is a thin (4-5 cm) surface debris avalanche deposit (Plate 2.10). Welding is absent, implying a localised collapse of the summit cone rather than emplacement under heat. Contrary to the findings of Chevalier and Verwoerd (1987), no pyroclastic flow deposits have been observed to date, although this does not preclude the possibility that deposits may have been eroded, or that they are not visible due to vegetation growth. Further, Chevalier and Verwoerd (1987) reportedly observed pervasive thermal activity on the summit of the Peak. It is unclear from their fieldwork descriptions whether they actually set foot on the Peak, or conducted their survey from a helicopter; possibly mistaking apparent thermal activity for radiating heat as the sun warmed the cool rocks. Islanders who frequently visit the Peak have never observed thermal activity.

Although dykes and other intrusive masses are exposed in the Main Cliff succession, they are most evident on the Peak, forming prominent features of apparently higher competence than the surrounding deposits. The dykes radiate from the summit and vary in width from 1-7 m and up to 15 m above the surrounding deposits (Plate 2.11). In places, the thicker dykes can be traced for 100's of metres, whilst the thinner ones appear and disappear in a sinuous fashion (Plate 2.12). The radial dykes do not vary in composition from lavas of the main sequence, although the prominent plugs which emerge from the summit crater and on the southern flank, are markedly trachytic.

To explain the apparent concentration of vents, direction of dykes and the shape of the island (described as rhomboidal), Chevallier and Verwoerd (1987) inferred that Tristan has built up on two radial axes (N170°E and N80°E), parallel to the main regional stress direction. Whilst this interpretation is possible, many of the dykes are unmapped, so any apparent directional concentration of the radial dykes may be misleading. At the time of publication, Chevallier and Verwoerd were also unaware that at least one large scale sector collapse had affected the island's shape (see Section 2.3 and Chapter 3), apparently elongating the island in a NNW direction. The work of Baker et al., (1964), and field observations from the current study, do not provide evidence that vent locations are concentrated along particular axes (Fig. 1 and Fig. 2.3), although it is possible that the N-S trend of the 1961 eruption, the penultimate eruption at Stony Hill and the linear explosion centres at Cave Gulch Hill is not coincidental (Fig. 1). The postulated model also does not explain the apparent absence of rift zones in the field.

2.2.2.3. Coastal Strips

Further post-shield volcanism is evident as low-lying constructional features known as coastal strips. There are two coastal strips on the island, a large one in the north-west and a smaller one in the south (Fig. 1). The plateaus are composed of lava and scoria, overlain by alluvial and colluvial deposits. Other small coastal strips exist around the island, but these are constructed entirely of alluvium so will not be discussed further.

The Settlement coastal strip in the north-west extends for about 6 km from Pigbite to Burntwood (Fig. 1). It is the only area presently suitable for permanent habitation and crop cultivation. Most livestock graze on this plateau. The coastal strip is locally subdivided into 6 main sections: Pigbite, the 1961-62 dome and flow (see Section 2.2.2.4), the Settlement, Hillpiece, the Patches and the Bluff. To the west of the latest eruption, Pigbite is a desolate, area of land locked between sheer cliffs and vicious surf, unsuitable for either habitation or grazing. The steep cliffs in this area are prone to rockfalls; evidence for which is preserved both in the cliff face and in the vast area of debris that partially fills the Pigbite plain. To the east of the 1961-62 lava outpouring is the Settlement (Plate 2.13). This rests on tephritic basement lavas and alluvium, which likely thins eastwards from Hottentot Gulch (Hards, 2004). The basement lavas are exposed in the low cliffs along the edge of the coastal strip. Two massive columnar jointed flows, originating from the Hillpiece centre, can be traced along most of the strip (Plate 2.14 and Plate 2.15). Underlying these massive flows are pillow lavas with hyaloclastite. Outcrops of pillow lavas are particularly prominent at Runaway Beach near the Patches and at the shoreline near the harbour (Plate 2.16). The low cliffs at the harbour display pronounced white patchy markings, similar to spherulites, which are the surface expression of concentrated interstitial leucite (Baker et al., 1964). The characteristic spotted surfaces are prevalent all over the Settlement Plain lavas and have been accentuated by weathering (Plate 2.17).

Between the Settlement and the Patches is the imposing Hillpiece-Burnthill parasitic centre complex. Attaining a height of 230 m a.s.l., Hillpiece itself is the most prominent feature on the coastal strip, particularly when viewed from the sea where extensive marine erosion has exposed red pyroclastics lying unconformably on bedded yellow tuffs (Plate 2.18). The complex evolution of the centres was interpreted by Baker et al., (1964) who infer that, due to the landward dip of the yellow beds and their exposed inclination in the hardies (stacks) and sea cliffs, the deposits must have originated from a tuff cone about 230 m north of the hardies. This implies that the Settlement coastal strip was once almost double its present size. Annexed to Hillpiece is the slightly smaller Burnthill centre, which is also composed of cinder, bombs and lava fragments. Superimposed on the centre is a small cone, which is the youngest of the complex.

To the west of the Hillpiece-Burnthill complex are the Patches (potato patches) (Fig. 1), a ~1 km^2 area of the Settlement coastal strip where islanders grow potatoes and other vegetables. The area is separated into several main units which are further sub-divided into individual vegetable plots bordered by dry stone walls. Sporadic scoria mounds, tumuli and hornitos are dominant features on the landscape (Plate 2.19), and are occasionally used as windbreakers for the ‘camping huts’ and sheds. These structures are composed of unconsolidated scoria with rare spindle bombs. Their formation is possibly attributable to rootless vents which formed when the lava flowed over wet ground or ponded water, resulting in small phreatic eruptions (Dunkley, 2002).

At the far west of the coastal strip, the Bluff marks the furthest extent of the Hillpiece-derived lavas, at the junction with deposits from the Burntwood centre (Plate 2.20).

The southern coastal strip is subdivided into the Seal Bay plateau and the Stony Hill plateau. It is possible that the two were originally connected and have been subsequently eroded by wave action to create Seal Bay and Deadman's Bay (Fig. 1) (Dunkley, 2002). Seal Bay plateau consists of lavas, extruded from the breached cone, Hackel Hill and overlain by alluvium and colluvium derived from the Main Cliffs. A succession of five or six flows, each up to 20 m thick and separated by a rubbly horizon, are exposed in a sea-cliff succession that extends from Gipsy's Gulch to Seal Bay (Fig. 1). The basalt-trachyandesitic lavas display columnar jointing, and spheroidal weathering is abundant on the lower flows, especially in the intertidal zone. At the shoreline there are several caves, many of which are preserved lava tubes.

Hackel Hill is a scoria cone about 55 m in height and about 270 m wide at the base (Plate 2.21). Composed of red and black scoria, the cone is breached on the seaward, south-west side from which two prominent levees extend for about 80 m and expose columnar jointed lavas. Beyond the levees, the lava field is well exposed in horizontal section near the cliff edge around the Caves and Cave Point (Plate 2.22). There are occasional flow structures and elongated vesicles showing flow direction – normally seaward. Other observed structures include fine ridges from contraction upon cooling, and very occasional ropes.

Rare pumice can be found on the shore of Seal Bay and at the Caves. Small (< 5cm) eroded clasts of pumice, interspersed with driftwood and pebbles, indicate that it is not a fresh deposit, and was probably remnants of the 2004 pumice rafts which were washed up mainly on the Seal Bay beach (Hards, 2004).

Stony Beach plateau extends from Bull Point to Stony Beach Bay (Fig. 1). The plateau is composed of basement lavas (likely sourced from the Blineye centre) and colluvial deposits. Superimposed on this colluvium are three young eruptive centres of the Stony Hill Group: Little Hill, Kipuka Hill and Stony Hill (Fig. 2.6). Little Hill (Plate 2.23) and Kipuka Hill are small breached scoria cones, and Stony Hill is a dome-tholoid complex similar in morphology and composition to the 1961-62 complex (Plate 2.24). The tholoid is about 300 m at its widest and rises steeply to a height of nearly 120 m. There are craggy pinnacles around the ill-defined summit of the tholoid and a high, narrow feature, probably an extruded spine (Baker et al., 1964) on the northern rim. Baker et al., (1964) measure the extent of the lava to be about 1300 m wide and the cliffs expose two 9 m thick flows separated by a 2 m rubbly horizon. All eruptive centres are vegetated with trees (*Phylica*), grasses, ferns, mosses and lichens. Stony Hill has markedly less vegetation, possibly due to its blocky morphology, but more likely suggestive of a young age. Baker et al., (1964) suggest Stony Hill is approximately 200-300 years old.

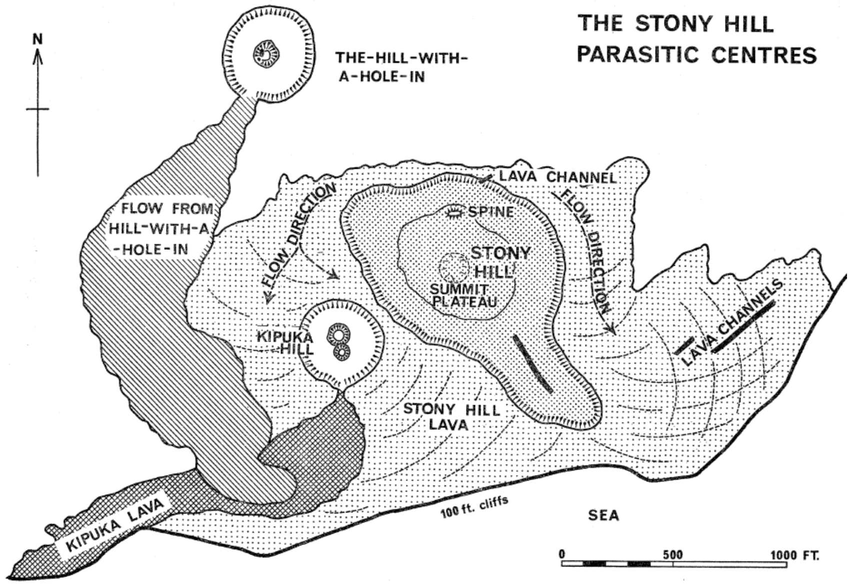


Fig. 2.6. Sketch of the Stony Hill parasitic centres: Stony Hill, Kipuka Hill and Little Hill (also known as the 'hill-with-a-hole-in'. Taken from Baker et al., (1964).

2.2.2.4. 1961-62 dome-tholoid complex

Fifty metres west of the Settlement is the imposing volcanic dome and flows (known locally as the *volcano*) which erupted in 1961 following two months of gradually intensifying seismic activity (Plate 2.25). Tremors began in August and reached a climax in October, reaching a 'D' grading on an improvised scale (A-D) roughly equivalent to an intensity level VI on the modified Mercalli Scale (Baker et al., 1964). Numerous rockfalls occurred during this time, especially from the volcanic plug in the cliffs behind the Settlement. Surface deformation followed, manifesting as small surface cracks which buckled pipes, doors and window frames. On the 9th October a mound began to form, which began to erupt the following day. Extremely viscous, blocky, tephri-phonolitic lava was extruded from the summit region of the dome which eventually grew to a height of 147 m (Baker et al., 1964). Blocks and clinker were reportedly seen rolling down the sides of the dome. Following a seaward breach in the dome, a small cone (known as the central cone) formed and from it flowed one blocky and two subsequent a'a flows into the sea (Fig. 2.7). The transition from blocky to a'a lava was likely due to magma ascending more freely following the initial extrusion of near-solid blocky material. During the final stages of eruption, a second dome was extruded from the central cone composed of blocky and slabby lava. A shallow peripheral crater at the back of the dome, nearest the cliffs, was the site of phreatic activity, producing ash, steam and lithic ejecta (Baker et al., 1964; Dunkley, 2002).

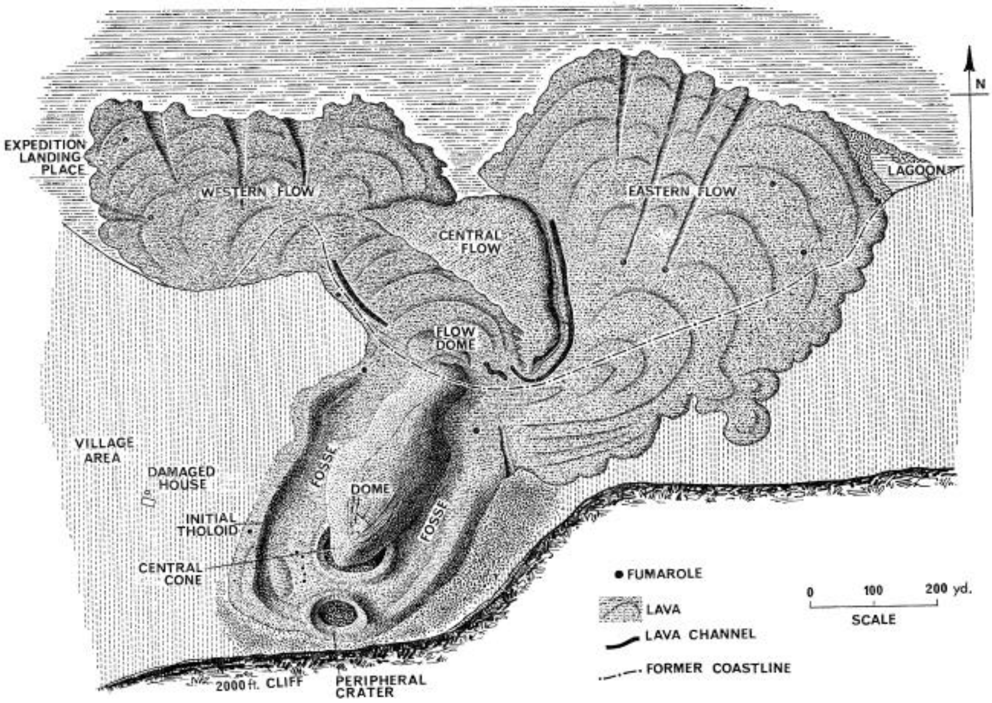


Fig. 2.7. Sketch of the 1961-62 eruptive centre. Taken from Baker et al., (1964).

The Royal Society Expedition estimated the area covered by the lava to be 0.59 km^2 and the total volume of material to be approximately 0.02 km^3. Although the precise eruption duration was not recorded, it seems likely that the eruption peaked in February and concluded towards the end of March, when the Expedition departed. Therefore, if the assumed eruption duration was 160 days, the average rate of extrusion would have been 1.44 $m^3 s^{-1}$. A considerable fraction of the lava flows have since been eroded by wave action, but three distinct flows and dome(s) are still preserved. Thermal activity has been gradually decreasing since it was measured by the Royal Society Expedition at 890°C (Baker et al., 1964). A record of temperature measurements and fumarole observations in 2009 and 2010 is provided in Appendix 2.

2.2.3. Geochemistry and Petrography

The first systematic petrographical review of Tristan was undertaken by Dunne (1941), during the Norwegian Scientific Expedition to the island in 1937-38. Further investigations, including geochemical analyses, were conducted by geologists of the Royal Society Expedition (Baker et al., 1964). Other detailed geochemical studies on Tristan and adjacent islands highlight some of the unique geochemical characteristics of the Tristan Island Group and provide interesting interpretations of magma genesis (e.g., Weaver et al., 1987; Le Roex et al., 1990; Harris et al., 2000).

For the present study, a further 100 samples were collected and 35 specimens were analysed petrographically and whole rock geochemistry analysed using XRF. Details of analytical procedures and analytical results are given in Appendix 3. Calibration data are provided in Appendix 4. Sample numbers and descriptions of sample sites are provided in Appendix 5 and Appendix 6. It should be noted that these analyses were conducted to inform and support the $^{40}Ar/^{39}Ar$ geochronology (see Chapter 3) and are, therefore, not representative of the entire eruptive sequence.

686 rock specimens were collected during the Royal Society expedition to Tristan. Using petrographic analysis, Baker et al., 1964 determined that the rocks belonged to the typical oceanic association of alkali basalt through to trachyte, owing to the lack of normative nepheline as a crystalline phase. In accordance with more recent nomenclature, (Le Bas et al., 1986; Le Maitre et al., 1989), the series has now been revised to a basanite-phonolite suite (Le Roex et al., 1990). Samples recently collected from the eruptive sequence on Tristan correspond to this high alkali, silica-undersaturated suite, and represent the full range from basanites and tephrites, to phono-tephrites and tephri-phonolites (Fig. 2.8). Highly evolved rocks straddle the divide between phonolites and trachytes. These analyses are slightly dissimilar to results presented by Le Roex et al., (1990) that identified most of these particular trachytes as phonolites (see Figs 2.8 and 2.9 for visual comparison). Discrepancies may be due to a slight underestimation, or overestimation, of Na_2O and K_2O in either study, or from sample heterogeneities.

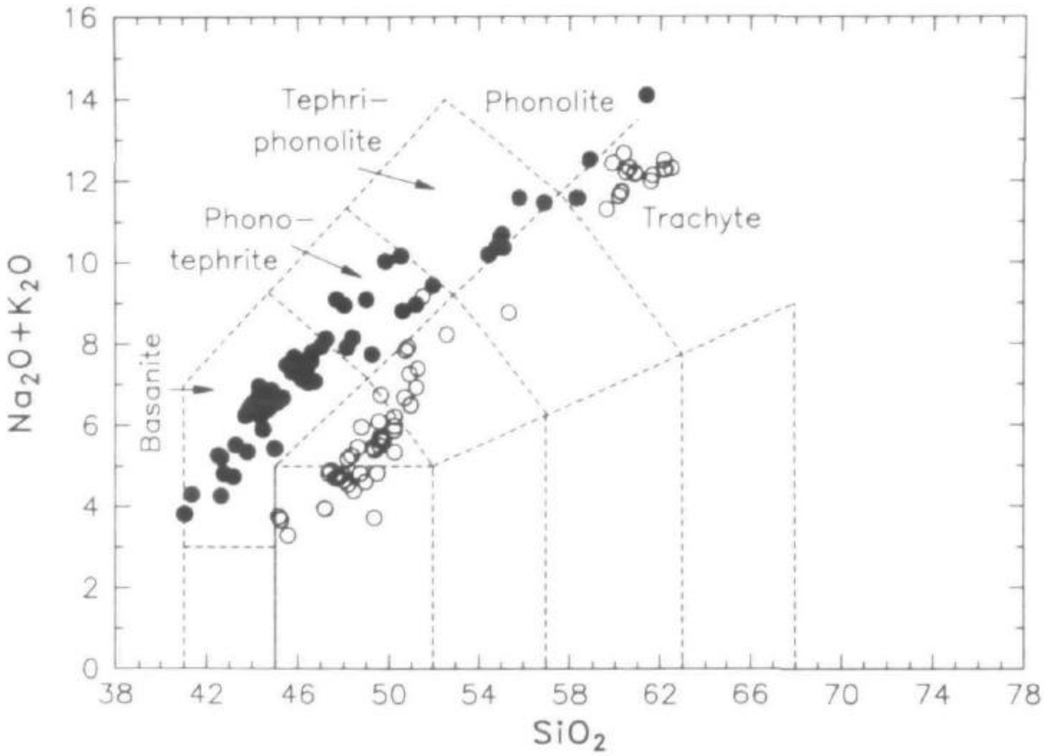


Fig. 2.8. Total alkali-silica diagram taken from Le Roex et al., (1990) Data for Tristan lavas (solid symbols) are taken from the 1990 study, data for Gough lavas (open symbols) are taken from Le Roex (1985).

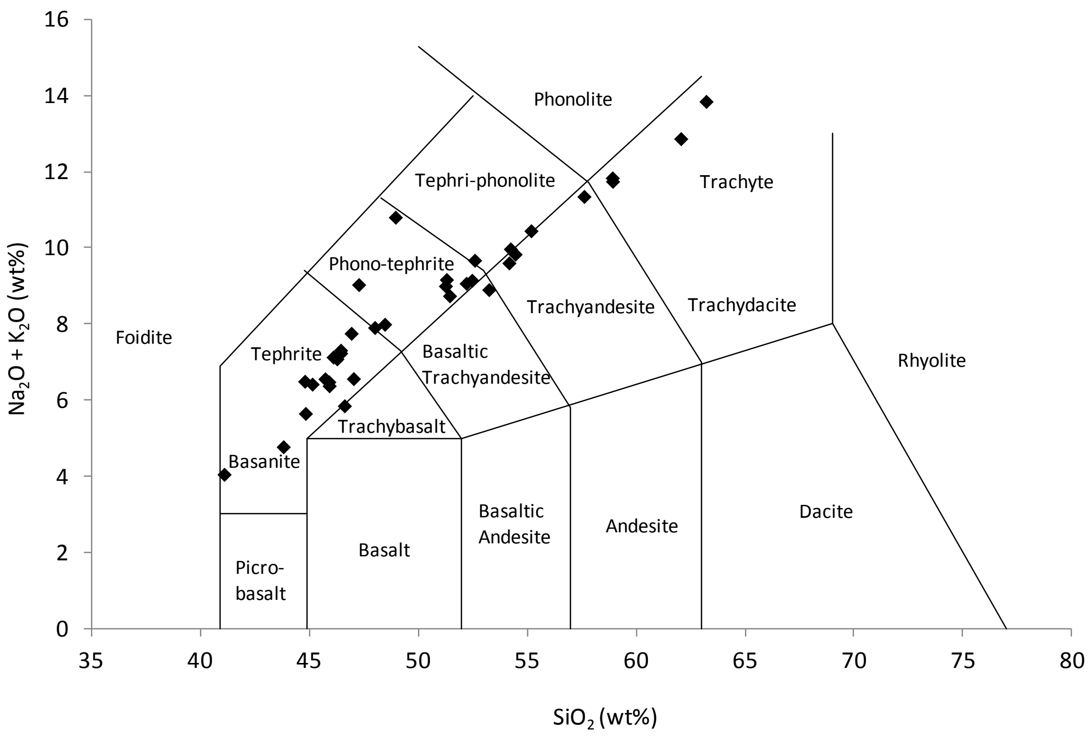


Fig. 2.9. Total alkali-silica diagram of samples from present study. Sub-divisions from Le Bas et al., (1986). Data have been normalized to 100%.

Mapped eruptive deposits on Tristan demonstrate a strong heterogeneity of compositions and volumes across the island (Baker et al., 1964; Le Roex et al., 1990; Dunkley, 2002; Hicks et al., 2012). At the mafic end of the spectrum, ankaramitic basanites are prevalent in the main succession as massive flows and contain abundant (20-30%) clinopyroxene and lesser (~10%) olivine phenocrysts. However, basanites and particularly tephrites (normative ol < 10%) dominate the main succession (the main edifice) volumetrically and are also widespread all over the island as dykes and parasitic centres. Deposits are normally aphyric though some porphyritic varieties contain small-to-medium phenocrysts of clinopyroxene, plagioclase, sporadic amphibole and olivine. In thin section, the dominant mineralogy is clinopyroxene, plagioclase, titanomagnetite (as inclusions) and some olivine. Minerals are relatively unaltered euhedral to subhedral phenocrysts and microphenocrysts with little zoning. Some resorption is evident. Phenocrysts are usually set in a crystalline, often trachytic matrix with occasional interstitial glass. In accordance with the findings of the Royal Expedition, many of the mafic samples collected in this study contained interstitial leucite (Le Maitre and Gass, 1963), indicative of the highly silica-undersaturated K-rich nature of the Tristan samples (Plate 2.26), although rare for oceanic islands in general (Baker et al., 1964).

There is evidence of a weak trend towards more evolved lavas with time (see Chapter 3), with the last three eruptions on and around Tristan discharging tephri-phonolite or phonolitic/trachytic lavas. Evolved deposits tend to be restricted to parasitic centres and breached lavas, as intrusive masses, or recent flows on the upper slopes of the Peak. These phono-tephrites and phonolites are more generally porphyritic than the mafic rocks, with microphenocrysts and phenocrysts of clinopyroxene, plagioclase, amphibole and rare biotite. Alkali feldspar is also present in small quantities. Trachytes occur in smaller volumes, usually as prominent plugs at the summit. Thin sections from plug samples display trachytic textures (Plate 2.27) and contain abundant fluorite which has important hazard implications in terms of saturation with dissolved fluorine. Additionally, plutonic xenoliths are relatively common in these deposits and range in size from 20 cm blocks to xenocrysts of only a few mm in diameter.

Major and trace element compositions for 35 fresh samples are presented in Appendix 3. Internal validation of the bulk-rock analyses is provided by lava samples sourced from the Hillpiece-Burnthill complex. Three analysed tephritic lavas from this centre show similar compositions (Table 2.1) despite being separated in age by several ka (see Chapter 3). The basanite was sampled from an older central tuff cone, likely a very early manifestation of the Hillpiece centre (see Section 2.2.2.3), hence the slightly less evolved composition.

Table 2.1. Samples sourced from the Hillpiece-Burnthill complex.

Rock Type	*basanite*	*tephrite*	*tephrite*	*tephrite*
Location	Hillpiece	Hottentot	Burnthill	Pillows
Sample No.	**003**	**007A**	**085A**	**100**
MgO	3.45	4.48	4.46	4.44
Al_2O_3	16.4	16.33	16.45	16.4
SiO_2	44.9	45.98	46.08	45.4
P_2O_5	1.03	0.95	0.93	0.95
CaO	7.8	9.06	9.04	9.1
TiO_2	2.73	3.22	3.23	3.21
MnO	0.17	0.18	0.18	0.18
K_2O	3.31	3.02	3.2	3.04
Fe_2O_3	9.94	11.58	11.68	11.76
Na_2O	5.26	4.2	3.96	3.96
Total	95.04	99	99.21	98.41
% LOI at 1050°C	*3.38*	*-0.22*	*-0.29*	*-0.19*
Total	**98.4**	**98.8**	**98.9**	**98.2**
Sc	10	12	12	10
V	159	195	196	198
Cr	<20	<20	<20	<20
Ni	<10	<10	<10	<10
Cu	<10	13	<10	28
Zn	113	100	108	111
As	<10	<10	<10	<10
Rb	77	72	73	67
Sr	1187	1208	1197	1243
Y	27	29	29	28
Zr	373	343	349	341
Nb	84	76	79	76
Mo	<10	<10	<10	<10
Ba	716	742	726	747
La	83	77	73	80
Ce	203	196	184	191
Pb	<10	<10	<10	<10
Th	12	11	13	12
U	<10	<10	<10	<10

Comparisons of new bulk-rock analyses with those of Baker et al., (1964) and Le Roex et al., (1990) generally reveal almost identical results (Table 2.2). Slight differences may be due to inconsistent instrumentation calibrations, inexact duplication of sampling locations, and/or sample heterogeneities. Eight sample sites from the Royal Society Expedition were duplicated in the current study, deposits from which all show very similar major element concentrations. Lavas at Jenny's Watron, the Blineye plug, Summit plug, Stony Hill lavas, Frank's Hill lavas and the Pillows at the Harbour are comparable. Also, sample 097A (1961 dome rock) is comparable to that of sample 518 (Baker et al., 1964), except for a slightly elevated iron content, due possibly to localised variations in oxidization. Sample sites of Le Roex et al., (1990) are numerous but not described in any detail, and only selected analyses are provided in the text. As such, there is little overlap with sample analyses produced for this study, except for sample numbers TR617 (1961 dome rock) and TDC1 (Jenny's Watron phonolite) (Table 2.2). Results show high similarity across studies.

It is noted that the tephrites from "Jenny's Watron" (samples 068 and 070), do not lie on the general compositional trend. These are interpreted as sub-aqueous deposits laid down in a shallow water environment, unconformably overlying phonolitic lavas (sample 062A). Subsequently, large loss-on-ignition values are associated with these saturated deposits.

Compared to other OIB's (http://georoc.mpch-mainz.gwdg.de/georoc/), Tristan rocks contain relatively high concentrations of Sr (≤ 1447 ppm) and Ba (≤ 1487 ppm). As concluded by Le Roex et al., (1990), the trace element patterns are consistent with dominant control of clinopyroxene, titanomagnetite and olivine in the basanites – phono-tephrites, with plagioclase, alkali feldspar and apatite becoming increasingly important phases in the more evolved rocks.

Table 2.2 Comparison of major and trace elements at similar sample locations across studies. Analyses by Baker et al., 1964 and Le Roex et al., 1990 are bold.

Rock Type	*tephrite*	***trachybasalt Baker et al., 1964***	*tephrite*	***trachybasalt Baker et al., 1964***	*tephrite*	***trachybasalt Baker et al., 1964***	*phono tephrite*	***leucite-bearing tracybasalt Baker et al., 1964***	*tephi phonolite*	***tracyandesite Baker et al., 1964***	*tephi phonolite*	*tephi phonolite*	***tephri-phonolite le Roex et al., 1990***	***trachyandesite Baker et al., 1964***	*tephi phonolite*	***sodalite plagioclase trachyte Baker et al., 1964***	*phonolite*	***phonolite le Roex et al., (1990)***	***phonolite Baker et al., (1964)***
Location	Hottentot	Hottentot	Pillow lavas	Pillow lavas	Frank's Hill	Frank's Hill	Blineye	Blineye	Stony Hill	Stony Hill	1961 Dome	1961 Dome	1961 Dome	1961 Dome	Peak Plug	Peak Plug	J.Watron	J.Watron	J.Watron
Sample No.	**007A**	**364**	**100**	**622**	**054/55A**	**619**	**019**	**194**	**023A**	**230**	**095**	**097A**	**TR617**	**518**	**035-038**	**86.3**	**062A**	**TDC1**	**30**
MgO	4.48	4.89	4.44	4.72	4.14	4.6	3.31	3.32	1.65	1.68	0.96	1.44	1.43	1.5	0.67	0.81	0.3	0.3	0.4
Al_2O_3	16.33	16.7	16.4	17.06	17.38	18.1	17.26	18	18.97	19	19.0	19.24	19.42	19.35	20.18	19.1	19.66	19.78	19.6
SiO_2	45.98	45.7	45.4	46.07	46.04	46.2	47.77	48.54	53.45	53.9	56.4	54.96	54.95	54.53	57.27	58.2	60.02	61.38	59.6
P_2O_5	0.95	0.84	0.95	1.22	1.2	0.5	1.05	1.18	0.49	0.74	0.24	0.38	0.39	0.38	0.14	0.21	0.06	0.06	0.05
CaO	9.06	9.91	9.1	9.35	8.4	9.4	8.26	8.49	5.74	6.25	4.08	5.46	5.62	5.76	3.08	3.58	1.22	1.31	1.3
TiO_2	3.22	3.65	3.21	3.08	3.08	3.5	2.69	2.98	1.7	1.77	1.26	1.65	1.64	1.62	1.04	1.33	0.5	0.51	0.5
MnO	0.18	0.17	0.18	0.18	0.16	0.2	0.18	0.18	0.18	0.18	0.17	0.18	0.19	0.18	0.12	0.08	0.23	0.18	0.2
K_2O	3.02	3.1	3.04	3.16	3.38	3.3	3.22	3.38	4.51	4.53	4.96	4.67	4.89	4.83	5.4	5.94	6.75	6.81	6.6
Fe_2O_3	11.58	11.01	11.76	10.91	10.11	9.8	10.18	8.96	6.55	6.42	4.68	5.89	5.45	6.05	3.28	3.52	2.29	2.3	2.5
Na_2O	4.2	3.96	3.96	4.01	4.21	4.7	4.64	4.74	5.3	5.04	6.13	5.72	5.72	5.84	6	6.3	5.68	7.28	5.7
Total	99	99.93	98.41	99.76	98.1	100.3	98.56	99.77	98.54	99.51	97.85	99.59	99.7	99.7	97.18	99.07	96.71	99.91	96.45
% LOI at 1050 °C	*-0.22*	*0.21*	*-0.19*	*0.18*	*0.52*	*0.2*	*-0.1*	*0.17*	*0.74*	*0.47*	*0.86*	*0.4*	-	*0.25*	*1.74*	*1.09*	*2.85*	0.93	3.6
Total	**98.8**	**100.1**	**98.2**	**99.9**	**98.6**	**100.5**	**98.5**	**99.9**	**99.3**	**100.0**	**98.7**	**100.0**	**99.7**	**100.0**	**98.9**	**100.2**	**99.6**	**100.8**	**100.05**
Sc	12	-	10	-	10	-	<10	-	<10	-	<10	<10	-	-	<10	-	<10	1.3	-
V	195	400	198	200	198	170	164	250	69	130	59	68	-	100	55	-	12	21	16
Cr	<20	-	<20	30	<20	-	<20	-	<20	-	<20	<20	-	-	<20	-	<20	<1.6	-
Ni	<10	-	<10	10	<10	10	<10	-	<10	-	<10	<10	-	-	<10	-	<10	<1.0	-
Cu	13	-	28	-	<10	-	<10	-	<10	-	<10	<10	-	-	<10	-	<10	<1.0	-
Zn	100	-	111	-	107	-	108	-	95	-	90	93	-	-	63	-	81	79	-
As	<10	-	<10	-	<10	-	<10	-	<10	-	<10	<10	-	-	<10	-	<10	-	-
Rb	72	170	67	170	71	180	84	220	104	200	121	112	-	220	155	-	173	176	400
Sr	1208	1600	1243	900	1459	1100	1292	1100	1390	1200	1289	1408	-	1400	920	-	77	54	40
Y	29	40	28	60	29	45	29	50	29	45	31	31	-	55	22	-	24	29	20
Zr	343	300	341	350	350	300	394	400	475	400	530	473	-	350	530	-	799	838	500
Nb	76	110	76	130	90	100	87	160	104	160	127	113	-	170	106	-	172	-	160
Mo	<10	5	<10	7	<10	4	<10	9	<10	5	<10	<10	-	6	<10	-	<10	-	<3
Ba	742	1200	747	850	825	950	805	950	1172	1100	1487	1289	-	1300	1308	-	<20	19.8	20
La	77	200	80	250	96	170	88	250	109	250	126	120	-	250	99	-	165	154	120
Ce	196	-	191	-	226	-	218	-	239	-	249	255	-	-	191	-	223	255	-
Pb	<10	11	<10	21	<10	35	<10	16	<10	17	11	<10	-	16	13	-	21	20.3	24
Th	11	-	12	-	13	-	13	-	16	-	19	17	-	-	20	-	28	-	-
U	<10	-	<10	-	<10	-	<10	-	<10	-	<10	<10	-	-	<10	-	<10	6.6	-

Isotope analyses were conducted by Le Roex et al., (1990) building on previous, limited data sets (e.g., Cohen and O'Nions, 1982). Except for the most evolved samples, 20 out of 23 samples showed limited, but significantly mutually correlated, variations of Sr, Nd and Pb isotopic compositions, broadly similar to those of the rest of the Tristan island group, but distinct from those lavas giving rise to the Discovery Seamount basalts (Sun, 1980) and the Walvis Ridge (Richardson et al., 1982). This suggests that the source material for the Walvis Ridge and the Tristan lavas is either heterogeneous or has changed over time (Le Roex et al., 1990). The other three samples, all phonolites from Jenny's Watron, measured substantially higher $^{87}Sr/^{86}Sr$ ratios than the other samples suggesting either that the phonolitic magma evolved from a, basanitic parent with a higher initial $^{87}Sr/^{86}Sr$, or that the erupted lava had incorporated Sr from seawater through alteration. Le Roex et al., (1990) favour the latter interpretation.

None of the Tristan lavas are considered to be representative of primary melts. Trace elements modelling and isotopic data suggest that compositional variations are controlled by fractional crystallisation (Le Roex et al, 1990). However, resorption features of some phenocrysts are suggestive of changes in the magmatic conditions, e.g. mixing, during evolution of the magma. Further, the slight variation in isotopic compositions could reflect minor heterogeneities in the source region of the parental magma(s) (Le Roex et al., 1990). It is possible, therefore, that both fractionation and minor mixing have occurred. To account for the range of alkali lavas erupted on the island, Le Roex et al., (1990) suggest that low degrees (< 5%) of melting of a heterogeneous source occurred at depths within the garnet stability field. This resulted in coalescing basanitic melts forming magma bodies which underwent fractionation and mixing in shallow conduits and transient chambers to produce the broad range of compositions encountered on Tristan (Le Roex et al., 1990). Baker et al., (1964) and Reagan et al., (2008) also suggest tapping of lavas by a heterogeneous parental magma.

2.3. Geophysical Hazards

The proximity of the volcanic dome is not only a stark reminder of the events of October 1961, but also a physical expression of the possibility that future volcanic activity may impact the Settlement. Unfortunately, Tristan's geographical location, tectonic position and morphology also render the population vulnerable to other geophysical hazards. In addition to the threat from future volcanic eruptions, hazards that have - or could - afflict the island include storms, flooding, mass movements, elevated seismicity, sea-level rise and tsunami.

On-island risk reduction strategies must also be tailored to consider the impacts of these geophysical hazards.

Storms are, undoubtedly, the most frequent occurrence. Tristan lies within a belt of fierce westerly winds known as the 'roaring forties', with strongest winds occurring in the Southern winter months (April - November). The worst recorded storm in island history was in May 2001 when hurricane-force winds tore through the Settlement. Although nobody was hurt, the hospital and village hall were substantially damaged; boats were tossed into gardens and almost every home required roof repairs. Another violent storm in 2010 damaged the harbour, which had recently been rebuilt, leaving critical gaps in the island's sea defences (Plate 2.28). The rapidity of harbour wall deterioration is an ongoing issue and extremely problematic. Its complete destruction would temporarily sever physical ties with the outside world and would likely be grounds for an evacuation of the population.

A frequent accompaniment to wind is rainfall, of which Tristan receives an unusually large amount. An estimated 5000 mm of rain falls annually on the Peak, with considerably lesser amounts on the coastal strips (1-2000 mm). The majority of rainfall is channelled by gulches out to sea, although a considerable amount percolates the porous bedrock and is held as groundwater within the volcanic edifice. Waterfalls only resume flow after prolonged, intense rainfall, whereas persistent natural springs increase in flow rate during the same period. Following an episode of relentless rainfall, large debris and mud flows frequently occur. Flows tend to be channelized via gulches but, occasionally, spill out on to the coastal plains, often obstructing roads. Flash flooding channelled down Hottentot Gulch has occasionally filled the 3-4 m high gulch with water and large debris, effectively blocking the main route out of the Settlement. Ponded and meteoric water may trigger phreatic, or phreatomagmatic, eruptions if magma or lava is present. Crater lakes are commonplace within scoria cones, and the large lake at the summit is particularly hazardous given its volume, elevated position and the summit connection to all major gulches transecting the island. Lahars have never been witnessed by islanders although lahar deposits were discovered by the Royal Society Expedition near Stony Beach Bay. Snow covers the Base and Peak for the majority of the winter months, increasing the likelihood of snowmelt-generated lahars.

The hazard with the highest probability of occurrence, but usually the lowest impact, is mass movement. Owing to steep topography, dyke emplacement and prolonged, intense precipitation, slope instability is widespread on Tristan. Ground failure is pervasive on several scales, from soil creep to large-scale sector collapse. Terracettes commonly form as a response to soil creep, especially on the vegetated slopes of scoria cones; exacerbated by the livestock grazing (Plate 2.29). These small displacements are an important forewarning of future failure. Evidence of instability is widespread on the Hillpiece scoria cone, which deforms frequently both on the seaward side due to marine erosion, and on the landward side as sinkholes and landslides (Plate 2.30). Large scars from localised outbursts of gas (produced by methanogenesis) are manifest on the surface of the Hillpiece (Plate 2.31), providing further evidence of the weakness of this area, and a possible trigger for larger scale slope failure.

Small rockfalls are relatively common (weekly), especially from volcanic plugs and thick flows in the steep cliffs that truncate the outer flanks (Plate 2.32). Falls normally occur following periods of heavy rain and subsequent heating from the sun. Those that occur on the Settlement coastal strip rarely impact the islanders, unless debris falls on roads or fences. Several rockfalls occurred during fieldwork for this study, usually in the form of one or two large boulders falling from the volcanic plug behind the Settlement, or from the 1961-62 dome-tholoid complex.

There is also evidence of larger rockfalls and landslides around the island which are triggered less frequently (years). In the 1970’s, a large landslide occurred at Pigbite, to the east of the Settlement (Plate 2.33). In February 2011, during the second phase of fieldwork, a sizeable portion of the cliff face fell from behind the Settlement (Plate 2.34). The debris destroyed the pathway to the summit of the 1961-62 dome; a route often taken by islanders and tourists. A safer, less challenging route has since been constructed further north.

Low frequency, large scale sector failures commonly punctuate the growth of ocean island volcanoes (e.g., Lipman et al., 1988; McGuire, 1996). These often produce massive collapse scars and debris flows, incorporating 10’s to 100’s of km^3 of material (Holcomb and Searle, 1991). The scalloped NW sector of Tristan suggests that lateral failure has occurred, at least once, during the island’s evolution. On review of GLORIA (Geological Long Range Inclined Asdic) sidescan sonar images from a 1989 survey of Tristan, Holcomb and Searle (1991) recognised distinctive contrasting backscatter - similar to that seen on sonographs around Hawaii (e.g., Lipman et al., 1988) - on the seafloor extending NW of Tristan. This backscatter was interpreted as a large-scale debris avalanche deposit (Fig. 2.10), and the arcuate cliff face behind the Settlement coastal strip was the residual scar of a large-scale sector collapse (Plate 2.35). Holcomb and Searle (1991) inferred that the deposit was about 100 m thick and approximately 40 km wide, with an estimated volume of 150 km^3;

comparable to the volume of the Monte Amarelo collapse on Fogo, Cape Verde (Day et al., 1999).

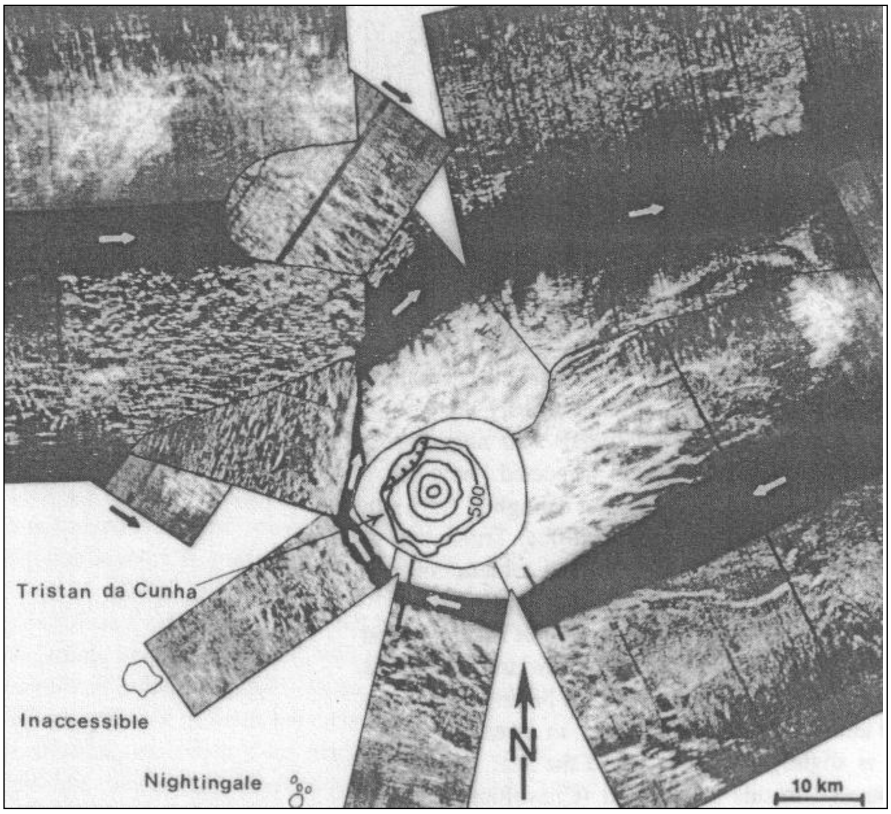


Fig. 2.10. Mosaic of GLORIA sidescan sonar images around the Tristan island group. White backscatter clearly shown in NW sector. It is possible that this survey and analyses have overlooked other debris avalanche deposits. Taken from Holcomb and Searle (1991).

It is possible that sector collapse has occurred more than once during Tristan's growth, as the island is particularly susceptible to most of the recognised volcanic and non-volcanic triggers. Non-volcanic causes of flank instability include steep slopes (slopes of the Peak reach 30°), persistent rainfall, natural springs and weak rock layers. The frequency of eruptions on Tristan has prevented residual soils from forming between flows (Hürlimann et al., 2001), however the edifice is of composite construction with alternating layers of lava and weak pyroclastics. Below sea level, Tristan's submarine portion is likely constructed of irregular layers of pillows lavas and hyaloclastite, lava flows and debris avalanche deposits, built on sediment-covered sea floor. Permeable layers are likely to hold meteoric water as perched aquifers, further reducing their strength. Trigger processes associated with volcanic activity include dike intrusion, inflation and deflation, earthquakes, and hydrothermal alteration. Particular geomorphological features can also reduce stability, and assert controls on the seaward and lateral boundary of the failure surface (Hürlimann et al., 2004). Features pertinent to Tristan include deep erosive canyons (gulches) which reduce the lateral strength of the slope and increase shear stress at the base, and high coastal cliffs which reduce local stability conditions.

Near-instantaneous, large scale sector collapse is likely to generate a tsunami which would impact all three islands, and potentially land further afield as waves propagate outwards. There have been several historical slide-generated tsunamis from volcanoes, including the 1792 debris avalanche which swept down the flanks of the Unzen volcanic complex (Japan), generating a tsunami that devastated surrounding areas (Goto and Takayama, 1992). In 2002, several landslides detached from the flanks of Stromboli, Italy generating two tsunamis which caused local destruction (Tinti et al., 2006). Tsunami deposits have yet to be discovered on Tristan or Inaccessible although, owing to the lack of marine mollusca, fossil-rich beds are unlikely to be found. However, on Nightingale, a boulder bed described as a raised beach deposit (Baker et al., 1964; Gass, 1967) may have been deposited by a tsunami given the chronological relationship to the sector collapse on Tristan (see Chapter 3). Crest elevations and run-up times of tsunami vary considerably depending on the source of the tsunami, and/or the speed and amount of material which enters the water. Simulations of extreme flank collapse scenarios on La Palma, Canary Islands have been generated which forecast catastrophic consequences (Ward and Day, 2001; Løvholt et al., 2008). The Cumbre Vieja volcano on La Palma is identical in height to Tristan although with slightly shallower slopes and west-trending vent arrays (Tristan's vents are diffuse). Simulations of a flank collapse on La Palma of identical size to the proposed volume of the Tristan debris avalanche (150 km^3), sliding at 100 m s^{-1} could generate an initial water dome several hundred metres in height and propagate outwards, spanning the Atlantic Basin and generating tsunamis on the coasts of the Americas between 3-8 m high (Ward and Day, 2001).

Earthquake and deformation-generated tsunamis could also afflict Tristan, either caused by rapid inflation of the volcano, a nearby seamount, or by tectonic activity. An active seamount to the east of Nightingale (inferred as the likely source of the 2004 phonolitic pumice) has been recently surveyed and the summit lies just 250 m below sea level (pers. comm).

Tristan is approximately 350 km from the axial rift of the MAR, and regional seismicity is dominated by activity on the ridge. Tectonic activity on the MAR has never been felt on Tristan, although seismic activity relating to magma movement has been detected. The most recent volcano-tectonic earthquakes were in 2004, preceding the submarine eruption offshore of Tristan. Felt activity also occurred in 1961 prior to, and during, the dome eruption near the Settlement. Other records include a magnitude 3 earthquake, felt by islanders at the Settlement in August 1986, and three tremors on New Year's Day in 1973. It is possible that these earthquakes were related to ridge activity, although more likely caused by magma movement within the vicinity of Tristan.

Currently, there are three seismometers on Tristan. Two seismic stations were installed by the Comprehensive Nuclear Test Ban Treaty Organisation (CTBTO) for the hydroacoustic monitoring of nuclear explosions, although they can also detect tectonic and magmatic activity. The stations are positioned on the Settlement coastal strip, one just to the west of the Settlement, and the other between Spring and Molly Gulch approximately 4 km away (Fig. 1). The third seismometer is monitored by the Incorporated Research Institutions for Seismology (IRIS) and is located in a vault next to the CTBTO station nearest the Settlement. Unfortunately, the co-location of two of the stations means that only limited analysis of data can be performed. Further, unlike the IRIS data, CTBTO data are not freely available, due to the potentially sensitive nature of the material.

2.4. Conclusions

This chapter of the thesis summarises the main volcanological and physiographical features of Tristan, drawing on previous work and new data from fieldwork conducted in 2009 and 2010.

Tristan is a remote, active, intraplate volcano in the South Atlantic Ocean. Volcanism is attributed to an intraplate melting anomaly, known as the Tristan hotspot, which is considered to have driven volcanism that created the Walvis Ridge and Rio Grande Rise as the South Atlantic Ocean opened up in the early Cretaceous. Tristan is the latest surface manifestation of this hotspot.

The island's moderately large edifice (2,060 m subaerial height) is composed of summit-sourced lavas and intercalated pyroclastics. The succession is often exposed in the high, sheer cliffs that truncate the island. Numerous parasitic centres, considered to be post-shield volcanism, are scattered across the flanks; many of which are breached. Young, low-lying coastal strips flank the north-western and southern margins of the island. Mapped eruptive deposits on Tristan demonstrate a spatial heterogeneity of compositions and volumes. Rocks represent the full basanite-phonolite suite and while tephritic rocks predominate in the main succession, more evolved lavas (phono-tephrites and tephri-phonolites) have erupted from parasitic centres, and as small volume flows from the summit. The two most recent sub-aerial eruptions (1961-62 eruption; Stony Hill) were low volume leaks of tephri-phonolitic lava, manifest as domes and flows.

Geochemical and isotopic studies of Tristan rocks suggest that lavas are tapped by melting of a heterogeneous source at depth, forming basanitic magma bodies that undergo fractionation and mixing in shallow conduits and transient chambers (Le Roex et al., 1990). Isotopic analyses on the 2004 phonolitic pumice indicate that it was generated by rapid, extensive fractionation of a small parental magma body, unrelated to the 1961 tephri-phonolitic magma (Reagan et al., 2008). This is further evidence that magmatism is not dominated by one large storage region but rather smaller individual pockets of magma that source rapidly from depth.

Information outlined in this chapter represents current geological knowledge of Tristan and informs methodological approaches outlined in Chapters 3, 4 and 7. Further data from Tristan are essential to improve knowledge of the forces driving volcanism on the island. Anticipating the timing, style and impact of future volcanic activity is dependent both on this data and on improved knowledge of Tristan's eruptive history.

Plate 2.1. Tristan da Cunha, viewed from the west.

Plate 2.2. Gulches radiate from the Peak and cut through the edifice. First Gulch is pictured, approximately 80 m deep.

Plate 2.3. High cliffs that frame the island, up to 900 m in places. Viewed from the west, just off the Settlement coastal strip.

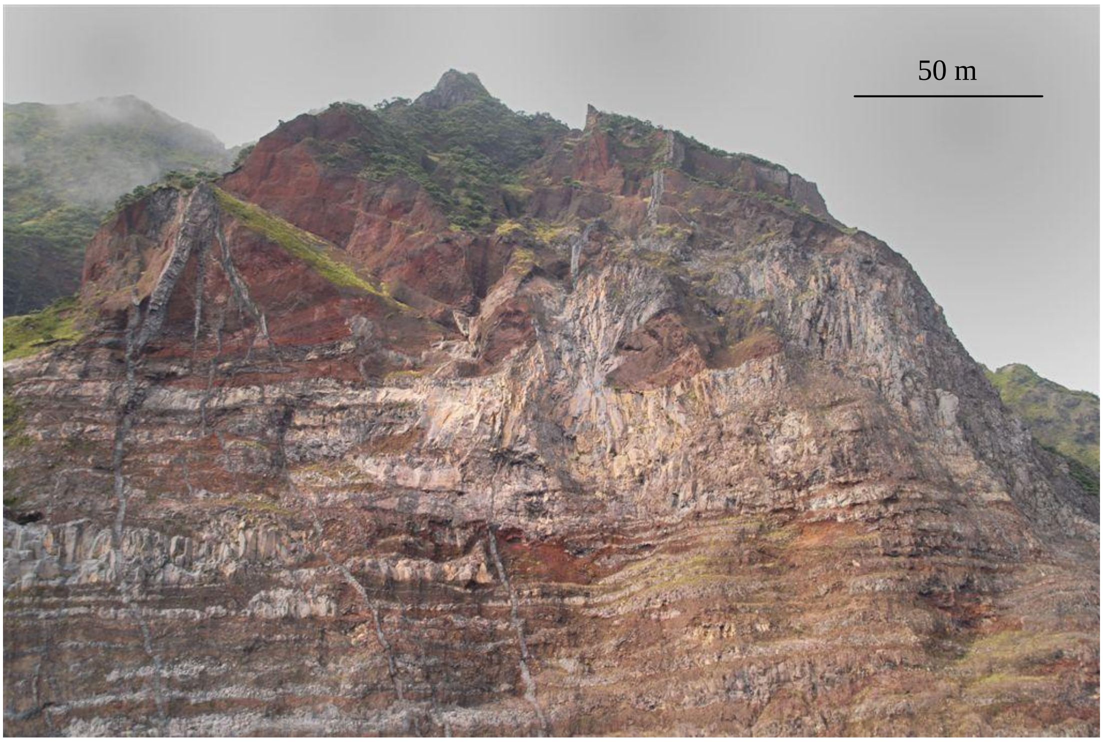


Plate 2.4. Main Cliff succession with locally interspersed parasitic centres.

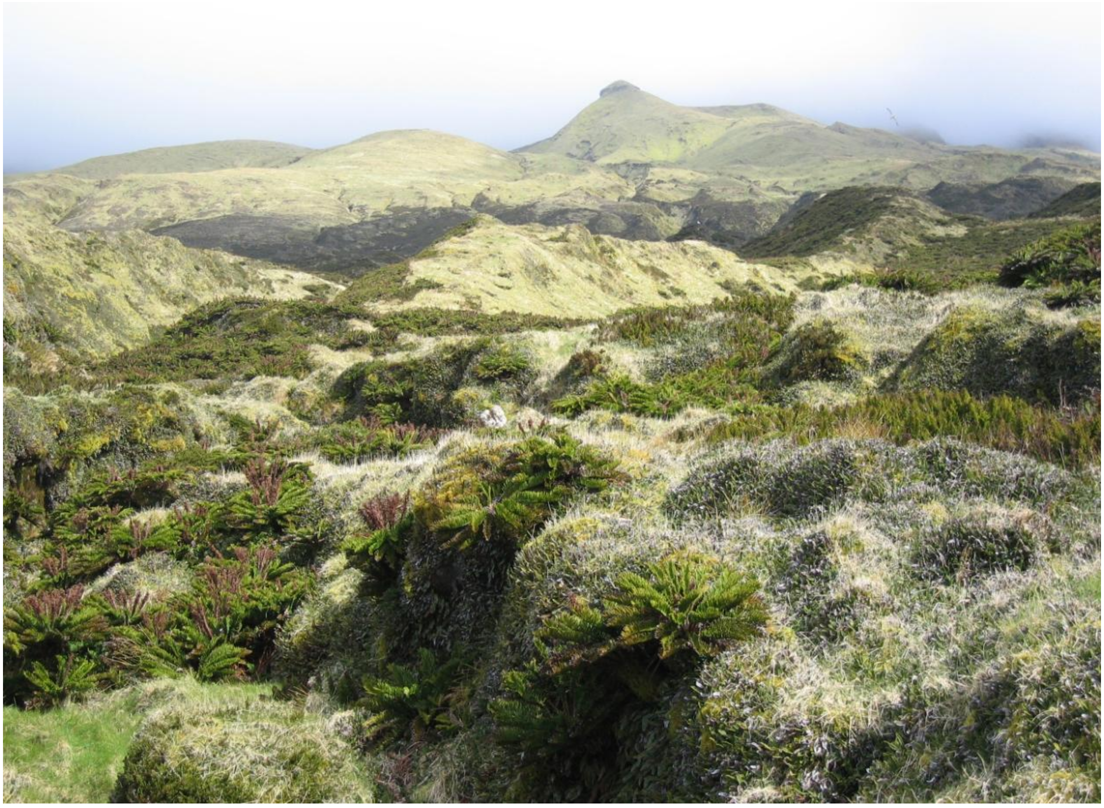


Plate 2.5. Typical vegetation on the Base. Image is taken from the Base/Peak intersection looking towards the north. For scale, the average size of a bog fern (shrub in foreground) is about 1 m high.

Plate 2.6. Lava mound issuing from breached Green Hill centre. View from the south-east towards the Peak.

Plate 2.7. Maars at the Ponds (left) and at Cave Gulch Hill (right). Left image is looking towards the north-east from the Peak. Right image is looking north from the Base towards the Peak

Plate 2.8. Lava flows capping the ridges that radiate from the Peak. View facing to the west from Big Gulch.

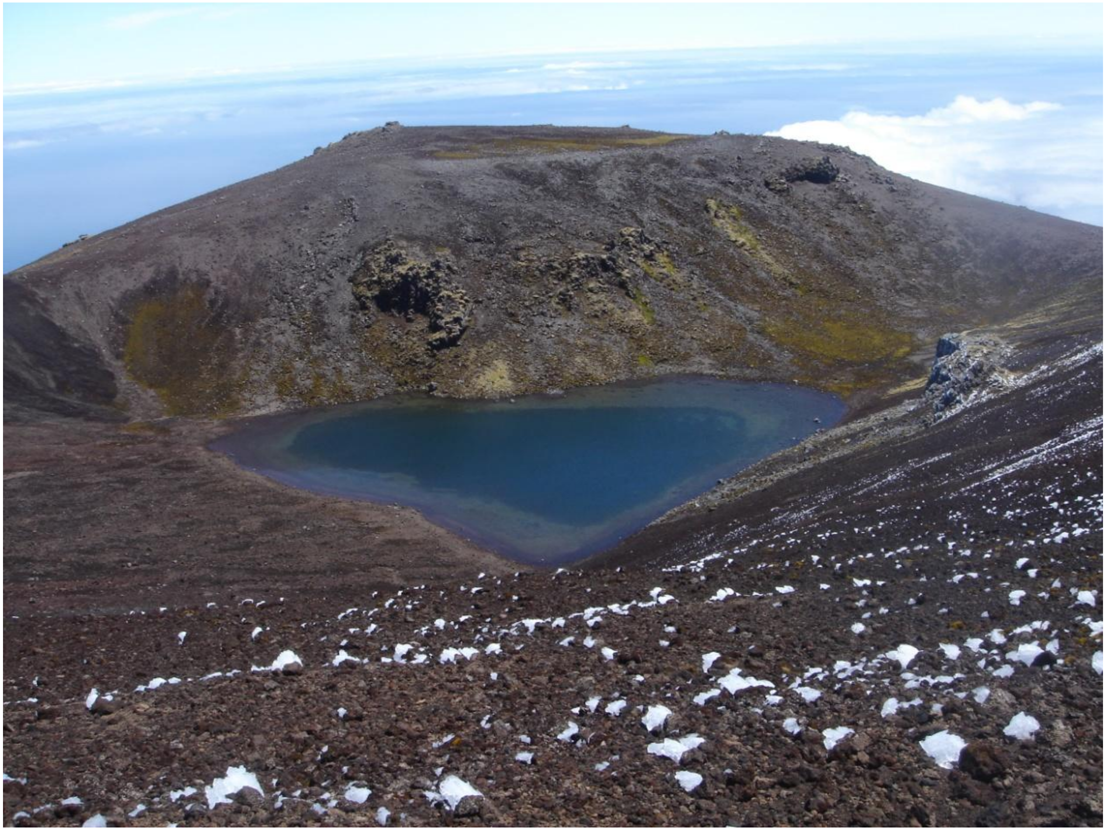


Plate 2.9. Peak lake. Trachytic volcanic plugs can be seen in the crater walls. View towards the south.

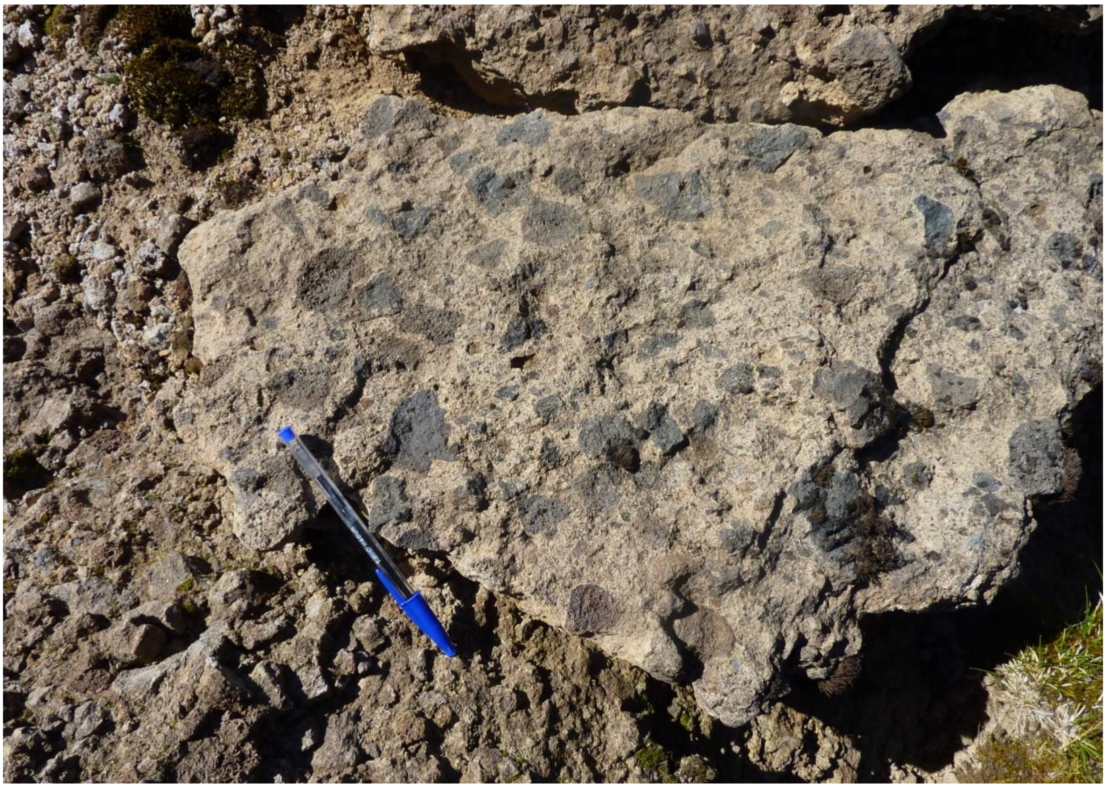


Plate 2.10. Section of debris avalanche deposit on eastern Peak flanks. 4-5 cm thick layer deposit overlying lava and scoria.

Plate 2.11. Dykes on Peak. As viewed from the summit looking towards the east.

Plate 2.12. Thinner, sinuous dykes appearing and disappearing. View from the Castles on the western flank of the Base/Peak intersection looking south-west.

Plate 2.13. Proximity of Settlement to the 1961-62 dome and flows.

Plate 2.14. Two columnar jointed flows with rubbly horizon. Flows can be traced for the entirety of the Settlement coastal strips and are, on average, about 10 m thick.

Plate 2.15. Columnar jointed flows seen in Plate 2.14 extending from the Hillpiece-Burnthill centre.

Plate 2.16. Pillow lavas at the Harbour.

Plate 2.17. Leucite spots in the basal tephritic flow at Runaway Beach.

Plate 2.18. Hillpiece as viewed from the sea looking towards the western Main Cliffs.. Yellow tuffs are visible with red pyroclastics unconformably overlain.

Plate 2.19. Hornitos at the Patches.

Plate 2.20. View down to the Bluff (left of image) from Burntwood.

Plate 2.21. View of Hackel Hill on the Seal Bay plateau. Breached flow is evident to the left of the image. View is towards the north-west.

Plate 2.22. Lava flows from Hackel Hill seen in sea cliff succession. Viewed from the sea looking north-eastward.

Plate 2.23. Prominent levees emerging south of Little Hill. Little Hill has a 37m deep vent at the summit.

Plate 2.24. Stony Hill as viewed from Little Hill, with Kipuka Hill to the right of the image.

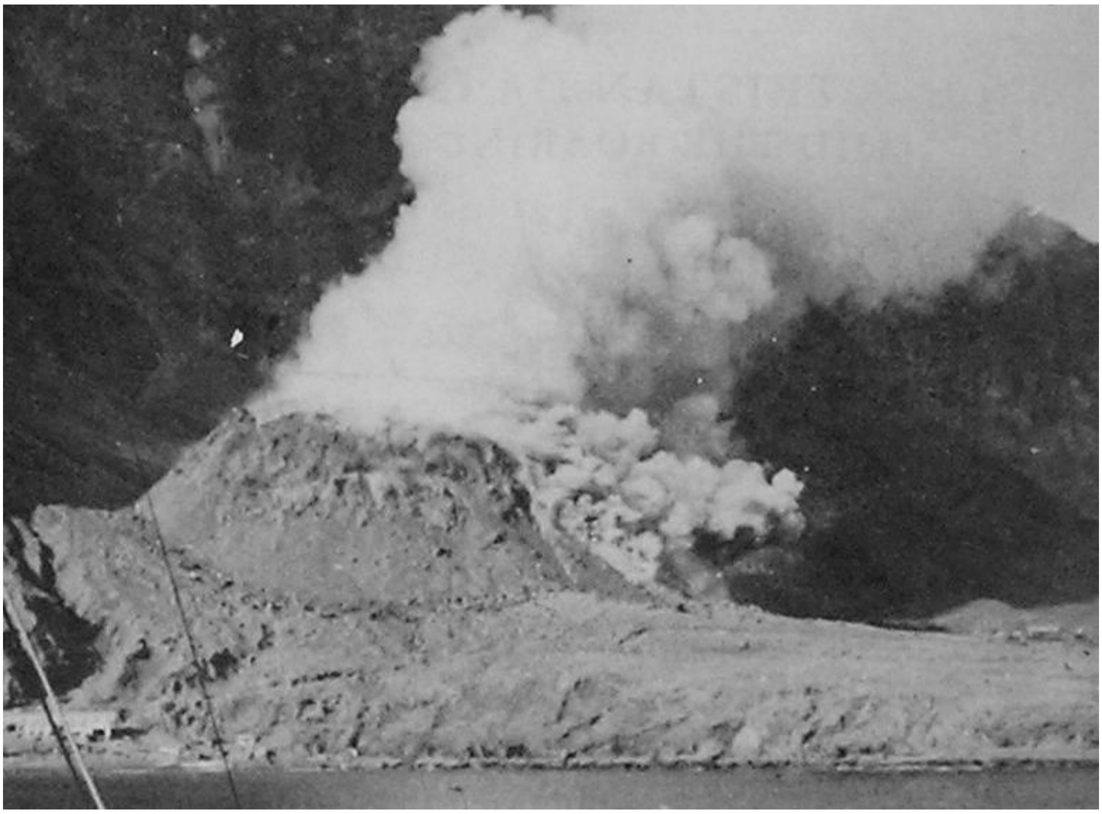


Plate 2.25. A view of the eruption of the volcanic dome in the north from aboard the *Tjisadane*. Photo courtesy of the Tristan da Cunha Portfolio.

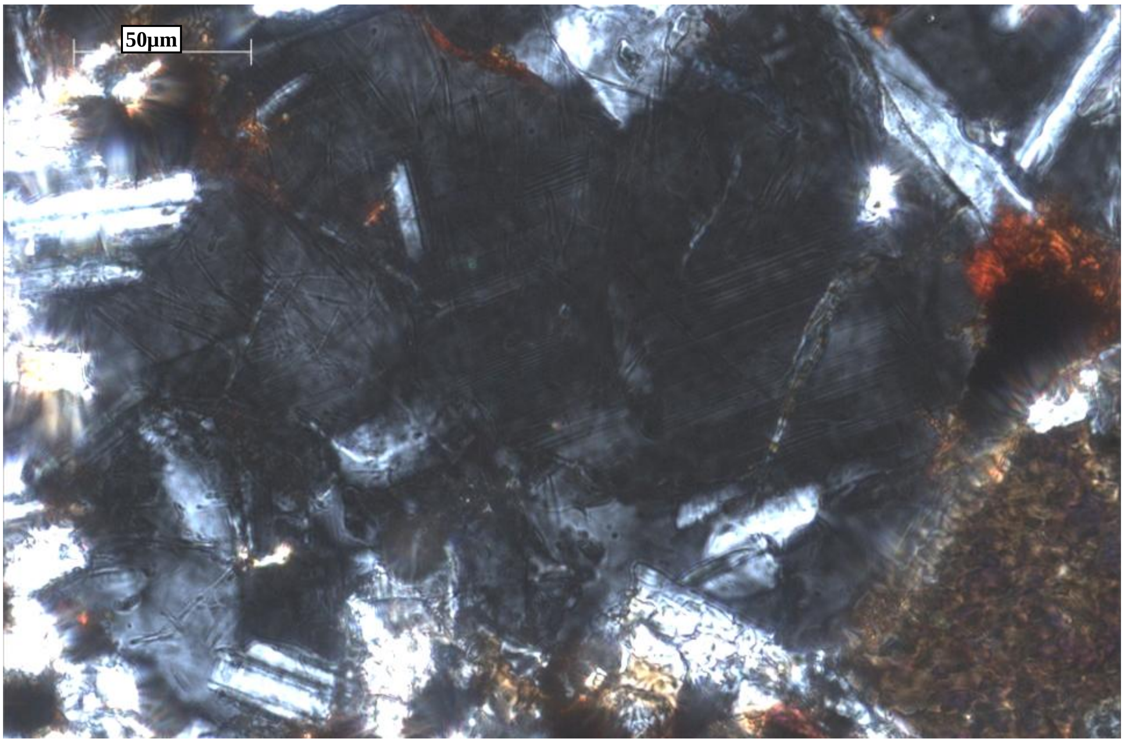


Plate 2.26. Thin section showing interstitial leucite in sample number 058A, sampled from a volcanic plug at Spring Ridge. Note lack of individual crystals of leucite, with interstitial material identified by distinctive cross-hatch texture.

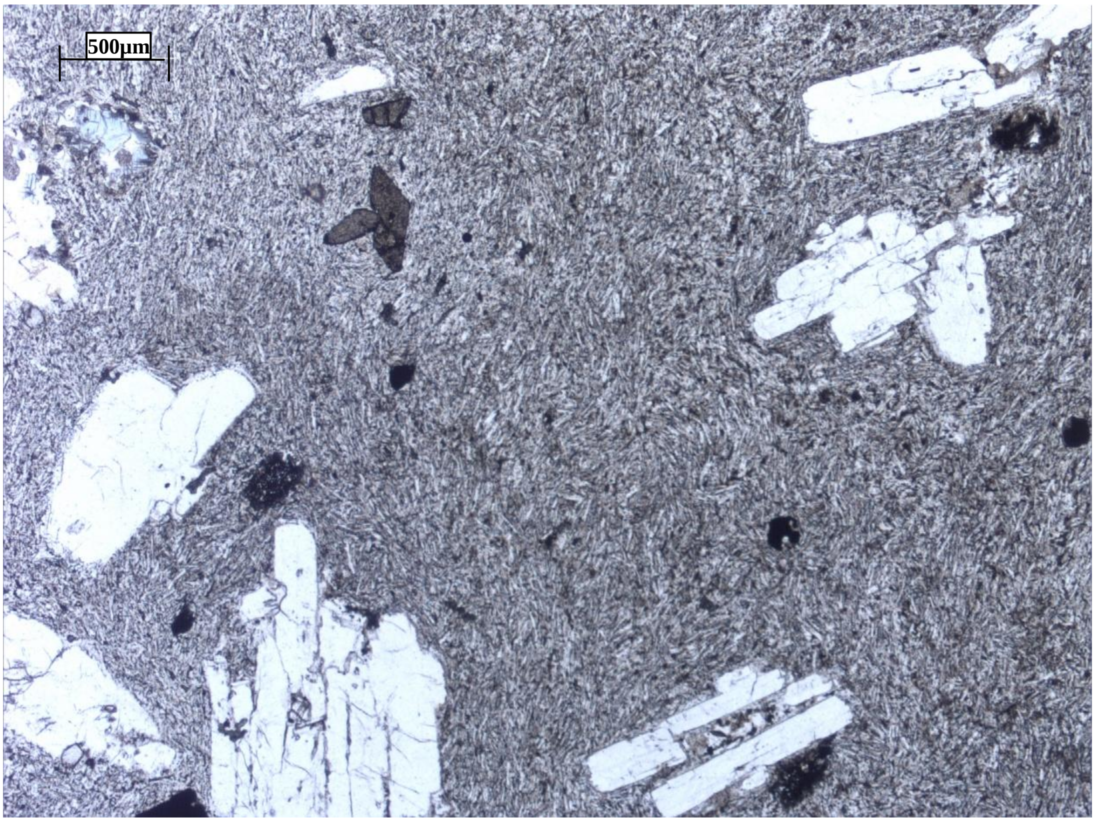


Plate 2.27. Thin section of sample 038A showing trachytic texture in volcanic plug at summit crater. Note presence of light blue fluorite in upper left corner of image.

Plate 2.28. Harbour under constant wave attack. Photo courtesy of Desiree Repetto.

Plate 2.29. Terracettes on Hillpiece. View looking south-west from the Hillpiece summit.

Plate 2.30. Sinkholes on the south-west flank of Hillpiece.

Plate 2.31. Scars on a ridge crest at Hillpiece, looking to the east. Scars were likely caused from methanogenetically-derived gases (from a bog at the base of Hillpiece) rising through the unconsolidated rock.

Plate 2.32. Frequent, small-scale rockfalls from the Main Cliffs between Little and Big Sandy Gulch

Plate 2.33. 1970's rockfall from the northern cliff face at Pigbite.

Plate 2.34. February 2011 rockfall from cliffs behind Settlement.

Plate 2.35. Residual scar of a sector collapse, viewed towards the west. Hillpiece-Burnthill complex is to the right of the frame.

CHAPTER THREE: Timing of volcanic events on Tristan da Cunha

3.1. Introduction

Determining the timing and frequency of past eruptive activity is one of the most critical components in evaluating the potential for when and how volcanoes are likely to erupt (e.g., Newhall and Hoblitt, 2002). By determining empirically a historic and prehistoric event chronology, a timeline for eruptive behaviour can be established and patterns in activity ascertained. In many cases, chronologies show volcanism can be episodic, usually with episodes of heightened activity punctuated by long periods (10s of ka) of dormancy or low activity (e.g., Harford et al., 2002; Le Friant et al., 2004). By combining high-precision age data with information from other geological techniques, a detailed history of both rates and changing styles of volcanism can emerge. This can form a quantitative basis for understanding and assessing the risk of volcanic eruptions (e.g., Sparks et al., 2008).

Earlier geochronological evidence suggest that Tristan has erupted frequently since sub-aerial emergence (McDougall and Ollier, 1982; Dunkley, 2002) and, although deposits from probable Holocene eruptions exist (Ljung et al., 2006), Tristan's recent colonisation (< 200 years ago) combined with extreme remoteness, mean that the only historical eruptions are the 1961-62 and probable 2004 event (see Chapter 2). As a consequence, there is a high degree of uncertainty about the possible timing, location and style of future eruptive episodes. Thus new chronological data, focussing on the younger eruptive products, could help to constrain the age, style and patterns of recent volcanism on the island.

Following a brief overview of the literature, this chapter will focus on the application of $^{40}Ar/^{39}Ar$ dating to young volcanism on Tristan; interpret that data in terms of relative locations and timing, and discuss possible implications for future eruptive behaviour.

3.2. Literature review

Geochronological techniques such as radio-isotopic dating are commonly used to determine the apparent ages of rocks. As crystal growth initiates and the temperature falls below that required for diffusivity (closure temperature), daughter isotopes produced by the radioactive decay of unstable parent isotopes (e.g., ^{40}K – ^{40}Ar) are retained (Dodson, 1973). The decay of a radioactive parent isotope occurs at a constant rate (half life) (equation 3.1):

$$-\frac{dP}{dt} = \frac{dD}{dt} = \lambda P\,, \tag{3.1}$$

where P is the number of remaining parent atoms at time *t*, *d*D*/dt* is the rate of formation of daughter atoms and λ is the decay constant. Thus, by rearranging equation 3.1, the parent to daughter ratio can be measured, if the number of pre-existing daughter elements can be accounted for (equation 3.2). Converting this to an age requires knowledge of the decay rate for that isotope:

$$t = \frac{1}{\lambda}\ln\left(1 + \frac{D - D_0}{P}\right), \tag{3.2}$$

where D_0 is the initial daughter element.

Calculating ages using any radiogenic isotope is contingent on two major assumptions. First, that the mineral and, therefore, the decay constant, has not changed over time. It is reasonable to assume that this is the case, as radioactive decay occurs at a fixed rate unaffected by pressure, temperature or chemical reactions. Second, it must be assumed that the rock or mineral has been in a closed system since its formation and is free of alteration, i.e. there has been no addition, or loss of the radiogenic component being measured. This can be inferred both from geological evidence, or age consistency, of more than one parent-daughter pair. Nevertheless, there are certain radio-isotopic dating methods, such as the incremental heating technique (step-heating approach) used for $^{40}Ar/^{39}Ar$ dating, that permit the investigation of the thermal history of open systems, where a loss or gain of isotopes has occurred (Faure and Mensing, 2005) (see Section 3.2.1.2).

3.2.1. The $^{40}Ar/^{39}Ar$ method

Since radioactivity was discovered by Becquerel in 1896, scientists have realised the potential of radioactive decay measurements to determine the age of geological materials

(Dalrymple and Lanphere, 1969). Initial attempts to date minerals occurred in the early 1900's using uranium-helium (Rutherford, 1906) and uranium-lead ratios (Boltwood, 1905; Holmes, 1911); although these early studies yielded erroneous results (Dalrymple and Lanphere, 1969). As knowledge, approaches, and mass spectrometers have improved with time, so have the precision and reliability of radio-isotopic ages; making geochronology a very useful and widely applicable scientific tool. One important 20th century application was the delineation and calibration of the geomagnetic polarity time-scale which, itself, played a significant role in building the foundations of plate tectonic theory (e.g., Dietz, 1961; Vine and Matthews, 1963). A wide variety of dating techniques are now employed to help answer pertinent geological questions.

Potassium has three naturally occurring isotopes, ^{39}K, ^{40}K and ^{41}K (see Table 3.1. for isotopic abundances). ^{40}K (with a half life of 1250 Ma), has a dual decay into ^{40}Ca (89.5%) and ^{40}Ar (10.5%). It is the accumulation of $^{40}Ar^*$ (radiogenic argon) over time that provides the basis of the K-Ar dating method, which requires modification of equation 3.2 to account for equation 3.3:

$$t = \frac{1}{\lambda} \ln\left(1 + \frac{\lambda}{\lambda_e + \lambda_{\acute{e}}} + 1 \ \frac{^{40}\mathrm{Ar}*}{^{40}\mathrm{K}}\right), \tag{3.3}$$

where the $\lambda_e + \lambda_{\acute{e}}$ are partial decay constants ratioed to the decay constant for ^{40}K (λ).

Potassium is an ideal element for this technique as it is the eighth most abundant crustal element. Argon is an inert gas present only in the atmosphere, or from decay of ^{40}K into $^{40}Ar^*$, eliminating many uncertainties in its origin when measured. The conventional K-Ar method was first used successfully as a geologic dating tool in the late 1940's (Aldrich and Nier, 1948), and is still widely used today. However, there are limitations. The approach relies on the assumption that there is no excess argon present in the mineral prior to time zero, and that all radiogenic argon is retained from decay of ^{40}K. If these assumptions are not true then the apparent age will not represent the sample's true age (Fig. 3.1). A further limitation is that argon and potassium have to be measured separately, therefore the sample being dated must be homogeneous with respect to both elements (Faure and Mensing, 2005).

Table 3.1 Isotopic abundances of potassium. Source: Garner et al., (1975).

Isotope	**Atomic abundances (%)**
^{39}K	93.2581 ± 0.0029
^{40}K	0.01167 ± 0.00004
^{41}K	6.7302 ± 0.0029

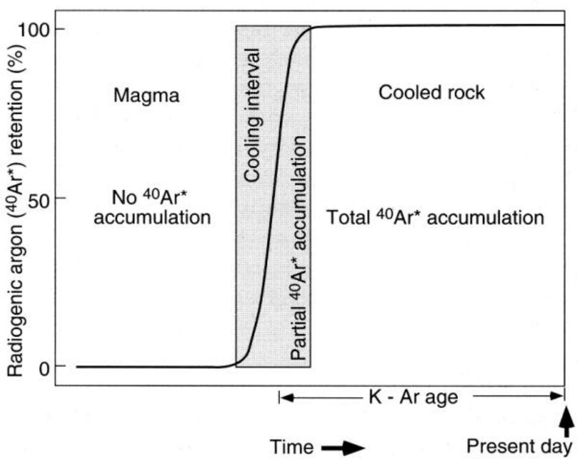


Fig. 3.1. Accumulation of argon in an igneous rock. Source: Dalrymple and Lanphere (1969).

In the mid-60's, Merrihue (1965), Merrihue and Turner (1966) and later, Mitchell (1968), described a variant of K/Ar dating, known as the $^{40}Ar/^{39}Ar$ method. The critical advance of this method overcame two limitations of its antecedent; only measurements of the argon isotopes were required, and all measurements could be made on one sample (Merrihue and Turner, 1966).

The technique is based on the formation of ^{39}Ar by the irradiation of ^{39}K with fast neutrons, the release of argon from the sample by total fusion or incremental heating, and the determination of $^{40}Ar^*/^{39}Ar$ ratios by mass spectrometry. To measure the neutron flux (J-parameter; conversion of ^{39}K to ^{39}Ar) samples are irradiated with standards of known age. The ratio of $^{40}Ar^*/^{39}Ar$ and thus the age of the sample is derived using equations 3.4 and 3.5 (see Section 3.2.1.2), after correcting for interferences. The main interference is non-radiogenic ^{40}Ar, which can be corrected by using measured values of ^{37}Ar and ^{36}Ar. The ages found are determined relative to the age of the standard used to monitor the J-parameter. The methodology is discussed further in the following sections.

3.2.1.1. Sample preparation

In principle, any rock containing measurable amounts of potassium and radiogenic argon can be used for $^{40}Ar/^{39}Ar$ dating. However, there are common rock-forming minerals which readily accept potassium into lattice sites and are, therefore, more suitable. Appropriate minerals in volcanic rocks include sanidine, biotite, hornblende, some feldspathoids (leucite and nepheline) and whole rock basaltic groundmass (McDougall and Harrison, 1999). Whole rock analysis is useful when mineral size and volume makes separation impossible and, if careful petrographic examination and preparation is done, has been shown to be as effective as analyses on separate mineral phases (e.g., Webb and McDougall, 1968). Volcanic rocks which yield precise $^{40}Ar/^{39}Ar$ or K/Ar ages (interpreted as the time elapsed since cooling or crystallisation) are usually fresh, holocrystalline lavas with limited alteration. Alteration of high-temperature phases is problematic as the alteration could promote the loss of radiogenic argon, and produce a measured age that is younger than the apparent age. Large amounts of glass are also problematic as glass is susceptible to devitrification or hydration; both processes that can promote the loss of radiogenic argon. Further, recoil of ^{37}Ar and ^{39}Ar during the energetic irradiation process can lead to erroneous ages (e.g., Huneke, 1976). Incorporated material also introduces problems as it may not have outgassed all of its radiogenic argon prior to incorporation within a magma. Xenocrystic olivine, pyroxene and plagioclase, particularly, may give anomalously old apparent ages owing to the incorporation of excess argon from the environment during crystallisation in the magma.

Measurement of ages on both mineral phases and whole rock samples depends on the effective separation of discrete phases (either groundmass from phenocrysts or phenocrysts from groundmass). Separations should be made at the coarsest grain size by crushing and sieving followed by magnetic separation or the use of heavy liquids. To achieve a truly homogenous separation, hand-picking under a binocular microscope is usually necessary. Small amounts of sample are usually required (< 0.1 g) but this will depend on potassium content and approximate age of the sample (i.e. amount of ingrown radiogenic ^{40}Ar).

3.2.1.2. Irradiation and neutron fluence monitors

Following sample preparation, samples are irradiated in a nuclear reactor, the purpose of which is to generate enough measurable ^{39}Ar from ^{39}K via the interaction of a fast neutron with the ^{39}K nucleus. The amount of generated ^{39}Ar will be proportional to the amount of ^{40}K within the sample as the ratio of ^{40}K/^{39}K is constant in nature. Therefore, the ratio of radiogenic argon (^{40}Ar*) to generated ^{39}Ar is proportional to age. However, it is not possible simply to substitute the measured ^{39}Ar into equation 3.3 as, amongst other factors, the amount of ^{39}Ar is dependent upon irradiation time, neutron flux at a given energy and the neutron capture cross section at a given energy (McDougall and Harrison, 1999).

The appropriate duration of irradiation is indefinable as it is dependent on the sample age and the flux characteristics of the irradiation facility (McDougall and Harrison, 1999). If the irradiation period is too short, then the resultant ^{40}Ar/^{39}Ar ratio is too high. Irradiate for too long and the amount of ^{39}Ar may exceed the amount of ^{40}Ar. A ^{40}Ar/^{39}Ar ratio of 10-100 is ideal. Interfering reactions during irradiation require a considerable amount of corrections to be made (see Section 3.2.1.4). If the length of irradiation is too long then the amount of corrections increases and the uncertainty associated with each correction propagates into the final age equation and, hence, the final age (McDougall and Harrison, 1999).

Rearranging equation 3.3 in terms of ^{40}Ar* and defining an irradiation parameter *J* to account for irradiation duration, neutron flux and neutron capture cross section gives:

$$\frac{^{40}\mathrm{Ar}*}{^{39}\mathrm{Ar}} = \frac{e^{\lambda t} - 1}{J},$$

(3.4)

which can then be re-arranged in terms of *t*, the age of the sample:

$$t = \frac{1}{\lambda}\ln\left(1 + J\frac{^{40}\mathrm{Ar}*}{^{39}\mathrm{Ar}}\right),$$

(3.5)

Age calculations are dependent upon the determination of parameter *J*. *However*, it is difficult to determine the absolute dose of fast neutrons that the sample received during irradiation. To avoid this, a standard neutron fluence monitor with a precisely known K-Ar age is simultaneously irradiated with the sample of unknown age. By re-arranging equation 3.4, parameter *J* can be established by measuring the ^{40}Ar*/^{39}Ar ratio of gas extracted from the fluence monitor:

$$J = \frac{e^{\lambda t} - 1}{{}^{40}\mathrm{Ar}*/{}^{39}\mathrm{Ar}},$$

(3.6)

The age of the unknown sample can then be derived by substituting the *J* value calculated from equation 3.6 into equation 3.5. Ages can be interpreted as rock forming ages, or age of thermal closure to argon loss.

Precise measurement of fluence monitors is essential, as any error in this value proliferates through all the calculations, resulting in a measure of the unknown sample age with a large uncertainty. Alexander and Davis (1974) outlined particular criteria for fluence monitors; a) the monitor mineral must have a uniform $^{40}Ar/^{40}K$ ratio to reduce the errors associated with sample inhomogeneity; b) the fluence monitor must have homogenously distributed potassium and argon to ensure precise separate measurements of the two elements using the conventional K-Ar method, and c) the fluence monitor should be of similar age to the unknown sample. Further refinements in the age determinations of neutron fluence monitors will further improve the accuracy of the $^{40}Ar/^{39}Ar$ method (Renne et al., 1997).

3.2.1.3. Incremental Heating

Following irradiation, samples are heated in a furnace, or by a laser, to release the trapped argon. Laser heating is advantageous as samples can be smaller, sample throughput is increased, and the lower volume system means that there is better sensitivity and lower blanks, thus improving precision. The disadvantage to heating with lasers is that the laser beam has a Gaussian energy distribution which heats the samples inhomogenously, making it difficult to discriminate between low and high temperature domains. However, potential 'smoothing' solutions have been developed which include moving the beam or sample to heat the sample evenly (see Section 3.6). There are two alternative methods of heating which can be applied to a sample. Total fusion technique involves heating the sample in one step (~1400°C) to release the argon. Incremental heating releases the gas in a step-wise fashion, starting below fusion temperature, resulting in a series of apparent ages for one sample (Dalrymple and Lanphere, 1971). Incremental heating is advantageous as analyses illustrate whether or not the sample has been closed since the time of initial crystallisation or cooling. If no excess argon is present, or no argon has escaped due to temperature alteration of the system, the $^{40}Ar/^{39}Ar$ ratios should be constant at each temperature step. This is known as a plateau (Fig. 3.2). However, if $^{40}Ar/^{39}Ar$ ratios vary when released at different temperatures, the system has been opened since inital crystallisation and cooling (time zero). The criteria for fitting of plateaus, as applied to this case, is they must include at least 60% of ^{39}Ar in three or more contiguous steps with the probability of fit of plateau to data > 0.05 (Mark et al., 2011a).

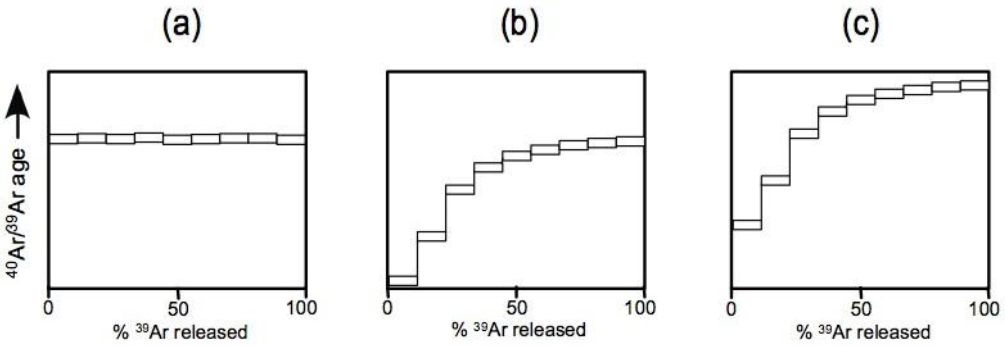


Fig. 3.2. Hypothetical schematic diagrams illustrating $^{40}Ar/^{39}Ar$ age spectra from measurement of argon extracted in successive steps from incremental heating: (a) illustrates a constant concentration profile, indicating that the crystal has remained undisturbed since initial crystallisation and cooling. This yields a steady plateau age. (b) indicates partial loss of $^{40}Ar^*$ in recent geological time by a marked gradient of $^{40}Ar^*$ across the crystal from zero at the grain boundary. (c) indicates that a reheating event has resulted in significant accumulation of $^{40}Ar^*$. The 0% value is the age of the reheating event; the 100% value marks the minimum age for initial crystallisation of the crystal. The thickness of bars in age spectra indicate level of uncertainty in ages. In this schematic, the uncertainty is nominal. Source: Harrison and Zeitler (2005).

3.2.1.4. Mass spectrometry and corrections

Following heating (by furnace, or laser) within an ultra-high vacuum system, the argon is extracted and then purified by getters (highly reactive metal alloy pumps which remove remaining active gases). It is essential that the entire system is clean and completely degassed prior to commencing new experiments. The atmosphere contains 1% argon and, as such, measurements are made in ultra-high-vacuum systems. Baking the whole system to about 250°C helps to achieve the lowest possible argon blanks (McDougall and Harrison, 1999). Following extraction and purification, the isotopic compositions of the gas sample can then be measured by a mass spectrometer. Relative abundances of ^{40}Ar, ^{39}Ar, ^{37}Ar, ^{36}Ar and, sometimes, ^{38}Ar are determined and, after applying appropriate corrections, $^{40}Ar^*/^{39}Ar$ ratios can be calculated.

In their 1971 paper comparing the $^{40}Ar/^{39}Ar$ method with the conventional K-Ar technique, Dalrymple and Lanphere (1971) state, “an inherent difficulty in applying the $^{40}Ar/^{39}Ar$ technique is the necessity of applying corrections for argon isotopes produced or removed during irradiation by reactions other than the nuclear reaction.” As no naturally occurring compounds of argon are known, the only argon existing on Earth is the atmospheric component and the radiogenic component from the decay of ^{40}K. In order to calculate the radiogenic component ($^{40}Ar^*$) of the argon within a sample, a correction must be made for the atmospheric component:

$$^{40}Ar^* = (^{40}Ar)_T - 295.5\,(^{36}Ar)_A\,, \qquad (3.7)$$

where T represents total argon and A represents atmospheric argon.

Nier (1950) reported the value of atmospheric argon as $^{40}Ar/^{36}Ar = 295.5$, derived from the rounded values of atomic abundance (Table 3.2).

Table 3.2. Isotopic abundances of atmospheric argon. Source: Nier (1950).

Isotope	**Relative atomic abundances (%)**
^{40}Ar	99.600
^{38}Ar	0.063
^{36}Ar	0.337

It is not uncommon however for samples to contain trapped argon where the $^{40}Ar/^{39}Ar$ ratios are > 295.5. By using an incremental heating approach, it is possible to check the assumption that all trapped contaminating argon is of atmospheric composition. By plotting the total $^{40}Ar/^{36}Ar$ measured at each step, ratioed to a primordial isotope of the daughter element (^{36}Ar) as an isochron diagram (Fig. 3.3a) (McDougall and Harrison, 1999), the ‘y’ intercept should reflect the initial isotopic composition of $^{40}Ar/^{36}Ar$. In the case of a sample containing only atmospheric argon, the value should be 295.5. The geological age of the sample is proportional to the gradient of the line. However, imprecise measurements of ^{36}Ar (common to both axes) could lead to potentially misleading linear correlations. To prevent error, an alternative form of isochron analysis known as an inverse isochron is used which plots $^{36}Ar/^{40}Ar$ against $^{39}Ar/^{40}Ar$ (Fig. 3.3b). As ^{40}Ar is the most abundant isotope, it can be more precisely measured, therefore reducing potential error in age and trapped composition measurement. An inverse isochron is essentially a mixing diagram showing the argon components as they degas at different temperatures. The age of the sample is shown at the 'x' intercept and the trapped composition (the inverse $^{40}Ar/^{36}Ar$ ratio) at the 'y' intercept. If other isotopic components are present, for example excess argon, this will affect the linear array. Data, displayed as both plateau and inverse isochrons, can be subjected to statistical tests that measure the deviation of individual measurements from the modelled age. By convention, the results from these statistical tests must be presented with the data from the age determination (see Table 3.3. below and Fig. 3.7. in Section 3.7).

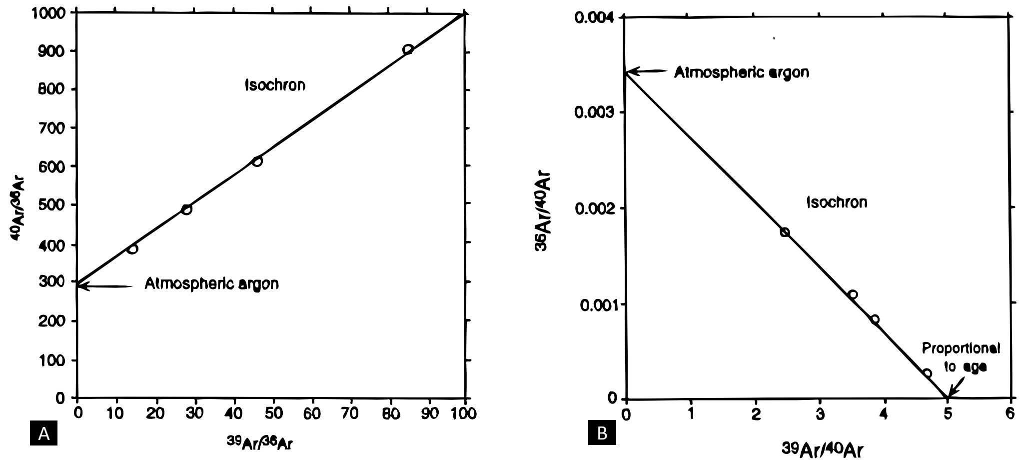


Fig. 3.3. Schematic isochron and inverse isochron plots. A: on the isochron plot the sample age is proportional to the slope of the correlation line. B: on the inverse isochron, the trapped components correspond to the y intercept and the age corresponds to the x intercept. Adapted from (McDougall and Harrison, 1999).

Owing to interfering reactions during irradiation, other corrections have to be made for argon produced during interaction with neutrons of calcium, potassium and chlorine. These corrections are particularly important for young samples, and for those having calcium potassium ratios < 10 (Faure and Mensing, 2005). Dalrymple and Lanphere (1971) derived an equation which corrects the $^{40}Ar^{*}/^{39}Ar$ ratio for all interfering reactions. If $F = {}^{40}Ar^{*}/^{39}Ar$:

$$F = \frac{A - C_1B + C_1C_2D - C_3}{1 - C_4D}, \tag{3.8}$$

where A = measured value of the $^{40}Ar/^{39}Ar$ ratio, B = measured value of the $^{36}Ar/^{39}Ar$ ratio, C_1 = $^{40}Ar/^{36}Ar$ ratio in the atmosphere (295.5), C_2 = $^{36}Ar/^{37}Ar$ ratio produced by interfering neutron reactions with Ca ($2.72 \pm 0.014 \times 10^{-4}$), C_3 = $^{40}Ar/^{39}Ar$ ratio produced by interfering neutron reactions with K ($5.9 \pm 0.42 \times 10^{-3}$), C_4 = $^{39}Ar/^{37}Ar$ ratio produced by interfering neutron reactions with Ca ($6.33 \pm 0.043 \times 10^{-4}$), and D = $^{37}Ar/^{39}Ar$ ratio in samples after correcting for decay of ^{37}Ar.

3.2.2. Applying $^{40}Ar/^{39}Ar$ geochronology to young volcanic rocks

For $^{40}Ar/^{39}Ar$ analysis to yield informative and reliable results, the sample being analysed must contain measurable quantities of potassium and radiogenic argon, and have remained in a closed system since emplacement. For volcanic rocks, $^{40}Ar/^{39}Ar$ dating is a particularly useful approach as argon is effectively retained by the crystal lattice (McDougall and Harrison, 1999). Magmas are often enriched in argon but, as melts rise to the surface, the concentration equilibrates with atmospheric levels ($^{40}Ar/^{36}Ar$ = 295.5). From the instant erupted lava begins to cool and crystal formation commences, potassium within the crystal lattice sites begins to decay into argon. Beneath the blocking (or closure) temperature, argon will become trapped within the crystal structure. Dating of young volcanic rocks (especially basalts) is particularly difficult as they are often deficient in potassium and $^{40}Ar^*$. Therefore, any measurement error of radiogenic argon increases exponentially as its proportion relative to the total argon decreases towards zero (McDougall and Harrison, 1999). A lack of measurable elements is a limiting factor and one unlikely to be overcome by technological or methodological refinements. Nevertheless, recent applications of the $^{40}Ar/^{39}Ar$ method to young volcanic rocks (< 100 ka) have yielded extremely reliable, and statistically sound, ages. Example study volcanoes include Mount Erebus (Esser et al., 2004; Kelly et al., 2008); Katmai volcanic cluster (Hildreth et al., 2003); behind-the-front (BVF) volcanoes in Guatemala and El Salvador (Walker et al., 2011); Mauna Kea and Kohala (Aciego et al., 2010), and the Newer Volcanic Province in SE Australia (Matchan and Phillips, 2011).

Some remarkable results from recent studies have increased the reported limits of detection and, thus, the age range of the youngest rocks that can be dated by this method. Many authors have now used it to date events much less than 100 ka with good precision (e.g., Hicks et al., 2012). Wijbrans et al., (2011) determined the ages of nine samples from the north-east flank of Stromboli to < 18 ka, using groundmass separates. The youngest sample yielded an age of 3.9 ± 1.6 ka (1σ). Jicha (2009) undertook $^{40}Ar/^{39}Ar$ measurements on six lavas from Koniuji Island, Aleutians. The previously undated lavas (groundmass) yielded extraordinarily young ages, the youngest being 3.1 ± 1.9 ka (2σ). Lanphere et al., (2007) and Renne et al., (1997) both conducted experiments on sanidine phenocrysts from pumice samples from the historically well documented AD 79 eruption of Mount Vesuvius. The youngest ages recorded are 1925 ± 69 years (ages determined in 2004) and 1925 ± 94 years (in 1997), respectively. Both ages and errors encompass the true age of the eruption. As Lanphere et al., (2007) state, "[this] demonstrates the validity of the $^{40}Ar/^{39}Ar$ method for reconstructing the history of young, active volcanoes."

3.2.3. Existing geochronology of Tristan da Cunha

There are few detailed studies of Tristan geology and volcanology, and even fewer which employ precise geochronological techniques (see Chapter 2). Twenty samples collected by members of the 1962 Royal Society Expedition were dated by the K-Ar technique, and two radiocarbon dates were determined from carbonaceous silt underlying Big Green Hill (Fig. 3.4.) (Baker et al., 1964; Miller, 1964; Wace and Dickson, 1965). ^{14}C determinations yielded dates of 10,770 ± 156 years B.P. and 11,310 ± 168 years B.P (Wace and Dickson, 1965) and are marginally consistent with the present $^{40}Ar/^{39}Ar$ results from a similar location (see results in Section 3.7; sample 093; 15 ± 1.9 ka)[5]. Of the 20 K-Ar dates, 12 were classified as 'recent' and 7 others dated between 0.5 ± 1 Ma and 3 ± 3 Ma. An anomalous date of 9 ± 2 Ma was also published, although it is noted by Miller (1964) that, as the exact locality of the rock could not be determined, the date was excluded from the overall analysis. Miller (1964) used the term 'recent' to indicate samples that contained > 99% atmospheric argon compared with radiogenic argon. Two subsequent dates (noted in Miller, 1964) were presented by R.L. Grasty who determined K-Ar ages of the lowermost lavas on Tristan's north shore as 0.80 ± 0.1 and 1.10 ± 0.15 Ma (Fig. 3.4). However, Gass (1967) later reported an unpublished age of 0.1 Ma for a sample from the cliff face in the same locality approximately 180 m a.s.l (Fig. 3.4). This was even considered a maximum age, although no error was reported. Given the relatively poor precision (where published) of measured ages, the application of K-Ar dating and the lack of information on the methodological approaches of either author, the ages are

[5] Carbonaceous material is rare on Tristan, hence why radiocarbon dating was not employed for this study.

largely considered too imprecise to be compared alongside the $^{40}Ar/^{39}Ar$ results from the present study.

A later study by McDougall and Ollier (1982) reported the K-Ar dates of 11 samples - mainly from the Settlement coastal strip in the north-west of the island - of which nine corroborate the present findings. However, two samples collected from the NW coast are anomalously old (0.21 ± 0.01 Ma [The Hardies] and 0.10 ± 0.03 Ma [Darley's Hill]) (Fig. 3.4) relative to the new dates. This could indicate the presence of excess argon (note that the K-Ar method can only correct for atmospheric Ar contamination, it cannot be used to interrogate the presence of excess Ar) or measurement error, owing to the small proportions of radiogenic argon in the young rocks. Further, the authors imply that no phenocryst separation was conducted prior to analysis, so xenolith/xenocryst contamination could, possibly, be the source of this error. The McDougall and Ollier (1982) findings will be discussed in more detail when compared with current results later in the chapter, although caution must be exercised when interpreting their results as errors could have propagated throughout the analyses. Recent $^{40}Ar/^{39}Ar$ ages presented by Dunkley (2002) (Fig. 3.4) do not meet the stringent statistical criteria for defining reliable plateau or isochron ages (see Section 3.2.1.2). As such, the data are not robust and cannot be used with respect to dating volcanic activity on Tristan. However, the ages were used as a guideline for the sampling strategy in this study (see Section 3.4). Three samples of ^{14}C dated peat (Dunkley, 2002) provide useful comparisons to the present $^{40}Ar/^{39}Ar$ dating of samples from a similar location and will be discussed in Section 3.8.

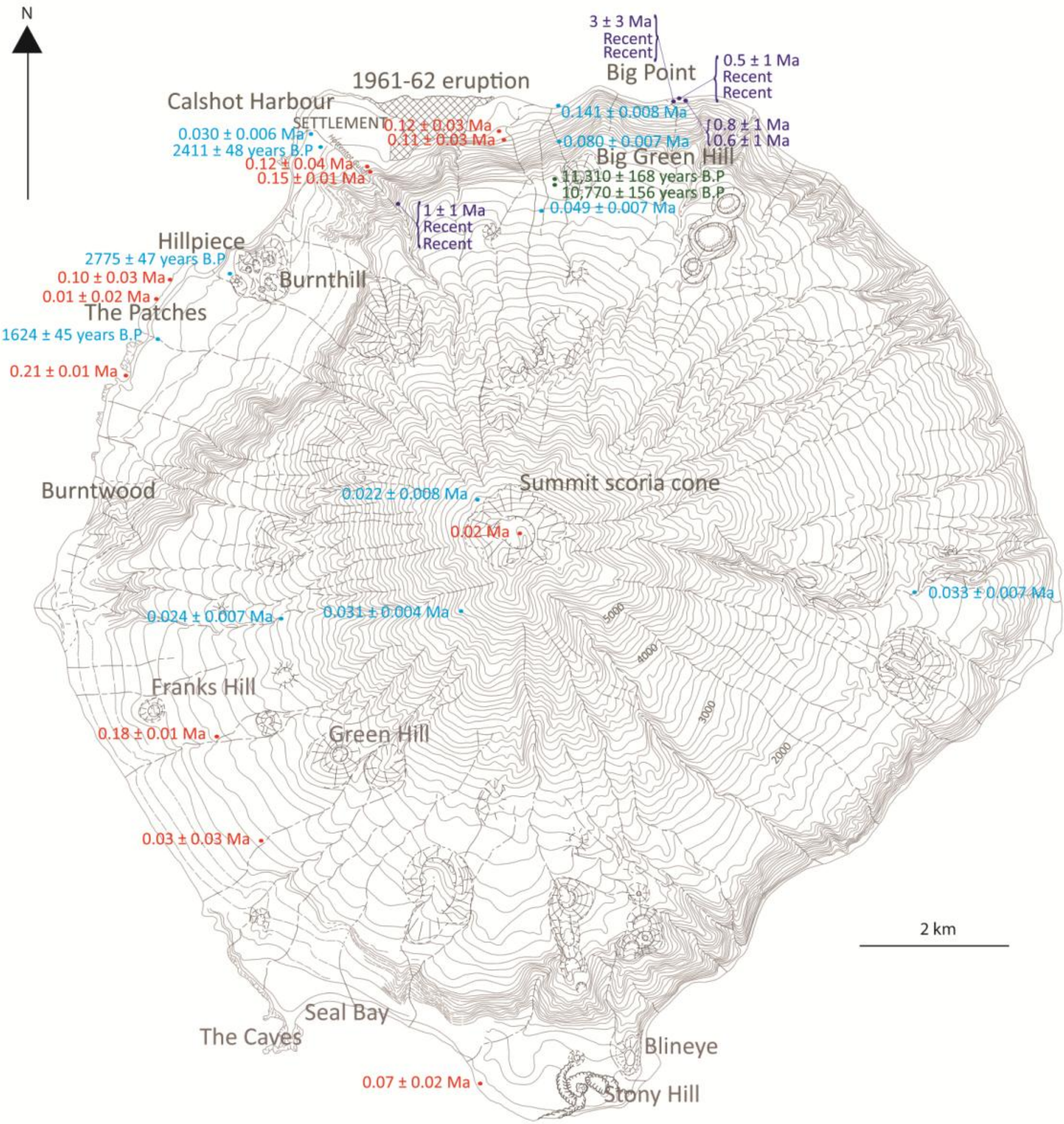


Fig. 3.4. Map of sample sites for dated deposits between 1964 – 2004. K-Ar ages of Miller (1964) are in dark blue; ^{14}C ages of Wace and Dickson (1965) are in green; K-Ar ages of McDougall & Ollier (1982) are in red; and $^{40}Ar/^{39}Ar$ ages & ^{14}C ages of Dunkley (2002) are in light blue. Contours and elevations are in feet. Base map is modified from Dunkley (2002) and can be seen in further detail in Fig. 1.

3.3. A new geochronology for Tristan - rationale

Given the lack of statistically sound ages from previous dating attempts on Tristan, reliable knowledge of the apparent timings of on-island eruptive activity remains unclear. Used as a guideline, results from earlier studies suggest that Tristan's edifice is young and that subaerial emergence probably occurred during the mid to late Pleistocene (McDougall and

Ollier, 1982; Dunkley, 2002). Since then, eruptions have been numerous and styles of volcanism, volumes and compositions of erupted material have been diverse (see Chapter 2 and Appendices 1, 5 & 6). This emphasizes the need to appraise the past eruptive phases of Tristan, constrain the relative timings of the differing styles of volcanism and to characterize magmatic processes in an attempt to forecast future eruption scenarios. However, this is challenging due to the wide dispersal of morphologically young (sub-50 ka) parasitic vents and the broad compositional range (medium-to-low-K) represented within erupted material, common to many ocean island systems.

As modern techniques such as $^{40}Ar/^{39}Ar$ dating have proven to provide accurate eruption chronologies, even for young volcanics (Renne et al., 1997; Lanphere et al., 2007; Hicks et al., 2012), the $^{40}Ar/^{39}Ar$ method was applied to 15 well-defined eruptions on Tristan (plus one from Nightingale Island).

3.4. Sampling strategy

The aim of the new geochronology was to ascertain spatio-temporal relationships of recent volcanism; explore relative timings and spacing of eruptions, and to establish if the most recent summit activity post-dated eruptions from the parasitic centres lower on the flanks. Therefore the focus of the sampling strategy was on the stratigraphically and morphologically younger deposits (ca. < 35ka; usually parasitic centres) which could help address the following three questions:

(i) Does the recent activity at this volcano occur in clusters, or at regular intervals? *This has important implications for the possible timing of future activity.*

(ii) Is there a relationship between repose interval and eruption size and composition? *With insufficient data the presence or absence of this relationship has not yet been established.*

(iii) Is activity at the summit and activity at the flanks of the volcano separated in time? *Summit activity has very different hazard implications to the localised coastal lava flow experienced in 1961.*

The sampling areas (Fig. 1 & Fig. 3.6; and Appendix 6) were carefully chosen to address these questions as well as provide a more complete chronology of the island and offer insights into the manner in which the volcanic edifice was constructed. The suite of samples represented the full range of eruptive styles and compositions, therefore addressing question (ii). By comparing samples 038, 040, 041 and 047 with ages for samples 011, 022, 024, 052, 054, and 093, question (iii) would be addressed. Sample 010 (lowermost exposed lava flow) was chosen to directly compare the age with results from McDougall and Ollier (1982) and Dunkley (2002), therefore giving a more accurate age of island emergence. Dunkley (2002) also reported conflicting age data related to the lava delta that formed the Settlement coastal strip, so samples 007, 085 and 100 provided additional data to resolve this. Furthermore, ages of these three samples permitted the examination of the longevity of eruptive activity at the Hillpiece-Burnthill complex; provided direct correlation with other dating methods (^{14}C ages in Dunkley (2002)), and constrained the timing of the large sector collapse (with the age of sample 089).

As whole rock separates are suitable for $^{40}Ar/^{39}Ar$ analysis, it was not necessary to choose porphyritic samples which would have severely limited sample availability. However, the occasional deposit contained hornblende as a phenocrystic phase so, where possible, fresh samples were collected to allow for analyses on both whole rock and hornblende separates as required. For each sampling area about 4-5 kg of rock was collected to ensure the preparation of homogenous separates.

3.5. Sample preparation

As Tristan rocks are commonly aphyric or aphanitic, only five samples were prepared as hornblende separates[6] and the other 11 as homogeneous phenocryst-free groundmass separates (Appendix 7) (e.g., Mark et al., 2010).

Each sample was cleaned of loose surficial material and then crushed in a jaw crusher to less than 2000 µm (2 mm) grain size. This was followed by repeated sieving (with sieve shaker) and crushing until the samples could be separated into four or five aliquots (>1000 µm; 500-1000 µm; 250-500 µm; 125-250 µm, and < 125 µm). The sieved samples were then thoroughly washed in de-ionized water until the water ran clear, and dried at T ≤ 100°C. A Frantz Isodynamic Separator (set vertically) was used to separate the iron-rich minerals. This

[6] Hornblende was the only viable phenocryst phase, in all Tristan rocks, suitable for $^{40}Ar/^{39}Ar$ analysis.

method was quicker and more effective than the traditional hand magnet approach. The weakly magnetic separate was then fed through the magnetic separator again, this time set horizontally, to effectively isolate the phenocryst phases (Rosenblum and Brownfield, 1999). A hornblende or groundmass homogenous separate was then hand-picked under a binocular microscope. Meticulous separation almost guaranteed (99% phenocryst free) elimination of sample heterogeneities.

3.6. Analytical methods

Following preparation, all samples were packaged into Al-discs and irradiated for five minutes in the Cd-lined facility at McMaster University in Ontario, Canada. Sanidine from the Alder Creek Tuff was used as the neutron fluence monitor for *J*-determinations with a reference age of 1.193 ± 0.001 Ma (Nomade et al., 2005).

Irradiated samples were heated incrementally (see Section 3.2.1.3) using an innovative, custom built CO_2 laser system equipped with a digital Scanhead (Plate 3.1). The Scanhead is advantageous as it allows rapid rastering of the laser over large pits of mono-layer groundmass (up to 500 mg). This overcomes one of the limitations of other lasers as the Scanhead modifies the Gaussian profile of the CO_2 laser beam, which normally heats in a non-uniform manner, to enable large samples to be heated uniformly.

Each individual sample was heated incrementally in 10 or 12 steps, starting at 500°C and finishing at 1300°C. Extracted gases were cleaned using two GP50 getters (one operated at 450˚C and one at room temperature) and a cold finger maintained at -140˚F. Data were collected using a fully automated MAP 215-50 mass spectrometer equipped with a Balzers SEV-217 electron multiplier. The mass spectrometer has a measured sensitivity of 1.13×10^{-13} moles/volt. Backgrounds were measured after every two analyses of unknowns. Average backgrounds ± standard deviations (^{40}Ar 1.02×10^{-15} moles, ^{39}Ar 3.10×10^{-17} moles, ^{38}Ar 1.90×10^{-17} moles, ^{37}Ar 7.85×10^{-17} moles, ^{36}Ar 1.38×10^{-17} moles) from the entire run sequence were used to correct raw isotope measurements of unknowns. Mass discrimination was monitored by analysis of air pipettes after every five analyses ($^{40}Ar/^{36}Ar = 289.61 \pm 0.57$). Isotope data were corrected for blanks, radioactive decay, mass discrimination and interfering reactions using the approach of Mark et al., (2011a). The decay constants of Steiger and Jäger (1977) were used and ages (see results in Section 3.7) are quoted at the 1σ confidence level.

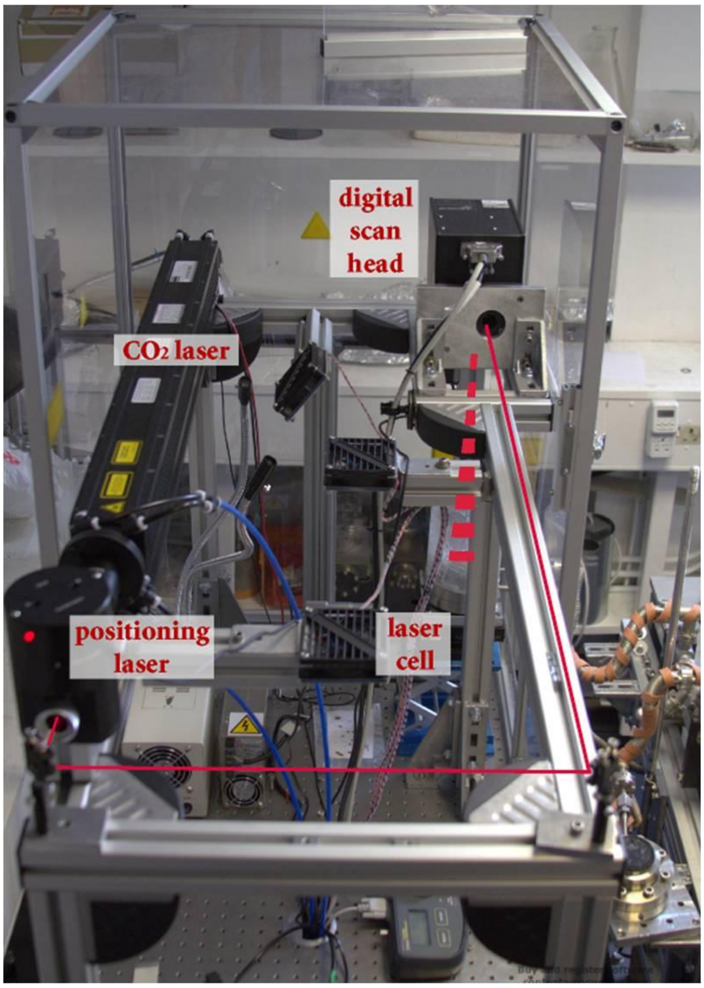


Plate 3.1. The CO_2 laser heating system with Scanhead, located at the Argon Isotope Facility (AIF), SUERC, East Kilbride. Image courtesy of the AIF.

3.7. Results

All 15[7] samples from Tristan yielded statistically sound $^{40}Ar/^{39}Ar$ plateau ages. As stated in Section 3.2.1.2, the criteria for fitting of plateaus is they must include at least 60% of ^{39}Ar in three or more contiguous steps with the probability of fit of plateau to data > 0.05 (Mark et al., 2011a). The presence of a flat plateau over > 3 heating increments in all samples suggested that they represent a simple closed system since cooling following eruption. Further, all plateau and inverse isochron (and most total fusion) ages overlap at the 1σ confidence level, whilst trapped components ($^{40}Ar/^{36}Ar$) all overlap with accepted

[7] Whilst the age of the 16th sample from Nightingale Island was also statistically sound with good precision (5.53 ± 0.18 Ma), it will not be discussed further.

atmospheric Ar isotope ratios (Nier, 1950). Results are presented as a summary in Figs. 3.5, 3.6 and Table 3.3 and as plateau ages & inverse isochron plots (Fig. 3.7) with uncertainties quoted at 1σ. Raw data are located in Appendix 8.

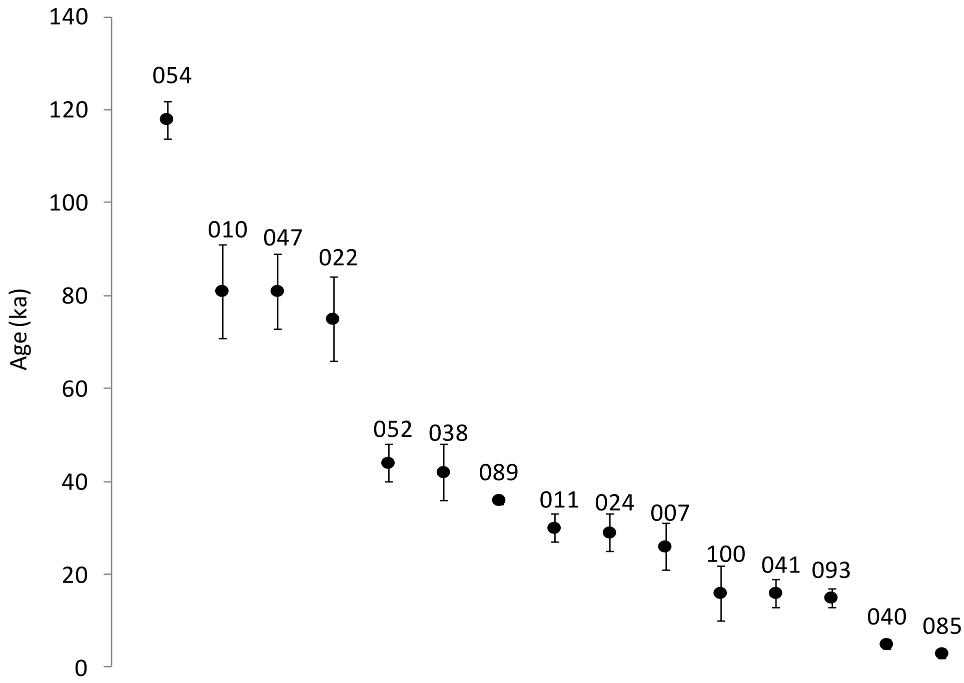


Fig. 3.5. Plot of $^{40}Ar/^{39}Ar$-derived ages, with associated errors (1σ) for fifteen sampled deposits from Tristan.

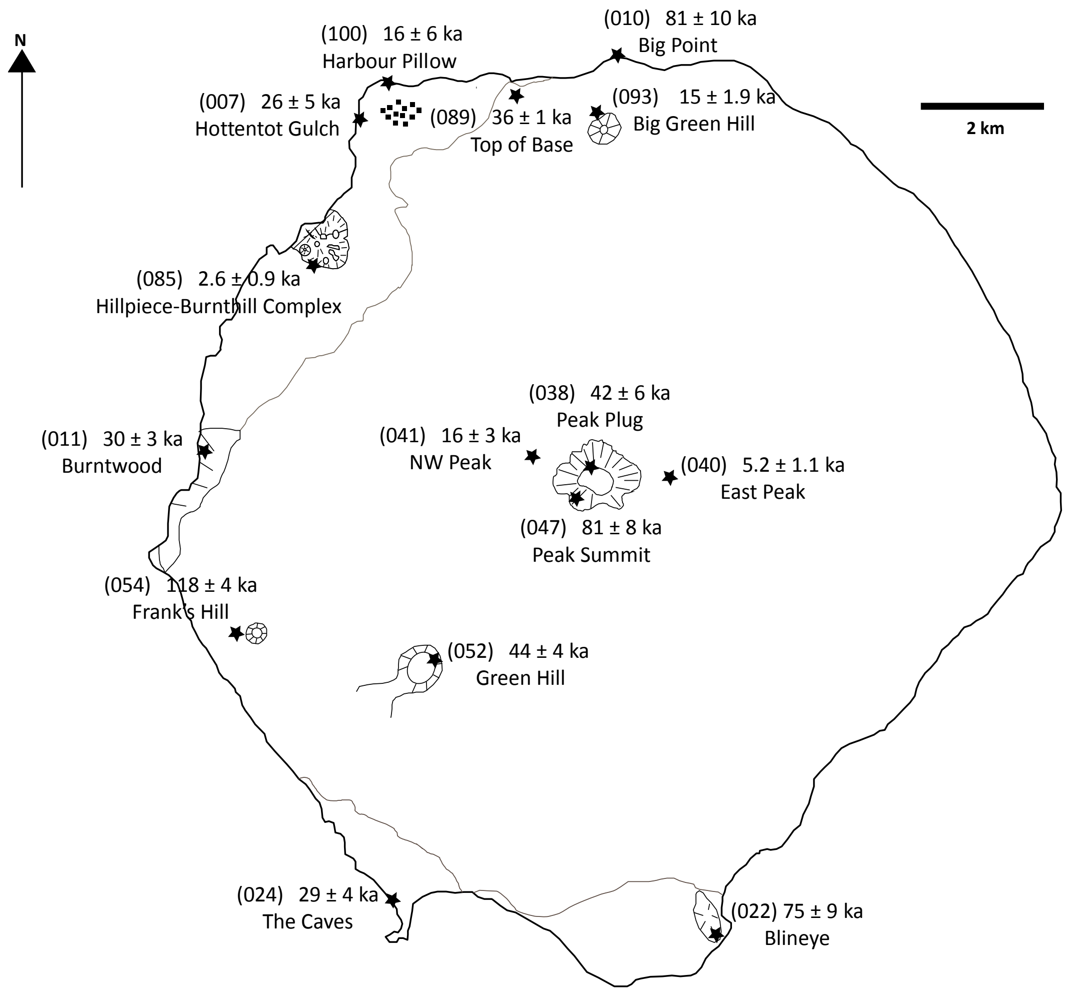


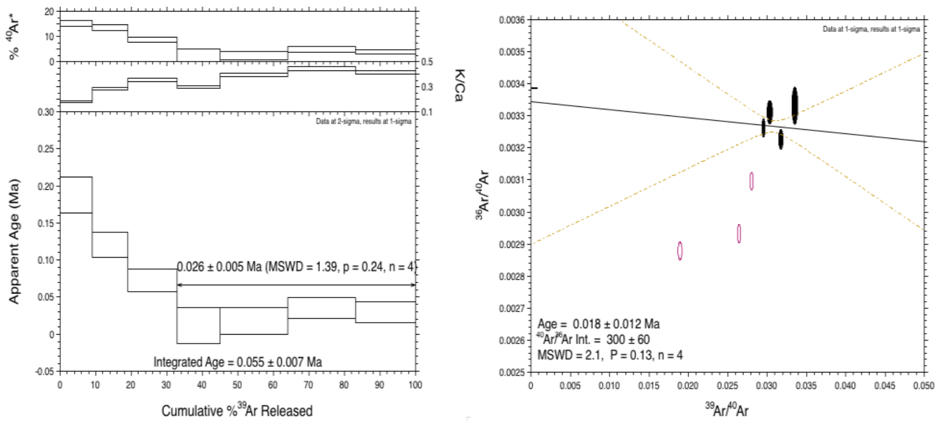
Fig. 3.6. Outline map of Tristan with new $^{40}Ar/^{39}Ar$ ages from sampled deposits. Sample numbers are in brackets. Junction between coastal strips and the cliffs are outlined.

Ages for dated parasitic centres considered to be post-shield volcanism, range from 118 ± 4.3 ka to 2.6 ± 0.9 ka (Fig. 3.6). Of those dated, older centres are concentrated in the south of the island and the youngest are situated on the north-western coastal strip and northern flanks. In the south-west, lava from the Seal Bay coastal strip (known locally as the Caves) (sample 024) yielded an age of 29 ± 4.ka; the uppermost of seven subaerial flows generated from Hackel Hill centre (Fig. 3.6). The lavas of the Stony Hill coastal strip to the east of Seal Bay are considered to have originated from the Blineye centre (Baker et al., 1964) and, although the flows were not dated, the centre itself yielded an age of 75 ± 9 ka (022; Fig. 3.6). The comparably large north-western coastal strip was constructed from lavas issuing from the Hillpiece-Burnthill complex. Two substantial lava flows outcrop above sea level, the oldest (007) yielding an age of 26 ± 5 ka (Fig. 3.6). Scoria deposits from the Burnthill cone (085) yielded a very young age of 2.6 ± 0.9 ka (Fig. 3.6). Nonetheless, these deposits are succeeded by a younger, low volume centre within the complex, and very young volcanic material (~500 years B.P) has been found in the vicinity (Ljung et al., 2006; Ljung and Björck, 2011).

The latest activity at the summit is constrained by ages yielded by summit flows (041 and 040), pyroclastic deposits (047), and a trachytic plug (038) (Fig. 3.6). These range in age from 81 ± 8 ka to 5.2 ± 1.1 ka, illustrating continued volcanism of varying styles (Table 3.3; Appendix 8) from this region since shield construction. Sector collapse has been constrained to a 14 ka window, between 34 ± 1 ka (089) and 26 ± 5 ka (007), assuming that the altitudinally highest lava flow cut by the landslide headwall is the last flow before collapse. The bottommost and, therefore, presumed oldest stratigraphic unit was dated at 81 ± 10 ka (010), sampled at Big Point, the most northerly locality on the island (Fig. 3.6 and Fig. 1).

Table 3.3. $^{40}Ar/^{39}Ar$ age summary of samples from Tristan presented in chronostratigraphic order. Gm = groundmass. Hb = hornblende. N = number of contiguous steps. MSWD = mean square weighted deviate – this allows critical evaluation of the step ages as they differ from one another by measuring the scatter of the individual step ages, with their associated errors, from the mean. Suggested rejection of straight lines as isochrons when MSWD > 2.5. Plateau ages used within text are in bold.

Sample	Locality and rock type	Composition	Material	Mass (mg)	Plateau							Inverse isochron					Total fusion	
					Age (ka)	**± 1σ**	% ^{39}Ar	*n* (total)	Ca/K	± 1σ	MSWD	Age (ka)	± 1σ	$^{40}Ar/^{36}Ar$	± 1σ	MSWD	Age (ka)	±1σ
#085	Burnthill Scoria	Tephrite	Gm	200	**2.6**	**0.9**	88	6 (8)	1.44	0.03	0.5	6.0	3.0	290	10	0.6	2.6	0.9
#040	East Peak Lava	Tephri-phonolite	Gm	150	**5.2**	**1.1**	96	7 (8)	1.20	0.04	0.3	4.0	3.0	297	12	0.4	5.2	1.1
#093	Big Green Hill Scoria	Basanite	Gm	175	**15.0**	**1.9**	100	8 (8)	3.37	0.09	1.0	15.0	4.0	296	6	1.2	15.0	1.9
#041	NW Peak Lava	Tephrite	Gm	175	**16.0**	**3.0**	100	8 (8)	2.00	0.04	1.1	9.0	7.0	299	15	1.3	16.0	3.0
#100	Harbour Pillow Lava	Tephrite	Gm	100	**16.0**	**6.0**	100	8 (8)	1.59	0.03	0.7	10.0	5.0	296	15	0.8	16.0	6.0
#007	Hottentot Lava	Tephrite	Gm	150	**26.0**	**5.0**	67	4 (8)	2.85	0.06	1.4	18.0	12.0	300	60	2.1	26.0	5.0
#024	The Caves Lava	Basaltic Trachyandesite	Hb	150	**29.0**	**4.0**	100	9 (9)	7.32	0.22	0.5	26.0	6.0	297	3	0.5	29.0	4.0
#011	Burntwood Scoria	Tephrite	Gm	150	**30.0**	**3.0**	100	8 (8)	2.56	0.05	0.6	19.0	8.0	300	6	0.6	30.0	3.0
#089	Top of Base Lava	Tephrite	Gm	100	**34.0**	**1.0**	70	5 (9)	1.17	0.04	0.3	33.0	2.0	297	5	0.4	33.0	1.0
#038	Peak Plug Lava	Trachyte	Gm	100	**42.0**	**6.0**	89	7 (8)	1.54	0.33	0.5	33.0	18.0	297	11	0.6	42.0	6.0
#052	Green Hill Lava	Tephrite/ Trachybasalt	Hb	100	**44.0**	**4.0**	100	8 (8)	8.26	0.03	0.4	45.0	9.0	295	4	0.5	44.0	4.0
#022	Blineye Scoria	Tephrite	Hb	100	**75.0**	**9.0**	100	7 (7)	5.96	0.04	0.8	83.0	17.0	294	3	0.9	75.0	9.0
#047	Peak Summit Scoria	Phono-tephrite	Hb	150	**81.0**	**8.0**	100	7 (7)	3.86	0.12	0.3	80.0	20.0	296	9	0.4	81.0	8.0
#010	Big Point Lava	Tephrite	Gm	175	**81.0**	**10.0**	100	8 (8)	1.38	0.03	0.1	100.0	60.0	294	6	0.1	81.0	10.0
#054	Franks Hill Lava	Tephrite	Gm	175	**118.0**	**4.0**	100	9 (9)	3.11	0.11	0.9	100.0	20.0	304	9	0.9	118.0	4.3



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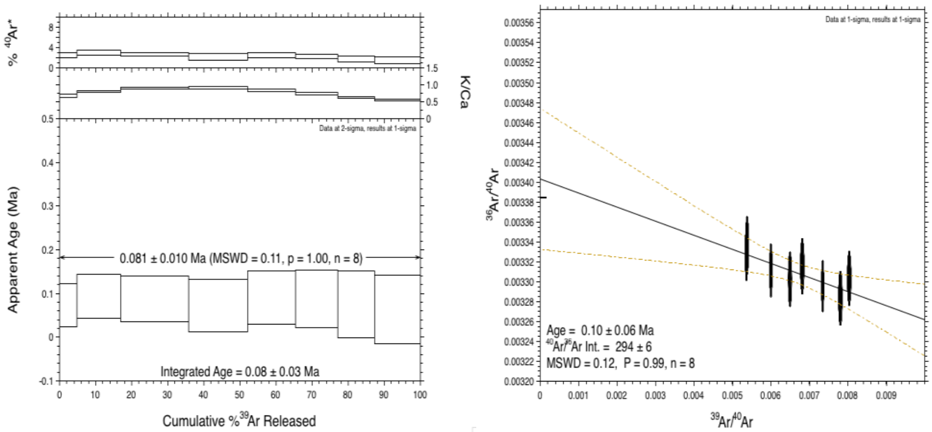

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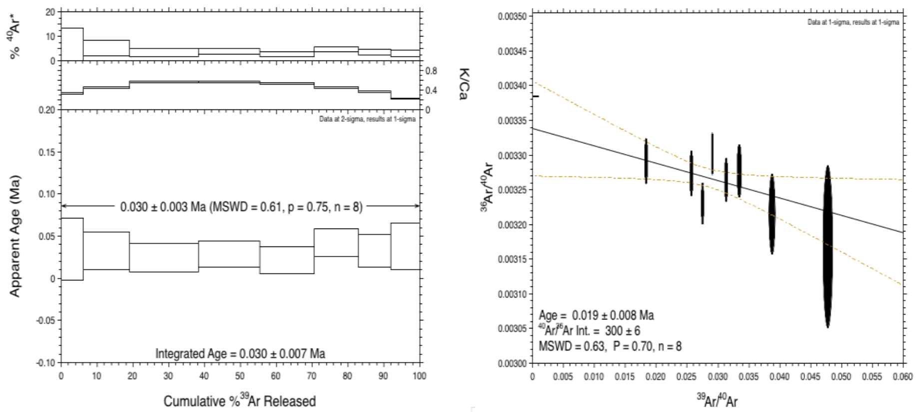

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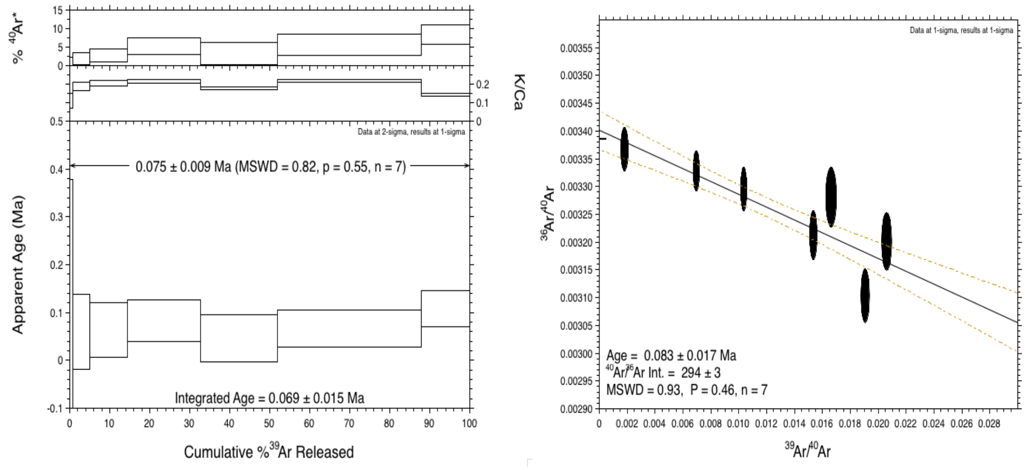
Fig. 3.7. Age spectra and inverse isochrons of fifteen volcanic samples from Tristan da Cunha. Both the plateau and inverse isochron ages are within error of each other, indicating that the $^{40}Ar/^{39}Ar$ ages are robust. MSWD and 'n' definitions as described in Table 3.3 caption. Probability values (p) must be > 0.05.



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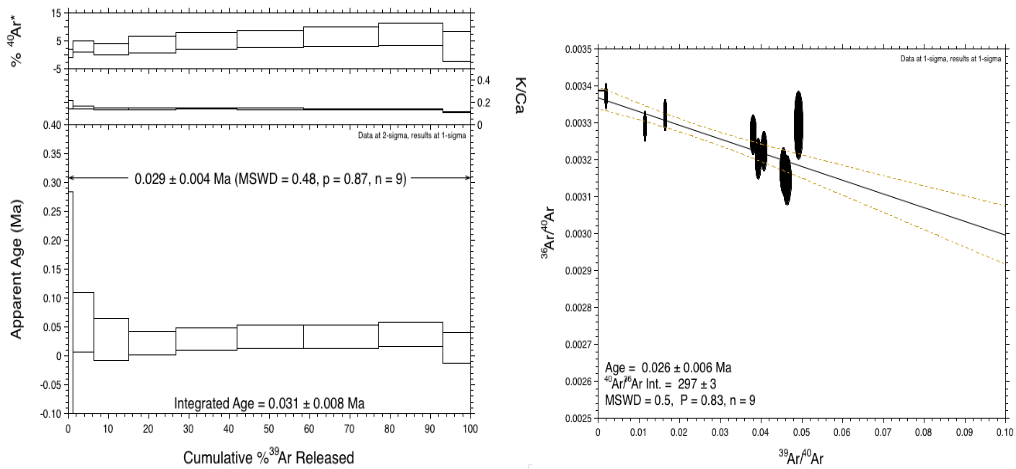

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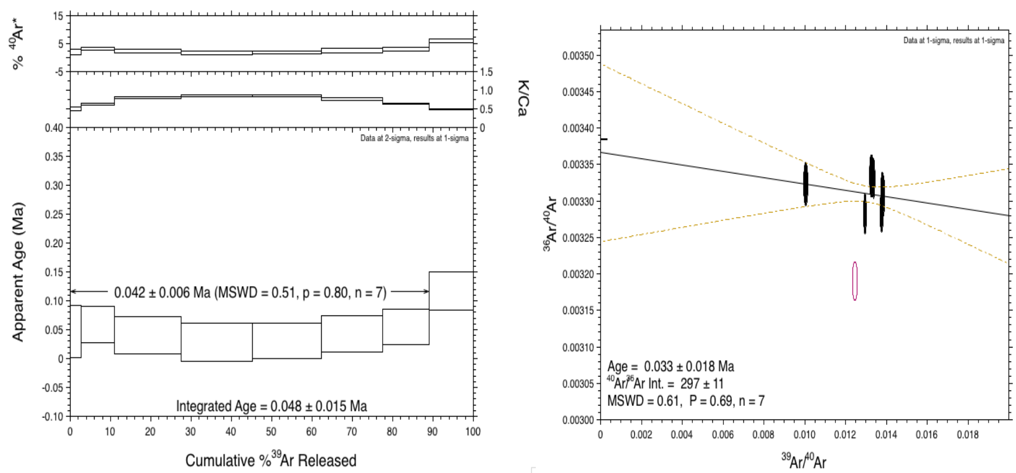
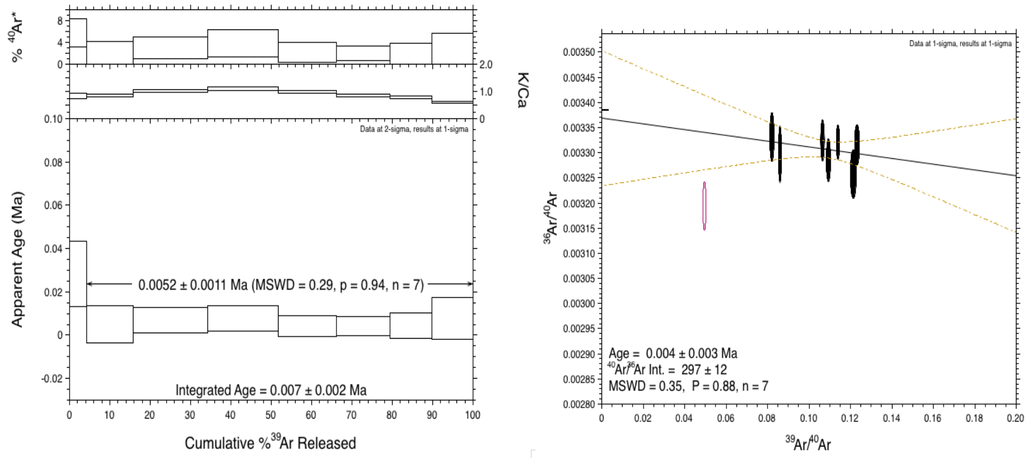


TDCAH038

Fig. 3.7. *Continued*



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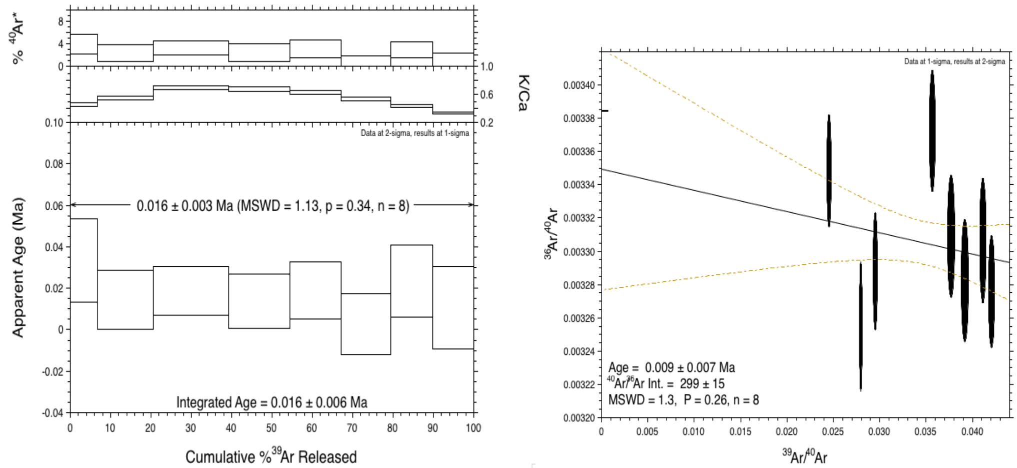

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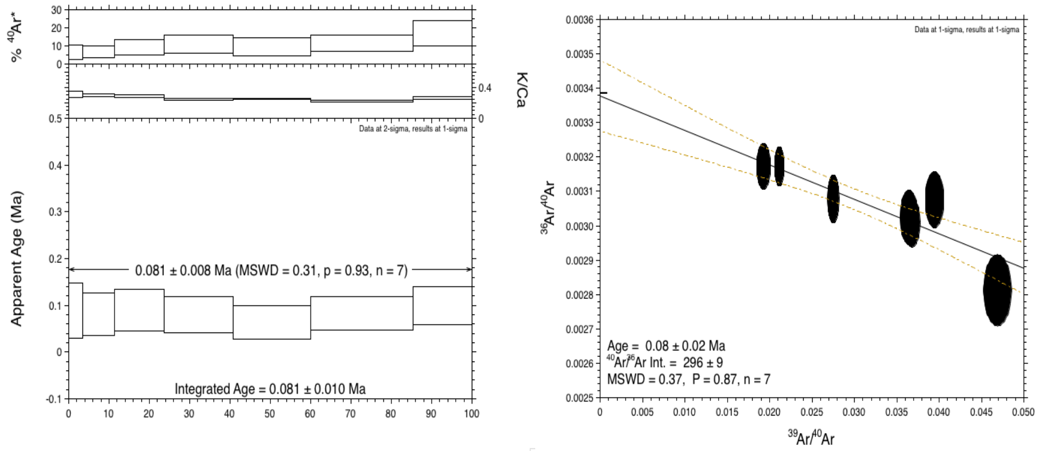
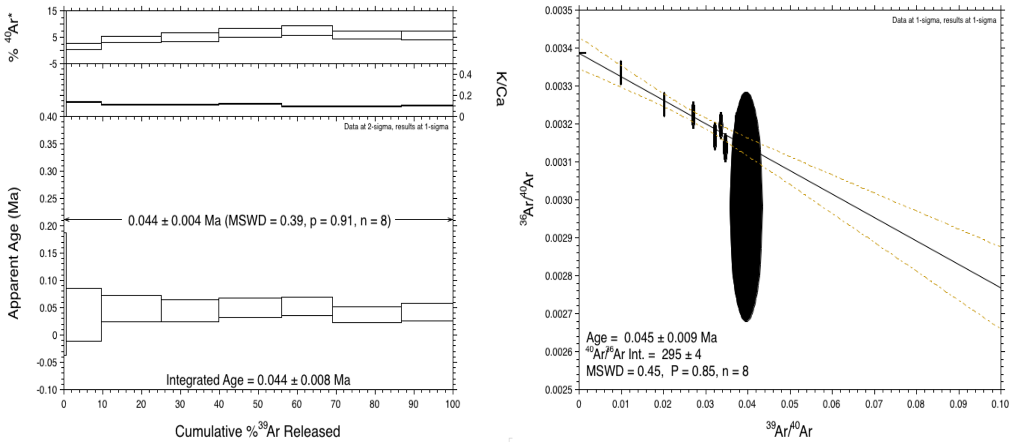


TDCAH047

Fig 3.7. *Continued*



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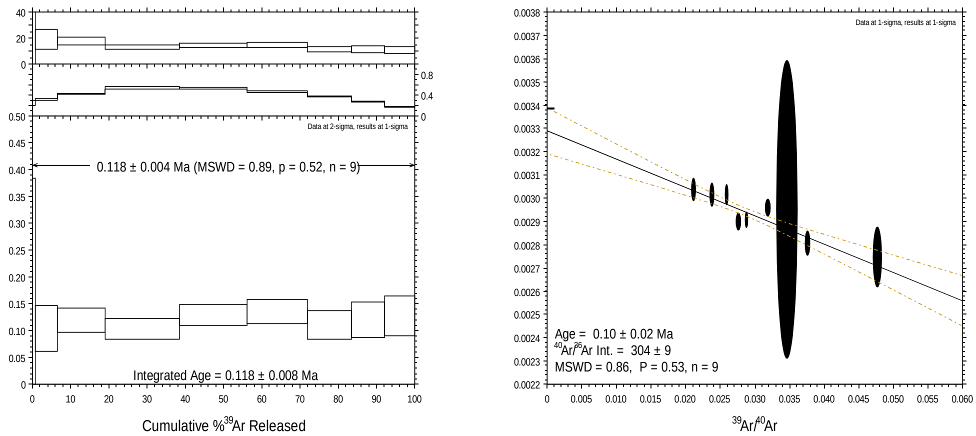

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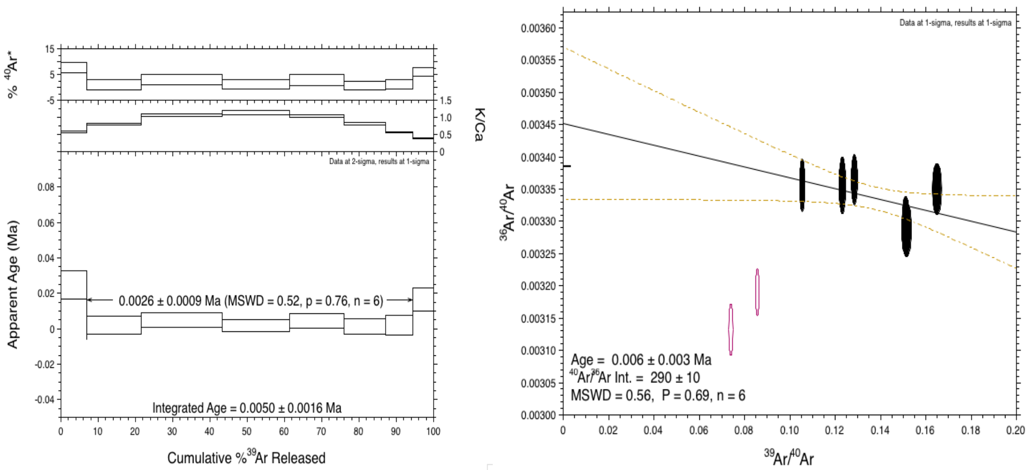
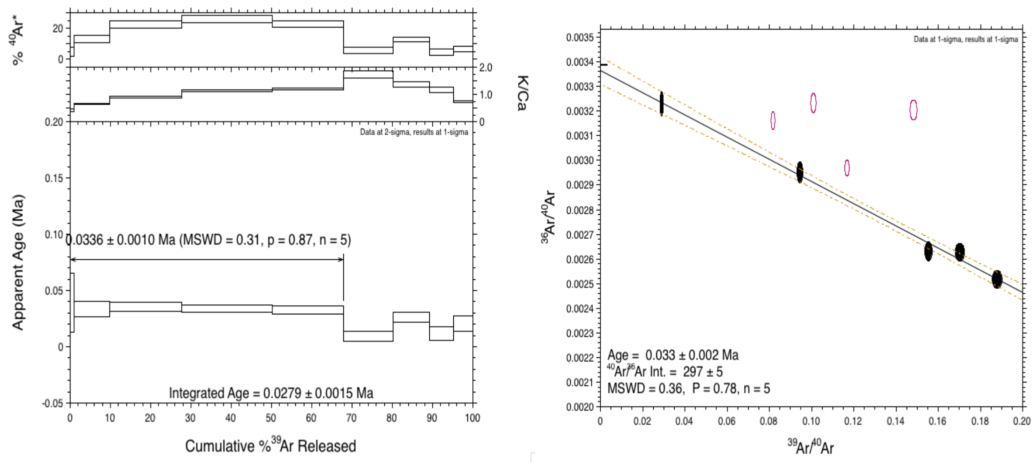


TDCAH085

Fig. 3.7. *Continued*



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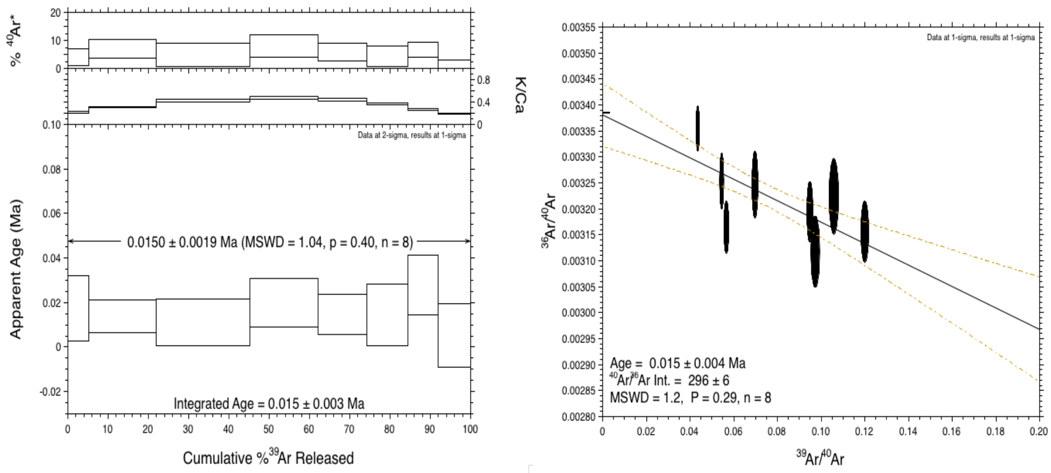
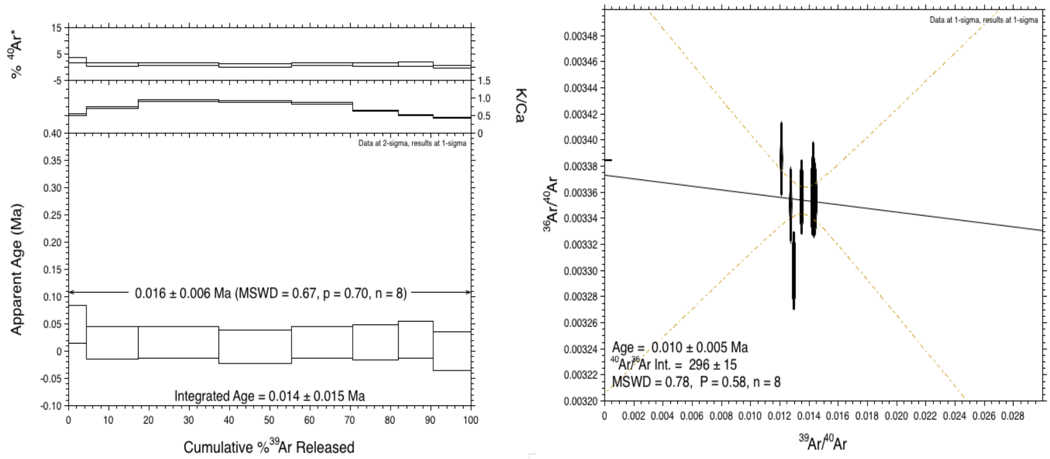


TDCAH093



TDCAH100

Fig. 3.7. *Continued*

3.8. Interpretation and discussion

The goal of this research component was to apply $^{40}Ar/^{39}Ar$ dating to 15 carefully chosen deposits on Tristan in order to gain a better understanding of the evolution and configuration of recent volcanism.

The following interpretations of the data help to address the three questions posed in the sampling strategy (Section 3.4) and present other hypotheses relating to island evolution. The conjecture required to make any interpretation based on 15 ages is acknowledged so, where possible, interpretations have incorporated supporting information from volcanoes with analogous characteristics. Well-studied intraplate island chains such as the Canary Islands, Hawaiian Islands, Azores and Cape Verde offer some insight into patterns of volcanism over time, although the majority of these volcanoes are at evolutionary stages very disparate from Tristan, and have often displayed markedly different eruptive behaviours. This will be discussed in more depth in later sections.

3.8.1. Island Construction

Until now, it has been assumed that the subaerial volcanic evolution of Tristan occurred in three stages. An initial shield-building stage (lavas and intercalated scoria) - which formed the Base and Peak - was followed by an explosive phase of volcanism from parasitic centres on the flanks. This activity was succeeded by the construction of two coastal strips. In light of the recent radiometric age data, it is possible to examine this assumption of a relatively simple configuration and consider a rather more complex evolution. The data imply that there were *at least* three growth stages, and that they were not consecutive, but somewhat contemporaneous.

Un-weathered pyroclastic material sampled from the inner crater of the summit scoria cone (047) yielded an age of 81 ± 8 ka (Fig. 3.6). This is comparable to the age of lavas at the base of the succession at Big Point (81 ± 10 ka; Fig. 3.6 and 3.8), suggesting the edifice was constructed piecemeal, and that there were several stages of shield building. This inference is supported by the eruption of the small parasitic centre, Frank’s Hill (054; 118 ± 4 ka; Fig. 3.6 and 3.8), on the lower south-west flanks and, therefore, assumes that the edifice underlying Frank’s Hill must have formed before the northern sector. This conclusion is corroborated by the age of sample T13 from the McDougall and Ollier (1982) study (180 ±

10 ka; Fig. 3.4) which was taken from the main edifice in Flat Gulch valley, slightly west of Frank's Hill (Fig. 2.1).

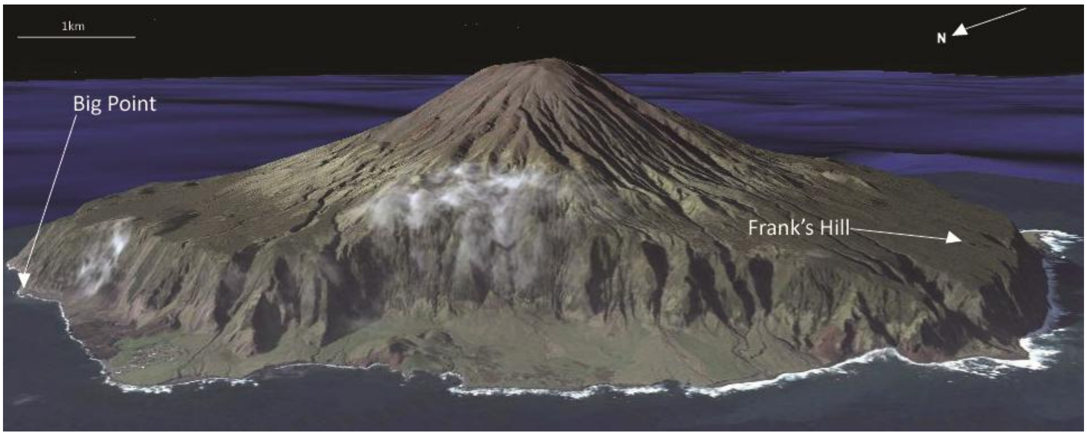


Fig. 3.8. Relative positions of Franks Hill (118 ± 4 ka) and Big Point (81 ± 10 ka).

Piecemeal construction of volcanoes is typical. Six of the seven Canarian islands, for example, have undergone more than one shield building phase, with only El Hierro, the youngest and smallest of the archipelago, currently in its first shield-stage period (Carracedo et al., 2001). Complex histories are typical of all intraplate island volcanoes. Although it is challenging to imagine progressive asymmetrical growth of Tristan due to its young age and presently spherical profile, a multifaceted evolution cannot be discounted. A basis to reject this piecemeal growth hypothesis would lie with further systematic dating of cliff stratigraphy and other eruptive centres.

New ages from the parasitic centres tentatively suggest also that the south of the island is older than the north (Fig. 3.6). Parasitic centres in the south yielded ages somewhat older than their erosional state suggested, for example Green Hill (sample 052; Fig. 3.6; Plate 3.2) at 44 ± 4 ka and Blineye (022; Fig. 3.6; Plate 3.3) at 75 ± 9 ka. In the north of the island, a flank surface flow (summit sourced) at the edge of the cliff (089; Fig. 3.6) presented a much younger age of 33 ± 1 ka and the scoria cone of Big Green Hill (093; Fig. 3.6) which overlies it at 15 ± 1.9 ka. It is noted however, that Big Green Hill is regarded as one of the youngest scoria cones (Baker et al., 1964) on the island flanks and may, just coincidentally, be situated in the north.

Rather than Tristan's evolution occurring in distinct stages (main edifice – parasitic centres – coastal strips), the new ages imply that activity on the flanks, at the summit and on the young coastal strips overlaps in time. Further evidence for contemporaneous growth of island 'stages' can be seen in cliff exposures, where thick units of inclined pyroclastic material intercalate with shallow dipping lavas centred on the summit. These units are probably derived from localized parasitic centres (Baker et al., 1964; Dunkley, 2002). Contemporaneous summit and flank activity has been documented at other well-studied volcanoes, particularly Mount Etna (e.g., Bonforte et al., 2009; Corsaro et al., 2009) and Mount Cameroon (Suh et al., 2003). Further, these volcanoes are also lava-dominated, and display similar morphological characteristics to Tristan, with steep inner flanks and more gently inclined outer slopes. Tristan's inner flanks are, however, several degrees steeper, creating closer morphological analogies with larger stratovolcanoes such as Mount Mayon and Mount Fuji.

In the northern sector; ~50 ka separates the lowest exposed and uppermost flows (81 ± 10 ka – 34 ± 1 ka. About 60 summit-centered flows streamed down the northern flanks to the coast during this time and are now preserved in the cliff face. Based on this sector alone, this suggests that the summit erupted relatively regularly. The interval over which other sector(s) of the shield grew remains temporally unconstrained. Such rapid construction is relatively rare on ocean island volcanoes, although there are exceptions. Notably, Gran Canaria whose entire edifice (5 x larger than Tristan) was built in less than 500 ka (Abdel Monem et al., 1971; McDougall and Schmincke, 1976; Herr et al., 2002). Other examples include the subaerial edifice of Cumbre Vieja, La Palma (Carracedo et al., 1999) and Furnas, Azores (Moore, 1992) (~100 – 180 ka). These volcanoes are comparable to Tristan both in terms of estimated age and volume.

However, it is also possible that Tristan's entire edifice was constructed in a more symmetrical fashion, and the northern sector of the island underwent a collapse event during construction. Unfortunately this cannot be corroborated as individual flows in the northern part of the island cannot be traced for more than a kilometre and, due to extensive vegetation growth, it is virtually impossible to trace any flows elsewhere in the cliff succession for any appreciable distance.

The age of the pillow lavas (100; 16 ± 6 ka) not only helps interpret the timing of the submarine-subaerial transition of volcanism from the Hillpiece-Burnthill parasitic centre, but also permits investigation of island uplift. The transition from submarine pillow lavas to massive subaerial lavas is abrupt and is coincident with present day sea level. However, during the time that the pillow lavas were erupted, global sea level was > 80 m lower (Lambeck et al., 2002), demonstrating that Tristan has been uplifted. Vertical movements of ocean island volcanoes are typical, particularly at hotspot ocean islands, which display freeboard change due to growth of the bathymetric anomaly. Examples of uplift in the Canary Islands (e.g., Carracedo et al., 1999; Carracedo et al., 2001; Acosta et al., 2003) and Cape Verde (e.g., Ramalho et al., 2010b) are well documented, with ocean islands recording significant vertical displacement in some cases (~450 m uplift of Santiago, Cape Verde) (Ramalho et al., 2010a). On Tristan, sea level palaeo-markers are difficult to detect due to extensive vegetation growth and problems of accessibility. Accordingly, only the pillow lavas near the harbour, pillows at Runaway Beach (Fig. 1) and the tuffs and agglomerates at Jenny's Watron (Fig. 1) are, to date, the only accessible sea-level palaeo-markers. Baker et al., (1964) inferred that the deposits at Jenny's Watron were laid down in a shallow water environment, but they are currently positioned between 80 and 100 m above sea level. Although these deposits have not been dated, their position on the island and at the base of the edfice suggests that they may be of similar age to sample 010 (81 ± 10 ka). However, if this were the case, one would expect to observe other sea-level palaeo-markers in the edifice at this height. It is possible that the deposits at Jenny's Watron represent volcanism that preceded the main shield-building stage. In terms of the extent of uplift, vertical movements appear to be localised as there is no evidence (yet found) of upward movement on Inaccessible or Nightingale. This supports the conclusions of Ramalho et al., (2010a,b) that differential magmatic additions at the base of the edifice are the primary cause of uplift at the scale of individual islands. Further, it is likely that vertical displacement of Tristan has been affected by extensive erosion and sector collapse.

Plate 3.2. Green Hill parasitic centre. The lava mound issuing from the seaward breach is clearly visible to the right of the image.

Plate 3.3. Southern section of the eroded Blineye centre. Part of the large depression of Blineye's original crater is seen to the left of the picture.

3.8.2. Sector Collapse

Large-scale sector collapses are now viewed as ubiqitous events during the evolution of a volcanic edifice (McGuire, 1996). Despite Tristan's young age, its growth has also been punctuated by at least one flank collapse. Holcomb and Searle (1991) first inferred this from examination of sidescan sonar images (GLORIA) which showed seafloor morphology they interpreted to be consistent with a large debris avalanche deposit extending from a horseshoe-shaped depression in the north-west of the island. Until then, previous authors had assumed the Settlement coastal strip was either fault bounded (Dunne, 1941) or a marine cut platform (Baker et al., 1964; Gass, 1967), rather than a post-collapse lava delta (see Chapter 2). Holcomb and Searle (1991) suggest that this sector collapse removed about 20% of Tristan's edifice and deposited in the region of 150 km^3 of material on the sea floor (see Chapter 2).

Greater understanding of the recurrence interval for sector collapse is important from a natural hazards perspective, despite the lack of large subaerial slides occurring in historical time (Longpré et al., 2011). Constraining the age of the sector collapse on Tristan was thus an important aim of the sampling strategy. Samples were gathered from three locations: the altitudinally highest lava flow cut by the landslide headwall (sample 089; Fig. 3.6; Plate 3.4), a post-collapse lava flow which created the lava delta (007; Fig. 3.6; Plate 3.4), and a tabular pillow lava sample from the foreshore (100; Fig. 3.6; Plate 3.4). The sample taken from the top of the cliff succession yielded an age of 34 ± 1 ka, and the lowermost flow of the lava delta that partially infilled the collapse scar was dated at 26 ± 5 ka. This brackets the age of the sector collapse to a 14 ka window. One critical assumption is that the sample taken from the top of the cliff succession (089) was the last flow to be erupted before collapse. The sample taken from the lava delta (007) unquestionably reflects the entire coastal strip, as this flow can be traced from its source (the Hillpiece-Burnthill complex) for its complete length. The pillow lava sample (100) was dated to further support the age bracket of the sector collapse. Assuming that the pillow lavas were formed during submarine eruptions from the Hillpiece-Burnthill centre, they should pre-date the first subaerial lavas of the Settlement coastal strip (007). However, the calculated age (16 ± 6 ka) is actually younger than that of the subaerial lava delta (26 ± 5 ka). Whilst it is possible that the source of these pillow lavas was an unmapped submarine vent and not the Hillpiece-Burnthill complex, the overlap of the associated uncertainties implies that the two deposits may still be part of the same eruptive sequence. As such, these ages still provide a useful constraint for the age of collapse and the period of transition from submarine to subaerial activity in this region.

Plate 3.4. Sample locations for constraining the age of the sector collapse. A: aerial view of the Settlement and 1961-62 dome and flows. Sampling area for pillow lava deposits (sample 100) is highlighted and refers to image E in detail. B: view of sector collapse scar and relative positions of sampling areas from Hottentot Gulch (sample 007) (refer to image D for detail) and the uppermost lavas at the cliff edge (sample 089) (refer to image C for detail).

Of particular interest is the apparent correlation of the age of the Tristan sector collapse with that of a boulder bed found on Nightingale Island, 38 km SW of Tristan. The horizontal boulder bed, located about 18 m above sea level, has been interpreted as a raised beach deposit which can be found all over the island (Baker et al., 1964; Wace and Dickson, 1965). Plant debris entrained within this deposit was ^{14}C dated to > 36,900 years B.P. (Wace and Dickson, 1965; Gass, 1967). Overlying this bed is the Younger Pyroclastic Sequence which marks the age of activity recurrence on Nightingale in the order of 10 Ma (Gass, 1967). Whilst available descriptions of this boulder bed are scant, it is possible that this anomalous layer is in fact a proximal tsunami deposit, generated from the Tristan sector collapse. No similar deposit has yet been recorded on Inaccessible, or Tristan.

A flank collapse of this magnitude may have influenced the magmatic plumbing system beneath Tristan. This has been recognised on other ocean islands, such as the El Golfo landslide on El Hierro (Manconi et al., 2009) and on Tahiti-Nui Island (Hildenbrand et al., 2004), where it was observed that higher proportions of denser, less evolved magmas were rapidly erupted following a collapse event. Decompression caused by sector collapse has been suggested to generate pressure gradients and instability within magma storage regions. The subsequent effects on feeding system processes such as storage, degassing, differentiation, transport and mixing may help to explain observed changes in eruption rate, petrology and geochemistry of post-collapse lavas (Manconi et al., 2009). On Tristan, whilst it is impossible to draw any relationships between the new temporal framework, vent locations, eruptive volumes or composition (see Section 3.8.3), the post-collapse lavas of the Hillpiece-Burnthill centre were atypically voluminous for Tristan (see Appendix 1), dense, and tephritic. There is no submarine information to inform us how large the Hillpiece structure is beneath the sea, however deposits from the Hillpiece Hardies (stacks) (Fig. 1) which are inclined to the south-east imply that there was another centre over 200 m to the north of the seaward hardy. This suggests that the entire Settlement coastal strip was at least twice as wide prior to erosion onset (Baker et al., 1964). Whilst available data cannot confirm that the Tristan collapse actually affected the magmatic regime, it is highly plausible that volcanism at Hillpiece was activated by flank failure. Further, the Hackel Hill centre on the Seal Bay plateau in the south was also contemporaneously active during the 14 ka window constraining the sector collapse (sample 024; 29 ± 4 ka).

The cause of the collapse cannot be determined, but it is likely to have been prompted by magma movement (and associated seismic trigger), or high pore water pressure. There are two large volcanic plugs evident in the Main Cliffs along the collapse headwall, one behind the Settlement and the other at Spring Ridge (Fig. 1). Both centres intrude the cliff succession, but as their vertical extent cannot be observed, it is unclear if the plugs were feeder systems for localised parasitic centres within the Main Cliff sequence, or for centres on the present surface of the Base. Whilst the ages of these intrusive masses have not been constrained, it is possible that magma movement represented by these plugs could have triggered massive slope failure. Further, it is possible that short periods of rapid topography build-up may have initiated sector collapse. This has been documented at other volcanoes where precise age data and geological information have been used to temporally connect rapid relief build-up with collapse (e.g., Wijbrans et al., 2011). On Tristan, the Burntwood centre dissecting the Base and Settlement coastal strip yielded an age of 30 ± 3 ka (sample

011) within the sector collapse age window. However, there are other large, as yet un-dated, parasitic centres which line the headwall of the collapse scar.

3.8.3. Compositional and spatio-temporal changes

Tristan displays a wide range of erupted compositions (basanites through phono-tephrites to phonolites), volumes and eruptive styles, but presents no correlation with vent location or eruption timing. Tephritic eruptive material predominates, but these deposits are spatio-temporally interspersed by eruptions of more evolved compositions (Fig. 3.9). Other well-studied young intraplate volcanoes do not exhibit such a complex spatial and temporal configuration of recent eruptive behaviour. At such systems, where mafic and much more evolved volcanism has occurred, episodes of differing types are normally separated by a considerable period of time and tend to be at the extreme ends of the compositional continuum. Tristan lavas display the full range of the basanite-phonolite suite (see Chapter 2). They show some relation to eruptive sequences on Cumbre Vieja (La Palma) and the El Golfo range on El Hierro, both of which are constructed of a succession of alkali lavas with phonolites and trachytes. However, on La Palma, and until the 2011-12 submarine eruption of El Hierro, very recent activity has been restricted to mafic outpourings (Carracedo et al., 2001). The spatial and temporal heterogeneities of recent volcanism on Tristan is likely to be due partly to a lack of rift zones on the island, and points to the role that the differing geotectonic situation and the plumbing system in the crust and mantle play in governing the construction of the volcanic island.

The new age data and field observations suggest that the plumbing system beneath Tristan is not dominated by one large storage region, but smaller individual pockets of magma that source rapidly from depth. This is consistent with the relatively low plume buoyancy flux (Sleep, 1990) that would be unlikely to sustain a larger magma reservoir, and to erupt lavas of markedly differing compositions in a relatively narrow time frame. The 2004 phonolitic pumice was inferred to come from rapid, extensive fractionation of a small parental magma body, unrelated to the 1961 tephri-phonolitic magma (Reagan et al., 2008). Although the significance and relationship of the recent tephri-phonolitic N-S aligned dome complexes have yet to be determined (Fig. 1), their positioning relative to regional compressive stress supports the absence of evidence for a sizeable crustal magma body (Nakamura, 1977). However, it is not inconceivable that these low volume leaks of evolved lava signal a prelude to a relatively small caldera-forming event as seen on, for example, Krakatau and Santorini (Druitt, 1983; Newhall et al., 1984; Bacon, 1985; Druitt et al., 1989).

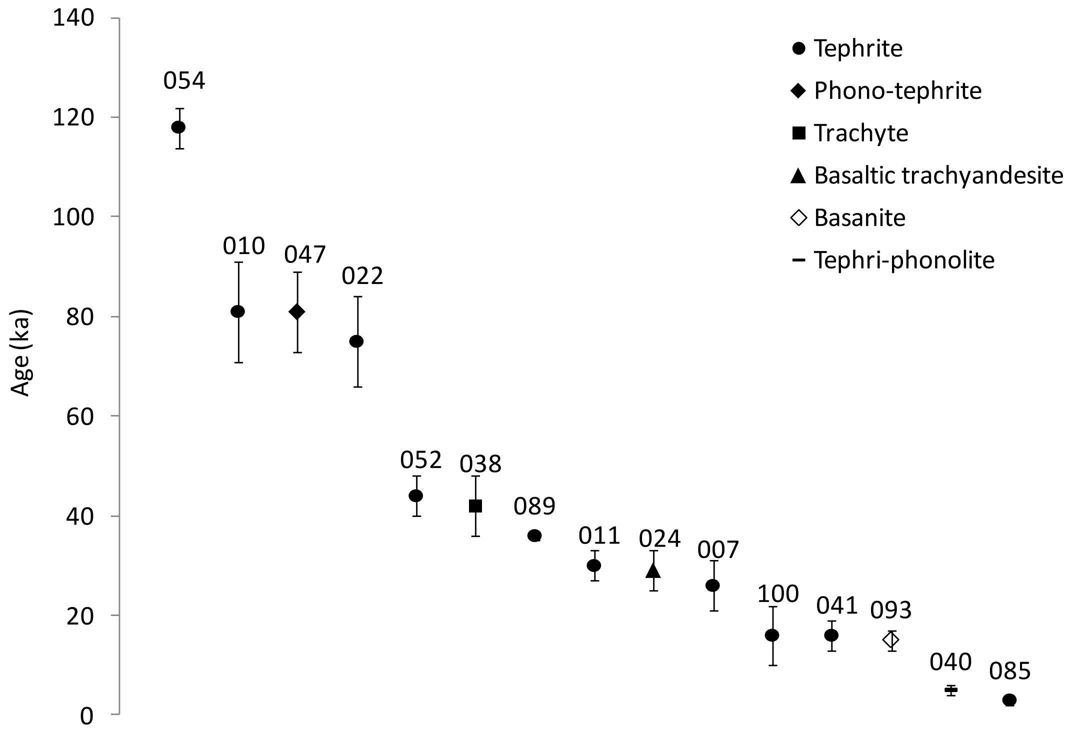


Fig. 3.9. Compositional variation of dated samples.

There appears to be a weak correlation in eruptive volume over time (Appendix 1). Of those dated, most of the older parasitic centres are larger than the younger cones. The two most recent effusive centres erupted very small volumes of material.. Baker et al., (1964) estimated the volume of the 1961 dome and flow at ~ 0.024 km^3 and, given the rapidity of erosion on Tristan, it seems likely that the penultimate eruption of the Stony Hill centre was probably initially of similar volume (it is currently slightly smaller). However, there are parasitic centres which oppose this apparent trend of reduced eruptive volume over time. For example, the parasitic centre of Franks Hill (118 ± 4.3 ka) has a very small volume, around 0.0006 km^3 and the Hillpiece-Burnthill complex would have been extremely large, prior to marine erosion. The two subaerial flows which issued from the Hillpiece-Burnthill centre and created the lava delta are presently approximately 0.12 km^3 but, as stated previously, the Settlement coastal plain could easily have been twice its present size.

3.8.4. Very recent volcanism

Defining the locations and patterns of very recent volcanism was an essential component of the Tristan volcanic hazard assessment. The initial hypothesis was that the coastal strips were the youngest regions and, since their construction, these low-lying areas provided preferential routes for magma. If the Blineye centre lavas created the East Beach/Calfyard plain in the south, this is the oldest coastal strip (sample 022; 75 ± 9 ka; Fig. 3.6). This age is also coincident with a K-Ar age of 70 ± 2 ka which McDougall and Ollier (1982) measured from a sampled deposit on East Beach. The second coastal strip to be constructed would have been the Seal Bay plateau (the Caves), formed from lavas issuing from Hackel Hill (024; 29 ± 4 ka; Fig. 3.6). The most recent coastal strip, (or perhaps coincidentally constructed with the Seal Bay plateau), would have been the Settlement coastal strip in the north-west (007; 26 ± 5 ka; Fig. 3.6) Since construction of all three coastal strips, there has been further very recent activity on two of these low lying regions. There are three young eruptive centres superimposed on the East Beach plain: Little Hill, 'Kipuka' Hill and Stony Hill (Fig. 1). There has been no subsequent activity on the Seal Bay plateau since the eruption of Hackel Hill, where the earliest age of activity has yet to be determined. On the Settlement coastal strip, the youngest dated sample was from Burnthill which yielded an age of just 2.6 ± 0.9 ka (085; Fig. 3.6). This age is corroborated by radiocarbon analyses of peat from Big Sandy Gulch (Fig. 1), just to the west of Burnthill, which yielded an age of 2775 ± 47 years B.P. (Dunkley, 2002). Younger vents within the vicinity of the Hillpiece-Burnthill complex are present, but the age of these deposits are presently unknown. Very recent (~500 years B.P.) plant matter entrained in tephra have been found in a bog near Hillpiece, but the provenance of the deposits have yet to be determined (Ljung et al., 2006; Ljung and Björck, 2011). The most recent activity on the Settlement coastal strip is the eruption of the tephri-phonolitic dome and flows in 1961-62.

Despite the relative youth of these coastal strips, 'young' fresh lavas were also collected from the Peak summit to determine an age of activity cessation. Previous authors suggested that central vent eruptions ceased about 15,000 years ago (Baker et al., 1964; Gass, 1967; Dunkley, 2002) , although this assumption was based on the superimposition of young parasitic centres on the flanks, such as Big Green Hill (Fig. 1). Ages of two separate lava flows issuing from the summit vent indicate that the summit region has been active very recently. Sample (041) yielded an age of 16 ± 3 ka and (040) was dated at just 5.2 ± 1.1 ka (Fig. 3.6). This indicates that not only was the summit area active during the same period as flank eruptions via parasitic centres, but it was also contemporanously active with coastal strip growth. Although neither summit flow was particularly voluminous, any summit eruption has vastly different hazard implications for the island's Settlement than an eruption on lower-lying areas. Given the elevation (2,060 m), steep slopes (~25°) and short distance to the Settlement (~5,000 m), any eruptive products would rapidly descend the flanks, with lavas, lahars and pyroclastic flows preferentially routed via deeply incised channels. Whilst there appears to be no compositional trend to eruptive activity through time, the last two eruptions have been effusive and deposits have been evolved. If this style of activity would continue at the summit, with the prospect of collapse and probable water-magma interaction, it would pose a much higher threat to the community than an eruption of similar size and style on low-lying areas.

3.9. Conclusions

This chapter presents the results of 15 new $^{40}Ar/^{39}Ar$ ages for Tristan. When coupled with compositional information and vent distribution, the ages not only place important constraints on the recent eruptive history of the island, but also provide insights into the manner in which the volcanic edifice was constructed. The ages help fill knowledge gaps relating to episodicity and offer insight into potential correlations with eruption size, compositional changes and relationships, as well as the migration of volcanism in time and space. This data was crucial for informing a volcanic hazard assessment and risk reduction strategies (see Chapters 4 & 7).

The 15 samples all yielded statistically sound $^{40}Ar/^{39}Ar$ plateau ages and, due to careful sample preparation and incremental heating with a new CO_2 laser system, even the youngest dated samples yielded small associated errors (e.g., 2.6 ± 0.9 ka). These data show that, with continued developments in Ar isotope extraction tools and noble gas mass spectrometer technology (e.g., Mark et al., 2009; Mark et al., 2011b), the Holocene will become increasingly accessible to the $^{40}Ar/^{39}Ar$ geochronologist, and precision and accuracy will continue to improve.

On Tristan, no spatio-temporal pattern to parasitic centre activity was found, and recent volcanism from these centres varies in style, volume and composition with time unlike recent activity from other well-dated ocean island systems. For example, the small volume tephritic eruption of Franks Hill (Fig. 3.6) on the southern flank (118 ± 4.3 ka) was followed by the eruption of larger, more evolved centres such as the basaltic trachyandesite eruption of

Hackel Hill on the southern coastal strip (29 ± 4 ka). The timing of the large-scale sector collapse in the north-west was constrained to a 14 ka window (34 ± 1 ka – 26 ± 5 ka), and dating determined that the northern sector of the edifice was built very rapidly (~50 ka; between 81 ± 10 ka and 34 ± 1 ka). It seems likely that the entire edifice was constructed piecemeal across the island and has a far more complex evolution than previously assumed. The summit was contemporaneously active with recent parasitic centre activity on the flanks and coastal strips between 81 ± 8 ka and 5.2 ± 1.1 ka. This has important implications for hazard assessment and will be further explored in Chapters 4 and 7. Holocene volcanism has occurred at a wide range of locations across the island, with no apparent alignment along regional or local tectonic features. Although the two most recent eruptions have occurred on low-lying coastal strips (1961-62 dome and flows; Stony Hill dome and flows [~200-300 years B.P.]), the new temporal framework reveals that future eruption on the flanks, or from the summit, cannot be discounted.

The content of this chapter is currently in press: Hicks, A., Barclay, J., Mark, D.F., and Loughlin, S., 2012, Tristan da Cunha: Constraining eruptive behavior using the $^{40}Ar/^{39}Ar$ dating technique: Geology.

3.10. Further research

This carefully constructed sampling strategy maximised the information obtained from just 15 ages. However, to better understand the stages of sector growth and their relation to post-edifice volcanism, a more detailed geochronology is required, including detailed sampling of multiple flows from the shield and post-shield activity at several differing locations across the island.

Although current evidence suggests that sector collapse has occurred once, subaerially, on Tristan, it is probable that the island has undergone more than one mass-wasting event during its growth, given the island's steep upper flanks, elevation, composite structure and high pore water pressure. An improvement in our understanding of submarine flank structure and sea-floor deposits would help detect other collapse phases.

The random nature of parasitic centre activity combined with varying rock compositions over time indicates that magma could be stored in small pockets within the crust. In other ocean island settings, alkali rocks fed by mantle upwellings tend to have a very deep-rooted source region, but it is possible that this source has siphoned off small pockets of magma which are independently differentiating at shallower depths (e.g., Stroncik et al., 2009). This hypothesis would have to be tested by both detailed petrological analyses, giving clues as to the location of the magma at depth, and seismic tomography which will give insight into the size, shape and location of magma reservoir(s). Other geochemical and isotopic studies could be employed to better understand fractionation trends and melt genesis. ^{238}U and ^{232}Th analyses on rock powder from the 2004 submarine phonolite (see Chapter 2) confirmed rapid fractionation (several decades to two centuries), suggesting that its source was likely to be the differentiated residue of a small body of mafic magma that had been injected into the crust, rather than the cap of a much larger body that has remained at depth (Reagan et al., 2008). In the future, similar rapid onset volcanism on Tristan itself would present a worst case scenario for the population due to their remoteness and limited evacuation options.

It would also be desirable to undertake full geological surveys of Nightingale and Inaccessible islands, and investigate any volcanological relationship with Tristan. The three islands are in markedly different erosional states and vary compositionally from each other, indicating distinct heterogeneities in the mantle, and/or differing mantle sources. It is also possible that Nightingale has undergone some kind of caldera subsidence which created a submerged plateau. Tristan is part of an exclusive group of ocean island volcanoes devoid of a caldera, thus future caldera-forming activity must be considered possible (see Section 3.8.3).

CHAPTER FOUR: Eliciting expert judgement on future eruptive scenarios

4.1. Introduction

When a volcano exhibits signs of unrest, decision makers invariably seek expert opinion concerning likely outcomes; typically in terms of size, location, style, speed of onset and duration of volcanic activity. Anticipating the timing and impact of eruptive behaviour is a fundamental goal of volcanology but, even with access to broad data sets, volcanologists continue to come up against the challenge of informing decision makers about processes and outcomes that are often highly uncertain. This uncertainty amplifies the pressure on authorities to make appropriate and timely decisions - such as declaring an evacuation - within the context of other community-based complexities, for example socio-economic requirements and vulnerability.

During the inevitable trauma accompanying volcanic crises, it is unsurprising that there have been occasions where the role and responsibility of the volcanologist in the decision making process has become blurred (e.g., Hadfield, 1993) and where a lack of scientific consensus has been made public, thus eroding trust in science (e.g., Fiske, 1984). Scientific indecision, lack of scientific rigour, and/or poor communication of uncertainty, potentially threatens lives and livelihoods. As populations continue to grow in active volcanic regions, this has driven a paradigm shift from deterministic evaluations to probabilistic modelling of the aleatory and epistemic uncertainties associated with volcanic processes, hazards and risks (Woo, 1999; Newhall and Hoblitt, 2002; Sparks and Aspinall, 2004; Baxter et al., 2008). Formalised procedures for handling uncertain information and reasoning about probabilities have since been applied and developed within a volcanological context. These include evidence based volcanology (Aspinall et al., 2003), representation of volcanic hazards as probability trees (Newhall and Hoblitt, 2002) and the application of structured expert elicitation (Aspinall and Woo, 1994).

A formalised procedure for eliciting expert judgement was first applied to volcanology in 1995 when the present eruption of Soufrière Hills commenced (Aspinall and Cooke, 1998; Aspinall, 2010). This was driven by the need to provide good advice to decision makers, and to integrate diverse opinions from experts with a variety of specialisms and experience. The application of this technique has subsequently evolved, but is still used successfully by the Scientific Advisory Committee (SAC) at the Montserrat Volcano Observatory (MVO), and for assessment of future activity at other volcanoes (e.g., Baxter et al., 2008; Martí et al., 2008a; Neri et al., 2008; Queiroz et al., 2008). The approach helps engender clarity of thought and reasoning about uncertainties, and the results provide a focal point for structured group discussion and decision making.

4.2. Expert elicitation – a brief review

Expert elicitation sensu lato has been used for a long time as a means for compensating for unreliable, or incomplete, scientific information. It is based on systematic eduction and synthesis of subjective expert judgement on an uncertain subject or question. As a useful way of making expert wisdom known (based on specialised knowledge and experience), the elicitation process also serves to drive discussion between scientists around substantial amounts of data where professional interpretation is inescapable. The use of expert judgement in decision making has been applied to numerous future scenarios, uncertain conditions or novel circumstances in a variety of sectors such as the environment, health, food and technology (e.g., Goossens et al., 2008). Drawing on expert judgement is not considered a substitute for actual research, but it can be a valuable way to effectively access knowledge when resources and time are limited. Consequently, it has rapidly become a key instrument in the risk assessment process in many fields.

Various methods for assessing and compiling expert opinion exist and they all attempt to confront the underlying challenge of how to effectively collect and integrate subjective judgements whilst minimising bias (e.g., Thurstone, 1927; Bradley and Terry, 1952; Dalkey and Helmer, 1962; Cooke, 1991; Slottje et al., 2008; Flandoli et al., 2011).

One of the earliest and most well-known methods is the Delphi procedure, created on behalf of the RAND Corporation in the 1950's as a tool for forecasting scientific and technological developments (Dalkey and Helmer, 1962). The method was designed as a way of obtaining a collective view by eliciting and refining individual expert opinion over a number of 'rounds' (Helmer, 1967). In the first round, experts are asked to answer one or two open-ended questions, the answers to which are then collated and restructured to inform a second questionnaire. Over subsequent rounds (at least three), experts review and revise their opinions in light of other expert judgements – which are made transparent by way of a median value and an inter-quartile range. Eventually, opinions converge and consensus is reached. To minimise bias from peer influence and to reduce process loss (impaired performance typical of interacting groups), experts remain anonymous from each other. However, the removal of opportunity for process gain has been suggested to reduce accountability of expressed opinions and to encourage hasty decision making (Sackman, 1975). Studies have shown that forecasts or assessments provided by the Delphi technique have been generally inferior to normal interacting groups (e.g., Riggs, 1983). Apart from being less costly to administer, the approach suffers in comparison to 'basic' mathematical aggregation, where individual opinions are elicited and combined with no follow-on process (Rowe et al., 1991). Further, Delphi has no way of appropriately treating the role that differing expert knowledge and experience plays in the decision making process. It assumes that a knowledgeable and experienced expert is also skilled at making judgements about uncertainty. Affording experts equal weight in an elicitation fails to take into account the variation between experts, and may bias results. This assumption is made by most elicitation techniques, including an innovative method developed by the US Senior Seismic Hazard Analysis Committee (SSHAC) in 1997. This technique involves each expert making their own judgement, evaluating the positions of all other experts within the group, and then integrating all the different group opinions to estimate the position of the whole informed scientific community. Not only is this extremely complex, but it is questionable whether any group of experts can truly assess the view of the whole informed scientific community on the entire range of relevant issues (National Research Council., 1997).

4.2.1. Classical model of expert elicitation

In recent years a more formalized quantitative basis for measuring uncertainty by weighting expert judgments has been developed using mathematical scoring rules to determine performance-based metrics. Known as the Classical Model (CM), 'Cooke' Method, or 'Delft' Method, this approach seeks to achieve 'rational consensus' between experts (Cooke, 1991). By pooling weighted expert opinion to create a synthetic decision maker (DM), a representative group distribution is produced. It is often the case that each individual within an expert panel will not adopt the DM result as his or her degree of belief, but will agree on the distribution. This rational consensus is seen as invaluable for decision support and encourages the creation of 'one voice', thus alleviating any ostensible indecision amongst scientists (Aspinall and Cooke, 1998)[8].

[8] The appeal for transparent handling of uncertainty in quantitative decision making support is persistent, and the CM, amongst other structured methods of obtaining and combining expert judgement provide essential tools. A special issue of Reliability Engineering and System Safety on expert judgement provides a comprehensive collection of state-of-the-art methodologies (Cooke, 2008)

The method is driven by four principles:

- Scrutability: all data and methodological procedures must be made available for peer review and results must be open and reproducible
- Fairness: the facilitator, or expert group must not presume individual competencies prior to processing results
- Neutrality: to avoid bias, experts must be encouraged to offer their true opinions
- Performance control: expert judgments are subjected to empirical controls (Cooke, 1991).

The last principle, measuring expert performance, is a critical element of the CM. While the starting point of the model is an 'a priori' presumption that all experts are of equal competence, informed and free of bias, the CM uses empirical evidence to differentiate experts from one another by means of a performance-based weighted score. The score is calculated by completion of a set of assessments (known as calibration or seed questions), to which the answers becomes known to the expert post hoc. An answer to a seed question is usually in the form of a subjective uncertainty distribution from quantiles or percentiles. For each question, experts provide a median value, an upper and lower quantile (5% and 95%). Put simply, an expert believes that there is only a 10% chance that the true solution (realization) to the seed question is higher or lower than their 'credible interval'.

Performance-based weights are calculated by two measures of competency: calibration and informativeness (Cooke and Goossens, 2008). Calibration is a measure of how much an expert's answer corresponds to 'reality', i.e. the solution to the seed question. A higher weight is offered to an expert who consistently presents an inter-quantile interval that is close to the true value, over a full set of seed questions (normally 10-15). Calibration is a 'fast' function; in that adding or removing a seed question from the set can significantly impact the calibration score for that expert. Informativeness is a measure of an expert's distribution concentration per seed question. This can only be measured relative to some other distribution; normally a uniform or log-uniform background measure is used (chosen by the analyst). As such, information scores cannot be compared across studies (Aspinall, 2011). Information scores are 'slow' in that, unlike calibration scores, removal or addition of seed questions will not noticeably alter an expert's overall score. A good expert will capture the true realization with a relatively narrow spread of uncertainty, whilst an over-opinionated expert will be penalized if his or her narrow quantiles fail to capture the true realization (Fig. 4.1.).

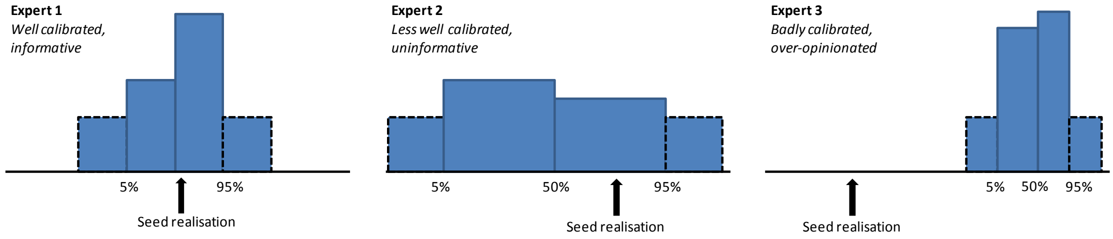


Fig. 4.1. Examples of calibrated expert responses over a set of seed questions. Expert 1 has 'good expertise' as they are well calibrated (median value close to true seed realization) and informed (narrow bounds of uncertainty). Expert 3 is not good at assessing uncertainty as they are over-opinionated and thus have not captured the seed realization within their credible interval. Adapted from Aspinall (2011).

After experts have been calibrated and given a weight, they are asked individually to offer their own opinion on several target questions. These questions are usually answered in a similar fashion to the seed questions, with a best estimate (corresponding to a median value), and a 'credible interval' of uncertainty. In order to produce a DM for each question, i.e. achieve rational consensus, expert judgements are combined by linear pooling of the weighted sums of individual distributions. At this stage, the principle of neutrality becomes important, as the method with which judgement combinations are used 'should not reward experts from giving an assessment at variance with their true opinion' (Cooke and Goossens, 1999). By applying strictly proper scoring rules, neutrality is achieved (e.g., Toda, 1963). Scoring rules assess the quality of probabilistic forecasts by assigning a real to number to an assessed distribution. A scoring rule is strictly proper if the assessor maximises his or her expected score for an observation drawn from their distribution. This encourages truthful assessments.

4.3. Heuristics and biases

Before continuing with a rationale for eliciting expert opinion on future eruptive scenarios on Tristan, it is useful to consider the role that psychology plays in individual assessments of probability and decision making.

Decision making under uncertainty is affected by the rationality of an individual. The theory of bounded rationality explains how decision makers arrive at an optimal solution after they apply rationality by constructing a simplified model of the world (Simon, 1956). The key principle is the notion of 'satisficing' – meaning that the decision maker seeks a satisfactory solution rather than the optimal one. Rationality of individuals is limited by the information they have, the cognitive limitations of their minds, and the finite amount of time they have to make decisions. It is widely understood that judgements about risk are made by employing intuitive heuristics, or mental short cuts (Tversky and Kahneman, 1973; Tversky and Kahneman, 1974; Kahneman, 2011) to find solutions to problems quickly. Heuristics are useful although they may also lead to severe and systematic errors, especially if the answer is a 'guesstimate'. Three types of heuristics that are often employed to assess and predict are 'availability', 'representativeness' and 'adjustment from an anchor'. These heuristics are blamed for inducing systematic biases such as the conjunction fallacy[9], base rate neglect[10] and mis-calibration. Judgement by representativeness assumes commonality between objects of similar appearance, or that the object belongs to a particular class, group or process. The availability heuristic is a strategy used to make an assessment of, or judgement of the probability of an event, by the ease with which that event is imagined. This is usually a reflection of the frequency that the event has occurred in memory, its familiarity or salience. The notion of availability is particularly significant in understanding our perceptions of natural hazards. Experience of the effects of particular hazards and the recency of that experience may distort perceptions. The third heuristic, anchoring and adjustment, defines a situation where judgements are influenced by a specific reference point (the anchor), normally a numerical prediction. As additional information is received, that anchor becomes adjusted to accommodate the new information. Decisions can be influenced by this anchor by either increasing, or decreasing, the judged likelihood of a particular event.

Reduction of bias can be achieved through, for example, appropriate questioning, training in probability calculus, and by employing computational aids to check assessments (Kynn, 2008). Using careful and explicit language in questions helps to reduce conjunction errors, for example, using a frequency representation or by negatively framing (e.g., 'which is least probable?') (e.g., Teigen and Brun, 1999). Improvement in calibration can be achieved through scoring and training, or a combination of the two (e.g., Savage, 1971).

[9] Conjunction fallacy is a logical fallacy that occurs when it is assumed that specific conditions are more probable than a single general one.

[10] Base rate neglect is an error that occurs when the conditional probability of hypothesis A given evidence B is assessed without taking into account the prior probability of A and the total probability of evidence B. Reasoners will tend to focus on the 'proof' provided by evidence B in order to prove or falsify hypothesis A without properly considering false positives or false negatives. Research into base rate fallacy has strongly concluded that people regularly ignore base rates when considering probabilities.

4.4. Rationale for Tristan

Unlike other well studied volcanoes where structured expert elicitations have been successfully conducted (e.g., Aspinall, 2006; Martí et al., 2008b), Tristan has a relatively poorly defined eruptive record, and little or no effective monitoring capability. Contingency measures and mitigation plans are needed for response to future eruptive activity, but the lack of baseline data presents considerable scientific uncertainty about plausible future eruptive scenarios and potential hazards.

Given this severe uncertainty, and the current inability to gather further data from the field, compiling scientific advice on future eruptive scenarios was appropriate. After conducting a needs assessment of on-island and off-island decision makers, the elicitation focussed on questions designed to responsibly inform civil contingency planning. A secondary goal of the expert elicitation was to examine the suitability and applicability of the approach in a data-impoverished setting.

4.5. Methodology

The Tristan expert elicitation was conducted via a structured protocol (CM) (Cooke and Goossens, 1999), customised for the Tristan hazard assessment problem by focussing on questions designed to inform mitigation measures. In parallel, experts were asked to conduct a paired comparison exercise. Paired comparisons were originally employed in psychology (Thurstone, 1927) and have since been used to study consumer responses (Bradley, 1953). Usually experts are invited to rank pairwise sets of alternatives according to particular criteria e.g., taste, attractiveness. A rank order is then produced. For the Tristan elicitation, experts were asked to rank particular volcanic hazards in terms of likelihood of occurrence and likelihood of impact.

Elicitations were conducted individually and in small groups in October and November 2010 among 18 UK-based[11] experts with a variety of expertise in volcanology (see Section 4.7.4). In light of the financial and time limitations of the research, a post-elicitation group discussion was not held.

[11] Four experts were elicited in Montserrat during a Scientific Advisory Committee meeting. Two were usually UK-based, two worked permanently at the Montserrat Volcano Observatory (MVO). One of the MVO-based experts was from St Vincent, the other was originally from the UK.

Details of the methodology are as follows:

Preparation

i. Case structure definition, or rationale for elicitation (see Section 4.4)
ii. Identification of target variables
iii. Identification of performance variables (seed questions)
iv. Identification and selection of experts
v. Mock elicitation

Elicitation

vi. Expert elicitation exercise (including expert training session)

Analysis

vii. Event tree analysis using Excalibur
viii. Paired comparison analysis using Unibalance

4.5.1. Preparation: identification of target variables

Firstly, variables of interest, or target variables were identified. It is known that Tristan has erupted at various locations; therefore one of the key problems to address was the likely location of the next eruption. A fundamental pre-requisite was quantifying the uncertainty around whether unrest would actually lead to an eruption.

Ten questions were designed to elicit uncertainties for three probabilistic target variables: (i) whether unrest would lead to an eruption, (ii) likely location of eruption (broad position), and (iii) likely location of eruption (defined position). These questions were devised to be answered as probabilities, rather than deterministic values, due partly to the nature of the target variables and also to facilitate communication with decision makers who were familiar with forecasting terminology. Eight further questions were constructed to obtain rank order and group uncertainty for two other target variables, i.e. the likely occurrence of particular volcanic hazards, and their likelihood of impacting the Settlement.

It is noted however, that a crucial variable of interest is timing, i.e. when will the next eruption occur? The ultimate goal of volcanological research is to better anticipate the timing of volcanic eruptions, but this is extremely challenging and requires the integration of complex suites of data across a broad range of disciplines. Given that Tristan is monitoring deficient, and that there is a general lack of understanding about the magmatic system and eruptive history, the extreme uncertainty surrounding this particular question deemed it almost impossible for experts to quantify and, as such, would serve no purpose for informing decision makers.

4.5.2. Preparation: identification of performance variables (seed questions)

To calibrate the experts in terms of their ability to quantify uncertainty, appropriate performance variables (or seed questions) were constructed. Seed questions are a major component of the structured elicitation procedure, and the most challenging element to design. Source information was selected from peer-reviewed journals and textbooks and checked carefully to ensure that models, findings and observations had not been superseded, or were widely disparate from other studies. To avoid ambiguous phrasing and terminology, advice was sought from non-elicited experts to determine any differences in understanding.

Unlike the variables of interest which were designed to quantify uncertainty as probabilities, the seed questions were to be answered with discrete values, although both sought to specify information about an expert's subjective distribution (as three quantiles). 17 seed questions were selected (Appendix 9) which is believed optimum to represent an expert's ability to quantify uncertainty (W. Aspinall; pers. comm.). In accordance with the CM protocol, experts were asked to provide a credible range of uncertainty and a central estimate of the median value. The credible range encompasses the true value with a 90% confidence, and consists of a low value or 5 percentile, and a high value or 95 percentile. Anything out of this range the expert would consider a surprise. It was explained that the credible interval need not been symmetric about the median.

While the purpose of CM is collective quantification of uncertainty, itself a form of expertise, it is possible that a well-calibrated 'expert' may be good at assessing uncertainty, but does not actually have any expertise in that particular field (see Section 4.6.2 for further discussion). Conversely, overconfident experts are poorly calibrated, yet can be leaders in their field. In an attempt to draw out possible correlations between spread of knowledge and impact on performance, the seed questions were categorised into particular fields of volcanology. Experts were asked to indicate their specific areas of expertise, which may have included one or more of the following categories: intraplate magmatism, volcano petrology, physical volcanology, volcano tectonics, volcano monitoring, degassing processes, effusive volcanism, explosive volcanism, volcanic hazards & risk, and environmental impacts of eruptions. Although it is noted that there are many more sub-fields of volcanology, the chosen ten were deemed most pertinent to the Tristan problem and experts were chosen accordingly.

4.5.3. Preparation: identification and selection of experts

As there is no quantitative measure of expertise, the selection of experts is a subjective choice by the 'problem owner'. Often experts are identified by means similar to 'snowball sampling', where colleagues suggest others which are knowledgeable within the domain of interest. Cooke and Goossens (1999) propose the following seven criteria for choosing experts: reputation in their field; experimental experience in the field of interest; number and quality of publications; diversity in background; awards; balance of views; and interest in and availability for the project. However, recent studies have questioned the efficacy of these 'traditional' measures of expertise, claiming them to be unreliable 'predictors' of accuracy in elicitations of uncertainty (Burgman et al., 2011). This will be discussed further later in the chapter.

Experts are also often selected for their familiarity with the case study in question (e.g., Krayer von Krauss et al., 2004) but, as Tristan was an unfamiliar system to volcanologists, experts were chosen because of their significant research record and experience in volcanology, their areas of expertise, and their link to a UK institution[12].

Objective selection of experts was particularly challenging. Volcanology is a relatively small scientific field with few UK-based experts; therefore every expert that fulfilled the aforementioned requirements was invited to participate. Due to financial limitations, accessing expertise from outside the UK was not possible. 36 experts were invited to participate in the elicitation, of which 18 responded positively and were happy to cooperate and share their opinions. The recommended number of experts is 8 - 10 (Cooke and Goossens, 1999) and beyond 12 - 15 experts, the benefit of adding extra opinions diminishes (W. Aspinall, pers.comm.). However, as this component of the research also sought to investigate possible correlations between calibration score and areas of expertise, eliciting 'extra' experts was favourable. The contributing experts were based at the following

[12] Except one expert, who originated from St Vincent.

institutions: University of Bristol, University of Cambridge, Lancaster University, Durham University, University of Reading and the British Geological Survey. Four experts were also elicited at the Montserrat Volcano Observatory during a workshop.

4.5.4. Elicitation: expert elicitation exercise

Prior to conducting any formal elicitations, a mock-elicitation was performed with six colleagues from the University of East Anglia. This vital step in the elicitation design encouraged candid discussion about question ambiguity, elicitation structure and timing. No expert on the 'dry run' panel was selected for the actual exercise.

Each elicitation began with a short statement of the purpose of the study and a brief training session of probabilistic tools, heuristics and biases. The experts were asked to indicate their specific area(s) of expertise and were offered an opportunity to answer and discuss an example seed question if they were unfamiliar with quantifying their degree of belief in terms of quantiles. It was explained that the elicitation results would be treated anonymously, and that experts could complete the elicitation under a pseudonym if preferred.

Following completion of the seed questions (Appendix 9), each expert was given a PowerPoint-based summary of Tristan's volcanology, eruptive history and geomorphology. This information had been collated and reviewed prior to elicitation design, and is described in depth in Chapter 2. Two exercises focussing on the variables of interest then followed. The first exercise was based around a three-stage event tree (Fig. 4.2). At stage one, experts were asked to propose quantiles for a question on unrest:

"Given unrest (earthquake swarms felt/activity seen or smelt by inhabitants at the Settlement), what is the probability (0-100, or 0-1) that an eruption would ensue?"

In accordance with the CM, the 5%, 50% and 95% quantiles were requested for each question. It was explained that, at each stage, the 50% quantiles had to sum to one (or 100%). For example, if an expert felt there was a 60% probability (their median value) that an eruption would ensue, there would have to be a 40% probability of no eruption. Their upper and lower distribution bounds did not have to sum to one, serving simply to reflect their uncertainty distribution on each value. At stage two, experts were asked to propose quantiles for a question on eruption location:

"Given an eruption, what is the probability of an eruption at each of these four locations?" (summit; flank; coastal strips and submarine)

The third and final stage required experts to provide a distribution for a question on location specifics:

"Given an eruption on the Flank or Coastal Strip, what is the probability of the eruption being proximal to the Settlement (< 2km radius), or distal (> 2km radius)?"

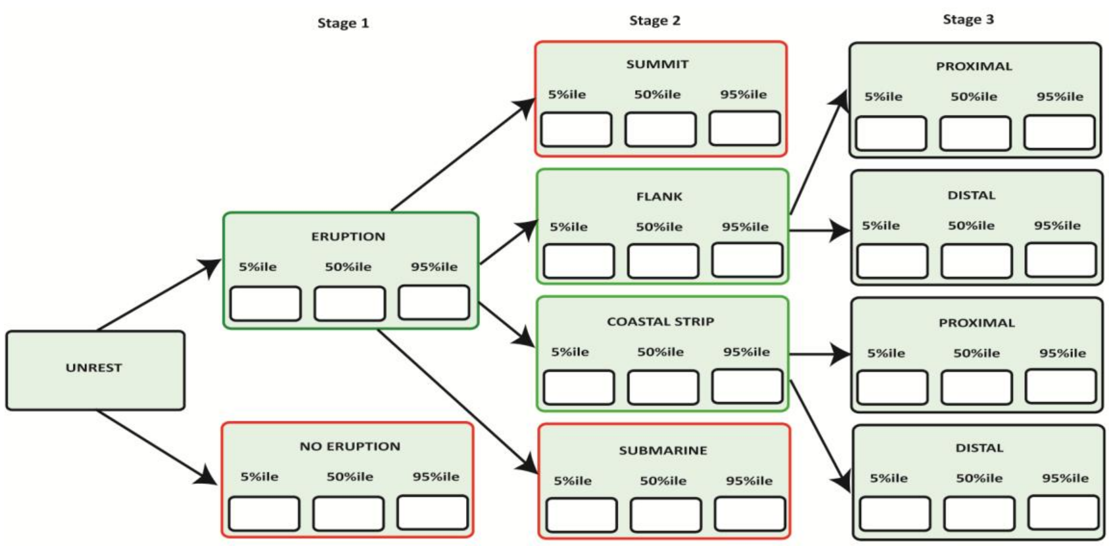


Fig. 4.2. Event tree exercise for eliciting uncertainties on probabilities for variables of interest. Stage one is composed of two branches: the probability of an eruption or no eruption in the event of unrest. Stage two is composed of four branches: the probability of an eruption occurring at the summit, on the flanks, on the coastal strips or from a submarine vent. Stage three also has four branches to indicate expert opinion of the probability of flank and coastal strip eruptions occurring proximal or distal to the Settlement. Black borders indicate starting and finishing points for this event tree, red borders indicate no successive stage, and green borders indicate that the event tree progresses to another stage.

The second task was a paired comparison exercise (Fig. 4.3). Experts were asked to rank hazard alternatives pair wise according to two criteria: the likelihood of occurrence and the impact to the Settlement of Tristan. Each expert was reminded to make *strict* preferences between each pair of items where possible, however preference equality or absence of preference could be expressed (see Section 4.5.6). For the Tristan problem, applying paired comparison was a rigorous practical and methodological way of obtaining quantitative estimates of risk-related parameters as it was more appropriate for experts to construct ranks, rather than offer point values or probabilities. Given the number of likely hazards during an eruption, it was not feasible to further populate an event tree (for example as a Stage 4, Fig. 4.2), a) due to the size of the dataset, and b) due to the analytical program requiring all 50 percentiles to sum to one (or 100%). Hazards associated with volcanic eruptions are often equally likely to occur and thus could not be analysed in this way.

Nine hazards were chosen (Fig. 4.3), so 36 comparisons were made for each of the two criterion. Experts were asked to rank using 'less than', 'more than', or 'equal to', symbols. The paired comparison was conducted for four different locations on Tristan: the summit, flanks, coastal strips, and submarine. 288 comparisons were made in total by each expert. The results were processed by probabilistic inversion to distil rank order from the data and make an assessment of expert agreement (see Section 4.5.3).

	tephra	ballistics	gas	lava flow	base surge	PDC	lahar	earthquake	rockfall/ landslide
tephra									
ballistics									
gas									
lava flow									
base surge									
PDC									
lahar									
earthquake									
rockfall/ landslide									

Fig. 4.3. Paired comparison exercise for ranking volcanic hazards. Experts were asked to rank nine hazards pairwise according to likelihood of occurrence and likelihood of impact to the Settlement.

Following the procedure, elicitees were asked to share their opinions about the elicitation process in general, and some were asked what they considered the worst case scenario for Tristan, in the context of future volcanic activity. Each elicitation took between 90 minutes to three hours, depending on the nature and number of questions raised by the elicitee.

Unlike elicitation exercises undertaken by the SAC in Montserrat, there was no qualitative discussion between experts following the elicitation, due to the time and financial restrictions. However, this eliminated the possibility of particular expert dominancy, and offered an opportunity to explore the method and test the value of the elicitation approach without group discussion. This will be considered further in Section 4.6.5.

4.5.5. Analysis: event tree analysis using Excalibur

Data from the seed questions and event tree exercise were analysed using Excalibur software. This software (Excalibur v.1.0 Pro) was designed originally by a team at TU Delft for combining expert probability assessments (Cooke and Solomatine, 1990).

The Excalibur software enables the analyst to control particular parameters (Fig. 4.4), allowing adjustments to be made to weighting schemes, calibration power and significance limits. The global weighting scheme assesses expert performance over all seed questions. The item weights analysis examines seed questions individually and calculates a weight per expert, per question. Equal weights refer to the assignment of equal weights to each expert, and user weights are assigned by the user. Calibration power can be selected from the interval 0.1 - 1.0, and determines the effective number of samples. The power of a statistical test is its ability to distinguish between rival hypotheses, and increases with the number of independent samples. For example, opting for a 50% calibration power would reduce the resolution of the significance test to that of a test with half the number of samples. The significance level determines the calibration threshold value. Calibration scores greater or equal to the significance level correspond to non-rejected statistical hypotheses. The significance testing entails that the weights become zero whenever the calibration score is strictly less than the significance level.

The parameters chosen for the Tristan analysis ensured the strictest mathematical scoring, with a calibration power of one and a significance level of zero. This would mean that no expert would receive a calibration score of zero; thus all views would be part of the decision process.

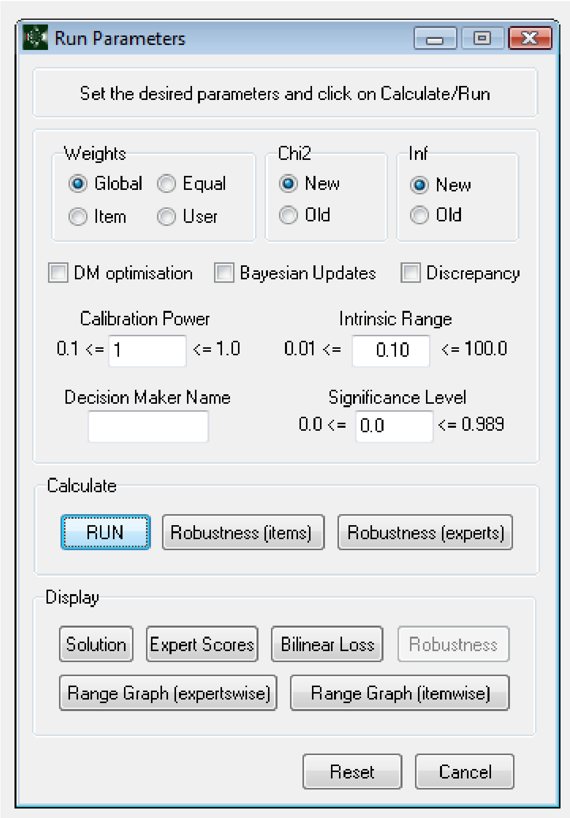


Fig. 4.4. Model parameter window in Excalibur. This panel allows the analyst to perform setting adjustments to modify analyses as required.

4.5.6. Analysis: paired comparison analysis using Unibalance

Data from the paired comparison exercise were analysed using Unibalance software. Also developed by TU Delft, Unibalance models expert preferences and calculates scale values for the objects being compared (Macutkiewicz, 2006). The software employs three models for analyses: the Bradley-Terry Model, Thurstone Model(s); the Probabilistic Inversion Models based on Iterative Proportional Fitting (IPF); and the Parameter Fitting for Uncertain Models (PARFUM) algorithms. It was most appropriate to apply the PARFUM algorithm to the Tristan paired comparison data. Due to fitting ‘infeasibility’ in some problems, the PARFUM algorithm cyclically adapts the starting distribution to each constraint and then averages the distributions to form an iteration. Several iterations are required to converge the algorithm. The other models are not relevant to the analyses and no further discussion will be presented.

Probabilistic inversion represents the process of inverting a function at a set of distributions, and estimates the joint distribution of scores by all combined experts. The method requires rank order inputs rather than precise quantifications, then mathematically identifies the quantitative scoring rule that fits the stated rank orderings of the various experts as well as possible, taking into account areas of expert consensus versus disagreement. The principle of probabilistic inversion can be illustrated by considering a function Y = G(X), where both X and Y may be vectors and G does not have a closed-form inverse. For example X may be a vector of target attributes (e.g., population; economic value) and Y may be a vector of target attractiveness. Experts are asked to provide rank orderings of Y at a number of different values of X, then weights are inferred for the various attributes in the vector X, so that Y values calculated from the weighted X values best match the rank orderings of Y provided by the experts (Kurowicka and Cooke, 2006; Kurowicka et al., 2010).

At the data input stage, expert rankings were entered into a matrix for each set of rankings (i.e. summit – impact, coastal strip – occurrence, etc), (Fig. 4.5). A summary of all expert rankings is presented as a preference matrix (Fig. 4.6).

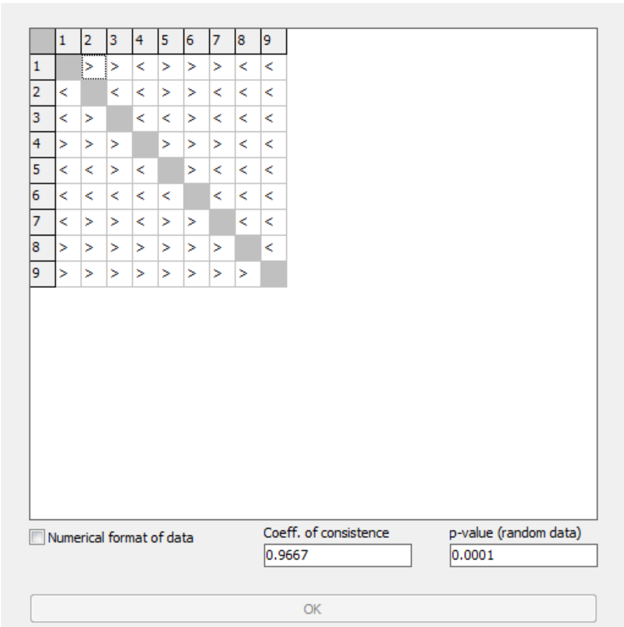


Fig. 4.5. Example of matrix displaying expert preferences for the likelihood of nine volcanic hazards impacting the Settlement from an eruption on the Coastal Strip. Note that the p-value is below 0.05 thus the hypothesis that the expert specified his/her preferences randomly can be rejected. Further, the coefficient of consistence reflects very minor inconsistencies in this expert's ranking.

Often, expert preferences display circular triads, i.e. for items a, b, c, if a > b, b > c and c > a. The presence of circular triads may indicate that expert preferences are being drawn at random, or that the items are indistinguishable. Simple tests can be performed to test the hypothesis that the expert specifies their preference randomly. The p-value represents the probability that the hypothesis of randomness is true. The threshold is set at 0.05 (confidence level). If the p-value is ≥ 0.05, it might be desirable to exclude the expert from the analysis. The coefficient of consistence (ζ) is another parameter which provides information about the presence of circular triads. If it reaches the maximum of one, there are no inconsistencies in the data. The value decreases as the number of circular triads increases.

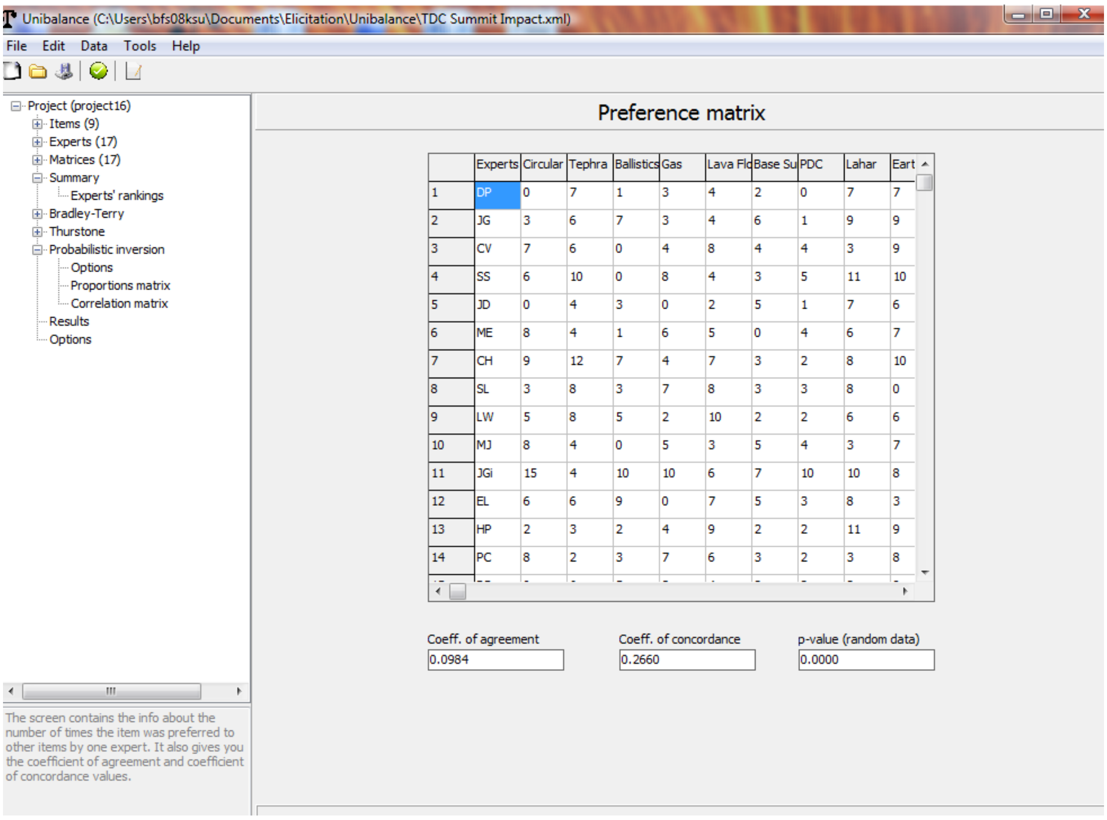


Fig. 4.6. Preference matrix of all experts for the impact on the Settlement of nine hazards in the event of a summit eruption. The coefficient of agreement provides information about the degree of similarity between expert answers. If all experts agree, the coefficient should be one, if they completely disagree in preference, it should be zero. The coefficient of concordance provides similar information than the coefficient of agreement, but uses different parameters.

By simulating the results using probabilistic inversion based on the PARFUM algorithm, increasing the number of samples and maximising the number of iterations (Fig. 4.7), the algorithm eventually converged. The results from the analyses are displayed as scores with a standard deviation (Fig. 4.8).

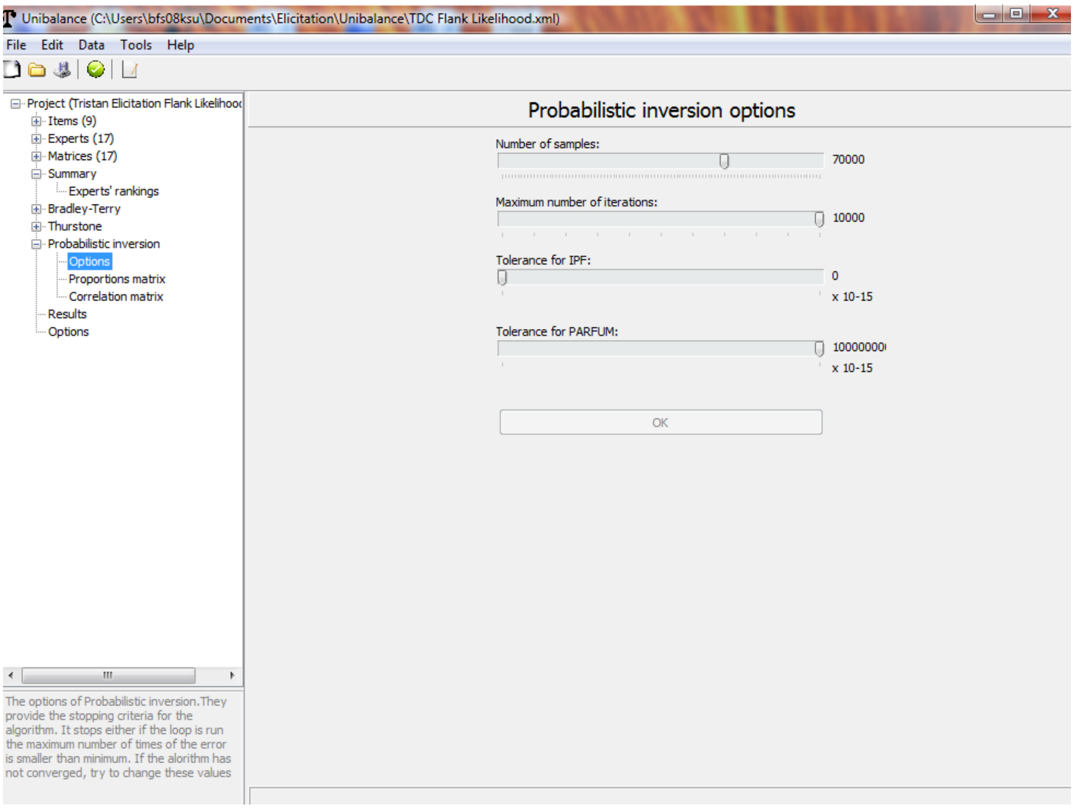


Fig. 4.7. Probabilistic inversion options for the paired comparison analysis. In order for the algorithm to converge, a large number of samples (70000) and the maximum number of iterations (10000) were toggled. The PARFUM rather than the IPF algorithm was used which cyclically adapts the starting distribution to each constraint and then averages the distributions to form an iteration.

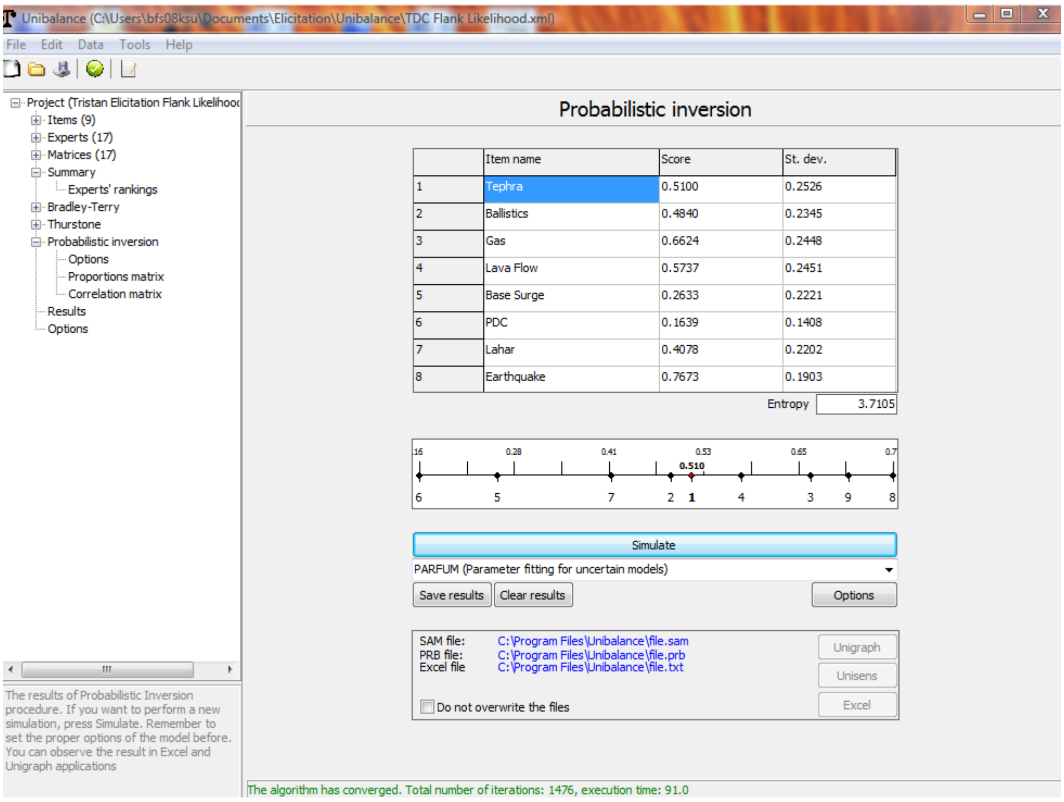


Fig. 4.8. Probabilistic inversion results for the hazard scores in terms of the likelihood of impact to the Settlement in the event of a flank eruption. Higher scores denote collective expert opinion of a higher likelihood of impact to the Settlement. Standard deviation informs the analyst of the variance of expert judgement. The scale marks the scores of each item (hazard) selected in the grid. The total number of iterations required to converge the PARFUM algorithm (1476) are shown in green at the base of the figure.

4.6. Results and interpretation

Results from both exercises (event tree and paired comparison) reveal that all experts consent to a highly uncertain eruptive future for Tristan. The event tree task produced instructive median probabilities, but very wide spreads of uncertainty at each node. It is possible that the associated spread of uncertainty is too considerable to justify this approach as a useful tool for decision making on-island. The paired comparison exercise, aimed at establishing relative probabilities of potential hazards, successfully produced expert rankings for hazards, and differences in the impact and occurrence of hazards were expressed at each location. The effectiveness of the paired comparison exercise for anticipating hazards from future eruptive activity, as well as its suitability as a communication device to diverse stakeholders will be discussed.

4.6.1. Seed questions

Before presenting results from the event tree exercise, it is vital to summarise the results from the seed questions. The full set of results, per question and per expert, are presented as range graphs located in Appendix 10 and 11. Range graphs are a useful way to easily and rapidly examine expert opinion and review how they assess uncertainty. Examples are presented in Figures 4.9 and 4.10. In Figure 4.9, all 18 expert assessments for seed question three are shown. For this question, expert credible intervals range from 0.1 to 5000 (the true realization was 122), and 8 out of 18 experts captured this true realization within their bounds of uncertainty. Experts 1 and 5, in this case, were over-opinionated (missed true realization) and experts 3, 11, and 16 were unsure of the answer and gave wide bounds of uncertainty, albeit still managing to capture the true realization. Expert 10 was sure of the answer, providing a median value that reflected the true realization with very narrow bounds of uncertainty. Figure 4.10 presents all seed question answers from expert 14. Overall, expert 14 showed a very good level of expertise (well calibrated; informative) and captured the true realization on all but two of the seed questions (questions 14 and 17).

Calibration and informativeness scores for all experts are presented in Figure 4.11. This plot suggests a modest (negative) linear trend between informativeness and calibration and, although perhaps surprising, illustrates an important aspect of expert judgement under uncertainty, only revealed by the CM approach. Full expert weighting data are shown in Figure 4.12, and the resultant DM solution for the target variables are shown in Figure 4.13.

```
Item no.:   3
Item name: Laki SO2
Scale: LOG

Experts
  1                                                     [*-]
  2                                             [---*---------------]
  3                 [-------------------------------*---------------]
  4                                 [---------------*-----------]
  5 [------*---]
  6             [-------------*--]
  7                 [---------------*---------------]
  8                                      [---------*-----]
  9                                 [-----------*---]
 10                                                  []
 11     [---------------------------*---------------]
 12                             [-------------------*-----------]
 13                                                      [----------*----]
 14                                      [--------*----]
 15                                 [---------------*---------------]
 16                        [--------------------*------------------------------]
 17                                 [------*----]
 18                         [---------*------]
DMaker 1                     [======================*===================]
Real::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::
                                                      122

    0.1                                                                    5000
```

Fig. 4.9. Range graph showing expert responses (created in Excalibur) for question 3 from the seed question group. Spread of uncertainty is reflected in the length of the bar (experts had spreads between 0.1 and 5000). Experts' 50 percentile is marked as a star. The true realization (#) is at the bottom of the range graph. The decision maker (DM) was calculated by applying global weights.

```
Expert no. :   14     Expert name:  14
Items
  1(U)         [--------*-----------]
Real   :::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::
  2(U)    [-----*-------]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
  3(L)                                     [-------*----]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::
  4(L)                                           [-*--]
Real   :::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::
  5(U)                                       [-----------*---------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::
  6(U)  [---------*-----------]
Real   :::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::
  7(L)                            [--------------------*---------]
Real   ::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::
  8(L)                                        [-----------*-------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::
  9(L)           [---*----]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::
 10(L)     [------*----]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
 11(L)                              [--------*-----]
Real   :::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::
 12(L)              [-----------*---------------------------------]
Real   :::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::
 13(L)                           [-----------------*---------------]
Real   :::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::
 14(U)         [-*--]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
 15(L)           [---------*------]
Real   :::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::
 16(L)                            [-------------------------*----------]
Real   :::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::
 17(U) [-*---]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
```

Fig. 4.10. Range graph (created in Excalibur) for all seed questions answered by expert 14. Spread of uncertainty is reflected in the length of the bar and the 50 percentile is marked (*). The true realization (#) for each question is shown beneath the bar.

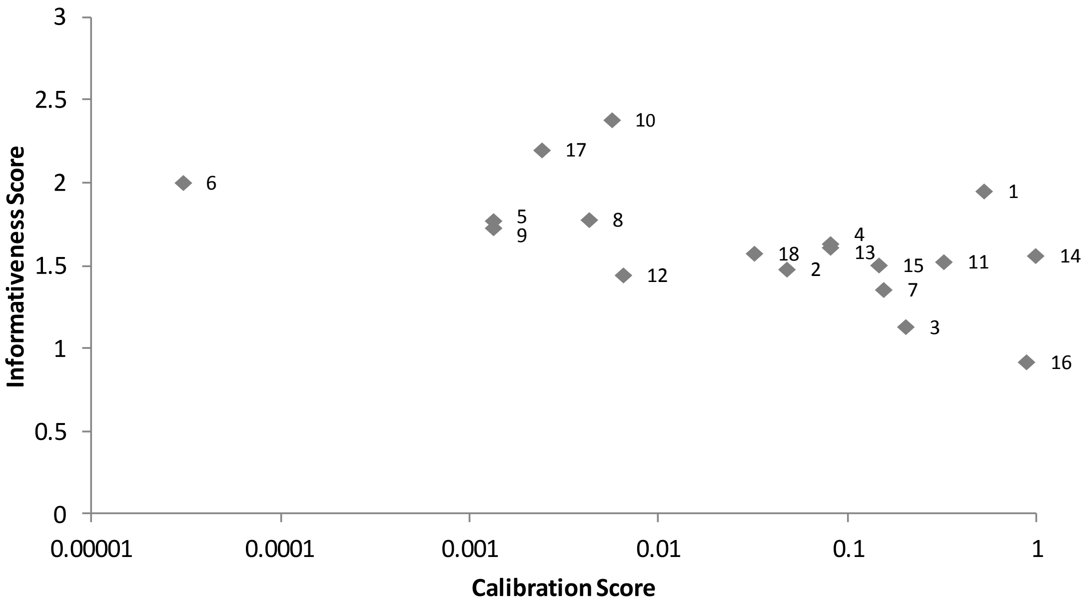


Fig. 4.11. Informativeness and calibration scores for 18 experts. An expert's informativeness score relates to the measure of his or her distribution concentration per seed question. The wider the distribution (i.e. the more uncertain the expert is), the lower the informativeness score. The calibration score is a measure of how much an expert's answer corresponds to 'reality', i.e. the solution to the seed question. A higher weight is offered to an expert who consistently presents an inter-quantile interval that is close to the true value, over a full set of seed questions (normally 10-15). In this graph, for clarity, a log scale has been applied and the calibration power has been reduced from 1 to 0.4. Note that it is possible to have a relatively good informativeness but low calibration (e.g. experts 17 and 10), which ultimately affects experts' overall weighting.

Results of scoring experts
Bayesian Updates: no   Weights: global   DM Optimisation: no
Significance Level: 0   Calibration Power: 1

Nr.	Id	Calibr.	Mean relative total	Mean relative realization	Numb real	UnNormalized weight	Normaliz.weight without DM	Normaliz.weight with DM
1	1	0.139	1.382	1.645	17	0.2286	0.1171	0.1079
2	2	0.0001924	1.078	1.179	17	0.0002268	0.0001161	0.0001071
3	3	0.00952	0.7999	0.8382	17	0.00798	0.004086	0.003768
4	4	0.0007936	1.053	1.329	17	0.001054	0.0005399	0.0004978
5	5	1.686E-008	1.335	1.469	17	2.477E-008	1.268E-008	1.169E-008
6	6	1.019E-012	1.516	1.733	17	1.766E-012	9.043E-013	8.338E-013
7	7	0.004553	0.8421	1.058	17	0.004815	0.002466	0.002273
8	8	3.468E-007	1.069	1.474	17	5.112E-007	2.618E-007	2.414E-007
9	9	1.686E-008	1.258	1.426	17	2.404E-008	1.231E-008	1.135E-008
10	10	7.157E-007	1.784	2.074	17	1.485E-006	7.602E-007	7.009E-007
11	11	0.03438	1.097	1.222	17	0.04202	0.02152	0.01984
12	12	1.023E-006	1.07	1.15	17	1.177E-006	6.026E-007	5.556E-007
13	13	0.0007936	1.217	1.307	17	0.001037	0.0005309	0.0004895
14	14	0.989	1.085	1.256	17	1.242	0.636	0.5864
15	15	0.003897	0.9601	1.207	17	0.004704	0.002409	0.002221
16	16	0.6715	0.5449	0.626	17	0.4204	0.2152	0.1985
17	17	7.782E-008	1.34	1.892	17	1.472E-007	7.539E-008	6.951E-008
18	18	6.735E-005	0.9927	1.272	17	8.565E-005	4.386E-005	4.044E-005
19	DMaker 1	0.3029	0.4648	0.5455	17	0.1652		0.078

Fig. 4.12. Calibration, informativeness and weight data for 18 experts. A decision maker (DM) is created from the weighted combination of the experts' assessments.

18	Eruption	UNI	3.416	56.67	89.58
19	No eruption	UNI	9.411	42.89	96.16
20	Summit	UNI	2.031	17.6	54.89
21	Flank	UNI	8.803	23.35	79.01
22	Coastal Strip	UNI	4.741	37.82	79.22
23	Submarine	UNI	5.071	21.83	84.23
24	Proximal Flank	UNI	0.2646	11.21	47.04
25	Distal Flank	UNI	53.08	90.51	99.77
26	Proximal CS	UNI	4.103	38.75	81.86
27	Distal CS	UNI	15.03	60.89	96.7

Fig. 4.13. DM 'solution' for target questions from event tree. The three columns of numbers refer to the 5 percentile, 50 percentile and 95 percentile.

Following all elicitations, three of the seed questions were omitted from the final analysis as experts considered the phrasing to be ambiguous (questions 9, 12 and 16). A new DM and solution was calculated (Figs. 4.14 and 4.15).

Results of scoring experts
Bayesian Updates: no Weights: global DM Optimisation: no
Significance Level: 0 Calibration Power: 1

Nr.	Id	Calibr.	Mean relative total	Mean relative realization	Numb real	UnNormalized weight	Normaliz.weigl without DM	Normaliz.weig with DM
1	1	0.1435	1.434	1.792	14	0.257	0.1283	0.1204
2	2	0.002202	1.068	1.183	14	0.002604	0.0013	0.00122
3	3	0.07235	0.7842	0.8195	14	0.05929	0.02959	0.02777
4	4	5.385E-005	1.08	1.433	14	7.717E-005	3.851E-005	3.614E-005
5	5	3.601E-008	1.358	1.537	14	5.533E-008	2.762E-008	2.592E-008
6	6	2.943E-010	1.458	1.679	14	4.942E-010	2.467E-010	2.315E-010
7	7	0.003316	0.8224	1.07	14	0.003549	0.001771	0.001662
8	8	8.296E-006	1.057	1.541	14	1.278E-005	6.38E-006	5.987E-006
9	9	2.943E-010	1.314	1.557	14	4.583E-010	2.287E-010	2.147E-010
10	10	0.0001566	1.811	2.184	14	0.000342	0.0001707	0.0001602
11	11	0.009843	1.134	1.313	14	0.01292	0.006451	0.006054
12	12	1.23E-005	1.041	1.117	14	1.374E-005	6.858E-006	6.435E-006
13	13	0.001261	1.233	1.354	14	0.001707	0.0008519	0.0007995
14	14	0.8985	1.107	1.331	14	1.196	0.5969	0.5601
15	15	0.08058	0.9579	1.256	14	0.1012	0.05051	0.0474
16	16	0.5691	0.5472	0.6474	14	0.3684	0.1839	0.1726
17	17	7.755E-007	1.322	1.98	14	1.536E-006	7.665E-007	7.193E-007
18	18	0.000362	0.9601	1.276	14	0.0004618	0.0002305	0.0002163
19	DMaker 2	0.2498	0.4295	0.526	14	0.1314		0.06154
20	DMaker 1	0.3029	0.4648	0.5455	17	0.1652		0.078

Fig. 4.14. Re-calculated DM after removal of three seed questions.

15	Eruption	UNI	3.77	55.33	89.53
16	No eruption	UNI	10.05	44.5	95.96
17	Summit	UNI	1.709	16.85	53.33
18	Flank	UNI	6.351	23.55	78.51
19	Coastal Strip	UNI	4.99	38.15	82.6
20	Submarine	UNI	4.333	21.11	82.98
21	Proximal Flank	UNI	0.2645	10.81	46.43
22	Distal Flank	UNI	26.37	89.24	99.74
23	Proximal CS	UNI	4.573	39.96	82.7
24	Distal CS	UNI	13.2	58.83	96.02

Fig. 4.15. Re-calculated DM solution after removal of 3 seed questions. The three columns of numbers refer to the 5 percentile, 50 percentile and 95 percentile.

4.6.2. Event Tree

The DM solution in Figure 4.15 is presented as an event tree with triangular distributions (Fig. 4.16). The DM median values show that experts consider there to be a 55% chance of an eruption in the event of unrest (earthquake swarms felt/activity seen or smelt by inhabitants at the Settlement) on Tristan. If an eruption ensued, the DM suggests that it is most likely to occur on one of the two coastal strips. The location accorded the lowest probability of eruption was the summit. In the event of an eruption on the flank or coastal strip, the DM shows the probability of eruption proximal (< 2 km) to the Settlement is less than a distal eruption (> 2 km). However, at almost every node, the spread of uncertainty around the median value is very large (between 73-86%). For only two events does the DM show a relatively low upper bound of uncertainty and a relatively narrow spread of uncertainty (summit eruption [51% spread and 53% upper bound] and proximal flank eruption [45.7% spread and 46% upper bound]).

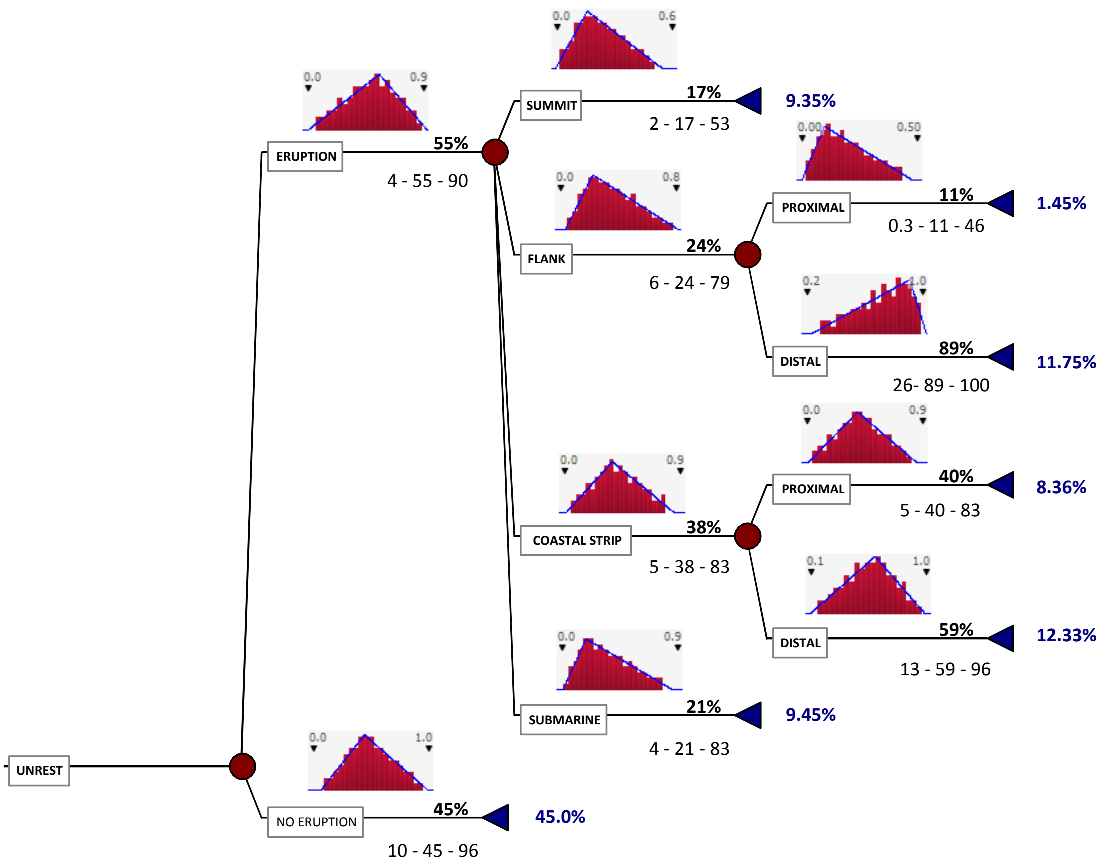


Fig. 4.16. Event tree presenting pooled expert opinion on the probability of eruption (or no eruption) following unrest and the probability of eruption at each of four broad locations and four defined locations. At each node, the median value (50%ile) is displayed above the line, along with a triangular distribution of all values (5%ile; 50%ile; 95%ile), which are also shown below the line. Overall probabilities for each event are shown at the end of each branch.

Excluding the credible intervals of uncertainty, the 50% quantiles are informative and indicate clear preference for likely locations of volcanic activity in the event of an eruption. However, this data alone does not provide an absolute account of expert opinion. The severe uncertainty associated with most nodes reflects expert perception of the degree to which uncertainty must affect attempts to forecast complex volcanic processes, timing and impact. In light of insufficient information about the volcano, these results illustrate that uncertainty of the fundamental processes that drive the risk are so large that a quantitative estimate only leads to obfuscation. Accurate forecasting would be unattainable. Nonetheless, it is noted that these probabilities are conditional on the present quiescent state of the volcano. In the event of unrest, possible acquisition of seismic data (however limited), observations and records of change may reduce expert uncertainty and improve the ability to better anticipate the timing, location and style of activity.

Regardless, expert opinions from this study further demonstrate the importance of quantifying uncertainty, and illustrate the vital role that effective communication of this uncertainty has in the decision making process (see Chapter 7).

4.6.3. Paired comparison

Despite the lack of monitoring data, experts did have access to field observations, geological maps and knowledge from analogue volcanoes which allowed them to pass judgement on the likely physical properties of eruptions on Tristan. Due to the range of possible volcanic hazards, too complex to be populated as probabilities in an event tree, a paired comparison exercise was conducted.

Results from the paired comparison exercise yielded clear expert preference for the occurrence and impact of particular hazards at each of four broad locations on Tristan: the summit, flank, coastal strip and submarine environment (Fig. 4.17). The experts considered rockfalls to most likely impact the Settlement from an eruption at the summit, although this was the hazard with the largest variance. Earthquakes were deemed most likely to occur in the event of an eruption at any location. In all but the submarine environment (where lahars would not occur and were thus ranked lower), experts were in agreement (narrow variance) that the hazard least likely to occur would be pyroclastic density currents. They also felt that this hazard was least likely to impact the Settlement. Irregularities in ranking position are seen in the likelihood of impact and occurrence of a lava flow on the coastal strip, where it is ranked higher for both impact and occurrence than at any other location, and most probable to impact the Settlement above all other hazards. Ballistics and gas occupy a mid-ranking position for all locations, except the likelihood of impact to the Settlement in the event of a summit eruption, where they are ranked lower than other hazards. Conversely, lahars are ranked third highest in terms of impact from a summit eruption (after rockfalls and earthquakes). Base surges from a submarine eruption are afforded a higher ranking for both likelihood of occurrence and impact to the Settlement than at any other location.

This exercise was useful in rapidly obtaining expert opinion on the impact and occurrence of volcanic hazards in the event of an eruption. As a group, the experts were relatively coherent in their response and there was little variance for each hazard ranking. In an attempt to reduce ambiguity in phrasing, the task was kept simple, but it was limited. In providing a rank order of hazards, experts express a preference for impact and occurrence. However, during a volcanic eruption it may be the case that, for example, gas output, earthquakes and lava flows all occur simultaneously. Similarly, both pyroclastic flows and gas may impact the Settlement in the event of a summit eruption, but the former is likely to have considerably higher impact than gas output - this exercise did not account for magnitude or degree of impact. Experts were sometimes unsure how to rank redundant hazards (some hazards would not have occurred at particular eruption locations). However, these would have been consistently ranked lowest so, for comparative purposes, have not been removed from the analysis. Future application of paired comparison may be more appropriate to comparing options such as ranking possible triggers, speed of onset etc.

In addition to speed of execution, one of the distinct advantages of the exercise was the application of ellipse plots as an effective communication tool (Fig. 4.17). The initiation of any risk reduction activities on Tristan cannot be wholly, or even partially, ascribed to the representation of the data itself. However, the plots provided a useful framework with which to inform and discuss different hazards and their properties with the Tristan Island Council, and prompted a discussion about how these hazards might be mitigated. This is discussed in more depth in Chapter 7.

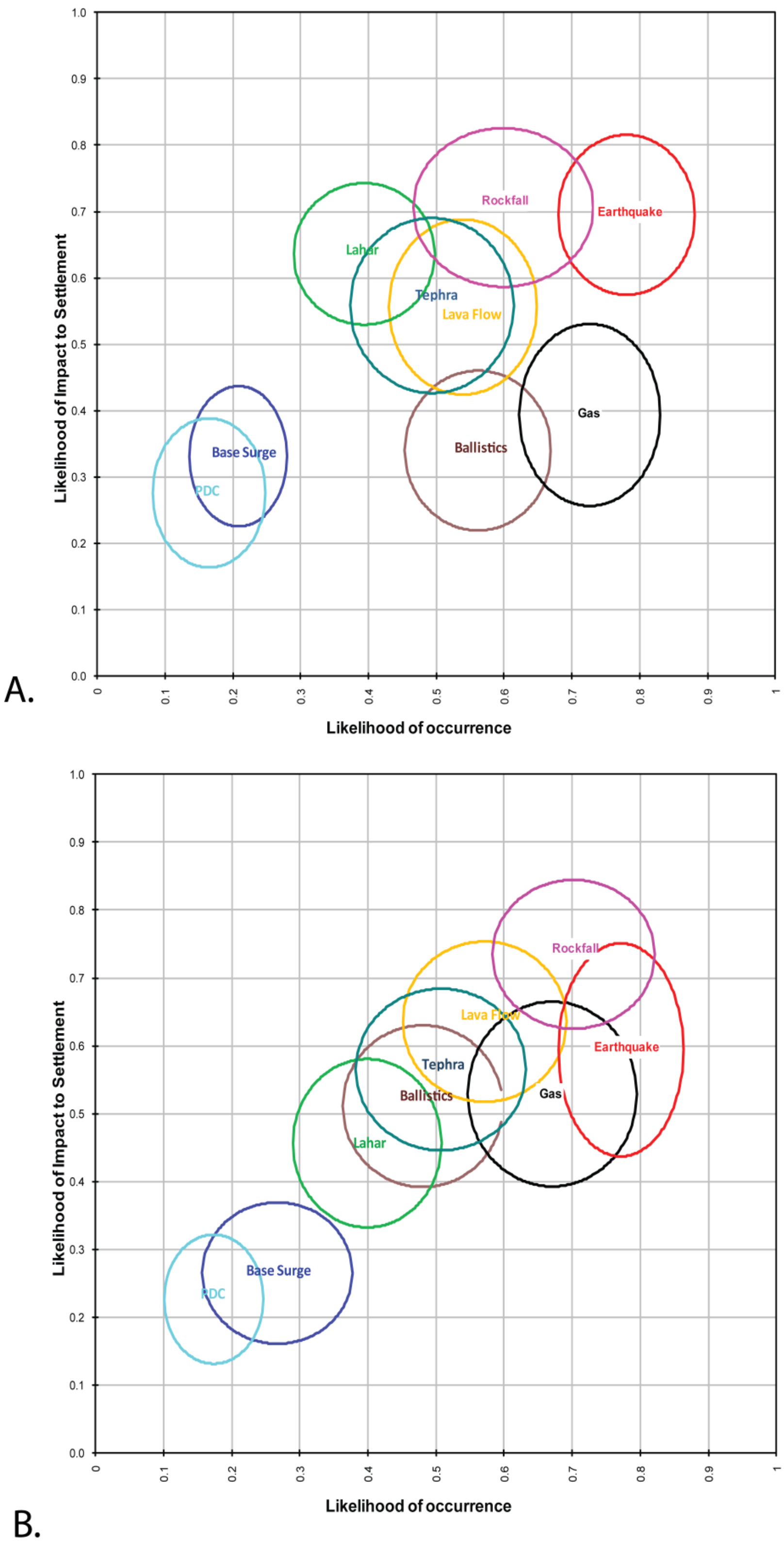
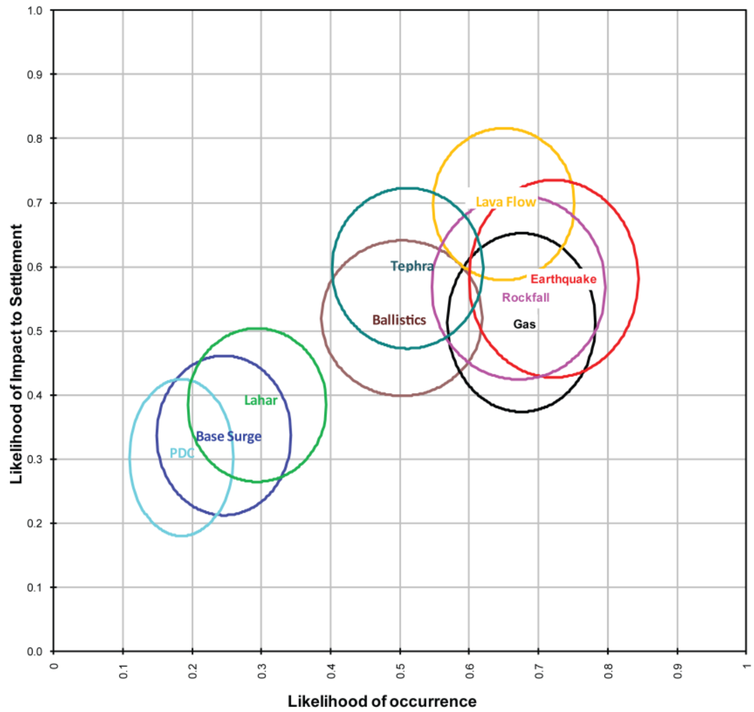


Fig. 4.17. Ellipse plots of nine volcanic hazards, ranked in terms of likelihood of occurrence and likelihood of impact to the Settlement. Width and height of ellipses refers to variance of expert judgement. **A:** Hazards ranked in terms of likelihood of occurrence and likelihood of impact given an eruption at the summit. **B:** Hazards ranked in terms of likelihood of occurrence and likelihood of impact given an eruption on the flanks of the volcano.



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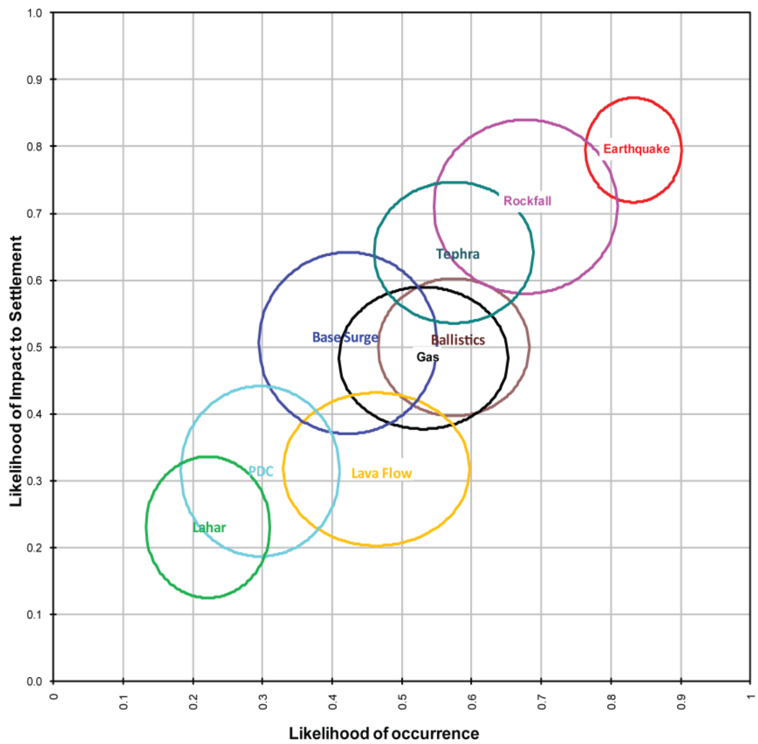


D.

Fig. 4.17 (cont'd). **C:** Hazards ranked in terms of likelihood of occurrence and likelihood of impact given an eruption on the coastal strips. **D:** Hazards ranked in terms of likelihood of occurrence and likelihood of impact given an eruption from a submarine vent.

4.6.4. Worst case scenarios

During several individual elicitations, experts were asked to state their opinion of a plausible worst case eruptive scenario for Tristan. Two experts considered Tristan's worst case scenario to be a sector collapse, ultimately resulting in a tsunami affecting the Settlement. Two experts deemed the worst case scenario to be flank eruptions proximal to the Settlement, or a summit eruption with voluminous outpourings of lava which occurs at night with no felt seismic precursory activity. One expert suggested that dome forming eruptions of evolved lava from the 1961 eruption and the penultimate Stony Hill eruption may signal precursory activity for caldera formation (see Chapter 3 for further discussion of this scenario). This information was vital to realize prior to the workshop with the Island Council. Although often challenging to visualise, consideration of extreme scenarios is imperative for development of a comprehensive range of mitigative strategies.

4.6.5. Establishing consensus without discussion

Group discourse is considered an essential extension of the elicitation process, sensu lato, and interpretations of results as part of a wider deliberative process with all elicitation participants, and better still, with all stakeholders. However, despite using DM probabilities (or values) as a focal point for deliberation (in an elicitation context), group discussions are still prone to the biasing effects of influential or dominant experts. Peer expectations of performance are often defined by qualification, track records and experience (e.g., Collins and Evans, 2007), but studies have shown that these criteria are, in fact, poor guides to the performance of experts under the CM procedure (Burgman et al., 2011). Vociferous experts, with perceived high status, can suppress the views of others, or even act to alter opinions, especially if theirs are pronounced with certitude.

Due to time and financial constraints of this research, a group discussion with all elicitees was not conducted. In assessing the associated advantages rather than disadvantages, it is possible that wide spreads of uncertainty shown in the CM results may have been suppressed during group discussion. Further, exclusion of further dialogue did create an opportunity to study the degree of consensus without it.

4.6.6. More data, less uncertainty?

In light of new geochronological data which improved knowledge of the eruptive history of Tristan (see Chapter 3), seven of the original experts were invited to participate in a re-elicitation. One of the fundamental conclusions from the new geochronology was the finding that volcanic activity at the summit overlapped in time with recent activity on the flanks and coastal strips. Given that this information could potentially alter expert opinion on likely location of the next eruption, this presented an interesting opportunity to compare results. After a brief review of the Tristan background information, the new data were presented to the group. As individual experts began to consider their opinions, a discussion was triggered and it rapidly became apparent that many experts became more uncertain about future eruptive scenarios. The attempt at a re-elicitation was abandoned, on the premise that heightened uncertainty would not be of further value to decision makers on Tristan. In hindsight, a re-elicitation would have provided interesting methodological insights and useful examination of the benefit, or detriment, of further data to decision making.

4.7. Discussion

The goal of this expert elicitation was to quantify the uncertainty around the location of a future eruption and to establish relative rank order (in terms of impact and occurrence) of potential hazards. A secondary goal was to examine the suitability of expert elicitation (and the CM) for informing a hazard assessment, and as a communication device to diverse stakeholders.

Examination of the CM focused on the performance-based weighting of expert opinion, via seed questions, and an analysis of the degree of consensus that emerges between experts in the absence of group discussion (normally a 'sine qua non' for an elicitation). Further, to explore how well the experts' calibrations correlated with particular specialisms, scores were filtered through each 'area of expertise'.

4.7.1. Expert feedback

Post-elicitation, a discussion was held with many experts to review the elicitation process. All experts found it challenging to provide quantitative estimates for most branches of the event tree due to insufficient evidence on which to base estimates. Not having visited the volcano was considered to be a severe obstacle. The purpose of the paired comparison exercise was unclear for some experts, conveying discomfort at ranking hazards redundant to the analysis (i.e. lahars would not occur during a submarine eruption). For those experts unfamiliar with the Classical Model, answering the seed questions was particularly difficult, and experts occasionally expressed defiance around ambiguities in question phrasing. During this stage of the process, the circumstances and settings of the elicitations appeared to have an effect on the experts. Those that were elicited individually occasionally asked for clarity with particular seed questions that seemed ambiguous, however some experts that were elicited in small groups chose to discuss ambiguities amongst themselves despite the request to conceal seed questions responses from one another. Whilst actual answers were not shared, occasionally experts (in groups) would deliberate approximate values. However, these discussions were rare and were usually ignited when particular questions were deemed unfavourable. Questions which almost all experts considered ambiguous were removed from the analysis (see Section 4.6.1). Despite being warned about potential bias from applying heuristics, experts often drew on experience when answering the seed questions. This is challenging to avoid as volcanologists normally use observations of past and current activity, and assume that the future will mimic the past, or follow a present trend (Newhall and Hoblitt, 2002). Given the central role of the calibration process in the CM, a comprehensive investigation of the process was undertaken.

4.7.2. Who is an expert? Some problems with calibration

To recap, the CM quantifies expert scores on the basis of two empirically determined measures: calibration (a measure of statistical accuracy reflected in the degree to which expert distributions deviate from the seed question realization) and informativeness (capacity to provide concentrated distributions over variables). From analysis of seed question performance, it was clear that several experts were systematically failing to encompass the true realization values due to understated credible intervals, often attributed to overconfidence. Overconfidence is common in expert elicitations and research has shown that overconfidence increases with, for example, an increase in information availability; increases in the difficulty of questions; lack of regular feedback and the influence of an expert’s particular cognitive style (Speirs-Bridge et al., 2010 and references therein). Whilst inaccurate overconfidence is an undesirable feature of experts, and methods have been proposed which seek to reduce it (Speirs-Bridge et al., 2010; Burgman et al., 2011), the apparent overconfidence of experts in the Tristan elicitation was demonstrated by the CM calibration process, which penalizes experts for not capturing the true realization, even if their credible interval barely misses it. To investigate the influence of the calibration measure over the informativeness measure, 15 environmental science undergraduates were invited to complete the seed questions. The results are presented in Figure 4.18.

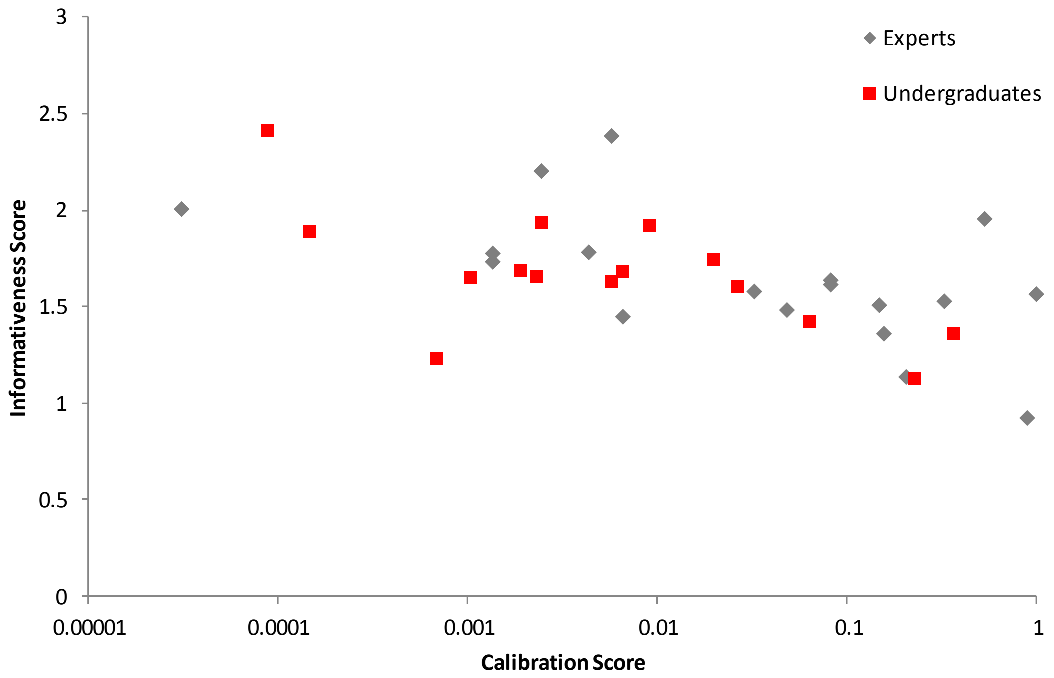


Fig. 4.18. Informativeness and calibration measures for 18 experts and 15 undergraduates calibrated with the same seed questions.

Results show that no undergraduate achieved a weighting higher than the ‘best expert’; however, most student scores were placed amongst expert scores. All undergraduates outperformed one expert. Whilst this result does not show that undergraduates are more proficient than the very best experts, it does illustrate the challenge of identifying *who* are the best experts, given that some methods are ‘no better’ than picking random people. The rationale that problem owners use to define and nominate an expert (e.g., publications, track record and experience) may not be most appropriate. This has been demonstrated in other, more comprehensive studies (Cooke et al., 2008).

4.7.3. Classical Model versus Expected Relative Frequency Model

The results from the undergraduate comparison highlight an important issue in the CM calibration process. Although the CM is considered most suitable for quantifying uncertainty ranges, the weighting process is designed to reward good statistical distribution characterization over the set of seed items, at the expense of precision of knowledge. As discussed in Section 4.7.2, experts, whose relatively narrow upper and lower quantiles barely fail to capture the true realization, are afforded a weight lower than some undergraduates, who have presented wide spreads which encompass the realization, albeit truly reflecting their relative uncertainty. Whilst it is important to seek out and 'penalize' overconfident experts, it is also essential to find and reward accurate and knowledgeable forecasters. It is the concern of the problem owner to find the best experts for their purpose. They need to decide whether experts who are good at assessing uncertainty are more suitable than experts that are precise in their responses. To investigate this further, the calibration data were analysed via a new model designed to reward ability in point-wise estimates (Fig. 4.19). The Expected Relative Frequency (ERF) model, developed by Flandoli et al., (2011), also applies empirically controlled performance-based metrics to produce expert weights. But it also rewards good location of central values, on average, by scoring experts using a default integration range (+/- 10% around the realization value)[13]. Comparison of the two models by cross-validation did not show one approach to be consistently better than another. However, the authors of the comparative study did observe a difference in the suitability of the models for providing either accurate point-wise estimates, or for quantifying uncertainty ranges. The authors conclude that choice of method (or a combination of the two) would be dependent on the nature of the problem to which it is applied (Flandoli et al., 2011).

[13] The ERF weighting scheme is different, but complementary to the CM scoring approach. It recompenses expert capability to give accurate central estimates (mode/median/50% quantile) against the true value of the seed question and to provide 5% and 95% quantiles that avoid peaked distributions (i.e. cautious uncertainty judgements). For each question, a triangular distribution is fitted and a score is computed by integrating the triangular probability density function over an interval centred around the true of the seed question. The integration interval smoothes out disproportionate differences in score due to minor variations or misjudgements. The scores across seed items are then averaged to provide a definitive reward. High scores are achieved if the 50% quantile is close to the true value. Low scores are due either to poor central estimates, overconfidence or excessive uncertainty (Flandoli et al., 2011).

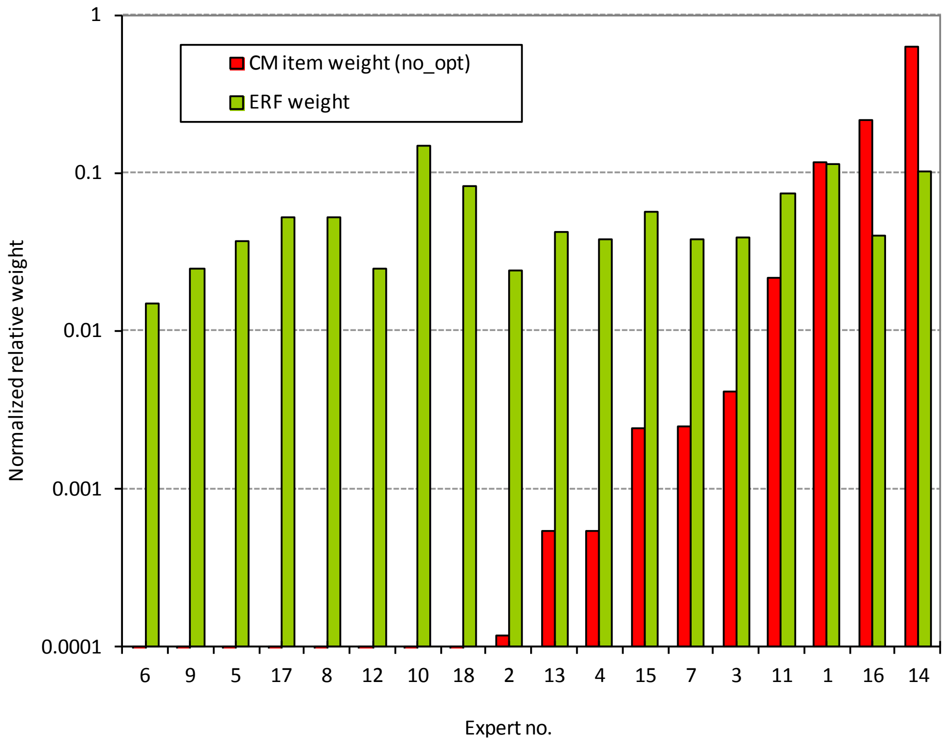


Fig. 4.19. A comparison of CM and ERF expert weights for the Tristan seed questions. The normalised weights for each expert have not been reduced in calibration power, hence experts 6 – 18 appear to have a zero weighting. The ERF score profile is less discriminatory within the group: the ratio of highest weight to lowest is about 10x, whereas the CM presents several orders of magnitude difference between top and bottom weights.

For the Tristan data, the CM identifies three experts with high relative weights: experts 14; 16; and 1 (Fig. 4.19). In the context of the CM model, expert 14 is rewarded for good statistical calibration coupled with good informativeness, whereas the second top weight, expert 16, gains their score by good statistical calibration achieved by wide credible interval selection (i.e. reduced informativeness). Under full DM optimization, expert 14 alone would attain a positive weight by the CM method – i.e. they uniquely, and most efficiently, capture the distributional uncertainty judgments of the whole group.

There is some overall commonality of trend across the alternate scores but with one or two notable exceptions. Experts 1 and 14 appear among the top three under the ERF model as well as the CM. But expert 10 – the top ERF scorer - and, to a lesser extent, expert 18 (placed fourth for ERF) have negligible CM scores and are below the halfway point in the group. Expert 16, ranked second under CM, finds him/herself just below the midway mark, at tenth place, in the ERF pack. This result suggests that there are slight differences in outcome between the two reward schemes, and highlights the importance of defining an appropriate weighting method as it may ultimately affect the decision outcome. Further investigation of differences that the ERF weightings have on the outcome of the target variables, if any, would be desirable. Additional theoretical and experimental research into the merits and application of different weighting models are necessary.

4.7.4. Fields of expertise

To explore how well the experts' calibrations correlated with their self-assessment of particular specialisms, weightings (CM and ERF-derived) were filtered through each ‘area of expertise’ (Table 4.1). The two highest ranked individuals for both models (experts 1 and 14) made self assessments of their expertise in numerous (> 6) sub-fields of volcanology. Expert 1 considered himself/herself expert in six out of ten fields, and expert 14 in nine out of ten fields. The average number of fields chosen was 3.67 and the subject area most frequently chosen was ‘physical volcanology’, with 13 out of 18 experts acknowledging expertise in this field. Other widespread selections were explosive volcanism, hazards and risk, and monitoring. The least common areas of expertise amongst experts were intraplate volcanism and volcano tectonics (Table 4.1). It is noted that selection of specialism is subjective and experts may be overplaying, or underplaying, their breadth of expertise.

Importantly, the small dataset does not allow for meaningful statistical analyses to be performed. There may be significant correlation between fields of expertise and calibration score, but only observations from the dataset can be made currently.

Table 4.1 Expert areas of specialism.

	Expert Number																	
Specialism	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Intraplate Volcanism												•						
Petrology				•						•		•		•				
Physical Volcanology	•		•		•	•	•	•	•		•	•	•	•	•			•
Volcano Tectonics													•	•				
Volcano Monitoring	•						•				•		•	•	•	•	•	•
Degassing Processes	•		•		•				•	•				•				
Effusive Volcanism			•		•		•					•		•		•		•
Explosive Volcanism	•		•		•	•	•		•					•	•		•	•
Hazards and Risk	•	•				•					•			•	•	•	•	•
Environmental Impacts	•	•				•					•			•				

There is a general decrease in CM and ERF scores with diversity in subject area, which tentatively suggests that 'super-experts' in one field are less useful than good generalists in informing the decision-making process. It could also be that the type of 'research personality', that leads one to become a generalist, tends to attract those better naturally at bounding their uncertainty. One obvious anomaly in the ERF scores is the highest scoring expert 10, who claimed to be a specialist in just two areas. Another anomalous score was expert 18, who acknowledged expertise in five areas, was not one of the top ten ranking experts by the CM, but was the fourth ranking expert by the ERF method.

Expertise in monitoring appears to be a reasonable indicator of good performance on the ERF weight function (Fig. 4.20). This may be due to the degree of clarity involved in identifying oneself as expert in this field. Expertise in hazards and risk is rather less indicative; but the highly ranked experts do seem to have identified themselves often as expert in both monitoring *and* hazards and risk (Figs. 4.21 and 4.22). Although a tentative conclusion, it is possible that being expert in both hazards and monitoring is a good predictor for a superior score by both methods. This may be due to extensive field experience of monitoring experts who would have made first hand observations and measurements of volcanic phenomena. Further, monitoring experts are likely to be more familiar with uncertain parameters than any other expert grouping. Hazard and risk experts would have superior knowledge of the range of eruptive styles, products and impacts, and thus be able to better visualise eruptive behaviour; although it is noted that this type of information is frequently used for seed questions, possibly biasing this expert grouping. In practical terms, this conclusion (although speculative) suggests that experts with recent experience in monitoring practices, and knowledge of hazard and risk, are the most appropriate experts to use in volcano crisis management. During a crisis, whilst it may be tempting for decision makers to ask the opinion of experts known to have a wealth of experience and a long track record, their judgement may not be as valid as judgements of experts ‘on the ground’.

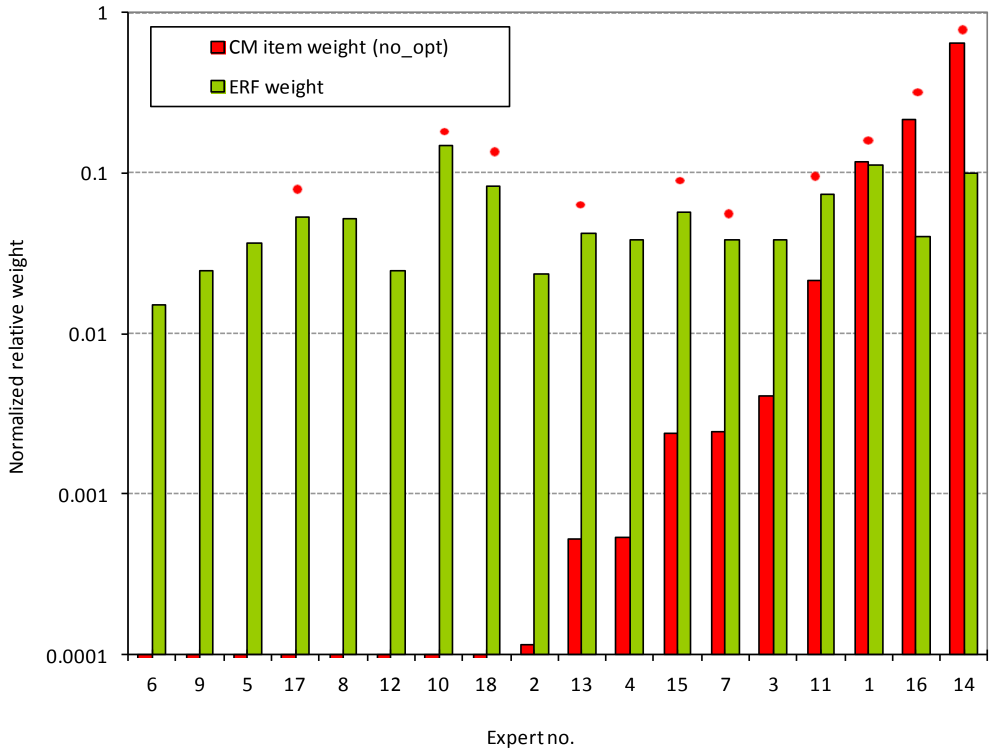


Fig. 4.20. ERF and CM scores for calibrated experts. Red dots highlights experts who acknowledged expertise in monitoring.

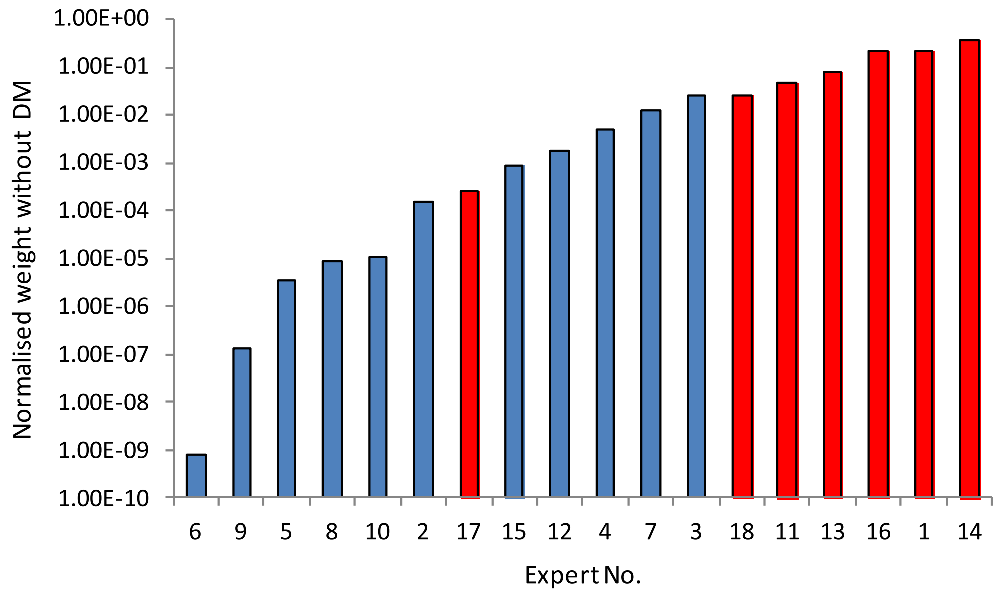


Fig. 4.21. CM expert weightings. Experts who acknowledged expertise in hazards and risk *and* monitoring are in red.

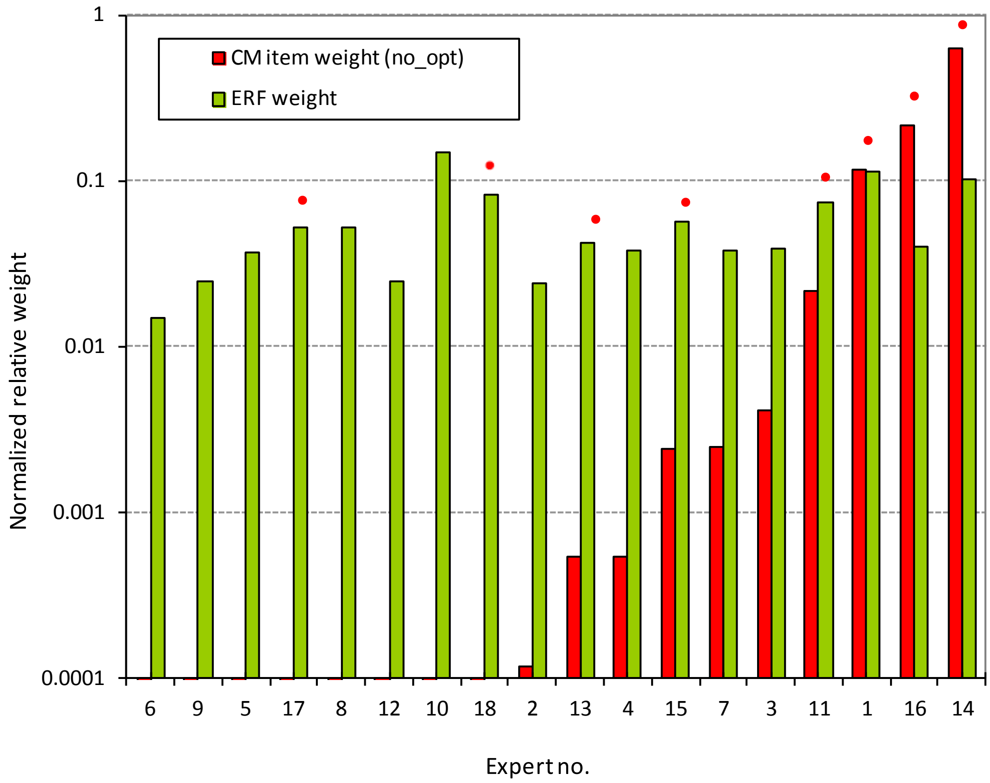


Fig. 4.22. ERF and CM scores with red dots highlighting experts who acknowledged expertise in hazard and risk *and* monitoring.

It was a concern that some of the seed questions were biased towards experts currently teaching undergraduates, particularly questions on effusion rates and typical parameters of eruption styles. By filtering the experts in terms of whether or not they had recent, regular teaching experience, there appears to be no trend in the score (Fig. 4.23). Again, the small dataset reduces the value of applying statistical tests.

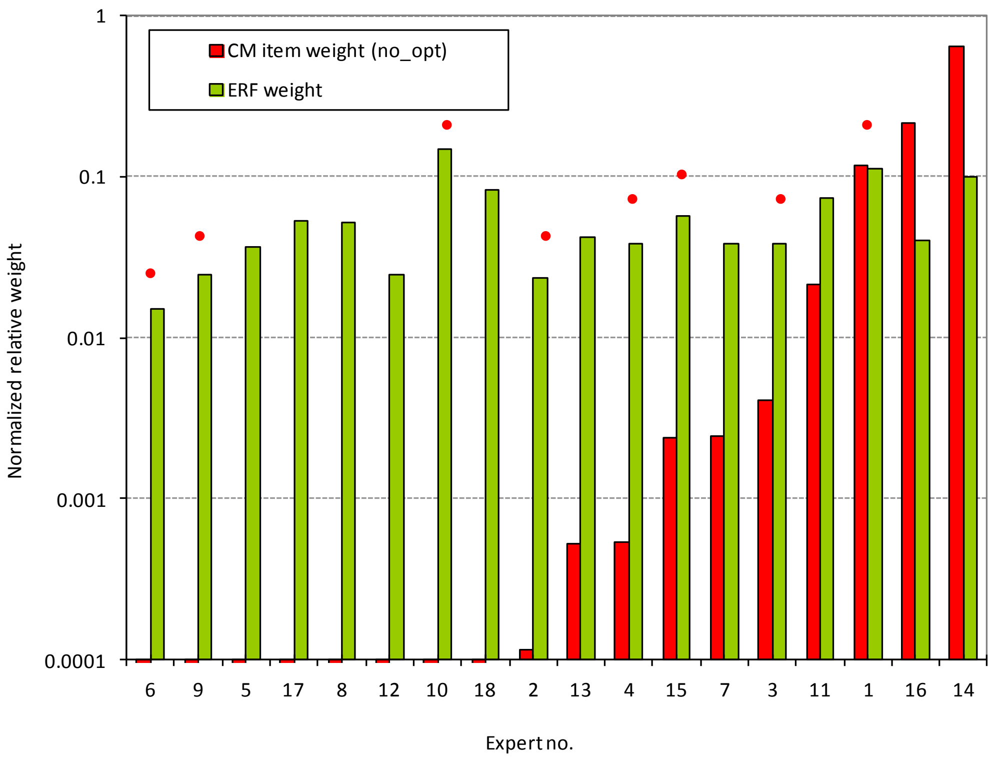


Fig. 4.23. ERF and CM scores with red dots highlighting experts who currently teach undergraduate students.

Despite brief probability training at the outset of each elicitation, it was also important to establish if experts familiar with the elicitation process performed better than experts who had never participated in an elicitation before. It is known that a poorly calibrated expert does not necessarily indicate a lack of knowledge, rather an unfamiliarity with quantification of subjective uncertainty (Cooke and Goossens, 1999), so it may be possible that there is a ‘training and feedback’ element to the comparatively higher scores. To test this hypothesis, expert weightings were filtered by pre-calibration (Fig. 4.24).

This plot suggests that there may be some correlation between pre-calibrated experts and good calibration scores. An alternative conclusion could be that some experts are just better than others at estimating uncertainty and 'knowing' about a subject. In volcanology, active research in the field of volcano monitoring and hazards analysis appears to be a good filter for that.

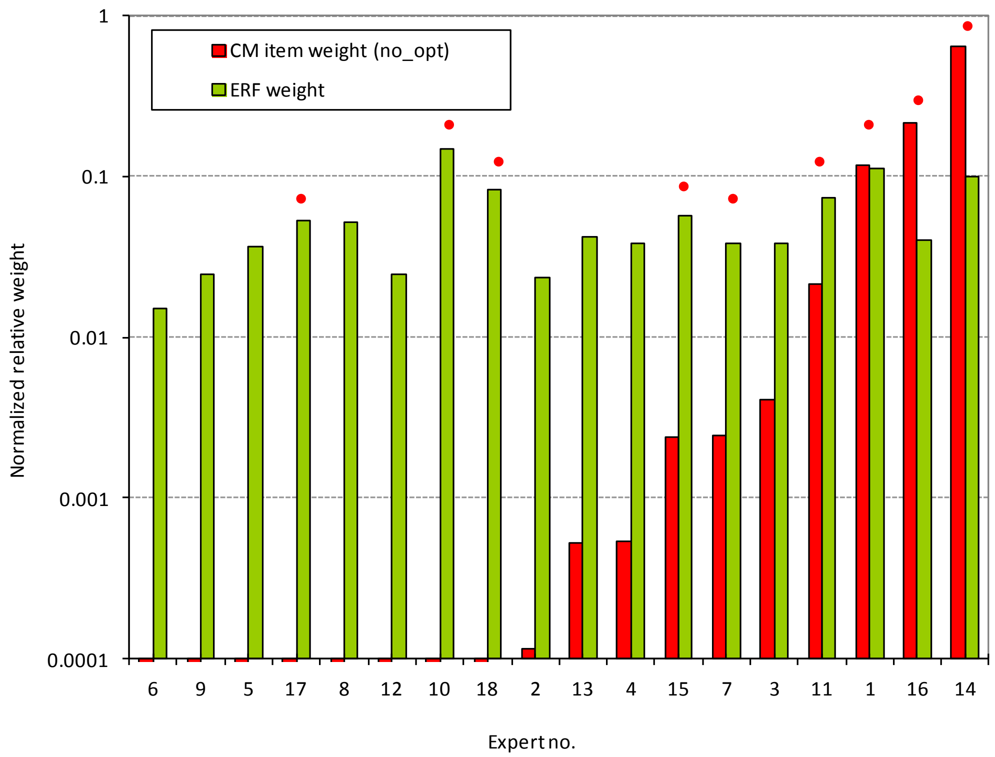


Fig. 4.24. CM and ERF scores. Red dots reflect experts who have been pre-calibrated.

These results tentatively imply that it is desirable for problem owners (in volcanology) to pre-select experts by way of areas of expertise. Expert selection is something that the CM explicitly avoids by calibrating a representative group of experts and then objectively determining which are best. It is important to remember, therefore, if expert selection was to become a subjective decision on the part of the problem owner, it would require him or her to take responsibility for the experts' advice.

4.8. Conclusions and further research

Uncertainty is inherent and universal in volcanology, and this creates a challenge for volcanologists and decision makers alike. Expert elicitation is a useful tool when decisions about uncertain futures must be made rapidly and with limited resources. However, it is crucial that expert elicitation is developed as part of the volcanologists' methodological toolkit and does not become a substitute for field research.

This component of the research sought to extract and synthesise expert opinion on future eruptive scenarios for Tristan, focussed on location of eruption (given unrest) and likely occurrence and impact of hazards. Results indicate that experts are extremely uncertain about the location of future eruptions on Tristan, with experts all expressing very wide credible intervals for answers to the majority of target questions. However, this is not unexpected, given that Tristan has not evolved a dominant central vent preference, unlike many ‘textbook’ volcanoes. Expert uncertainty was reflected in the DM solution. In the event of an eruption *(4-55-90)*, the DM suggested the most likely broad location of eruption to be the coastal strip *(5-38-83)* and the least likely location to be the summit *(2-17-53)*. It is possible that experts considered a summit eruption to be less probable due to early geochronological evidence suggesting the summit had been inactive for at least 15 ka, whilst the coastal strip, flanks and offshore areas had been active more recently. When presented with new geochronological evidence proving that the summit had been active very recently (see Chapter 3), many experts conveyed more uncertainty about future eruptive scenarios on the island. Perhaps this reflects a tendency for some volcanologists to confuse absence-of-evidence with evidence-of-absence – a dangerous source of bias in any decision making process. Expert opinions on the likely occurrence of, and impact of, particular volcanic hazards, in the event of an eruption, were more consistent. Of particular importance to hazard assessment is that experts considered lava flows most likely to impact the Settlement in the event of an eruption on the coastal strip. Base surges and pyroclastic density currents were deemed least likely to occur and impact the Settlement in the event of any on-island eruption.

This elicitation was a useful trial of the value of the CM for an ill-defined volcanic setting, but it also presented an opportunity to investigate the technique for methodological deficiencies when applied to a volcanological context. Preliminary results highlight the importance of applying a calibration process that is fit for purpose, in order to obtain the best expertise. Comparisons of CM calibration scores of experts and undergraduates (calibrated with the same set of seed questions) showed overlap between undergraduate and most expert scores, suggesting that people can still be a good judge of uncertainty regardless of knowledge and experience. Results also showed possible correlations between high scoring experts and previous calibration experience, suggestive of learning. It is impossible to know whether experts may have learned to better assess uncertainty, or whether they have learned how to achieve a higher calibration score. On one hand, one would hope that the latter is untrue and that experts have faithfully represented their opinion. The CM claims that it is not possible to ‘game’ the system in a properly conducted, structured elicitation with the sort of safeguards (empirical control) in place that allow experts to express their true opinions. In other words, it should be very difficult for experts to consciously improve their calibration score. Conversely, it may be *desirable* for experts to improve their calibration scores via learning. Ultimately, problem owners applying the CM want experts that are good assessors of uncertainty. If experts can learn to become better at appraising uncertainty (especially reducing overconfidence), then expert consensus and resultant probabilities may prove more robust.

Structured expert elicitation is a relatively new technique in volcanology but, as the method becomes employed (and potentially exploited) more extensively in real-life circumstances, it is imperative that the advantages and weaknesses of expert elicitation are thoroughly explored and communicated widely within the volcanological community.

For Tristan, finding extensive uncertainty is not a failing of the elicitation, but an objective expression of the existence, extent and significance of that uncertainty. Whilst this information may not be welcome to decision makers, it is better than giving them 'spin', or a false sense of certitude on the part of scientists. Nevertheless, the elicitation underscores the need to reduce uncertainty around future eruptive scenarios on Tristan. Monitoring data, particularly, would provide long-term baseline information and may allow signs and signals of unrest to be detected earlier. Given the paucity of knowledge about historical eruptions, further and more detailed geochronological and geochemical data should be combined with volcanological field studies to constrain past eruptive behaviour and provide realistic hazard evaluations. As new information becomes available, it would be desirable to re-elicit experts, even if uncertainty remains high – as noted earlier, it may actually increase. Further treatment of probabilities with sensitivity analysis and Monte Carlo simulation techniques are required. Despite the risk of uncertainty suppression, group discussion would have been advantageous, if only to record how experts reacted to the DM solution. More research into real world applications of the calibration process of both the CM and ERF approach would be interesting and valuable. Ways in which experts might be selected, according to areas of expertise, may be worthy of further investigation. Expert groups composed of both generalists and domain specialists, pertinent to the problem at hand, may present an effective formula for discussion around eruptive scenarios.

CHAPTER FIVE: Social context of Tristan da Cunha

5.1. Introduction

Tristan islanders are considered to be the most isolated population in the world (Plate 5.1). All 262 inhabitants[14] reside in Tristan's only village, Edinburgh of the Seven Seas, known locally as the Settlement. Situated over 2,800 km WSW from Cape Town and over 3,350 km from Rio de Janeiro, the only access to the island is by ship. The journey normally takes between 7 - 10 days from Cape Town. As Tristan has only a small harbour, the seas must be calm enough to allow small boats to access the island. However, as the Settlement's position is exposed to the prevailing north-west winds, this makes it vulnerable to frequent bad weather, often preventing boats leaving the island (fishing) and visiting it (tourism).

Location is the main root cause of vulnerability to natural hazards on Tristan. Islanders are at risk from a multitude of geophysical hazards (see Chapter 2), the effects of which are amplified due to the time it takes to obtain outside assistance and adequate resources to cope and recover. Further, the lack of habitable land on the island limits options for evacuation if the Settlement was threatened directly. This situation necessarily focuses attention on the capabilities and capacities of islanders to prepare, respond, and recover, and the means by which these can be improved (if they need to be). Any measure designed to help attempts to strengthen resilience needs to be tailored for the particular circumstances. Therefore, knowledge of the specific social dimensions of risk is required, particularly the economic, political, social structure and culturally constructed behaviours.

By presenting new observations and work by other authors, this chapter will describe the current social context of Tristan and will draw attention to particular vulnerabilities and resilient characteristics that will be developed in Chapter 6, in a risk reduction context. Many of these characteristics are inherent within the present day community and reflect the decisions and adjustments made following key historical events. Therefore, it is also important to examine the history of settlement on Tristan, the choices and laws that were made and the reasons for those decisions. Examining the drivers of vulnerability, resilience and adaptation through time is an important part of understanding the conditions of daily life that have and could prefigure disasters. The following section will describe the short, yet

[14] Population size correct as of May 2012.

eventful history of settlement on Tristan and highlight some of the key characteristics of the islanders who have helped to shape this unique community.

5.2. Historical and sociological background

Tristan was first discovered by Portuguese explorer Tristaõ d'Acunha in 1506 (e.g., Brander, 1940 and references therein) who gave the island his name despite never setting foot on the shore. The first recorded landing at Tristan was in 1643 by crewmembers of the Dutch flute *Heemstede*, although results from pollen research suggests that Tristan may have been occupied several decades before this first official landing (Ljung and Björck, 2011). Reports of occasional landings to fetch water during the 17th century were succeeded by accounts of frequent visits by whalers and sealers in the 18th and 19th centuries. Crewmen occasionally chose to stay on the island - some of whom claimed it as their own - but it was not until a British garrison took possession of the island in 1816 that the political future of Tristan was secured.

The garrison was established to prevent the French from using Tristan as a base following Napoleon's imprisonment on St Helena, ~2,000 km north. When the garrison was withdrawn, Corporal William Glass, a Scotsman, opted to stay on the island. Glass, his South African wife, children and two civilian stonemasons created the first permanent settlement on the island and set about evolving a communalistic existence based on rules laid out in a document known as 'the agreement'. Glass' motivations for creating a community are unknown. He may have shared previous temporary settlers' desire for independence and prosperity (Fichter, 2008), or he may have grown weary of being a servant and employee[15]. Munch (1971) reflects that Glass could have made the decision to remain on Tristan following the sinking of H.M.S. *Julia*, a ship which had been sent to collect the remaining members of the garrison. At that time (early 19th century), social experiments to create 'utopian societies', based on desires to live by religious or spiritual values, to reject order, and to build social harmony were popular ideas (Kanter, 1972). Whilst Glass was a deeply religious man (Munch, 1971), it is not known whether he ever considered creating an idealized way of life until the possibility presented itself. Regardless of his motivations, a co-partnership ('The Firm') was conceived and the first permanent settlers created a community based on principles of communal ownership, integrity, and equality:

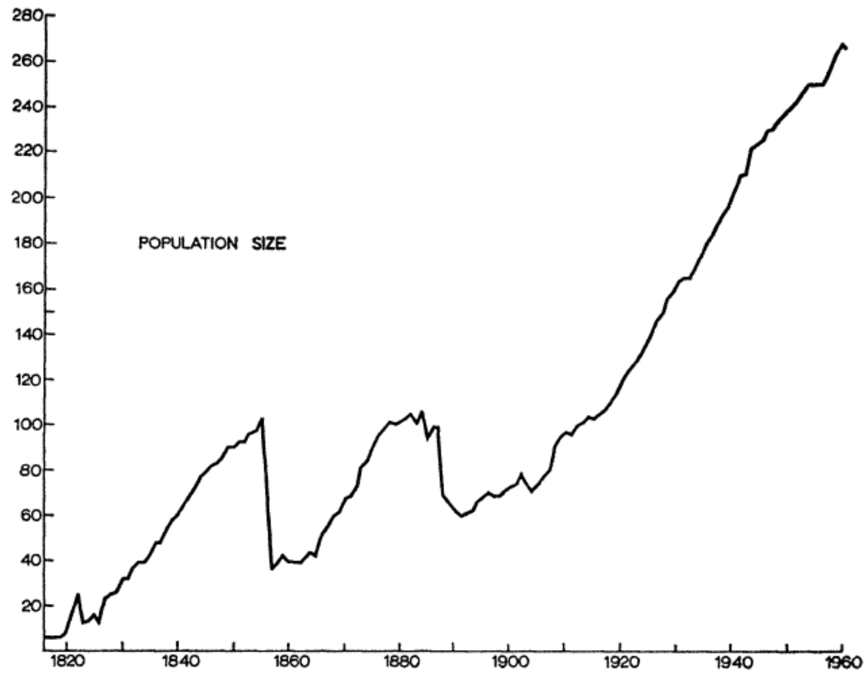
[15] It is noted, however, that whilst Glass had been a gentleman's servant for a wealthy family and then a personal attendant for a Royal Artillery officer, at the time he elected to remain on Tristan he was a well respected corporal in charge of a team of artillery drivers.

> "We, the undersigned have entered into Co-Partnership on the Island of Tristan da Cunha, have voluntarily entered into the following agreement- Viz ~
>
> That the stock and stores of every description in possession of the Firm shall be considered as belonging equally to each ~
>
> That whatever profit may arise from the concern shall be equally divided ~
>
> The purchases to be paid for equally by each ~
>
> That in order to ensure the harmony of the Firm, no member shall assume any superiority whatsoever, but all to be considered as equal in every respect, each performing his proportion of the labour, if not prevented by sickness ~
>
> In case any members of the Firm wish to leave the Island, a valuation of the property to be made by persons fixed upon, whose evaluation is to be considered final ~
>
> William Glass is not to incur any additional expense on account of his wife and children ~"

This founding vision is a significant marker in Tristan's history as the cultural homogeneity that accompanied these established values and principles prevails today.

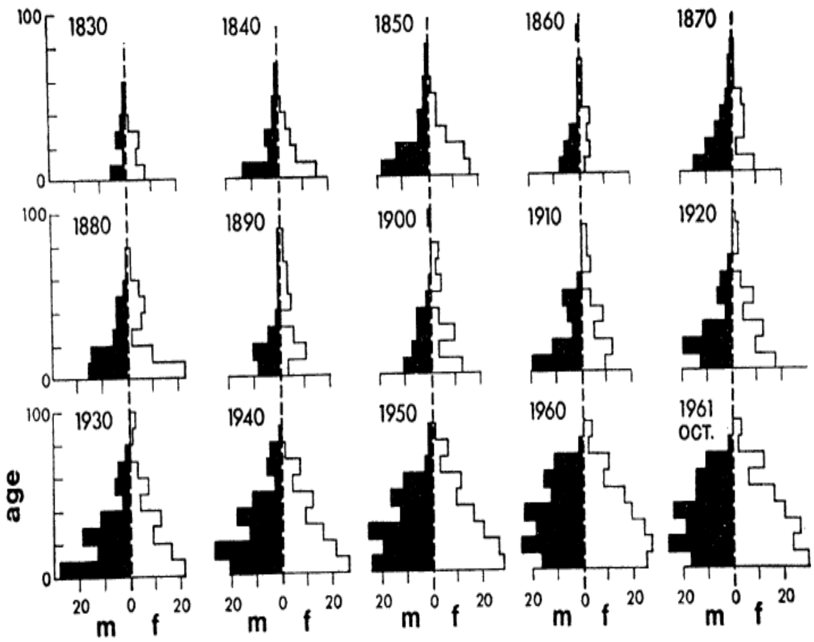
Following the introduction of five women from St Helena, the population grew slowly but steadily (Fig. 5.1) with many shipwrecked sailors opting to stay on the island and join the 'utopian' community (Plate 5.2). During the early 19th century, Tristan was an ideal trading post and frequent bartering with passing ships ensured island life was relatively prosperous. The rudimentary 'laws' were upheld and rarely breached. An island leader or form of government was never needed, or wanted, although Glass naturally developed a more autocratic role and became known as the 'Governor'. A mass exodus followed his death in 1853, jeopardising the future of the Tristanians. A Dutch sailor, Peter Green, decided to stay and assume Glass's role as the island's unofficial spokesman. Unfortunately, the next 40 years were particularly challenging for Green and the other islanders who became truly isolated following the decline in the whaling industry, the introduction of steam, and the diversion of ships through the Suez Canal. Sometimes as many as 18 months passed without a ship visiting the island. In 1885, 15 islanders were lost at sea as they attempted to trade with a passing ship. The bodies of the men were never found, igniting much speculation as to why the boat was lost, as the weather was fine that day. Thirteen widows were left on the island; and only 16 men over the age of 22. The tragedy was followed by another mass emigration in 1892, leaving the island with a population of just 50. Faced with the perils of isolation, the islanders were forced to recover and began honing their self-sufficiency skills. The transition from a barter to a subsistence economy also reduced the communality of the islanders and encouraged independence, normally as family units or households. The development of an 'atomistic' community reduced collective action, but did not erode group activity. For example, small selected groups would work on the potato patches (the Patches), others would assemble for a trip to the mountain, or for an excursion to Nightingale Island.

Despite increasing hardship and generous offers to leave Tristan and establish elsewhere, the islanders chose to remain on Tristan and persevere, demonstrating a stoic determination to maintain their independence and anarchic lifestyle. The fortitude to prevail through adversity is demonstrated throughout Tristan's history (Fig. 5.2).



A.

Fig. 5.1. **A:** Population size on Tristan da Cunha from 1817 to 1960. **B**: Population pyramids of Tristan da Cunha from 1830 to 1961 (see following page). Taken from Roberts (1971).



B.

Fig. 5.1. Cont'd

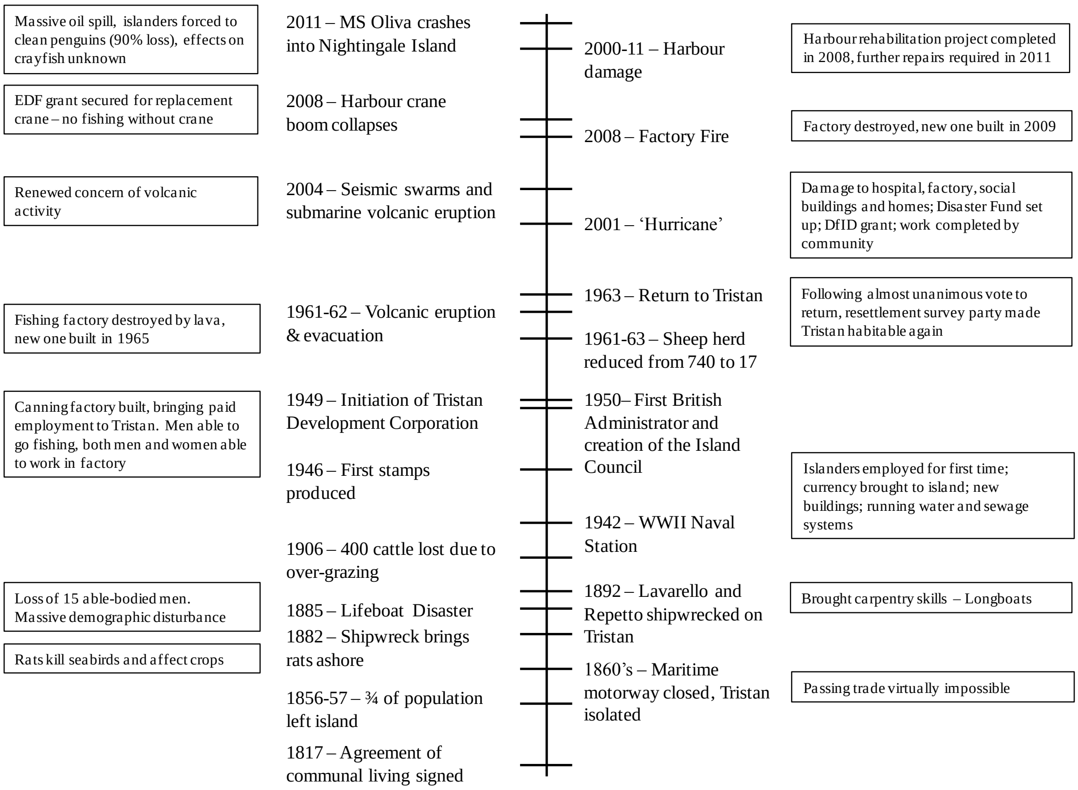


Fig. 5.2. Summarised timeline of key events in Tristan history.

When the British Royal Navy established a garrison on Tristan during World War II, contact with the outside world was permanently re-established. Physically, community transformations were rapid, with the construction of a shop, hospital, accommodation, school (which was compulsory for Tristan children to attend) and wireless station. Islanders were employed to help run these facilities and, for the first time, given cash wages. Until then, potatoes were considered currency. Their 'anarchic' form of social organisation eroded gradually as islanders began to enjoy an improved quality of life which accompanied the new infrastructure, most of which continued to function following the war.

Tristan never returned to its former degree of isolation as a formal administration was established and the island fell under the jurisdiction of St Helena (see Section 5.3.2). Until then, the egalitarian islanders had resented the notion of a luminary or indeed any sort of hierarchy. Following World War II, the first resident British Administrator was appointed to oversee interactions between the islanders and the new Tristan Development Company, an externally-initiated enterprise to exploit the crayfish resource. Shortly afterwards, the first Island Council was appointed. Although the Island Council was representative of the community, exclusive power resided with the Administrator and islanders were often coaxed into actions and changes that the Administrator felt was best for the island. Although they could no longer ignore the power of this authority, the council continued to play along, albeit knowing that all important island decisions were out of their control (Munch, 1964). Nevertheless, the commercial fishery created an economic boom, and brought technical and agricultural improvements (e.g., modern sanitation and effective grazing methods), most of which were met with approval by the islanders. They were able to purchase 'luxury' goods and thus raise their standards of living in line with those of the 'outside world' (Munch, 1964).

This good fortune was short-lived. In August 1961, earthquakes were felt and rocks began falling from the cliffs behind the Settlement. The frequency and intensity of the activity increased during the following weeks and, on the 8th October, many families in the eastern part of the Settlement moved in with relatives residing in westerly homes. The next morning, a fissure opened up between the Settlement and the canning factory to the east. At a village hall meeting, the Administrator decided to evacuate the whole Settlement to the Patches. Following a very uncomfortable night, the Administrator was advised that a new volcanic dome had erupted and opted to evacuate the entire population to Nightingale Island, ferried via longboats. Many of the elderly were picked up from Boatharbour Bay, but those that left from Little Beach (now partially covered in lava) saw the eruption at close proximity.

Coincidentally, the Dutch ship *Tjisadane* arrived the following day to collect two island women for nurse training in Cape Town. By sheer good fortune, the ship only had 20 passengers onboard but was equipped to carry 400, so the entire population was evacuated at once. The islanders arrived in Cape Town five days later and then boarded the RMS *Stirling Castle* which took the population to Southampton, UK.

The islanders were first housed at Pendle Camp in Surrey; then they were moved as a unit to the former RAF Calshot Camp in Southampton. They successfully applied for jobs and the children were sent to school. Some islanders, especially the younger faction, enjoyed their time in the UK and several were happy to stay and continue their new lifestyles to which they had adapted so rapidly. For the majority though, adjusting to their new lives was particularly challenging, exacerbated by crime, probing journalists and medical researchers, poor weather and lack of immunity to common ailments. When reports from the Royal Society Expedition in 1962 confirmed that activity was waning and that the impact to the Settlement was relatively minor, the islanders lobbied to return to Tristan. A resettlement survey party of 12 islanders landed on Tristan in September 1962 to begin the massive restoration project (Plate 5.3). In December of that year the islanders voted 148 to five in favour of returning; a move that was finally completed in November 1963 when the final 198 islanders departed the UK.

It is widely viewed by the islanders that, had the Colonial Office not kept the community together in one location, resettlement on Tristan would have been unlikely. When sociologist Peter Munch visited Calshot camp in 1962, he reported that the community had actually become closer than when he had first visited Tristan in 1932. It was his understanding that the islanders were trying to preserve their heritage and identity within a world that they struggled to comprehend. This strengthening of collective identity gave the islanders the courage to stand up to the authority they had regarded as absolute, and to use their own initiative and action to defend their individuality against the pressures from modern society and external threats to their culture (Munch, 1964).

However, in 1966, 37 islanders returned to the UK, followed by another 15 in the ensuing two years. It is possible that these islanders had felt coerced into making the trip back to Tristan, or that they had irreversibly adapted to the UK way of life and could not contend with the challenges of recovering their Tristan livelihoods. Regardless, exposure to the outside world had permanently changed the traditional Tristan lifestyle; a common occurrence within traditional societies following natural disasters or ‘system shocks’ (Gaillard, 2007). Modern dress was adopted and traditional dances were replaced by contemporary music such as rock and roll. The community also transformed psychologically. Prior to the eruption, Munch (1947) reflected on the islanders' self-perception as inferior to outsiders. They were acutely aware of how primitive their lives must seem and tended to see themselves as socially subordinate. When outsiders visited, islanders behaved deferentially. This self-perception and behaviour was possibly exacerbated by perceived racial differences and the prestige historically accorded, on Tristan, to fairness of skin (Munch, 1947). Following the UK sojourn, a strengthened collective identity and greater cultural confidence - gained from pride in their will and ability to survive - weakened social and cultural subordination. This change may, in part at least, be attributable to the turn away from an identity rooted in highly individualistic subsistence culture to one that situated islanders in relation to a wider "external" world. A new sense of collective identity was formed, and this required defending.

5.3. Present day social context

The events leading up to the present day have undoubtedly influenced the islanders as individuals and as a community. Exemplified by many small island communities, their cultural identity, heritage and core values are still strongly upheld and defended. However, the various obstacles that the Tristan population have encountered since the Settlement's inception have acted to alter the community as they tried to adapt to changing circumstances. Although events such as the lifeboat disaster of 1885, the construction of the naval station during World War II and the 1961 volcanic eruption thrust the islanders into alternative realities, other slower drivers have also shaped the community. The effects of these drivers on vulnerability to, and capacity to cope with, natural hazards in the present day will be highlighted in the following sections and discussed in more depth in Chapter 6.

Today, the Tristan community is characterised by a small, cohesive population shaped and organised according to kinship. Social solidarity is still strong, although the homogeneity of the population has lessened with greater access to the outside world. Despite the transformations that have occurred with the arrival of technology, communication and travel opportunities (see Chapter 6); islanders still retain many of the original social principles, especially independence and integrity, as well as a sound sense of place and pride in their way of life.

In terms of physical appearance, there have been few changes since the early settlers created the community. The genealogy of Tristan is well-documented and the current population is thought to have descended from seven females and eight males (Soodyall et al., 2003). Racially, their origins are heterogeneous, with a dominance of white European and some African ancestry. Clues to their hybrid ancestry still prevail, with features such as blonde hair and blue eyes through to dark skins with great variability in between the extremes. Seven of the original settlers' surnames have survived to the present day: Glass (Scottish), Green (Netherlands), Swain (England), Rogers (USA), Hagan (USA), Lavarello (Italy) and Repetto (Italy). While intermarriage among these families is commonplace, there are only minor genetic deficiencies (Jenkins et al., 1985), except the prevalence of asthma which is thought to have afflicted five of the original settlers (Zamel et al., 1996; Slutsky et al., 1997).

Despite the forced fusion of cultures, the Tristan community is markedly European, with a significant British influence. Of 31 settlers that lived on Tristan during the first 20 years of settlement history, at least 21 came from Britain or British colonies (Munch, 1947). This is reflected in the language, currency and house building techniques, the latter markedly Scottish in character. There is a well defined social heritage with a strong social order (Munch, 1947), partly a consequence of the isolated position and small community, where the identity of an individual can rarely be concealed. Social discrimination is mainly focussed around industriousness, with those that are willing to work hard and offer help held in high regard within the community. However, despite a strong history of challenging hierarchy, opportunities for social mobility are increasing, thus acting to threaten values of equality by encouraging social stratification focussed around level of education.

Other major community changes have resulted from the introduction of technology, media and communications (see Chapter 6). Most islanders have embraced technological advances and believe that such progress has benefitted society. However, it has also encouraged the development of consumerism among many islanders, who compete with each other to purchase the best and biggest imported consumer goods as a signifier of social distinction and status. Accommodation may still look basic from the outside but conceals a modern interior comparable to most British homes. The effects of technology, media and communications on vulnerability will be discussed further in Chapter 6.

5.3.1. Population size

As of May 2012, the population size of Tristan is 262. There is a slight excess of females (139:122) due, in part, to the relatively large number of women aged over 70 and the imbalance of girls to boys in the 11-15 age bracket (Fig. 5.3).

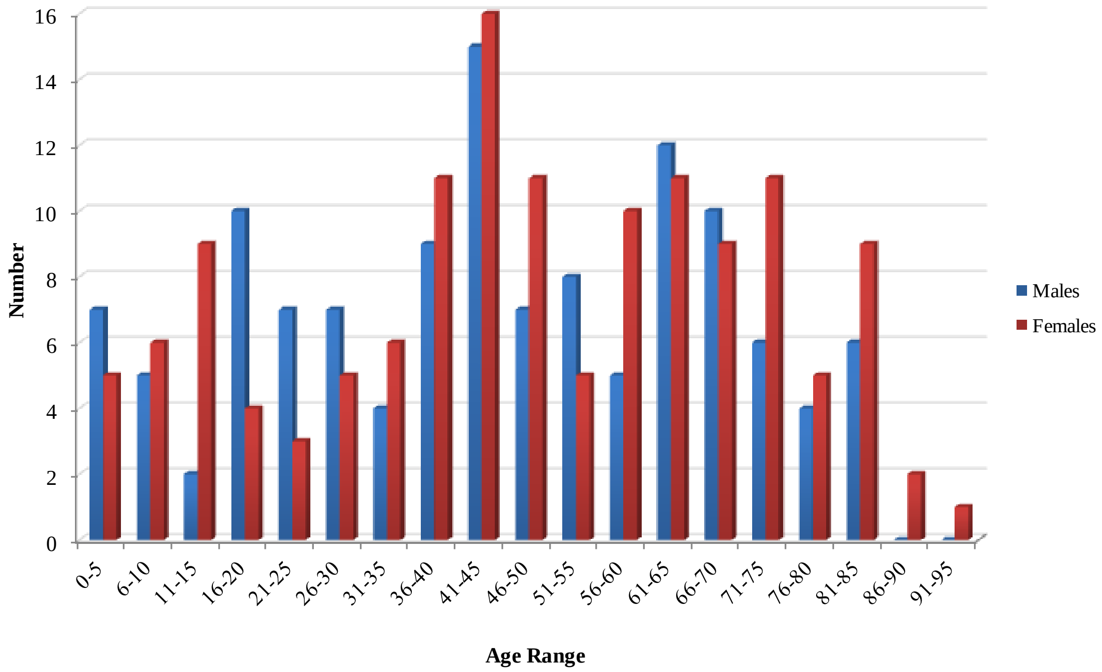
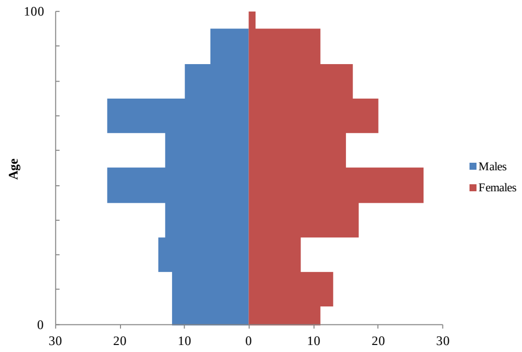
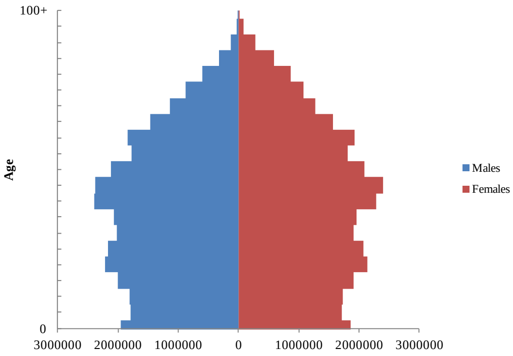


Fig. 5.3. Age ranges of the Tristan da Cunha population.

Due to the small population numbers on Tristan, it is difficult to make direct comparisons with population structures elsewhere. However, the island's 2011 population pyramid (Fig. 5.4) compared with those up to 1961 (Fig. 5.1b.) exhibit relatively rapid changes in population structure that are worthy of mention. According to data from the U.S. Census Bureau, Tristan now shows comparable demographics to those of developed countries such as the United Kingdom, Germany and the United States. Similar characteristics include a very gradual increase in growth to a peak at the 40-50 age group, followed by a steady decline with age. The key differences are the apparent aging population of Tristan and the relatively low numbers of young children and under 20's. These trends certainly pose a problem for the future of Tristan's economy, with challenges of funding health care for an ageing population, low birth rates and the possible loss of a few educated and skilled young people to out-migration. Further, these population characteristics serve to increase the vulnerability of the community to the effects of natural hazards, for example, mobilising older people in the event of an evacuation will require more time and resources.



A.



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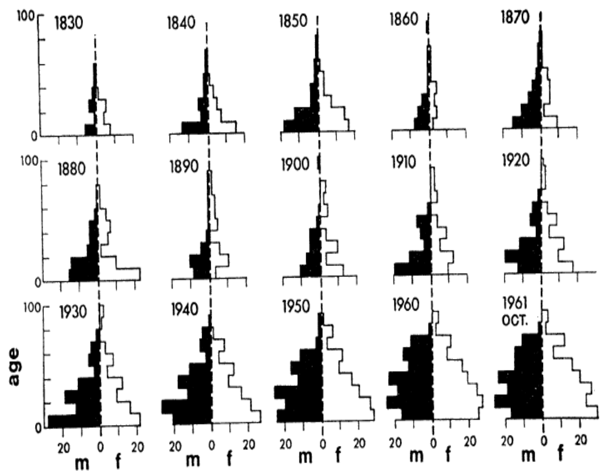


C.

Fig. 5.4. **A:** Population pyramid for Tristan da Cunha in 2012. **B.** Comparative population pyramid for the United Kingdom in 2012. **C:** Population pyramids for Tristan da Cunha from 1830-1961 to ilustrate growth (data in A and B are from the Tristan da Cunha records and the U.S. Census Bureau; data for B are taken from Rogers, 1971. See also Fig. 5.1b.).

5.3.2. Political structure

Tristan has been a British possession since the island was garrisoned in 1816. Formerly part of the territory known as St Helena and Dependencies, a new constitution of 2009 ordered that the territory be identified as, St Helena, Ascension and Tristan da Cunha. The new constitution gives equal weight to detailed provisions for the island which encompasses a bill of rights for Tristan citizens.

Governance of the island lies with the Governor of St Helena and an appointed resident Administrator of Tristan. Both are Foreign Office employees and normally retain their posts for 4 and 3 years respectively. The Governor resides on St Helena and retains responsibility for external relations, internal security, defence and the Tristan public service. He appoints an Administrator to represent him on Tristan. The current Administrator of Tristan is the 21st British Administrator since 1950. A further role of the Administrator is as president of the Tristan Island Council and chairman of the Heads of Department meetings. Off-island, governance is overseen by H.M. Queen Elizabeth II, Members of Parliament, the Foreign Secretary and employees of the Overseas Territories Department of the Foreign Office.

The Tristan Island Council consists of the Administrator, three appointed members and eight elected members. The Chief Islander is representative of the community and is normally required to become acting Administrator when the post-holder is on leave. Council members also supervise a range of sub-committees, such as disaster management[16], and must report activities at regular Island Council meetings. Although the Island Council and Administrator can make decisions, the Governor of St Helena is not, as stated in the constitution, "obliged to act in accordance with the advice of the Island Council in exercising his or her powers....but in any case where the Governor acts contrary to the advice of the Council any member of the Council shall have the right to submit his or her views on the matter to a Secretary of State". This exposes the very limited decision-making power of the Island Council, further demonstrating the importance of small-scale, sustained risk reduction efforts (see Chapter 8), which are designed and initiated by the Island Council (and the islanders), rather than relying on the implementation of likely contentious top-down, extensive risk reduction programmes.

5.3.3. Economy and employment

The Tristan economy is based on subsistence farming and fishing. The first canning factory was built in the late 1940's and the islanders began to export the endemic Tristan rock lobster (*Jasus tristani*), also known locally as crayfish or crawfish (Plate 5.4). Tristan's fishing

[16] A disaster management coordinator (an islander) was employed in 2008 to help prepare a disaster management plan and to design and build the evacuation centre.

industry has suffered two setbacks; one in 1961 when the lava razed the factory and then in 2001 when a fire destroyed the new building next to the harbour. In July 2009, a new factory was built in the same location. About 78% of Tristan's economy is hinged on the crayfish industry (E.Mackenzie, pers.comm.), which mainly exports to the United States, Japan and China. The Tristan Fishery was granted Marine Stewardship Council accreditation in 2011 for sustainable, well managed fisheries, which should help facilitate access to EU markets and thus reduce economic vulnerability.

Subsistence farming is an island-wide activity and vastly reduces reliance on the import of meat and vegetables. Each family owns potato patches where potatoes and other vegetables are cultivated – forming the main part of the Tristan diet and providing animal feed. Livestock (cattle and sheep) graze the Settlement Plain, cattle are kept at Stony Hill, the Caves and Sandy Point and sheep on the mountain. In order to control numbers, each family is allocated a certain number of livestock. Chickens and ducks are also kept in abundance, but used solely for eggs. In general, islanders are very proud of their sustainable living and a great deal of time is spent tending to Patches on the weekends and after the normal working day (Plate 5.5). Most islanders would consider Tristan to be uninhabitable should the Patches be destroyed.

Other island income comes from the sale of postage stamps and tourism. Stamps and coins are often sold to philatelists and numbers of tourists are limited to a few cruise ships, visiting yachts and a fortunate few who secure rare berths on scheduled ships able to bring passengers to shore via small boats. As there are no hotel facilities on the island and only enough guest houses and spare rooms to comfortably accommodate up to 100 tourists, the tourism 'industry' relies mainly on day visitors from visiting ships purchasing handicrafts and tourists purchasing handicrafts and souvenirs. There is therefore a limit to how much Tristan can rely on income from tourism, although the recently built tourism centre and online souvenir shop has encouraged growth.

Wildlife is often the greatest attraction for visitors to the island. The Tristan island group is home to many endemic flora and fauna including the Northern Rockhopper Penguin, numerous species of Albatross (Plate 5.6 and 5.7), and the Island Rail, the world's smallest flightless bird found only on Inaccessible Island. In 1996, a modern conservation ordinance was written to provide environmental protection laws as well as sustainably preserving many of the traditional hunting activities of Islanders. Shortly afterward, the Tristan conservation department was created and has fostered links with the RSPB to help protect rare wildlife from rats and other invasive species.

An essential lifeline for the Tristan economy is provided by the cargo and fishing boats that visit Tristan around 9 or 10 times per year. As part of a contract to help manage the Tristan fishery, two ships transfer fish, cargo, mail and passengers back and forth from Tristan to Cape Town. A South African polar research vessel, the *SA Agulhas II*, makes an annual trip to Gough Island (via Tristan) to service the meteorological station. The *Agulhas* is the most favourable ship for visitors to travel to Tristan, as helicopters are used to transfer passengers from the ship to the island, eliminating the risk of 'no entry' due to unfavourable weather conditions.

In terms of employment, islanders often have more than one occupation, especially fishermen who have to supplement income to account for frequent non-fishing days. Many islanders have regular day jobs and then work in the evenings to package crayfish following a fishing day (Plate 5.8). When tourists or researchers visit the island, islanders are temporarily employed to act as guides or as host families. Some islanders also rent out guest houses for visitors. This type of locally developed community tourism accommodates visitors by using a rota among different families, similar to the once successful model developed in Taquile, Peru (Zorn and Farthing, 2007). Other permanent roles are associated with the provision of services and amenities in the Settlement (see Section 5.3.4).

Due to the relatively low cost of living (no rent or water bills, although food prices are high), wages are extremely low compared to the UK and South Africa (average £200 p/m). Although the prospect of high wages elsewhere provides an incentive to move, most islanders cannot afford the resettlement costs associated with a move to Europe or South Africa. Despite the wide range of skills, formal qualifications are almost absent which also reduces opportunities to relocate. This means that skilled and educated islanders are retained within the community.

The Tristan government also offers a small weekly pension for the elderly (~£11p/w) who are exempt from medical contributions and get free prescriptions (normally £1). The cost of importing medicines and sending patients to Cape Town for medical treatment will become an increasing burden on the Tristan economy as the population ages. To help offset these costs; working adults are now required to pay income tax from which a small contribution goes towards medical cover and the Tristan Disaster Fund - the only insurance option established in 2001 following the 'hurricane' (see timeline in Fig. 5.2). The lack of insurance is not perceived as a major concern and actually saves the Tristan government from paying high premiums. However, the absence of this risk-spreading mechanism serves to increase vulnerability in the event of a high impact-low probability disaster and would reduce speed of recovery (see Chapter 6).

5.3.4 Religion and beliefs

Both a Catholic and Anglican church are located in the Settlement and the beliefs and practices of both churches are upheld. To belong to either church, or not to attend at all, is an individual choice (although there is a familial connection) which is not discriminated against. While almost all islanders attend church services, there are emerging generational differences in beliefs with several younger islanders choosing not to practice any faith or attribute protection to some higher power. However, islanders that do perceive some degree of heightened protection do not fail to respond to threats, as exemplified by the rapid response to the 1961 eruption.

5.3.5. Crime

Crime is virtually non-existent on Tristan. During the day, doors are left unlocked and thievery is extremely rare. Problems are usually ignited by disagreements between people that know each other and are often remedied by merely calming the situation. While there is a police station and permanent police officer on Tristan, there has never been cause to arrest or imprison an islander.

5.3.6. Infrastructure

Calshot harbour, named after the Hampshire village which was home to islanders during their UK sojourn, was built in 1965/66 following the return to Tristan. The harbour is essential to sustain Tristan's economy and permanent settlement, but its size and position are problematic. The small harbour does not permit the entry of ocean-going vessels or yachts which have to anchor offshore and ferry cargo and passengers via small boats (Plate 5.9). During frequent periods of poor weather, ships cannot be loaded or off-loaded; costing the

Tristan government a fee for every day a ship is anchored offshore. The shallow harbour prohibits fishing boats from leaving the island during bad weather, essentially remaining closed for 250-300 days of the year. Its exposed position also makes the harbour susceptible to the strong currents from the west (Plate 5.10), so it is constantly at threat from wave attack. Major rehabilitation work was carried out in 2008 at a cost of >£7,000,000, but further strengthening was required in 2009 and again in 2010. The Department for International Development (DfID) are actively considering options for a new site.

There is a small network of roads within the Settlement and one main route which leads from the Settlement to the Patches. Roads are liable to flooding and blockage by flood debris; especially where Big Sandy Gulch intersects the Patches road (Fig. 1) and at Hottentot Gulch where large boulders are often washed down, entirely blocking the only route out of the Settlement.

In terms of public services, all Tristan homes are now plumbed, with untreated waste carefully pumped out to sea. Drinking water is supplied by the nearby natural spring and alternative sources have been identified should the supply be contaminated, or in the event of a change to the island's hydrological system. Electricity is provided by diesel generators within the factory and is wired to all homes and public buildings. Diesel and unleaded fuel (shipped from South Africa) are also available for vehicles. There are streetlights in the Settlement, but these are turned off at midnight. There is no central heating on the island; homes are heated by oil or gas fires during colder months. All homes have imported propane gas bottles for cooking and heating water. To manage waste products, refuse is collected weekly and disposed of at a waste site in the shelter of the 1961 eastern lava flow. Recycling facilities are currently being considered. Communications include a postal service, telephone network, television and broadband wireless internet. The telephone network is heavily subsidised by the UK government, allowing islanders to phone family and friends in the UK for the cost of a local call. Television is provided by the Services Sound and Vision Corporation (SSVC); a charity set up to broadcast information and entertainment to British Armed Forces around the world. Two channels are offered which present live news, weather and sports as well as popular entertainment shows, soap operas and films. Internet access is provided at an internet cafe and is gradually being extended to individual homes.

Other 'soft' infrastructure supplies key services for islanders. The Settlement is roughly split into two sectors. The residential sector lies to the south, east and west of the Hall, and the 'business' sector lies to the north (Fig. 5.5). Settlement amenities are as follows: Village

Hall, Pub, Hospital, Supermarket, Post Office, Catholic Church, Anglican Church, Factory, Bank, Cafe, Swimming Pool, Playground, School, Crèche, Petrol Station, Police Station and Waste Disposal Site. A brief description of the school, hospital, village hall and supermarket is outlined below. The administration building also houses a council chamber and offices, and there are separate buildings which house communication and public works departments. Islanders have access to several rigid inflatable boats (RIB's) which are used for offloading ships, accessing other parts of the island and trips to Nightingale and Inaccessible.

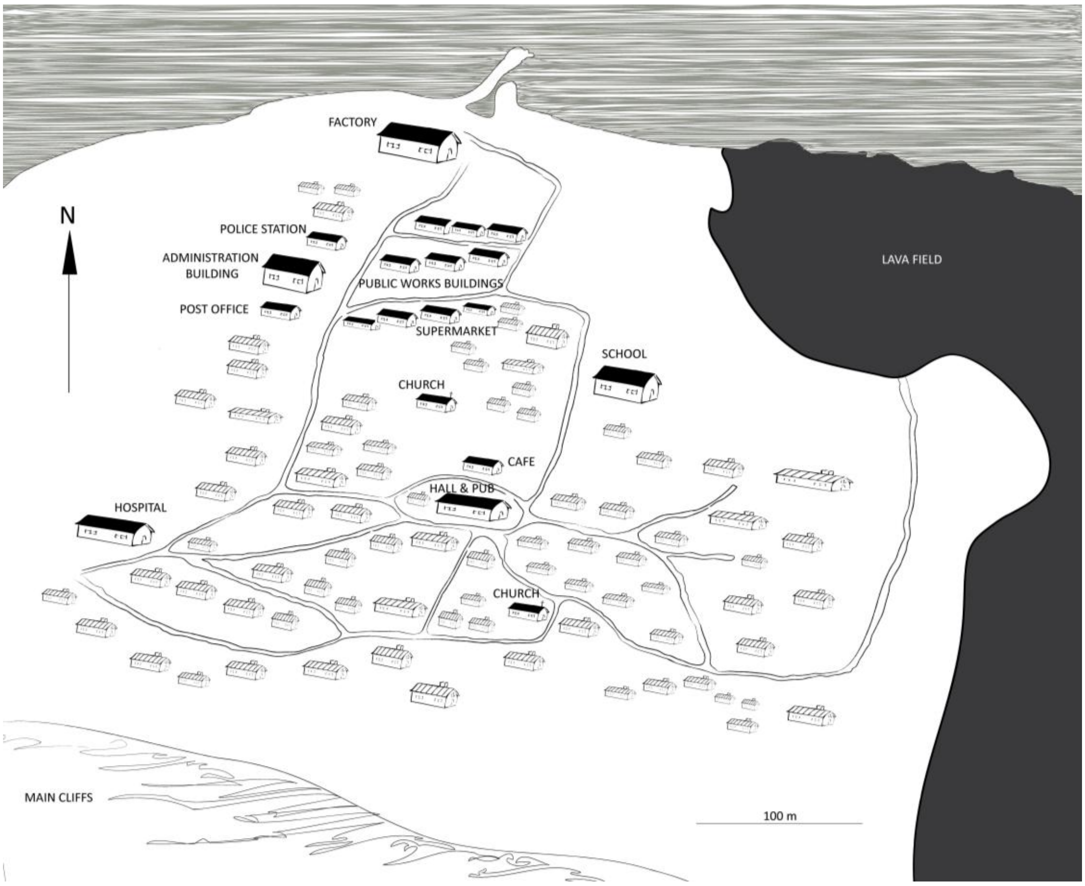


Fig. 5.5. Sketch of Settlement with positions of accommodation, public buildings and offices. Scale is approximate.

St Mary's School educates children from 3-16 and holds a Cambridge Examination Centre certificate, allowing pupils access to take UK standard GCSEs. There is also a Tristan Studies course which fosters enthusiasm for Tristan history, endemic plant and animal species and conservation. Often visitors come to Tristan and offer specialist training in areas that are useful for an island lifestyle, e.g., rope work and scuba diving. Resident ex-patriate teachers were employed on Tristan from the 1940's until 1991, and recently, an education advisor has been employed to train teachers, update the curriculum and improve school buildings. Regular opportunities to progress to further education overseas have decreased in recent years and few adults have A-Level or formal vocational qualifications. Following school, pupils can enter into a Youth Training Scheme which allows them to experience working in several different island 'departments' (e.g., public works or fishing) before taking up their first post.

Camogli Hospital supports one doctor (usually South African) and five nursing staff. The hospital has a small operating theatre and basic equipment equivalent to a mobile army hospital. Most small injuries or non-critical illnesses can be successfully dealt with, and visiting doctors are capable of undertaking minor surgical procedures. Patients requiring specialised diagnosis or treatment are sent to Cape Town, although they still have to wait for a ship to arrive at Tristan and then undertake the seven day journey to South Africa. The hospital does not have the facilities to cope in the event of mass casualties – a significant vulnerability given Tristan's isolation. A dental nurse is employed to perform check-ups on patients, but a dental team visits Tristan annually to manage more complex problems, build and repair dentures. An ophthalmologist also visits on an annual basis.

Prince Philip Hall and the Albatross Bar are located in the centre of the Settlement and host public meetings and weekly entertainment. Wedding receptions, christening parties and milestone birthday celebrations are often held in the hall, usually with the entire population invited (Plate 5.11). Other key events centred on the Hall and bar include prize-giving and celebrations for the annual Ratting Day (rat hunt competition initiated to control the rat population) and Queen's Day (an activity-filled holiday to celebrate the Queen's birthday). Although a weekly dance is held on a Saturday, nowadays this tends only to be attended by young people, as other home-based entertainment is available. This discourages group interaction, particularly in the over 30's, with people opting for small family gatherings or parties with close friends (see Chapter 6). Other Settlement-wide events include Sheep-Shearing Day, when the entire population travel to the Patches; Breaking-Up Day, held on the last Friday before Christmas where each department holds parties to celebrate the holiday; midnight mass on Christmas Eve, and Old Year's Night; a Tristan tradition where a party is held at the Administrator's house and attended by 'Okalolies' - a group of costumed, masked men who scare young women and children (Plate 5.12).

The supermarket sells essential products to supplement home-grown produce, including tinned goods, household items, health products, alcohol, soft drinks and snacks. Basic leisurewear can also be purchased, but almost anything can be ordered months in advance of incoming ships. Although items are cheap in Cape Town (relative to the UK), there is an enormous mark-up to cover the costs of shipping so items can often be 70% more expensive by the time they are placed on shelves. Reliance on imported goods means that islanders and the Tristan economy are vulnerable to the effects of shipping regularity and continuation of buyers in South Africa.

5.3.6.1. Building construction

Traditionally, Tristan homes were built entirely from local materials: blocks of lava and flax for roofing thatch. In order to withstand strong westerly winds, houses were built facing north towards the sea with narrow thick gable ends (Plate 5.13). Interiors were small and simple, with two or three rooms – a bedroom or two, a kitchen and an 'outside room'. Floors, ceilings and walls were lined with wood 'panels' usually made from old packing cases or driftwood (Crawford, 1962).

Modern building materials and techniques have replaced traditional methods, with new buildings (almost all still single storey) created around a timber frame, set with concrete (Plate 5.14). Several of the older houses still retain their gable ends. Flax has now been replaced by brightly coloured aluminium or zinc-coated corrugated roofing, which reduces building time, cost of replacement and lowers fire risk. The unfortunate implication of this upgrade is the loss of thatching skills. Other local materials are used for building, such as scoria and beach sand for cement. Wooden windows have been replaced by metal frames, but traditional wooden stable doors are still used. All homes have plumbing and electricity and most of the standard modern conveniences. Most houses also have garages to reduce corrosion of vehicles. All homes and most public buildings (except the fishing factory) are not protected against seismic activity or severe storms, rendering buildings and inhabitants vulnerable to the effects of these hazards (see Chapter 6).

5.4. Conclusions

Despite a short history of settlement (~200 years), the Tristan population has been frequently confronted with adversity, with almost all events caused or exacerbated by Tristan's geographical position. However, despite their isolation and years of hardship, islanders have proven ability to react, manage and recover from these events. This resilience is likely a function of isolation, a traditional lifestyle, no formal governance, and a strong social fabric. Research on other remote populations has demonstrated that traditional and marginalised communities often develop coping strategies to overcome the effects of natural disasters (e.g., Bates and Peacock, 1982; Passerini, 2000). Nonetheless, there is often damage to the physical or socio-economic environment which may trigger societal change. Alterations to community way of life may be transitory or permanent; fast, slow or incremental, and are dependent on the nature of the hazard, the social fabric of the community, geographic setting and rehabilitation policies (Gaillard, 2007).

This multitude of scenarios prevents the creation of any universal framework for assessing vulnerabilities and characteristics of resilience. However, it is possible to identify local variations by examining the present day social, political and economic context and the drivers of change through history. Consideration of the unique community characteristics may improve ability to better anticipate likely response to natural events and inspect trajectories of cultural change.

This chapter briefly described the history of settlement on Tristan, and highlighted some of the main system shocks the community has endured and overcome. By examining the present day social context, many of the cultural changes that occurred following these events can be observed. The next chapter will further explore the social context through the lens of vulnerability and resilience and focus on the drivers of change which have affected, and may continue to affect responses to natural hazards in the future.

Plate 5.1. Tristan da Cunha: home to the most remote population in the world.

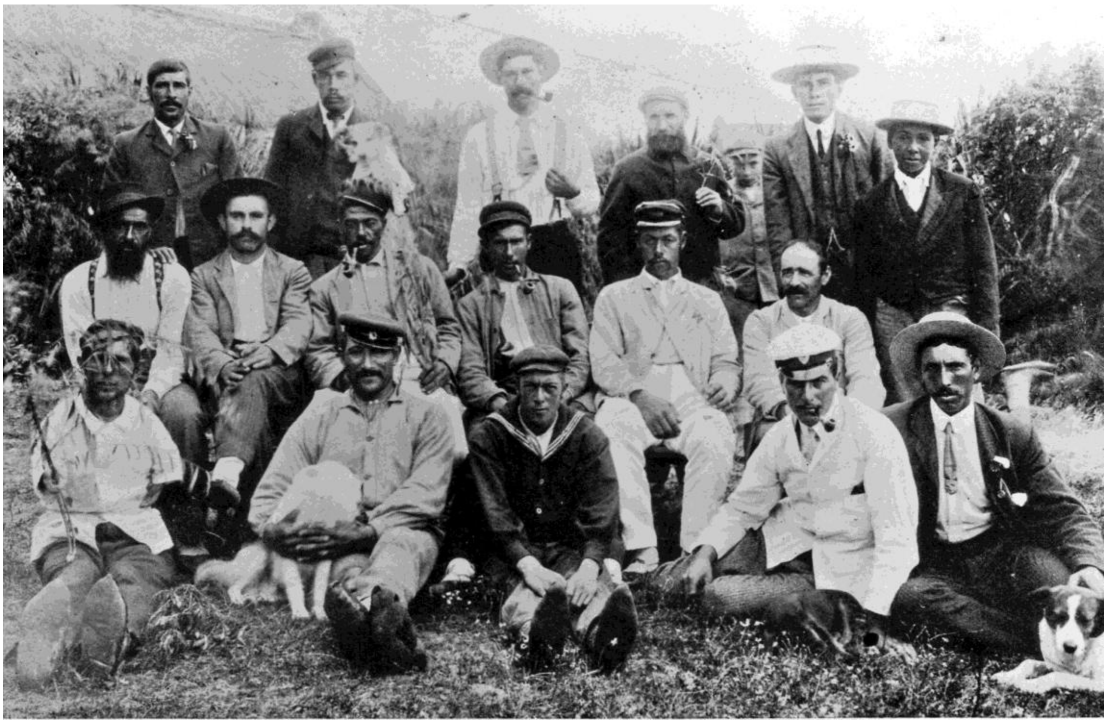


Plate 5.2. Male islanders in 1906. Two of the original settlers, Gaetano Lavarello (middle row, 2nd left) and Andrea Repetto (middle row, far right) are pictured. Photo courtesy of the Tristan da Cunha Photo Portfolio.

Plate 5.3. Restoring Tristan homes following the 1961-62 volcanic eruption. Photo courtesy of the Tristan da Cunha Photo Portfolio: Jim Flint.

Plate 5.4. The Glass family working hard at the Patches 'planting in'.

Plate 5.5. Atlantic yellow-nosed albatross with chick.

Plate 5.6. Northern Rockhopper Penguins.

Plate 5.7. Preparing the crayfish for export.

Plate 5.8. Visitors leaving Calshot Harbour to a waiting ship anchored offshore. Photo courtesy of Desiree Repetto.

Plate 5.9. Harbour under constant wave attack. Photo courtesy of Desiree Repetto.

Plate 5.10. Dance at the village hall. Photo courtesy of the Tristan da Cunha Photo Portfolio.

Plate 5.11. Tristan Old Year’s Night revelers known as Okalolies.

Plate 5.12. Traditional Tristan house with thick gable ends composed of volcanic tuff. Photo courtesy of the Tristan da Cunha Photo Portfolio: Jim Flint.

Plate 5.13. Contemporary housing with sheet roofing and metal window frames. Gable ends have been retained on some homes.

CHAPTER SIX: Vulnerability and resilience on Tristan da Cunha

6.1. Introduction

Disasters are a complex mix of natural or man-made hazard(s) and social causation. Until recently, there has been disproportionate emphasis on research of the hazard itself and, in some disciplines, relative ignorance of the unique set of social characteristics in response to risk (Pelling, 2003). While exposure to hazard is undoubtedly a major component of disaster, it is also important to investigate the complex and dynamic interactions between the social, economic and political systems - and the power relations within them - with the same degree of importance as the assessment and understanding of the natural hazard(s) (Wisner et al., 2008).

Characteristics that affect the vulnerability of a population (e.g., gender, class and race discrimination; lack of entitlements) as well as resilient features (e.g., sustainable livelihoods; personal security; social capital) can, and should, be identified, in order to capture a snapshot of the social context of a community in time and space. Additionally, emphasis on unearthing drivers of vulnerability and spatial and temporal changes, are essential. By appreciating the complexity of social systems and investigating variations in vulnerability through time, attempts can be made to anticipate vulnerability and response to natural hazards in the future (Cutter and Finch, 2008).

Vulnerability is an important concept in disasters and risk reduction research. Successful strategies to reduce vulnerability and build resilience are dependent on bridging the gap between the production of scientific knowledge, international and national policies, and practice within local communities (Gaillard, 2010). It is therefore important for risk reduction research to have a comprehensive understanding of the unique social context so that the underlying risk factors can be addressed.

A brief description of Tristan history and the present day social, political and economic context was presented in Chapter 5. This chapter explores that environment in terms of vulnerability and resilience to natural hazards. Origins of particular community characteristics which have, or may have, affected response and recovery to the effects of natural hazards are examined, as are change drivers (slow and fast) evident through time.

These results will be integrated with knowledge of the volcanic hazard and uncertainty (see Chapters 2, 3 and 4) to inform communication and risk reduction strategies tailored for the Tristan community (see Chapter 7). First, it is necessary to briefly outline the concepts of vulnerability and resilience.

6.2. Vulnerability and resilience

A wealth of literature exists on the identification and assessment of vulnerability from across a broad research base, including socio-ecological systems (SESs), natural hazards and livelihoods. Owing to application in different fields, a plurality of definitions, interpretations and understandings of resilience and vulnerability exist and as such, a thorough review of the existing knowledge on analytical approaches to assessing vulnerability is beyond the scope of this thesis. However, there are common fundamental attributes to these concepts and interrelated theories of adaptive capacity, exposure and sensitivity.

Conventional meanings of vulnerability normally refer to the term negatively, such as susceptibility to harm. In research, the concept stemmed from disaster literature in the early 1970's (e.g., O'Keefe et al., 1976) and whilst divergent analytical approaches have developed over the years, definitions often refer to the characteristics of a person, group and their situation that affects their ability to anticipate, cope with and recover from the impact of disturbances, such as natural hazards (Janssen and Ostrom, 2006; Wisner et al., 2008). Common indicators include: class, occupation, ethnicity, gender, disability, health, age and social capital (e.g., Cutter et al., 2003). The livelihoods literature tends to focus on entitlements and vulnerability indicators in the social realm, whereas natural hazards research also highlights environmental risks and the psychological role of risk perception in creating a more or less vulnerable state. In some studies of SESs, vulnerability is often discussed in terms of availability, distribution and management of resources (Adger, 2006). Others place importance on the institutional conditions of an SES (i.e. social, political and economic organisation), or that a vulnerable state stems from disproportionate interactions between four different forms of capital: natural, human, social and physical. Whilst these differences create problems for locating common ground and promoting cross-disciplinary learning, the different approaches share commonality in that they all see vulnerability as driven by, a) the degree to which a community (system[17]) is exposed to a hazard, b) the sensitivity of the community (i.e. the degree to which a community can absorb impacts without suffering harm

[17] It is noted that most of the terminology used in this section stems from systems research, yet it is more appropriate for this thesis for the term system to be replaced by community.

or significant change) (Adger, 2006; Gallopin, 2006) and, c) the adaptive capacity of the community (some disciplines treat adaptive capacity as response, resilience or carrying capacity) (Cutter et al., 2003; Adger, 2006; Cutter and Finch, 2008).

Resilience is often considered as the reciprocal of vulnerability, and refers to the characteristics of a person, group and/or their situation which positively influence resistance, coping capacity and recovery. It is also commonly referred to as the ability to 'bounce back'. The concept of resilience has its roots in ecology and has been defined by ecologist C.S. Holling as the capacity to persist in the face of change. He proposes that resilience, "determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist" (Holling, 1973). Another aspect of resilience considers the capacity for renewal, reorganisation and development (Gunderson and Holling, 2002; Folke, 2006). Following 'shocks', it is possible for a community to 'bounce forward', following a unique recovery trajectory (Paine et al., 1998) and creating opportunities for positive change and growth.

It is acknowledged that any set of resilient or vulnerable characteristics are context-specific and must be understood from the perspective of the unique social, economic and political environment. After all, a single community can be vulnerable and resilient to certain disturbances and not to others (Gallopin, 2006). Further, it is important to recognise that communities are not static and that vulnerability and resilience are likely to change over time and space as well as scale, e.g., individual and household, to communities, regions and countries. The dynamic nature of communities is central to the concept of adaptive capacity.

Adaptive capacity refers to the ability of a community to cope with, manage or adjust to changing conditions brought about stress, hazard, risk or opportunity (Smit and Wandel, 2006). The concept originated from biology where the ability to adapt rested with a particular structural, functional or behavioural feature of an organism (Dobzhansky, 1968). In a social context, these features are central to creating resilience, and thus enhancing adaptive capacity. Structural features might include, for example, strong institutional networks. Sustainable farming is an example of a functional feature, and behavioural features might include the sharing, and cooperation that comes with strong kinship ties. In times of change, whether rapid or gradual, an adaptive community is able to reconfigure without significant decline in vital functions such as productivity or erosion of social relations and capital (Folke et al., 2002).

Social capital refers to the connections within and between social networks accessed and utilised by actors for actions (Lin, 2001). It is a concept used to explain some of the reasons why communities thrive politically, socially and economically (Bourdieu, 1977; Coleman, 1990; Putnam, 1993, 2000). Whilst a large, somewhat disparate, body of literature exists on social capital, it is Putnam's (1993) definition that is frequently used: 'features of social life – networks, norms and trust – that enable participants to act together more effectively to pursue shared objectives' (Putnam, 1995, pp. 664-665). Social capital is created by trust, reciprocity, bonds and bridges formed by interpersonal relationships. Bonding ties refer to the relationships held between people with a shared social identity, for example, religious or ethnic groups. Bridging ties are social relationships that connect people with shared interests and goals regardless of, for example, class hierarchies. Social capital is usually considered to have a positive effect on communities and has been highlighted as central for local capacity to handle crises and adapt to change (e.g., Lourenco-Lindell, 2001; Adger, 2003). However, there is increasing recognition that strong social ties may in fact serve to increase vulnerability of communities by reproducing perceptions of resilience and restricting adaptation (Wolf et al., 2010; Eriksen and Selboe, 2012).

Determinants of resilience have a clear temporal and spatial component and it is the interaction of determinants in space and time that act to generate adaptive capacity. It is important to acknowledge that characteristics which modify vulnerability and resilience develop temporally and differentially, with both positive and negative consequences (Wisner et al., 2008). In a similar way to investigating vulnerability and resilience, it is important to examine the dynamic drivers at various hierarchical levels, temporal and spatial scales.

In practice, it is challenging to examine and assess these dynamic drivers, especially given the temporal component of vulnerability. For example, gradual changes in exposure or sensitivity, e.g., 'creeping hazards' (Wisner et al., 2008), may be unobservable in real time and studies of effects may be limited to retrospective analyses (e.g., Cutter and Finch, 2008).

Whilst there are a variety of tools and techniques for assessing vulnerability across disciplines, few have been successful at identifying and mitigating the determinants of, and processes that lead to, a vulnerable state. Critics of the social vulnerability concept attribute this in part to the view of vulnerable populations as 'passive victims' (Hewitt, 1997). Others argue that the lack of success with risk reduction strategies stems from Western researchers working with socially constructed representations of what constitutes risk, disaster or a vulnerable population (Bankoff, 2003). Despite the range of epistemological positions on risk, researchers working within the vulnerability paradigm (rather than the hazard paradigm, e.g., Gaillard, 2010), agree that to be successful, risk reduction and resilience-building strategies must integrate improved knowledge of the hazard with understanding of local socio-cultural and political-economic processes, and be developed through engagement with, and continued involvement of stakeholders and decision makers.

The following section describes some of the models frequently employed in natural hazards, disasters and SESs research, in order to assess characteristics of vulnerability and resilience within a population. Each has particular drawbacks, so specific elements have been selected as tools to inform this research (see Section 6.4).

6.3. Models for understanding vulnerability and resilience

The pressure and release model (PAR) (Fig. 6.1) is a way of understanding disaster as the intersection between two opposing forces: a vulnerable population and physical exposure to natural hazards. By way of a chain of causation, a population reaches a vulnerable state by progressing from root causes (e.g., economic, demographic and political processes), through localised pressures (e.g., migration patterns or deforestation) to unsafe conditions, whereby forms of vulnerability are expressed (e.g., lack of social cohesion, gender, race, or age discrimination) (Blaikie et al., 1994). Pressure can come from both sides, but in order to relieve ('release') the pressure, vulnerability has to be reduced.

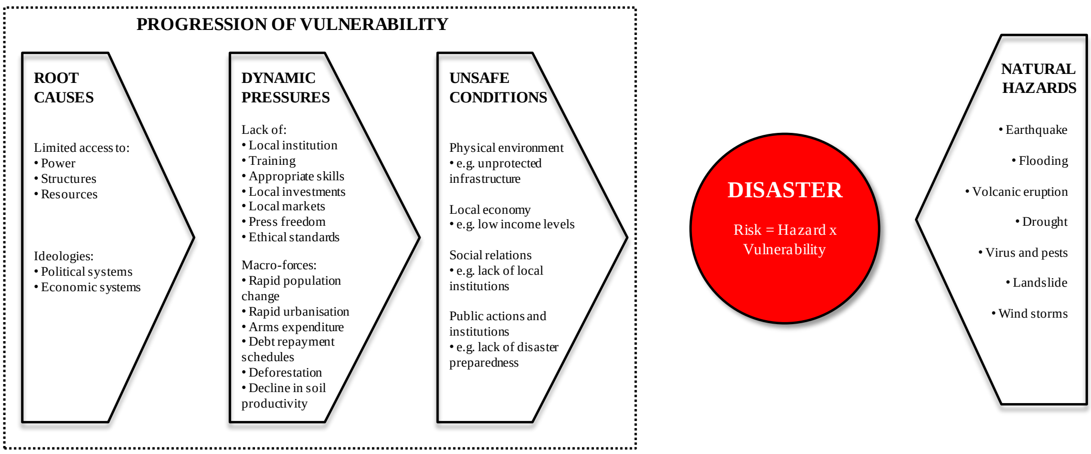


Fig. 6.1. The progression of vulnerability within the Pressure and Release (PAR) model. Adapted from Blaikie et al., (1994).

However, this model is essentially static and does not account for the structure of the hazard's causal sequence before, during, or after a disaster unfolds. It also fails to provide adequate detail on the feedback beyond the system of analysis. An alternative, although complementary, model known as the 'Access' model (Fig. 6.2) expands the analysis of factors that contribute to vulnerability and exposure, by focusing on the detail of 'normal life' before the disaster. It explores complex sets of social events and longer term processes which contribute to the amount of access people have to particular resources (e.g., economic or political resources) and the progression of vulnerability to a 'pressure point' (Wisner et al., 2008). It attempts to help acknowledge variations in vulnerability between individuals and households (or even at wider scales), and understand how and why that vulnerability is established and its trajectory to the point of disaster. The model also sets out to analyse the impacts of disaster and how people cope and recover. Unlike the PAR model, it does not separate hazard from social processes. However, both models focus on the economic and political processes of everyday life, yet fail to acknowledge important non-tangible assets such as social capital and other social capacities that enable coping or adaptation.

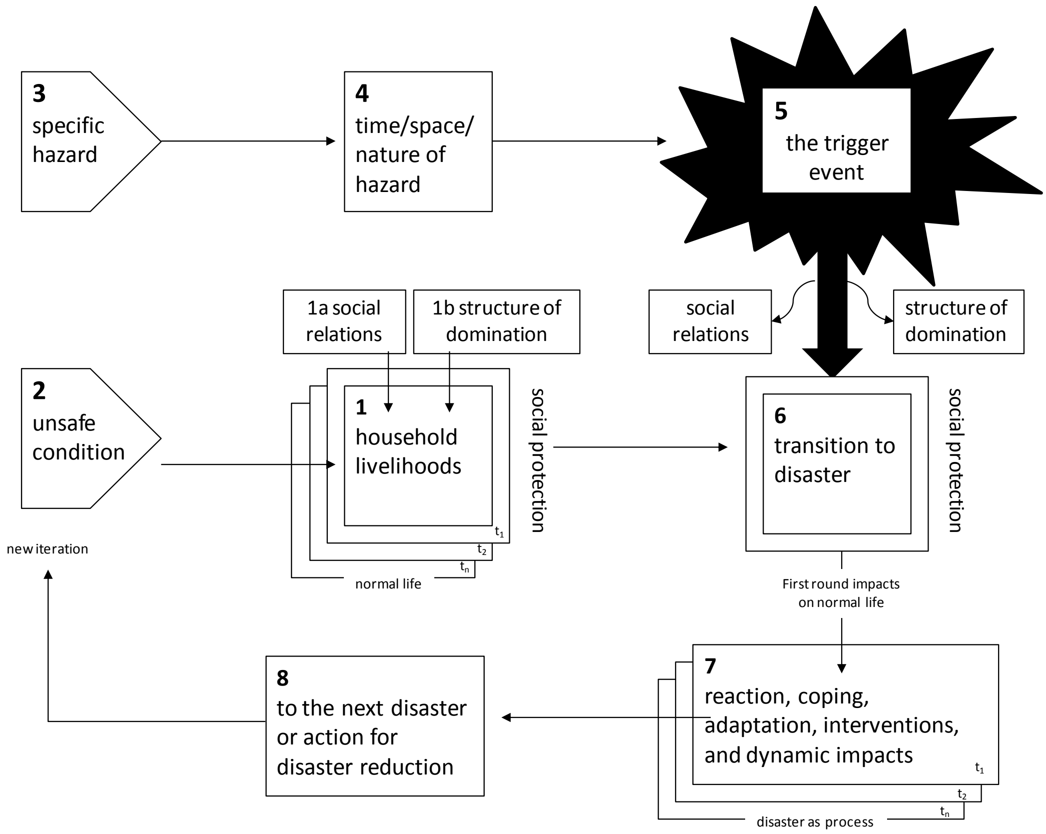


Fig. 6.2. The Access model in outline. Each numbered box represents a set of related ideas or an event. The arrows are cause and effect linkages. Where multiple box layers are present (Box 1 and 7), these can be 'unpacked' to reveal iterations of livelihood decisions or disaster scenarios. Adapted from Wisner et al., (2008).

A related model, although not specifically designed with disasters in mind, is the sustainable livelihoods (SL) approach (Fig. 6.3). This approach was created from developmental strategies such as poverty reduction and sustainable development, and similarly to the Access model, implies that system shocks or stresses are related to non-sustainable livelihoods. However, instead of focussing on vulnerability to hazards (of which livelihoods are a part), an SL approach takes a developmental perspective and puts livelihoods at the centre of the analysis (Scoones, 1998). The approach explains livelihoods as drawing on five sources of capital: human (e.g., skills and knowledge); social (e.g., networks and shared norms); physical (e.g., infrastructure and technology); financial (e.g., savings and credit), and natural (e.g., resources and water). By focussing on these five groups of capacities and the vulnerability context in which people live their lives, analysts can then work outwards to examine the structures and processes (i.e. government and policies) that generate livelihood strategies and lead to particular outcomes. The route to achieving desirable livelihood outcomes such as improved food security or increased well-being can then be discussed and appropriate entry points for supporting livelihoods visualised (Twigg, 2001). Unlike other vulnerability models, it recognises the diversity of actors and influences that determine vulnerability, as well as the dynamic nature of those determinants in space, time and scale. It is used as a tool for stakeholder engagement and is designed to be participatory.

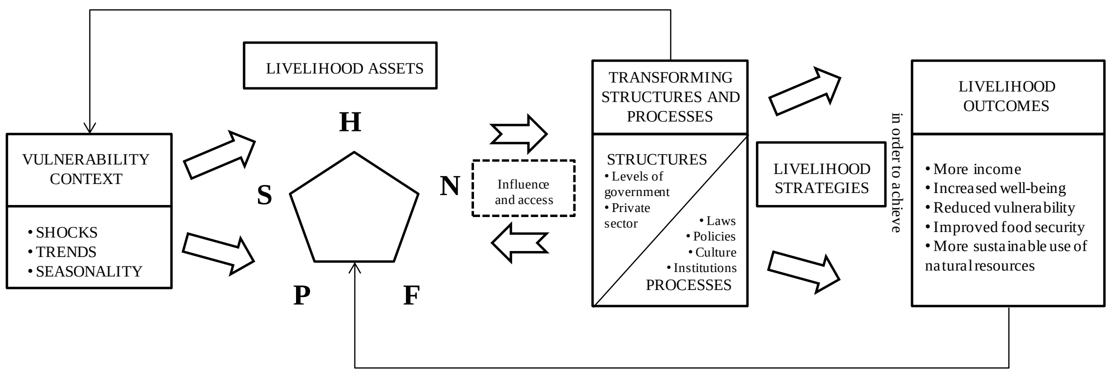


Fig. 6.3. Sustainable livelihoods approach. H = human capital; N = natural capital; F = financial capital; P = physical capital; S = social capital. Source: Ashley and Carney (1999).

A capacities and vulnerabilities analysis (CVA) is a simple matrix for analysing the vulnerabilities and capacities of a population in three broad, interrelated areas: physical/material, social/organisational and motivational/attitudinal (Fig. 6.4). This is a practical approach commonly used by NGO’s for designing and evaluating projects and for disaster preparedness and mitigation (Twigg, 2001).

	Vulnerabilities	Capacities
Physical/material What productive resource, skills and hazards exist?		
Social/organisational What are the relations and organisation among people?		
Motivational/attitudinal How does the community view its ability to create change?		

Fig. 6.4. Capacities and vulnerabilities analysis (CVA) matrix.

This analytical framework helps to 'map' a complex, yet real situation and, critically, highlights the importance of identifying capacities. Acknowledging the 'strengths' of a population facilitates tailored and effective design and implementation of disaster responses that can have positive developmental impacts. Unlike other analytical tools, the CVA matrix also gives equal weight to analyses of the particular social context, encouraging researchers to identify sources of social capital (e.g., group organisation, cohesiveness, shared values and beliefs) which may act to increase resilience to hazards. Although this model can be easily operationalised, it fails to provide specific indicators of vulnerabilities and capacities and their spatio-temporal variation, and like the SL approach, focuses on the human aspects of disasters and downplays the importance of natural hazards.

While some of the models acknowledge the role of the hazard and do not disconnect the social and physical context, none of the models actually examine the physical hazard processes, for example, variability, uncertainty, return periods, etc, and their relationship to social capacities and processes. A further limitation of all of these models is that they fail to adequately address the dynamic nature of vulnerability. Vulnerability is a complex concept and the multidimensionality of each unique community cannot be effectively represented by any number of indicators, frameworks or definitions. While these models offer a useful guide, they must be used in conjunction with the participation of stakeholders in order to keep analyses context-driven.

Tools from systems research can provide useful ways of considering the dynamics of communities and the creation and reduction of vulnerability. The adaptive cycle (Fig. 6.5) is a model originally designed to study the dynamics of ecosystems (Holling, 2001), although the concepts can be applied to other systems. The cycle is composed of four recurring phases: growth/exploitation; conservation; release and reorganisation. The growth, or exploitation, phase reflects the availability of resources in a system (or community). A system usually transitions rapidly through to a phase of conservation, where resources are depleted and changes are slow. This is succeeded by a release stage, where resources are suddenly released and changes are very rapid, followed by a reorganisation or stage of renewal, where capitals (e.g., human, social, financial) are altered and innovations or 'windows of opportunity' can be presented. The cycle then begins again. In reality, there might be multiple transitions through the phases and it may not reflect a cycle at all. There may also be smaller, faster adaptive phases within large, slower cycles. This nested hierarchy of adaptive cycle is a concept known as panarchy (Gunderson and Holling, 2002). In a social context, panarchy can be a useful way of considering multiple spatio-temporal adaptations within communities.

A disadvantage of the adaptive cycle, in terms of its efficacy for natural hazards research, is that it does not incorporate major 'system shocks', especially infrequent events.

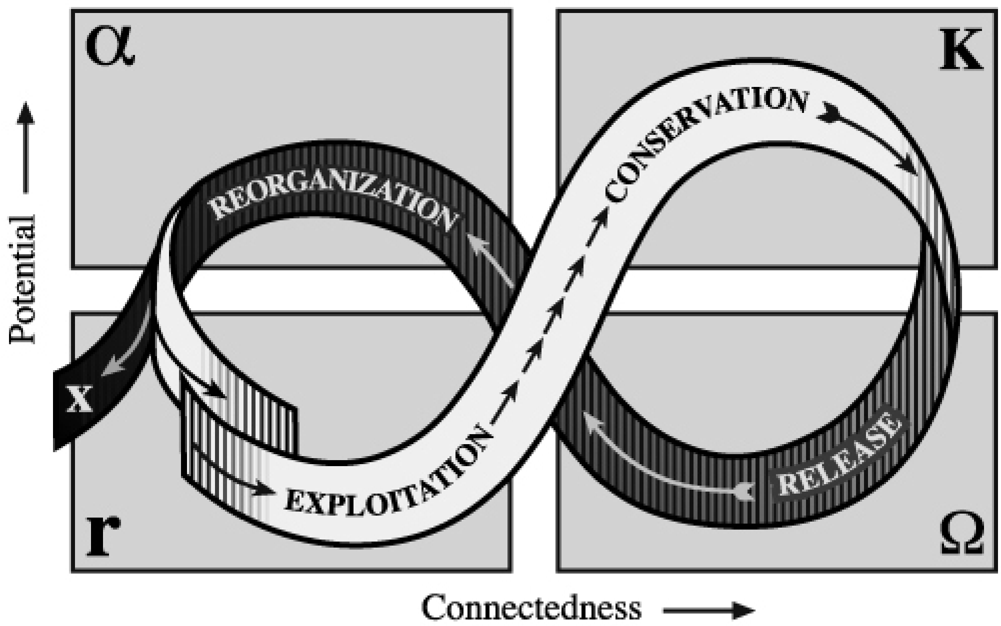


Fig. 6.5. The adaptive cycle. The cycle is composed of four recurring phases: growth, conservation, release and reorganisation. Source: Gunderson and Holling (2002).

The remainder of this chapter focuses on the socio-cultural, political and economic characteristics of the Tristan community, identifying and examining them as dynamic drivers of resilience and vulnerability to hazards. No particular model was considered completely appropriate for the case study context and the research aims, so to avoid 'shoehorning' the context into a specific model, relevant components of several models were used as tools to frame data gathering and analysis. The methodology is discussed below. Reflections on the effect of major 'system shocks' during the history of the community will be discussed, alongside the potential community transitions those shocks have instigated or catalysed. Present day social, economic and political characteristics will be examined with a discussion of potential trajectories which may serve to alter community vulnerability and resilience in the future.

6.4. Methodological approach

The aim of this research component was to become familiar with the Tristan community with a focus on both identifying vulnerable characteristics which may act to weaken risk defences, and recognising ways in which resilience could be strengthened. It was important to first determine broad facts about the community e.g., economic conditions; political structure; history; details of infrastructure; resources and entitlements (see Chapter 5). From this informed position, complex intra-island relationships, group dynamics and differing risk perceptions could be investigated, and the connections, causal relationships and feedbacks between them unravelled. In order to recognise the highly dynamic nature of risk, it was also important to consider community alterations through time, alongside this static snapshot. This element of the research was sensitized around community transformations in light of the forced displacement in 1961-63, and a consideration of the type (if any) of community transformation following the recent introduction of multi-media.

In order to avoid observational bias, no one concept or model (see Sections 6.2 and 6.3) was applied to examine the social context. Rather, particular components were used as sensitising tools. These initial ideas provided a general sense of reference and signalled possible lines of enquiry (Blumer, 1954; van den Hoonaard, 1997). Further research defined the applicability (or not) of these frameworks to the particular social context and, by employing selected elements of the models, a more comprehensive exploration was undertaken in the second field season. Community vulnerability and resilience were analysed within a framework similar to the CVA matrix and the spatial and temporal component of the adaptive cycle enabled an analysis of the changes within the community over time, as well as acknowledgement of how those changes may have altered levels of resilience to risk.

Similarly to framework design, methods of data collection were drawn from a broad 'toolkit'; with selections becoming more defined as research progressed. In this way, initial impartiality could be achieved and this particular component of the research could evolve in an iterative-inductive manner. Method choices had to be carefully balanced with gaining and keeping trust with islanders. Mixed methods (i.e. qualitative and quantitative) included: questionnaires, structured, semi-structured and unstructured interviews, surveys, participant observation techniques and focus group ideas. However, as research progressed it became apparent that certain methodologies were inappropriate for the Tristan context. In practice, approaches were restricted on practical grounds (e.g., range of literacy levels), psychological reasons (e.g., reticence with some outsiders due to unpleasant experiences with probing scientists and journalists), and because any method other than purposeful conversations and observation, on Tristan, would fail to achieve the degree of trust required to fulfil project aims (see Chapters 1, 7 and 8).

Therefore, an ethnographic approach was adopted, integrating participant observation techniques with interview data gathered from on-and off-island decision makers; discussions with Tristan association members; historical records and relevant published and unpublished literature. Given the time constraints of the project, 'doing' ethnographic fieldwork in its traditional sense, i.e. living with a community for an extended period of time (usually a year or more), was impossible. As the phrase micro-ethnography (in terms of scale, not time) is somewhat oxymoronic (Wolcott, 1999), a more appropriate label for this style of research is ethnographic reconnaissance.

6.4.1. Ethnography

Ethnography, however detailed, is not a prescribed set of methods but is most commonly associated with participant observation. This involves the researcher participating in the daily lives of other people, listening, asking questions, collecting documents and assembling any available data that inform research. The strength of an ethnographic approach is that access to the 'native's point of view' is granted (Schwartzman, 1993). Researchers can understand parts of the world as they are experienced and understood in the everyday lives of people who actually 'live them out'' (Cook and Crang, 1995). Whilst critics of the ethnographic approach usually focus on the perceived subjectivity of conclusions, it is precisely this subjectivity which gives ethnographic data reliability. 'Doing' ethnography involves a challenging process of drawing out, recording and understanding the numerous ways in which people make sense of events around them. These inter-subjective truths reveal much about how different people perceive the world and the larger social, cultural, economic and political processes that shape those perceptions (Cook and Crang, 1995). Simultaneously, ethnographers must acknowledge and incorporate the role of social and cultural theories (and build new ones) whilst continuously reflecting on their position and effect on the research process. Reflexivity is an important concept in social research; acknowledging the unique biographical particulars of a researcher and the effects of individual values, beliefs and interests on the community under study (Hammersley and Atkinson, 2007). After all, the worldview and values held by the researcher; or indeed of those being studied may, whether consciously or unconsciously, act to shape the research. The quality of ethnographies, and thus research, are therefore dependent on openness throughout all stages of the research process, with particular attention paid to possible bias.

Ethnographic studies are commonly employed in disasters research, although studies usually focus on recovery or post-disaster events (e.g., Klinenberg, 1999; Klinenberg, 2002; Cox and Perry, 2011). Due to the unpredictability of disasters, it is rare that ethnographies study pre-disaster conditions[18], although the benefit of such data for measuring change and for tailoring risk reduction strategies are obvious (e.g., Sheets, 1979; Doughty, 1999). In the face of rigorous time constraints (both from a research perspective and in light of potential crises), it is difficult, if not impossible, to capture ethnographic thoroughness and researchers are often restricted to employment of ethnographic 'methods' in a relatively expeditious fashion, such as rapid rural appraisal or participatory rural appraisal (PRA). PRA provides a useful 'insider' perspective and is an often purposeful way to enable rural people to share, analyse, plan and act (Chambers, 1994). Whilst there have been some very innovative studies in volcanic risk reduction which demonstrate sensitivity to traditional knowledge and community empowerment (Cronin et al., 2004a; Cronin et al., 2004b; Haynes et al., 2007; Mercer et al., 2007; Mercer et al., 2008; Donovan, 2010), few studies delve into the complexities of the historical and present day socio-cultural context, key social, economic and political drivers.

[18] In the case of Tristan, this ethnography could be considered as a study of pre-disaster circumstances, but also a study of post-post disaster conditions, i.e. not only after the 1961 eruption but also after the return and recovery.

6.4.2. Ethnographic reconnaissance on Tristan

Ethnographic studies are often fraught with difficulties of gaining access and the manner of field relations (Hammersley and Atkinson, 2007). Gaining access to Tristan (both the island and the community) was discussed in Chapter 1, although it is noted that a volcanic hazard assessment and risk reduction program was a shared goal (between the researcher and the Island Council) and facilitated access to the island. As research progressed it became clear that gradual immersion into the community was essential to develop trust with islanders and cultivate valuable connections (and also, to have a pleasant research experience). As Giacomi et al., (1993) state, “the only way of gaining access to the activities of the community is to assume an active role; simply being an observer to events is not acceptable”. As a Western society with British traditions, Tristan’s cultural rules and situational roles were not unfamiliar, yet considerable time and care was taken to participate in everyday community activities, e.g., “planting in” (potatoes) or attending birthday parties, in order to learn and understand particular values, practices and thought-ways, with the aim of tailoring risk reduction strategies appropriate to the local context.

While most of the qualitative data gathering was observational and not conducted overtly, the role of the researcher and the aims of the research were not concealed from community members. Historical records and relevant research data (e.g., Munch, 1964) were integrated with information gathered in the field about the community and their activities. This required the active involvement of community members and the engagement of decision makers. Purposeful conversations were held when appropriate, almost always under informal circumstances and often within homes as one-to-one discussions, or at the local bar with a larger group. Astute questioning was balanced with empathetic listening in order to identify current knowledge and discern what information islanders required (Pidgeon and Fischhoff, 2011). No one particular person or viewpoint was relied upon more than another and data sources were triangulated to cross-check. A detailed log of interactions, observations and conversations was kept. Results from this ethnographic reconnaissance, and work by other authors, are presented and discussed below.

6.5. Results & discussion

Many of the present day characteristics of the islanders, and their practices, reflect the decisions and adjustments made following major events in local history. As the community adapted and reorganised following ‘system shocks’, for example the 1885 lifeboat disaster and the 1961-62 volcanic eruption (see Chapter 5), new circumstances and behaviour modifications also altered vulnerability.

The following sections describe and discuss present day vulnerabilities and characteristics of resilience, and examine the temporal effects on vulnerability of the 1961-62 eruption and the recent introduction of multi-media. Examining the drivers of vulnerability, inherent resilience and adaptation through time is an important part of understanding the conditions of daily life that have and could prefigure disasters.

6.5.1. Vulnerability on Tristan – present day

Causes of vulnerability on Tristan are rooted in the island's geographical location. Physical isolation has created disproportionate vulnerability to a spectrum of threats from natural hazards to societal, biological, ecological and economic risks. Located over 2,800 km from the nearest mainland, Tristan has very restricted access to global economy networks, aid resources, employment and training opportunities, and emergency healthcare. Further, dependence on one mode of transportation (ship) to and from Tristan controls speed of access. For example, in the event of mass casualties or damage to the Settlement, aid would take many days to arrive, even if mobilised immediately. In addition to the handicap of delay and inconsistency, the limitations of transport by ship create further problems, both in terms of the challenges of navigating in rough seas and poor weather, the restricted number of berths available for passengers (~12) and the lack of direct access to Tristan's small harbour. Great risk is attached to navigation between anchored vessels and the harbour, in terms of life and limb (access to ships is often restricted to rope ladders), but also in terms of cargo. Due to the high premiums levied by insurance companies, imported goods are not insured. The financial risk of losing cargo presents quite a gamble for islanders wishing to procure expensive items such as a refrigerator or a car. Further, an anchored vessel that cannot be offloaded or back-loaded due to poor weather creates economic stress for the Tristan government (and thus the islanders).

Location currently restricts Tristan from diversifying its economy. Since the fishing industry was established in 1949, Tristan has been exporting crayfish to US and Japanese markets, and approximately 78% of the economy depends on this single resource (E. Mackenzie, pers. comm.). Therefore the economy is vulnerable not only to poor weather (which prevents fishing), but also to global economic change, environmental change and ecological disaster.

In March 2011, the bulk carrier MV Oliva ran aground on nearby Nightingale Island, spilling approximately 1,500 tonnes of fuel oil and 6,000 tonnes of soya beans into the sea. Although the effect on the local wildlife was immediately devastating (< 10% survival rate of rescued Northern Rockhopper penguins [endangered]), the impact on the crayfish industry has yet to be determined. The Nightingale fishing grounds remain closed and a monitoring program has been created to ascertain the effects on the juvenile lobster population which, in turn, may affect the fishery and thus the economy in the future. Islanders are not resistant to diversification and additional revenue is created through tourism and philatelic services, although tourism is restricted to visitors from passing yachts, expedition ships and the annual visit of the Gough Island relief vessel (the *SA Agulhas II*). Changeable weather means that landings from all but the relief vessel (which has a helicopter) are not guaranteed. Irregular and undefined earnings weaken Tristan’s economic defences, and the reliance on a high income, high risk export means that the financial system is susceptible to global economic downturns.

Further, the environmental and ecological system is also vulnerable. Many endangered species, for example the Northern Rockhopper Penguin and Yellow Nosed Albatross are endemic to Tristan and neighbouring islands. Whilst these species live on Tristan *because* of the location, their concentrated numbers means that they are highly vulnerable to environmental fluctuations (e.g., climate variation, ecosystem shifts, over-fishing). In 2006, a Brazilian semi-submersible platform became stranded at Tristan and brought with it an abundance of foreign species, some of which have now become established around the island and may have had impact on native species. Although Tristan has a conservation department (established in 2008), and a Conservation Ordinance which stipulates bio-security measures such as clothing and equipment checks (for foreign seeds), this is not currently not enforced, particularly for the small number of passengers arriving on fishing or cargo ships. Despite eradication attempts, endemic bird species continue to be threatened by rats and mice, which were introduced to Tristan nearly 130 years ago. Conserving wildlife is not only an important activity for the future of the species; it attracts tourists to the area, promotes environmental management and heritage conservation, and fosters responsibility and community participation.

Tristan’s location means the population is at risk from a range of geophysical hazards, such as storms, earthquakes and tsunami (see Chapter 2). As the latest manifestation of the Tristan hotspot, the volcano is also likely to erupt again in the future, although the location, size and style of eruption are uncertain (see Chapters 3 and 4). Remoteness would hamper the rapid transfer of aid in the event of natural disaster; however, physical aspects of the island also serve to increase vulnerability. As a high, steep mountain, Tristan's slopes rapidly transport material (e.g., water, rock, eruptive products) downhill, normally channelled via deeply incised gulches. Flash flooding is common following heavy, prolonged rainfall, yet there are currently no monitoring measures in place to determine the quantity of rainfall, record mass movements or assess slope instability. Sheer cliffs also make it difficult for islanders to safely access the mountain and would certainly prevent infirm islanders and many of the elderly from reaching the Base. In an event where the Settlement coastal strip was deemed uninhabitable, the only way for the entire population to be 'safely' transferred to another part of the island, or elsewhere, would be by boat.

In terms of infrastructure vulnerability, the fishing factory (Plate 7.1) is the only building on the island constructed with earthquake engineering or storm protection in mind. The distinct, two-storey structure was constructed to withstand wind speeds up to 100 knots and seismic activity up to 7.5 on the Richter scale. Due to the paucity of volcanic eruptions and seismic activity, no buildings have been constructed with a view to moderate the effects of likely eruptive products or seismicity. Therefore, buildings present several structural vulnerabilities to volcanic hazards and are of relatively high risk to occupants in the event of an eruption proximal to the Settlement. For example, sheet roofs are particularly vulnerable to collapse from tephra fall; single storey buildings present higher risk of injury and fatality to occupants than two or three storey buildings; windows would not withstand the impact of small ballistics; and timber framed buildings would be at risk from lava flows (Pomonis et al., 1999; Spence et al., 2005; Spence et al., 2007). Further, many homes, especially older ones have been built directly on to the ground and have no foundation walls (Munch, 1971). It is noted, however, that although many of the Tristan buildings were damaged (but not beyond repair) by seismic activity associated with the 1961 eruption (approximately $M \leq 6$), none suffered damage from the $M = 4.8$ activity in 2004.

A seemingly infinite supply of clean spring water is one resource that is often taken for-granted. Large-scale slope failure, tectonic or magmatic activity, for example, could alter the hydrological system, possibly contaminating water, reducing flow or stopping it altogether. It was suggested that the drainage system changed following seismic activity in 2004 (Hards, 2004), so future alterations to meteoric water flow are possible. This makes islanders highly susceptible to environmental threats which could affect water supply. In order to reduce this vulnerability, it is important for islanders to locate all alternative springs, investigate ways in which that water can be transported to the Settlement, and retain an emergency stock of drinking water.

Plate 6.1. The distinctive fishing factory, built in 2009, can withstand wind speeds up to 100 knots and seismic activity up to 7.5 on the Richter scale. Photo courtesy of the Tristan da Cunha Photo Portfolio.

Vulnerability to natural hazards (and other risks) is also exacerbated by a complex network of social interaction and behaviour, some of which can be traced to recent developments within the community and others which have historical roots. For example, as mentioned in Chapter 5, asthma and other bronchial conditions are prevalent, likely a genetic condition that was introduced by the early settlers (Slutsky et al., 1997). Over 50% of the islanders are afflicted with the disease and the majority of the rest suffer with similar, less chronic bronchial conditions. This has consequences, for example, in the event of a volcanic eruption. Even small volumes of ash and gas are likely to aggravate breathing difficulties and may influence the type of evacuation measure and speed of response. Remoteness has weakened immunity from common infections and there is a persistent risk of cold and influenza epidemics initiated by transmission from passengers on visiting ships (Samuels, 1963). Extreme actions such as school closure are occasionally required in order to prevent further transmission. Joint problems in the elderly (likely caused by labour-intensive work in the Patches) and diabetes (likely exacerbated by unhealthy diets) are also common. Whilst islander diet still relies heavily on meat, fish, potatoes and eggs; processed foods, snacks, sugary drinks and alcohol are in abundance and regularly consumed. From observations alone, fat and alcohol consumption has escalated since the last nutritional study in 1966 (Chambers and Lewis, 1969). Combined with the increased reliance on motor vehicles, a rise in sedentary occupations and a lack of recreational exercise, fitness levels have diminished. Health problems create strain on island health provisions and the increasing number of patients requiring medical treatment overseas is a burden on the economy. As islanders do not have medical insurance, the Tristan government incurs vast costs associated with sending patients (and a carer) abroad for treatment. This strain is likely to increase with escalating health problems and an aging population. In terms of vulnerability to natural hazards, weak health, moderate fitness levels and an elderly population will be problematic in the event of an incident of rapid onset that necessarily requires a swift response.

Also of direct significance to vulnerability to natural hazards is the decline in knowledge of the mountain. The few islanders that do walk up to the Base (almost always men) tend to frequent the same areas (to tend to sheep, for example) and rarely visit relatively distant locations for recreation or out of curiosity. Therefore, alterations in the natural environment are unlikely to be observed or recorded and an innate understanding of what constitutes 'normal' will diminish.

6.5.2 Cultural adjustments: drivers of vulnerability and resilience

There have been many events in Tristan history which brought about change in the community, for example, the World War II garrison introducing cash transactions, and the establishment of the first British Administrator altering community organisation. However, no event initiated cultural change as rapidly as the 1961 eruption and evacuation.

The volcanic eruption in October 1961 initiated a cultural transformation of the islanders. Until the eruption, many islanders were unaware of the possibility the volcano was active. Prior to 1961, the community was in a period of economic growth, but the rapid, reactive evacuation of the community propelled them into an alternative reality. The evacuation itself was decided by the Administrator, but was facilitated by the knowledge that a ship was passing Tristan and was capable of evacuating the entire population. If this ship had not been in the vicinity, the islanders could have monitored the eruption from Nightingale, or a group could have stayed at the Patches to monitor the progress of the eruption and its effects on the Settlement. It is possible that an evacuation may have been avoided with better scientific advice, knowledge of volcanology and improved communication with UK scientists. When the islanders finally arrived in the UK, they were subjected to a barrage of media and medical attention, because they were seen as a largely forgotten community with a distinct genetic heritage. Owing partly to this attention, the Chief Islander at the time decided to fight for the community to be kept together and so eventually the whole community was housed in one location. As stated in Chapter 5, this was a very significant decision in Tristan's history. If the Chief Islander had not achieved this, it is highly probable that people would have been separated throughout the UK and ultimately may have reduced the number of islanders who decided to return to the island, if they returned at all. When interviewed in 2011, one islander acknowledged the significance of this decision, "but the mistake the government made was that he put us in one plot, a little army RAF base at Calshot. If he had of dotted us all over the country, the Tristan people couldn't got together to say right, we wanna sign a petition, we is going back to our home." By staying together, the community defended and retained much of their cultural identity, although certain changes were inexorable.

During their stay in the UK, islanders became accustomed to the British way of life. They had access to modern music, style of dress, entertainment, modern conveniences and other luxuries. When the islanders decided to return to Tristan, they took with them a set of new skills, knowledge of the latest trends, a more cosmopolitan outlook and sense of equality between them and 'outsiders'. Even though they returned to their island, the cultural alterations were unmistakable. Once the community had stabilised and become re-established, life on the island assumed a new, more urbane, normality. Some changes were fairly obvious, for example the replacement of longboats with motorised dinghies; the introduction of cars; adoption of modern dress, music and furnishings. Changes in the attitudes of islanders were also apparent. The social distance between islanders and outsiders had narrowed, likely a result of equal access to modernity and the establishment of the British Administration ten years prior (interactions with the outside world gradually became less unusual) (Munch, 1971). These changes had consequences for the vulnerability and resilience of the islanders. On the one hand, these alterations increased vulnerability as traditional practices were replaced with modern ones that relied on machinery and outside assistance. On the other hand, these changes strengthened the community, increasing stocks of social capital, and thus building resilience. Regardless of being submersed in an industrial society for two years, the islanders had retained their original values of equality, mutual aid and selective reciprocity. As Munch (1971) recalls when he visited Tristan in 1964, "if anything, the islanders had developed a greater awareness of their own identity as Tristan[ians], and a deeper appreciation of their own way of life as a value to be cherished and preserved, as something that set them apart and made them unique but far from inferior to the man from outside." Further, while the British Administration could be seen to have removed control from islanders (although, arguably, they never wanted to retain control), these links with the UK were, and have since been a source of support for Tristan. Both the resilient qualities of the islanders and the support of the UK government have been essential in overcoming the damaging effects of other natural and accidental events, for example, the severe storm in 2001, the factory fire and the harbour rehabilitation (see timeline in Chapter 5, Figure 5.2). An unintended consequence of this, however, is the tendency for some islanders to expect the UK government to 'rescue' them in the event of a crisis. This view has likely been motivated further by good communications reducing the perceived distance between Tristan and the 'outside'.

The recent introduction (early 2000's) of modern media, technology and communications to Tristan has resulted in other transformations in the community, especially regarding islander interaction. Telephones have facilitated simple and rapid transfer of information, and islanders regularly make quick calls to each other rather than visiting. Conversing with family and friends overseas via telephone or the internet is now cheap and effortless. Although a wireless system is yet to be fully functional (broadband was installed on the island in 2004), islanders now have access to the World Wide Web and regularly use email and social networking facilities. Whilst these new forms of communication have added to the range of communication options, rather than completely destroying old ones, they have altered the significance and functions of earlier methods (Meyrowitz, 1985). The effects of new media and entertainment are analogous. Almost every home has a television and British Forces programmes such as national news, soap operas and popular evening entertainment are streamed continuously. Television has been promptly accepted into the community, probably as a result of earlier introduction during the 1961-63 UK sojourn. However, television has had significant consequences for the usage and purpose of social spaces in the Settlement. Before television, Tristan's isolation imposed a set of boundaries, whereby social interaction was restricted purely to those within the community, with the occasional visit from outside. At this point in time there was a strong relationship between physical and social 'place'. Islanders frequently used to visit the local pub or attend the weekly dance at the village hall to socialise. The advent of television and the introduction of digital entertainment have changed the frequency of social interactions, with some individuals and families preferring to stay at home and watch a film or enjoy popular Saturday night entertainment shows instead of socialising with friends and family. New media and technological innovations may not be the sole explanation for any unintended social change, but they are likely to have been a major contributing factor. Tristan has now entered the communication age and whilst the effects on the community may seem adverse, adaptations are currently at work to accept and find advantage in this newly introduced technology.

From a vulnerability perspective however, it is important to consider the consequences of these social adaptations for community cohesion and stocks of social capital. For example, in terms of response to the effects of natural hazards, it is possible that altered interactions, as a result of communication changes, are undermining the cultural characteristics necessary for resilience. While group activity is still widespread, there is a sense that, in cultural terms, the community is gradually returning to the 'atomism' of pre-1961 culture (independent working or as family units), albeit with declining self-sufficiency. At present, however, any apparent eroding effect (on resilience) is negligible. A clear sense of community persists and it is likely that collective capacities are still inherent within the population. Nevertheless, it is prudent to recognise that the effects of modernisation processes, including changes in the provision and consumption of media and communications, which can be observed today, may signal a developmental trajectory in which a future Tristan community might not retain these inherent capacities and may become increasingly reliant on imported goods and 'outside' assistance. In those circumstances, given that their geographical isolation will not change and that similarly, the physical hazards associated with that will also remain constant (and in the case of climate change perhaps even represent greater extremes of behaviour), the Tristan community may become increasingly vulnerable to the effects of natural hazards.

The demonstrable effects of media on society exemplify a relatively rapid transition from a homeostatic, 'traditional'[19] society to one which is under increasing pressure from modernisation. Modernisation has adversely affected many customary practices, especially knowledge of traditional crafts and skills such as sailing and thatching. Few islanders know how to make Tristan moccasins, for example; a skill that is no longer required and likely to vanish with the next generation. Whilst the reduction in traditional skills may not be seen as an obvious vulnerability, especially when more convenient alternatives exist, any societal change may act to alter behavioural norms, affecting social capital expressed as community cohesion. Further, modern tools and equipment often require complex maintenance which cannot always be accomplished by islanders. Faulty machinery may remain idle for months

[19] It is noted that 'traditional' implies a long history of settlement, heritage and extensive development of indigenous practices. However, traditions are inevitably invented as people construct their identities and therefore do not necessarily have a temporal component (although traditions do become modified over time) (Linnekin, 1983). The Tristan community was created from a 'modern' society in 1817, but became traditional by way of social phenomena and practices that were independently developed, specifically for the Tristan environment, using local resources and techniques.

until a technician can be sent to the island to repair it. Although seen as progressive, reliance on modern, often complicated equipment actually weakens resilience.

Further, increased access to the outside world (via television and communications) has amplified consumerism (e.g., the purchase and display of cars or large screen televisions; see Chapter 5). This may illustrate a shift from a traditional 'defence' mode, where motives for action were driven by survival and resources were defended, to 'expansion' mode, where increased wealth and security have triggered growth (Lin, 2001). While sustainable farming and traditional practices in the Patches continue (see Section 6.5.3), reliance on imported goods has increased. A very small minority of islanders have even expressed a desire to discontinue work in the Patches and import potatoes to Tristan. This has direct implications for food production, but also indirect implications for fitness. This opinion may illustrate modification of risk perception, a key component in creating or reducing individual and group vulnerability (e.g., Slovic et al., 2000b; Paton and Johnston, 2001; Nathan, 2008; Jóhannesdóttir and Gísladóttir, 2010).

6.5.3. Risk perceptions – present day

How people perceive risk depends on a host of inter-related social, economic, cultural, environmental and psychological factors (for example, the psychometric paradigm) (Fischhoff et al., 1978). Risk perception studies have shown that people have a far more comprehensive awareness of risk than just probability and consequences (Kasperson et al., 1988) and that risk perception is a function of values, beliefs, fear and memory (Sjöberg, 2000a; Lindell and Hwang, 2008). It is important to attempt to recognise differing perceptions of risk in order to understand how people respond to, and organise themselves during a crisis situation, and therefore better inform societal decision-making (Slovic et al., 2000a).

Despite Tristan being culturally homogenous (regarding values and social behaviour), there is a spectrum of risk perceptions regarding natural hazards, likely a consequence of event frequency, hazard effects, experience and control. Some risk perceptions seem contradictory, for example, there is a comparatively low risk perception of the sea and the mountain despite both taking numerous lives through history. Being at sea is an important part of Tristan heritage and whilst islanders are never complacent, there is a sense of control that derives from an inherent knowledge of boat handling, local ocean currents and weather patterns. In contrast, there is heterogeneity of perceptions of the risk from a high impact, low probability event, such as a volcanic eruption (from fear, to complacency, to fatalism). When considering and discussing the possibility of future eruptions, many of the elderly who clearly remembered the events of 1961 display relative impassiveness. Some refuse to believe it will ever erupt again. Many middle-aged women, on the other hand, have a comparatively heightened perception of the risk of a future eruption. There is widespread awareness of the risk from rockfalls and concern about people walking to the east of the Settlement (Pigbite and Plantation Gulch; Fig. 1) or around the 1961-62 dome where rockfalls are frequent. This sensitivity is likely due to the death of an islander in 1964 from a rockfall. Knowledge of the risk from infection is extensive, due to personal experience, and often people (especially the elderly) remain indoors when ships visit in order to reduce the risk of contracting an illness. The reaction to new, previously unconsidered threats was observed in February 2011, when there was a suspected bio-security problem from the outbreak of an insect unknowingly brought to the island within wood used for harbour repairs. There was widespread concern that the wood-eating insect would spread across the Settlement, posing a substantial risk to homes and buildings, most of which have wooden frames. This initiated panic-buying of insect killer. Luckily, the insect was confined to the harbour and the wood was returned to Cape Town.

These examples illustrate that not only do individuals differ in their judgements of risks (even in a culturally homogenous society), but also that individuals may perceive some hazards or actions to be more risky than others, even if the statistical risk of harm is lower (Slovic et al., 2000b). One of the main influences on risk perceptions, according to the psychometric paradigm, is the dread dimension, where hazards that elicit greater feelings of fear are perceived to be worse. These fear responses can then plunge people into denial of the risk. The Protection Motivation Theory (Rogers, 1983) suggests that there are two major conceptual processes that take place in response to a threat – threat appraisal and coping appraisal. If, during the initial stages of threat appraisal, the threat is deemed to be significant then the coping appraisal stage is initiated. Dependent on the level reached in the coping appraisal, an individual will then either take protective or non-protective actions. Examples of non-protective actions are those which are evident in the Tristan population as mentioned earlier (fear, fatalism, complacency), and are likely to occur because the individual does not feel that there is anything they can do to cope with the risk. There are many different reasons for risk perceptions and why people continue to live in areas that have been determined as ‘risky’. These range from emotional attachment to the place, a lack of alternatives, a lack of awareness of the risk, or perhaps the result of weighing up what people perceive to be the various costs and benefits for themselves and deciding that a particular risk is one they are prepared to live with (e.g., Siegrist and Cvetkovich, 2000; Sjöberg, 2000b; Barberi et al., 2008; Chester et al., 2008b; Gaillard, 2008; Haynes et al., 2008b). However, a discussion of these factors is beyond the scope of this chapter. Overall, it is important to recognise that people do not make judgements about risks from natural hazards in isolation. There are many other factors which are at play in making a decision, which is why these 'subjective' assessments often appear to differ from the 'objective' scientific 'calculation' of the risk.

6.5.4. Resilience on Tristan – the present day

Whilst the effects of remoteness on vulnerability are manifest, geographic detachment combined with the unique set of circumstances that led to the establishment of this community, have also acted to strengthen resilience and counteract the impacts of extreme events. Many of these inherent and adaptive capabilities and capacities are prevalent today.

Sustainable living was forced on the islanders in the late 1800's following the opening of shipping lanes elsewhere and the subsequent decline of Tristan's barter economy. Food security was essential during these 'isolated' years, and to avoid low (or no) potato yield, a work ethic and fervent frugality developed (Munch, 1970). Both characteristics still prevail on Tristan: food is still accumulated during times of security, and laboriousness is still seen as a sign of responsibility. Despite the challenges of creating and maintaining a sustainable lifestyle, and the increase of imported foods in the last 50 years, islanders continue to work hard to tend to their Patches and livestock. Agricultural resilience has also improved with better knowledge of grazing practices and reduction in animal allowance per family. Work at the Patches is seen as an important part of Tristan's heritage and an expression of kinship activity. The original principles of communal ownership and equality are reflected in the management and distribution of the Patches, as every member of the community has an equal share of the land and livestock, and potato patches are shared out amongst families. Family bonds and cooperative kinship networks were vital when hardship was most pressing, and these sustained relationships still offer a rich source of social capital (see Section 6.3) and an essential means for communities to absorb stress.

Social capital is a concept that brings attention to the role of social interactions in explaining individual and collective outcomes (Brunie, 2009). It has been recognised as an important indicator of resilience to natural hazards (and other risks) and is used to explicate some of the reasons why certain communities thrive (Coleman, 1990; Putnam, 1993, 2000; Murphy, 2007; Rubin and Rossing, 2012). On Tristan, it is possible that stocks of social capital were sourced at the outset of the community through the creation of communitarian ideals and the shared objectives to live by particular norms. If this was the case, stocks have either been inherited (and possibly accrued) over the short period of settlement, or perhaps dormant social capital was awakened by system shocks, especially involving external interventions that created societal incentives (Fukuyama, 2001), for example, the introduction of cash wages and construction of new station buildings during World War II. Nowadays, the interpersonal relationships within the community can be viewed as bonds and bridges, and as trust and reciprocity. Bonding ties are often created during the recovery stages of a natural disaster or conflict (Pelling, 2003). An example of strong bonding ties (see Section 6.2) was immediately evident when the evacuees from the 1961-62 eruption were housed at Calshot Camp, when the group withdrew from maintaining associations with wider society and turned inwards, becoming independent. Due to the small size of the community, this actually acted to increase their collective action, exemplified by their resolve to return to Tristan. Bridging ties (see Section 6.2) are atypical on Tristan, possibly due to an aversion to hierarchy. The role of Chief Islander, therefore, is particularly challenging to manage as he/she must intersect two disparate groups (authorities and islanders) (see Chapter 5).

Trust and reciprocity are the other two agents of social capital and are abundant in islander interaction. Trust is defined as, ‘the expectation that arises within a community of regular, honest and cooperative behaviour, based on commonly shared norms on the part of other members of that community’ (Fukuyama, 1995, p. 26). Trust between islanders is displayed as the regular surfacing, and commanding, of societal norms. Reciprocity is defined as, ‘a social attribute through which trust is enacted in interpersonal transfers of information or resources’ (Pelling and High, 2005, p. 311). Islanders display both balanced and generalised reciprocity. For example, gifts are exchanged at particular celebrations of roughly the same value (balanced reciprocity) and tasks are often performed for a friend or relative without the expectation of return, except for the knowledge that the favour may be returned sometime in the future (general reciprocity). This relies on the ‘propagation of reputation’ (Pelling and High, 2005) where the risk of removal is seen by others in the community as a ‘free ride’. Reciprocal behaviour is innate, and again, likely sourced early in community history. For example, longboats were owned jointly by select groups of men (usually six or seven) as were heads of cattle and huts on Nightingale. Whilst the longboats are no longer used, joint ownership of large or expensive items still exists (e.g., huts at the Caves). Examples of generalised reciprocity, or mutual aid, is evident when assistance is called from select individuals to help with tasks that cannot be completed alone, such as building, spinning and carding, or commonly nowadays, helping prepare for family celebrations. Rewards are usually in the form of a return of assistance, should the invitation arise, a meal or a drink. Further, while may traditional community activities (such as longboat sailing, for example) have been replaced, the islanders still maintain special, annual community celebrations, such as Ratting Day and Queens Day (see Chapter 5). These unique events illustrate the sense of community that the islanders still share and offer a chance to engage in healthy competition.

In terms of resilience to natural hazards, maintaining these stocks of social capital is vital. A history of reciprocity has fostered an innate understanding of different capacities of individuals. In the event of a disaster, individual roles, responses and actions are assumed; islanders rapidly self-organise and react quickly and orderly. There has been little need for pre-determined responsibilities.

Other resilient characteristics have evolved from remoteness, particularly the ability of islanders to respond to and function normally under uncertain conditions. This is likely a product of a history of coping under unanticipated and unpredictable circumstances, such as, for example, ship arrivals, shipwrecks and weather extremes. As islanders are knowledgeable of individual roles and capabilities, they are reactive when faced with unforeseen and uncertain events. On a daily basis, islanders have to cope with weather uncertainty, which is highly variable on and around Tristan. Weather affects most island activities, for example, fishing, and ship loading. This has subsidiary effects on amount and arrival time of imports; arrival and departure of mail; arrival and departure of islanders and visitors; regularity of earnings; and fluctuating costs of imports (dependent on the Sterling to Rand conversion). However, islanders are accustomed to delay and uncertainty and possess a sense of calm that comes from considering the passage of time more slowly. This composure is a particularly valuable asset in the response to uncertain and unforeseen natural events.

In addition to food and water security (although potential problems with water security have been outlined in Section 6.5.1), islanders also have income security. Although employment and further education opportunities off-island are scarce, there is almost no unemployment on Tristan and from school-leaving age, everyone is offered the opportunity to earn a wage. As many positions are dependent on the weather, income options are diverse and there is often the possibility of having two or more occupations.

Earnings are very low in comparison to Europe and South Africa, so it is often impossible for islanders to afford to emigrate and establish themselves elsewhere. Further, whilst skills are diverse and appropriate for life on Tristan, it is not possible to gain formal qualifications on-island, thus reducing perceived employability. Whilst any apparent, unforced discouragement of out-migration can be viewed as vulnerability in terms of entitlements or access to opportunity, retaining and honing on-island capacity (especially young people) and organisation is important in creating and maintaining a disaster-resilient community. There has been, and is currently a scheme in place for some students to obtain further education elsewhere, as is the possibility for adults to receive training, on condition that skilled workers return to Tristan. There are currently no indications that these schemes are adversely affecting population numbers and are seen as a benefit for the community. However, fairness and transparency will be vital to avoid hostility and retain social cohesion.

In terms of any temporal effects on resilience to natural hazards, it is vital that stocks of social capital are retained. Reciprocal behaviour is unlikely to change as this is deeply rooted within community values and conduct. However, bonds may be affected by social adjustments evident from adaptation to modernity and the technological age. Technology has reduced vulnerability to natural hazards in some ways, namely the introduction of efficient communication has facilitated the speed with which advice can be offered and assistance, if required, could be mobilised. The use of online tools has encouraged tourism, improving the economy and thus resources. However, television has effectively brought the 'outside' in, (e.g., Meyrowitz, 1985) and bonds strengthened by social interaction and sense of place are loosening. De-traditionalisation is eroding social cohesion, potentially reducing resilience and catalysing change. If there is no desire to live on Tristan and opportunities are presented elsewhere, this is likely to encourage out-migration of younger people (especially the educated islanders). The demographic effects of any migration are likely to be pronounced, with an aging and unskilled remnant population. There is always a fear of tendency towards rapid increase in entropy, as experienced by the population of St Kilda (Outer Hebrides) who deserted the island in 1930 following an intense period of tourism, the development of an attraction to the outside world and unviable demographics (Fleming, 1999, 2000).

6.6. Conclusions

Disasters and natural hazards research has moved beyond a focus on understanding the natural phenomena to acknowledgement of the social dimensions of risk, particularly the role of vulnerability, resilience and their various drivers (Gaillard, 2010). It is important to note, however, that communities are dynamic and that vulnerability and resilience are likely to change over time. In order to investigate the temporal dimension, a historical autopsy can be a useful way of investigating past behaviour of communities, especially in response to sudden system 'shocks' or slower transitions. Coupled with a present day snapshot of the social context, this information may provide clues as to future developmental trajectories. Whilst models such as the adaptive cycle are useful to encourage consideration of past, present and future 'stages' of development, new models and interdisciplinary approaches are required to fully capture the complexity of social systems and the way they renew, reorganise and achieve resilient development across multiple scales (Bunce et al., 2009).

This component of the research developed some of the themes outlined in Chapter 5 by characterising the major vulnerabilities and resilient features (to natural hazards) of the Tristan community. Further, inferences were made about potential drivers and possible future trends. Two models (the CVA matrix and the adaptive cycle) were used in order to frame the data collection. These frameworks were deemed most suitable for developing the qualitative research component; the simplicity of the CVA matrix supported systematic data gathering and the adaptive cycle proved an effective framework for sensitising the research towards the dynamic drivers of vulnerability and resilience. An ethnographic approach was taken to collect data. By using participant observation to monitor events and actions and integrating data with information from interviews, previous authors and historical facts, a present day representation of the community could be presented.

Results suggest that, whilst location and seclusion have, on one hand, augmented a vulnerable state (to natural hazards), on the other, they have lead to the formation of successful coping mechanisms (Lewis, 1999; Howorth, 2005; Kelman, 2007). The trade-off of these features has kept the community relatively balanced in terms of being able to cope under uncertain conditions and recover from traumatic events. However, recovery does not necessarily imply a return to pre-disaster 'normality' and post-adversity cultural change (positive and negative) has almost always resulted from interaction with the 'outside world'. Adjustment to new circumstances has sometimes irreversibly affected the vulnerability-resilience balance. By examining the temporal dynamics of vulnerability and resilience on

Tristan, it is possible to anticipate the capability of the community to overcome the effects of natural hazards in the future.

Today, islanders still possess many of original values and norms that were ordained when the first permanent settlers came to Tristan in 1817. This cultural homogeneity has helped to generate plentiful stocks of social capital, mainly founded on strong community bonds and reciprocal behaviour. However, change is currently in progress on Tristan, not due to the effects of a natural disaster, but due to the recent establishment of modern media, communications and technology. The marked change in social behaviour and interaction are signals that social capital is eroding in response to modernism and consumerism. Stocks of social capital act as a community adhesive and depletion may reduce resilience.

The challenge for Tristan will be to address this perceived erosion of resilience and restore balance within the community. In order to remain resilient to the effects of natural hazards, it will be important for the community to consider possible new futures and design disaster management programs that are suitable for present day needs and capabilities of the islanders.

It is possible that adaptations are currently at work to find advantage in new forms of communication, media and from changing interactions within the community. Cultural adjustments, therefore, may not necessarily be negative and current community change may initiate developments which many enhance their lives and strengthen resilience.

CHAPTER SEVEN: Communicating risk, hazard & uncertainty

7.1. Introduction

As populations living on and near active, and potentially active, volcanoes increases, so does the risk of harm in the event of an eruption. This has been reflected in the increase in volcano related deaths and lethal volcanic events through the last century (e.g., Tilling, 1990; Siebert et al., 2010). This has increased the priority both to improve emergency plans and to encourage risk reducing behaviour in communities facing danger. The former is dependent on development of seamless communication of the hazard, risk and uncertainty between the main stakeholder groups (e.g., McGuire et al., 2009). Behaviour change, however, is a far more complex challenge and requires, amongst other things, effective communication techniques tailored in content and style appropriate to the audience, and conveyed by a trusted source. However, heterogeneity within communities often affects the distribution of message uptake and interpretation of it, especially in the case of low-probability, high-impact events. Ultimately, this has implications for the ability and willingness of individuals to make efforts to protect against danger (Paton et al., 2008). To be successful, volcanic risk communication initiatives depend on accessing and assessing community beliefs, values and risk perceptions, and integrating evidence with volcanological data and uncertainty assessments. Further, attempts to evaluate success empirically are required so that lessons may be learned, shared and carefully applied elsewhere.

This chapter is the apex of this research and describes the integration, application and communication of information discussed in earlier chapters. Every component of the research has informed another in an analytic-deliberative manner, drawing on a broad suite of quantitative and qualitative data across a range of disciplines. This iterative process provided time to research and reflect on a range of communication strategies that were both suitable for the audience and maximised the quality of the dataset. Strategies used on Tristan are outlined in Section 7.3 and were designed using lessons learned from previous research, briefly reviewed below.

7.2. Risk communication – a brief review

Risk communication is intended to equip the layperson(s) with the information they require to make informed, independent judgments about response to risks (Morgan et al., 2002).

Effective risk communication encourages those at risk to adapt their behaviour and develop willingness to participate in risk reduction measures. Therefore it is vital that the content of the communication is focussed on the primary issues of importance, and the style of delivery is in a familiar or, at least, an understandable format for the audience. This requires communicators to conduct a needs assessment, and understand the social context, in order to tailor messages that are appropriate to the unique circumstances surrounding people at risk (Bier, 2001). Further, the style and content of communication efforts must reflect the shared goal. For example, if the aim is to educate or inform an audience, clarity of the message is more important than developing participatory processes, which may be more effectively applied if the shared goal is to reach agreement (e.g., Rowan, 1991; Bier, 2001).

The development of risk communication over the last 30 or 40 years reflects this need to think carefully about the goal of communication and to tailor the style and content accordingly. Early risk communication efforts stemmed from a public need for assessors and managers to explain quantitative risks and numerical probabilities. However, these early approaches assumed an ignorant public, deficit of knowledge, and were designed to merely 'tell them the numbers' in formats similar to their original form (e.g., corporate reports). This lack of interaction (known as 'one-way' or 'top-down' communication), ignores the perspectives of the receiver, and the message often fails to get through. Developments in risk communication increasingly highlighted the importance of interaction (two-way exchange) and framing the message within the particular institutional and cultural context. More recently, risk communication efforts have focussed on empowering the risk-bearing groups, creating a societal discourse and enabling the public to openly deliberate and participate in the decision making process (Pidgeon et al., 1992; Fischhoff, 1995). Citizens now have growing expectations towards decision makers and rarely tolerate risks unless they understand them, their probability and potential effects.

Developing a credible risk message depends, broadly, on the effective translation of the science from technical terminology into user-friendly language, and addressing uncertainties and knowledge gaps (Leiss, 2004). There are numerous guidelines for successful risk communication which necessarily vary between disciplines, but principles common to most communication strategies include:

- Demonstrate a commitment to maintaining flow of information
- Distinguish hazards from risks

- Provide awareness of possible harms, especially those that elicit feelings of dread or alarm
- Provide an indication of the quality of the knowledge
- Include a qualitative description of the uncertainty
- Include a qualitative and quantitative description of any probabilities
- Justification of what is considered to be an acceptable or tolerable level of risk
- Justification of reasons for chosen response and recommended actions
- Provide contact information for a source to which to direct questions (checklist adapted from the Tilling and Lipman, 1993)

The actual content and style of risk communication will depend on nature of the hazard and the goals of the communication. For example, communication designed to create societal discourse in an effort to build consensus and share meanings over controversial issues is appropriate if the risk is not imminent, but in the case of natural hazards, particularly, communication in the event of an emergency needs to achieve an immediate aim (Handmer, 2000). In this case, communication efforts are concerned with persuading those at risk to adopt protective behaviour immediately.

Regardless of the method of communication, however well-composed the content or carefully considered the style of delivery, the message may not achieve the desired effect if the communicator is not a trusted and credible source (Poortinga and Pidgeon, 2003). Trust is associated with believing that the source is expert, authoritative, unbiased, objective and not sensationalising (e.g., Breakwell, 2000; Morgan et al., 2002). Additionally, communicators who display a vested interest in community well-being, and who share similar values, are also likely to be better received (Earle and Cvetkovich, 1995; Frewer et al., 1996). Personality and emotional intelligence, rather than positionality, may play a more important role under some circumstances (Moser, 2008). Identification of the most trusted communicator is thus an equally important component of effective risk communication. A study of trust during the ongoing Montserrat volcanic crisis concluded that the most trusted source for information concerning the volcano were friends and relatives. Scientists were the second most trusted source (Haynes et al., 2008a). Similar results have been recorded during other volcanic crises (Perry and Greene, 1983; Ronan et al., 2000). Whilst this is an important finding, and identification of trusted sources can be a strategic way of effectively disseminating information (e.g., Punongbayan et al., 1996), scientists (and other experts) still have an important role to play in effective communication of hazard, risk and uncertainty (e.g., Newhall et al., 1999). Conveying uncertain information, particularly, is challenging due to the threat of devaluing the information or destroying trust in scientific data and scientists. Trust is difficult to gain but is easy to lose (Pidgeon et al., 1992; Slovic, 1993), especially in uncertain situations where precautionary attitudes may lead to the perception of 'false alarms', or when precise predictions neglect implications of uncertainty (Haynes et al., 2008a).

Uncertainty, or rather incomplete knowledge, is important to appraise at the early stages of research, so that appropriate analytical and communication methods can be applied to account for differing levels of risk knowledge. For example, while probability calculus may seem most desirable for both scientists and decision makers, 'traditional' risk assessments applying probabilistic methods are likely inadequate in addressing intractable uncertainty, ambiguity and ignorance (Stirling and Gee, 2002).

7.3. Strategies for communication

The challenges of effective risk communication are clear and there appears to be no universal solution for effective information delivery. It is dependent entirely on the particular hazard, what is known and not known about it, as well as the specific situation and community. Therefore it is crucial that the communicator takes the time to learn about the community, and understand their needs, in order to appropriately customise the content and style of communication.

On Tristan, it was impossible to address all knowledge gaps, so structured communication strategies were prioritised to particular groups which were considered to have the greatest impact on risk reducing behaviour. Those were children, Island Council members and the interested public. Other communication strategies were employed throughout the research and tailored to specific situations. Discussions were held with FCO members at the beginning, middle and end of the study to keep UK-based decision makers informed of progress, to reiterate project objectives and to communicate results. Within the island community, results and relevant information were discussed with different social groups at several, carefully designed, stages of the work. Interspersed with these formal 'meetings' were frequent and unstructured 'one-to-one' and group conversations; almost always held under familiar circumstances. These conversations formed a valuable part of the iterative process of data gathering and analysis, as well as an essential 'opportunity' to discuss the research, individual concerns, beliefs and perceptions. Strategic conversations were also a useful way of reducing rumour and misinformation.

Structured communication strategies for the three high-impact groups included: outreach initiatives with school children and school curriculum updates; presentation of project results to the Island Council; a presentation and question/answer session with the community; and a scenario planning workshop. The following sections describe the purpose of, and approach to, each of these communication strategies.

7.3.1. Outreach initiatives with school children

The students of St Mary's School were an important target group for risk communication efforts, not only as they represent the next generation of the community (and influential future Island Council members), but because it enabled communications to simultaneously reach a wider demographic (often the hard-to-reach groups) as children often tell parents what they learned at school.

Outreach initiatives are known to be an important tool for inspiring and informing people, stimulating interest in a particular area and encouraging better understanding. Various initiatives were designed for the school children with the aim of promoting interest in earth science and improving knowledge about their volcano, the hazards and risks.

As an annex to the 'Tristan Studies' course (see Chapter 5) which includes some information about the 1961-62 eruption and very basic information on Earth structure and dynamics, two lectures for classes 3 and 4 (pupils aged 11-15) were given during the first field season. These were structured to introduce pupils to the key concepts of plate tectonics, volcanoes and earthquakes. This platform also provided an opportunity to discuss the BGS School Seismology Project, a programme designed to offer students practical seismology lessons using, amongst other resources, a simple seismometer (horizontal motion with modern amplifier system) which was permanently set up at the school (Plate 7.1). Pupils were able to come in regularly to view the helicorder and to analyse the magnitude and location of large earthquakes anywhere in the world (Plate 7.2). The school seismology project was also designed to encourage pupils to exchange and compare data with other schools around the world, although improved internet facilities will have to be established before that element of the project can commence on the island.

Learning outside of the classroom is a good way of enthusing students and promoting information uptake. Although Tristan is a natural laboratory, many of the pupils had not visited other parts of the island, so two field trips were organised to enable pupils to observe geological features and discuss the processes that gave rise to them. First, several pupils (and interested others) were taken on a tour of the 1961-62 dome and flows. This provided an opportunity to discuss the progression of the eruption, the geology and morphology, and the dome's present thermal activity. The pupils were encouraged to become involved in the research and searched for fumaroles, recording temperature and other observational data around the vents (Plate 7.3 and Plate 7.4). Secondly, the pupils were taken on a boat tour, which circumnavigated Tristan. This presented an important opportunity to show the students the volcanic features around the island, their similarities and differences between the 1961 dome and flows. This was also another opportunity to collect data, including recording the position of dykes around the island (Plate 7.5). Other techniques such as the well known 'coke and mentos' experiment were used to educate the students about eruption dynamics (Plate 7.6), and a scenario planning exercise was designed to give the students a sense of how an eruption might progress, the inherent uncertainty within the system, and the difficulty of making timely and effective decisions to keep the community safe. The school curriculum was updated to include geophysical hazards and disaster risk reduction themes, as well as new data about the volcano (see Chapter 3).

During the final field season, several pupils were involved in a film project, designed as an opportunity for students to learn about filmmaking, question design, interviewing and directing (Plate 7.7 and Plate 7.8). The project was initiated following the school Christmas play, written by an islander about the 1961 eruption and evacuation. Students were asked to design interview questions about the eruption and to arrange interviews with willing islanders who could remember the events. The filmed interviews gave students an opportunity to learn first-hand what happened during that time, thus helping to retain social memory of the events surrounding the 1961 eruption. Given the irregularity of eruptions on Tristan, this is an important component of risk reduction efforts.

Plate 7.1. Introducing the basic concept of seismology to pupils of St Mary's School using a simple seismometer donated by the BGS.

Plate 7.2. Pupils checking the helicorder for world-wide seismic activity detected by their seismometer.

Plate 7.3. Getting closer to some of the features of the 1961-62 volcanic dome.

Plate 7.4. Collecting data from fumaroles around the dome.

Plate 7.5. Circumnavigating Tristan on a school field trip.

Plate 7.6. Exploring eruption dynamics with the ‘Coke and mentos’ experiment.

Plate 7.7. Riaan Repetto interviewing Harold Green about the events surrounding the 1961-62 eruption.

Plate 7.8. Caryn Green interviewing Edwin 'Spike' Glass.

7.3.2. Communicating results to the Island Council

Communication and discussion of results with the Island Council was carefully planned and disseminated over two meetings, with a shared goal to improve preparedness measures and update the disaster management plan. The first meeting was relatively 'top-down' in its approach and the other was designed to be deliberative and collaborative, based on two-way communication channels. Merging top-down and bottom-up approaches showcased the advantages of both, thus maximising benefit: control and collaboration, clarity of goals and transparency of processes; leading to co-ordination and collective action.

Results from the research (Chapters 2, 3 and 4) were presented in the first meeting. This style of communication was chosen as the Island Council expressed a desire to learn about the volcano, and to discuss new observations and the implications of results. A summary of the eruptive history of the island was presented (with new data, see Chapter 3), in addition to information about different eruptive styles and products that have shaped Tristan. Questions were posed by the council where further information or explanation was required. It was also important to discuss future activity, and uncertainty, with the council members. Given the lack of data and paucity of historical eruptions, the challenge of forecasting future eruptions was explained. A few visual examples from the expert elicitation event tree were presented to emphasize expert uncertainty (see Chapter 4). Council members reflected on the difficulties involved in forecasting under uncertain conditions, and voiced concerns about having to wait for signs of volcanic unrest (if at all) before scientists could refine opinion. Given the challenges of geographical dissociation and the possibility of rapid onset of volcanism, the group realised the importance of on-island preparedness. At this point, the concept of scenario planning was introduced as a useful tool for developing response strategies. Council members were keen to try, and agreed to participate in a workshop the following week (see Section 7.3.4). The meeting was also used as a platform to propose a community evacuation drill and to discuss how to prepare and conduct it effectively.

On reflection, it is acknowledged that the willingness and enthusiasm of the Island Council to discuss volcanic hazards and risk reduction measures, as well as of the wider community to conduct a drill, was encouraged by gradual and steady discussion of the volcano and possible future eruptive scenarios by the researcher. It is unlikely that the islanders would have been as inclined to participate if the field seasons had been considerably shorter.

7.3.3. Informing the wider population

In an effort to reduce misconception, the emergence of rumour, and to offer equal access to information; results and recommendations were also disseminated verbally to the community. A presentation was held in the village hall at the end of the fieldwork, in between the two Island Council meetings. The goal was threefold: to reduce the education deficit about volcanoes, to encourage people to take risk reducing action, and to discuss details of an evacuation drill (see Section 7.4.3).

The content of the presentation was carefully constructed to appeal emotionally to the audience (e.g., reducing risk to yourself and your family) and, where possible, familiar words and phrases were used in order to reduce ambiguity, acknowledge acquaintance with the community and preserve a hard-earned social position. The presentation attempted to balance technical information (hazard and uncertainty), knowledge of the risk and social effects of eruptions, whilst being empathetic to the social context. One recommendation was made, advising islanders to assemble small personal emergency supply kits containing essential items[20], and to keep it in an accessible place.

Attendance was good. Approximately 130 islanders, Island Council members and the Administrator (~55% of the total population) were present. The audience was fairly representative of age and gender, although more women than men attended, probably due in part to the fact that out-of-hours harbour work was being undertaken. It was also well attended by the elderly.

Following the presentation, an opportunity to answer questions was offered. All of the questions were relevant to further information about the evacuation centre and the drill (see Section 7.4.3). There was a sense of misunderstanding and resistance about the rationale for building an evacuation centre, possibly due to a lack of good communication during the planning stages. Several people did not understand that the centre was precautionary, and that its main function was to store backup medical, food and water supplies should an emergency affect the hospital or supermarket. Regarding its purpose in the event of a volcanic eruption, some islanders were puzzled by the prospect of an eruption at the Patches, thus rendering the evacuation centre unsafe. It was explained that, depending on the size of

[20] Suggested essential items included: a torch and extra batteries, first aid kit, emergency food and water, essential medicines, sturdy shoes, toilet paper, warm, waterproof coat and a pocket knife.

the eruption, remaining in the Settlement would be the primary option under those circumstances. It was emphasized that the evacuation centre was not considered a ‘safe-house’ for every conceivable scenario.

7.3.4. Scenario planning

The final communication strategy, a scenario planning workshop, was deliberately designed to take place at the end of the research, once data had been gathered, analysed and interpreted (see Chapters 2-6). The aim of the workshop was to help increase the capacity of the Tristan community and island administrators to act to reduce risk under conditions of uncertainty. This deliberative, anticipatory approach created a platform for islanders to acquire further information about potential volcanic hazards and risk, and to develop ownership of suitable actions required before, during and after a ‘system shock’. Although the workshop was designed to generate strategies for managing different eruption scenarios, the scenario planning framework could be used for multi-hazard scenarios and to identify and mitigate against other man-made risks on Tristan.

From a theoretical perspective, the reason for selecting scenario planning as a method was due to the severe uncertainty about future eruptive scenarios, as discussed in depth in Chapter 4. By acknowledging the work of Stirling (Stirling, 2003, 2008; 2010), who recognised that incomplete knowledge should not be solely focussed on risk, other methodological options (rather than risk assessment, or expert consensus, for example) could be considered. In the case of Tristan, there was limited basis to define probabilities; therefore our knowledge of risk was at the extreme end of that continuum (Fig. 7.1). However, due to relatively comprehensive assessment of the field geology by the Royal Society (Baker et al., 1964), the British Geological Survey (Dunkley, 2002) and from this study, it was possible to present knowledge of a discrete set of outcomes, thus approaching the ‘unproblematic’ end of the possibilities spectrum in Figure 7.1.

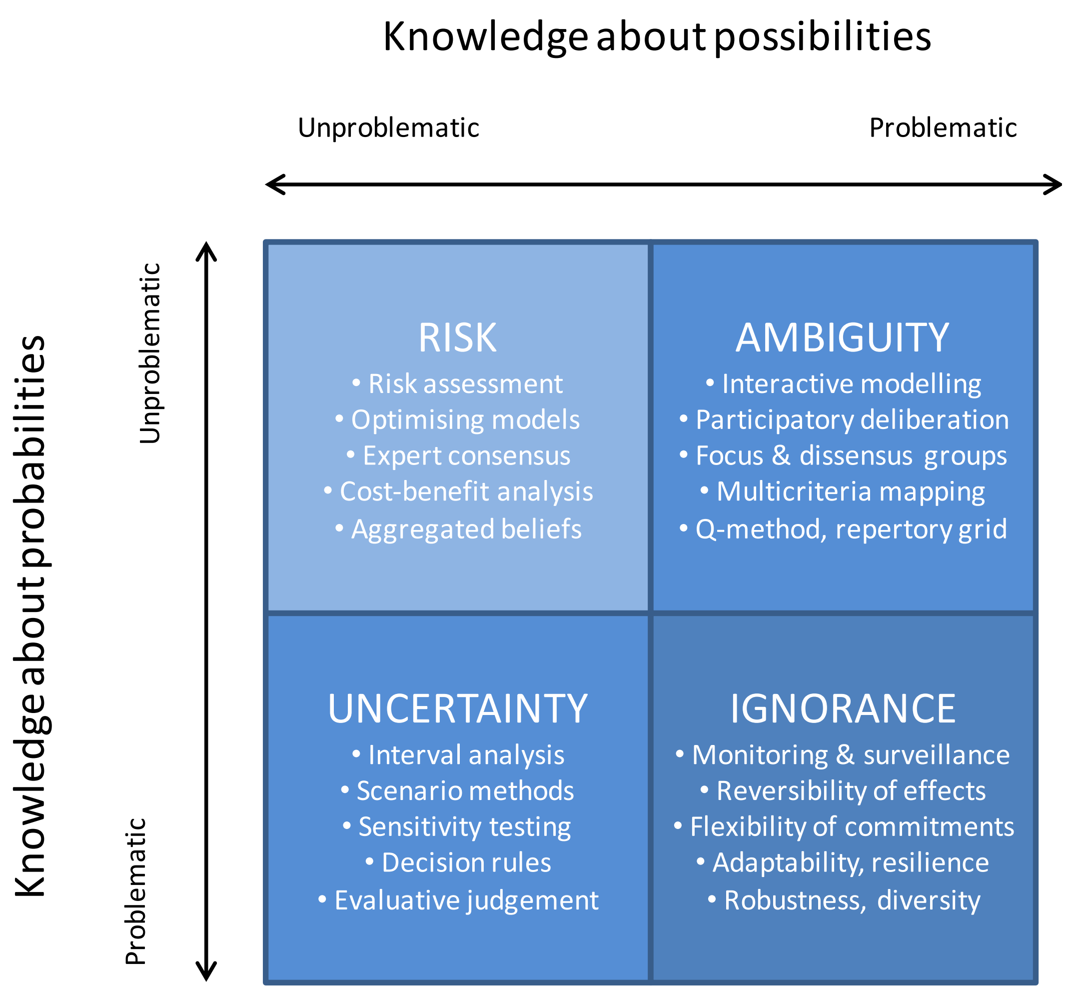


Fig. 7.1. Dimensions of incertitude. Adapted from Stirling (2003; 2010).

7.3.4.1. A brief review

Scenario planning is a way of engaging people in a 'thinking' process to understand possible and plausible future events in relation to the position of distinct stakeholder groups. By considering the responsibilities, attitudes and assumptions of separate groups during an imagined crisis in terms of, for example, uncertainty, resources and/or politics, this can enable those involved to identify what questions need to be asked, and of whom, as well as to design strategies to protect communities from the worst consequences. This deliberative, anticipatory approach serves to identify risks, strengthen resilience and build capacity within a community.

A scenario is a synopsis of a conceived future event. It need not always portray a problematic outlook and can often describe optimistic futures in which a community may find itself. A set of scenarios can be incompatible or congruent; the latter often used to explore different change drivers. The former, although occasionally startling, can be helpful in setting the outer bounds of what a community is inclined to consider. Although there may be an infinite number of possible futures, a carefully selected set of scenarios can help to place a benchmark against which current strategies can be evaluated, or facilitate the development of new ones (Rhydderch and Alexander, 2009).

A scenario planning approach is advantageous when uncertainty is severe and there are few or no historical precedents (Schnaars, 1987). On Tristan, given the lack of geophysical monitoring, paucity of historical eruptions and relatively limited knowledge of the island's eruptive history, this technique was particularly appropriate. Further, the deliberative style of communication presented a suitable way of engaging with islanders who rarely acknowledge visions of the future, and whose thoughts are rooted in the present day. Anxiety of engaging with the future, or outside world, is an obstacle frequently recognised in futures research from other disciplines. The success of scenario planning activities depends on acknowledging and surmounting this and other hurdles, which also include: biased assumptions of scenario planning, e.g., unwillingness or hesitancy to change normal management or decision making style; and group state of mind, e.g., unhealthy degree of groupthink (Burt and van der Heijden, 2003). Overcoming these hurdles is dependent on trust between the scenario planner and the decision makers. The importance of trust has been discussed in previous chapters, and drawing on a trust account with islanders was integral for building allegiances and encouraging the Tristan Island Council to assemble.

7.3.4.2. Methodological variations

There is a relatively chaotic plethora of methodologies for generating and examining scenarios, most likely resulting from users adapting scenario planning to different contexts (Varum and Melo, 2010). Whilst most scenario typologies fall into the categories of probable, possible and preferable future events, in order to think carefully about how scenarios are actually used it is useful to pose three questions: what will happen? (*predictive)*; what can happen? *(explorative)*; and how can a specific target be reached? *(normative)* (Fig. 7.2) (Börjeson et al., 2006). Although these questions are commonly applied in business environments, the concepts can be applied to natural hazard-related contexts.

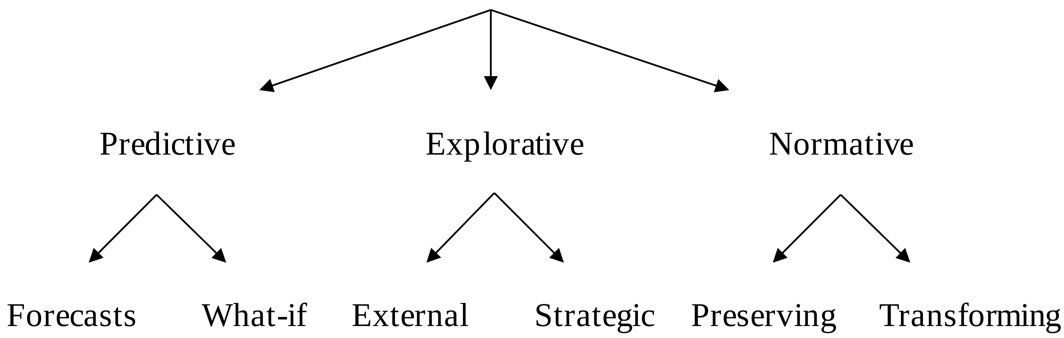


Fig. 7.2. Scenario typology. Taken from Börjeson et al., (2006).

Predictive scenarios encourage people to consider what is going to happen in the future. In these scenarios, probabilities, if carefully used, can play a useful part in strategic planning, making it possible to prepare for situations that are 'expected' to occur. Predictive scenarios consist of two closely related types: forecasts and what-if's. Whereas forecasts predict what will happen if the most likely development unfolds, what-if scenarios investigate what will happen on condition of some specified event, or chain of events. Predictive eruption scenarios might focus on short-term forecasts of the direction of eruptive product or eruption duration; or could consist of a group of forecasts considering what might happen if one of two or more events occur in succession. These could be within or outside the system, (e.g., sector collapse triggering a phreato-magmatic eruption) although no single event would be considered the 'most likely'. In volcanology, a combination of both what-if and forecast scenarios are now often represented as event trees (Newhall and Hoblitt, 2002).

Explorative scenarios aim to explore situations that could possibly occur (what can happen?). Whilst this presents an almost exhaustive number of plausible developments, a set of wide-scope scenarios could be used. For eruptive scenarios, this reduces the risk of making predictions. The two types of explorative scenarios are external and strategic. External scenarios focus on factors beyond the 'control' of the system, e.g., weather or time of day. Strategic scenarios incorporate policy measures and describe how the consequences of decision making can vary depending on the choice of future development, e.g., promoting tourism.

The third group, normative scenarios would, if using a volcanic eruption as an example, be focussed on the socio-economic and political effects of an eruption or 'false alarm'. In this case, normative scenarios would be focussed on either sustaining normal way-of-life (e.g., in the event of precursory signals and no eruption), or using the event(s) to transform the socio-economic system in some way to achieve a specified or unspecified future (e.g., evacuation or migration).

7.3.4.3. Scenario generation

As Schnaars (1987) states, "the content of scenarios should be determined by where the uncertainty lies." For Tristan, although little is known about the volcanic system, there is also uncertainty within the social system, especially regarding community and governmental response to a volcanic crisis. Although we can learn lessons from previous 'successful' responses (i.e. reaction to the 1961-62 eruption), there is no certainty that a community will react and behave in exactly the same way. On Tristan, it is unlikely that the volcano will erupt in the same location, for a similar duration and in a similar style as the 1961-62 eruption. Further, it is unlikely that the community will react consistently. Community interaction and local resources have changed since the last eruption and are likely to have an impact on manner and speed of response (see Chapter 6). Accordingly, the scenarios were designed to focus on community response to different styles, location and onset speed of volcanic activity. Using the methodological concepts described above, a combination of predictive and explorative scenarios, drawing on both qualitative and quantitative data (see Chapters 2, 3, 4, 5 and 6), were constructed.

Scenarios were devised by the researcher on the basis of field knowledge, experience and understanding of the Tristan geology. No pilot study or expert elicitation was deemed necessary. Actual content of the scenarios was informed by all elements of the research, although principally field and reported evidence from previous eruptions was applied. Size, style and volume of past eruptions are preserved in the stratigraphic record and offer clues as to the range of possible future activity. Unknown variables such as type and style of precursory activity, speed of onset and eruption duration were also described and given as plausible figures. Although it is acknowledged that community response in 20 or 50 years might be different than responding to a crisis today, the timeframe of the eruption was comparatively unimportant as the main goal of the scenario planning exercise was to generate recommendations for present-day preparations.

To emphasise interaction and information exchange, scenarios were discussed at a workshop. This style of meeting offered a deliberative space for participants to explore roles and actions for each scenario, and was a format with which group members were familiar. Prior to the workshop, eight scenario 'summaries' were produced (Fig. 7.3). These spanned a range of plausible eruptive outcomes on Tristan. Each was given an associated *relative* risk level, to enable the group members to easily identify the differences between them as well as to encourage them to choose scenarios presenting very different impacts on the Settlement: These relative risk levels were allocated by acknowledging the size of the eruption in the scenario, proximity to the Settlement, speed of onset, quantity and type of precursory signs and signals.

1. Dome growth and lava flows just to the west of the volcano. Preceded by 2 months of earthquakes (copy of 1961)	MED
2. 6 hours of earthquakes followed by submarine eruption and pumice rafts west of the Settlement (copy of 2004)	LOW
3. Scoria cone growth on Base above Settlement, subsequent breaching by lava flow. No earthquake warning	MED
4. Maar formation (large explosions that form deep craters like the Ponds) on the Base near Big Gulch. No warning	MED
5. Dome growth and lava flows near the Caves. Earthquakes only felt by those near the South of Tristan	LOW
6. Large, explosive eruption from summit, with volcanic bombs reaching the edge of the Base. Ash clouds erupted and ground collapse occurs. 2 weeks of earthquakes	HIGH
7. Scoria cone growth near Hillpiece, erupted without warning	MED
8. 4 months of earthquakes felt at the Settlement, but a volcano never breaks the surface	LOW

Fig. 7.3. Eight scenario summaries with associated 'risk level' for the Settlement.

Regarding the number of scenarios, there is some disagreement in the literature regarding how many a group should investigate (e.g., Wilson, 1978; Schnaars, 1987; Rhydderch and Alexander, 2009), but the general consensus is that three scenarios are best. Given the time limitations of the workshop, it was only possible to investigate three scenarios, which included a best, most likely, and reasonable worst case. These were selected by the workshop participants (see Section 7.3.4.4). Worst cases are often taken from the stratigraphic record, i.e. the worst known event, which makes it clear to the group that the worst can happen with no historic precedent.

Each scenario was designed to develop as a narrative, enabling participants to imagine responding to particular events. The progress of the scenario would then be 'frozen' at key points to allow the group to discuss assumptions, examine responses and consider measures to reduce risk. This approach also encouraged the group to explore alternative external factors at different points in time, such as weather change, a geographically separated population, secondary hazards, or a lack of external assistance.

7.3.4.4. At the workshop

The workshop was conducted in February 2011 with a group of 12 people: the Island Administrator, his secretary, the chief islander, the disaster management coordinator, and 8 out of 10 Island Council members. The council members were relatively representative of the community both in terms of age, gender and vocation. In an ideal situation, a wider range of participants would be involved, such as volcanologists and UK-based government officials.

The workshop began by a reiteration of objectives, an explanation of the workshop format and what would be required of the participants. A brief outline of each scenario was offered to the group and, rather than insisting on particular scenarios, participants were invited to select three scenarios to investigate. They opted for a low, medium and high impact scenario (scenarios 6, 7 and 8; see Fig. 7.3); although this choice was seemingly guided by the coloured 'risk levels' in Figure 7.3. To aid with communication of the chosen scenarios, the developing story was conveyed via PowerPoint. As each scenario was played out, 'time was stopped' at key stages, and discussion of responses, roles and resources developed (see Appendix 12). Initially, participants were wary of voicing opinions and conversation was dominated by the Administrator but, by careful facilitation, others were encouraged to offer their judgements and suggestions. The order in which the scenarios were played out (from low to high risk) certainly helped facilitate discussion. Starting with the high impact event may have been too astonishing to prompt any meaningful conversation.

In the first scenario (scenario 8 – 'false alarm'), the participants explored an outcome where the eruption was insignificant, or magma failed to reach the surface. This scenario was designed to encourage the group to consider not only their responses and requirements in that situation, but also to consider longer term effects of decisions that may, in hindsight, have been seen as excessive precaution. 'False alarms[21]' are a major problem for decision makers and scientists who risk being held accountable for a 'wrong' decision (e.g., Fiske, 1984; Hadfield, 1993). There may be severe economic consequences or, in the case of Tristan, may result in permanent population re-settlement elsewhere. During this discussion, the Island Council were unanimous that a precautionary approach was best and, in the absence of scientific evidence, would have supported the Administrator's decision to evacuate. This scenario discussion also highlighted the importance of seeking scientific opinion and triggered the need for improved links between Tristan, the FCO and the BGS.

[21] In volcanology, the term 'false alarm' is rather ambiguous as if precursory activity (unrest) occurs, but no eruption ensues, then the alarm itself is not false.

The other two scenarios (scenarios 6 and 7) were designed to explore responses to eruptions that either had no precursory activity or warnings of insufficient time to send volcanologists to the island. This encouraged participants to consider their own capacities and the resources they would need to most effectively respond. A list of recommendations was devised (see Section 7.3.4.5). Similar to scenario 8, scenarios 6 and 7 also prompted islanders to actively investigate off-island evacuation and the resources they would need to safely and effectively conduct it. Off-island evacuation is seen very much as a last resort on Tristan, but the likelihood of being forced to conduct one is higher here than at other islands, due to the lack of habitable land. Even relatively small eruptions could drive people away, for example, if ash is blown into the Settlement (most islanders suffer from breathing difficulties; see Chapters 5 and 6) or if the natural water source became contaminated. This scenario presents another severe challenge for decision makers who have to assess the risk of remaining on-island against the risk of evacuating off-island in poor weather or adverse sea conditions.

7.3.4.5. Recommendations

The scenario planning exercise brought to the forefront hazards, risks and outcomes that had remained psychologically distant to the islanders, probably due both to lack of knowledge and denial of the issues. By framing the problem in a way that focussed on actions, resources and individual and collective responses, rather than the ‘science’, workshop participants were more amenable, almost eager, to ‘play the game’. The workshop also presented an opportunity to informally assess the islanders on their knowledge, and messages communicated in the earlier meeting and at the community presentation.

The quantity of recommendations devised as a result of the workshop was indicative of the amount and nature of resources required to prepare in the event of an eruptive crisis and mitigate the effects of the hazard, should an eruption ensue. Recommendations were mainly focussed on the need to reduce uncertainty and to provide effective early warnings by monitoring. Ideally, monitoring equipment would be deployed, particularly a seismometer array and strain-meters. Monitoring, ideally, should be real time, although with training, processing could be completed on-island simply to detect change as part of an emergency warning system (such as thermal changes or gas increase). Citizen, or community, science would be a valuable addition alongside formal real-time monitoring.

In the absence of permanent monitoring stations, workshop participants realised the importance of increasing on-island capability. Recommendations focussed on protocol amendments, infrastructure and resource improvements. By discussing each scenario and exploring the effects that external factors would have on response (e.g., poor weather), the workshop prompted the discussion and clarification of roles, amendments to the disaster management plan (Section 7.4.1) and design changes to the evacuation centre (Section 7.4.2). Other infrastructure recommendations were suggested, including the active exploration of the use of Nightingale as a temporary off-island evacuation site.

7.3.5. Evaluating effectiveness

Although there is a clear rationale for tailoring and varying communication strategies for particular audiences, it is important to conduct rigorous evaluation of the effects of those communications. Risk communication strategies and, to an extent, the research on which it is focussed, is of limited value if the message does not initiate sustained alterations in opinion, behaviour and willingness to act.

However, despite having access to a range of research techniques that allow scientists to obtain reliable, objective and accurate information on the effects and understanding of communications, there is little empirical evidence of their efficacy (Pidgeon and Fischhoff, 2011). This is likely due to the lack of objective standardised reporting on effectiveness from the field, and a focus on rapid and straightforward subjective appraisals of the pros and cons of the communication 'campaign'.

At the very least, it is desirable to assess audience response and the impact and influence of communications, such as recording favourable and unfavourable reactions. A better approach would be to quiz audience knowledge by surveys, or ask them to express their beliefs through open-ended interviews. However, choice of approach will depend on the audience, for example, if literacy levels limit the effectiveness of written communications. Another approach is to observe how many people do what the communication suggests. This requires audience members both to understand the message and see it as personally relevant (Walker and Meyer, 1980; Morgan et al., 2002).

Risk communication strategies used on Tristan were evaluated by this latter approach (see Section 7.4). An evaluation of this type is easier in a small, contained community where individual and collective action is readily apparent. Further, for similar reasons outlined in Chapter 5, it was not appropriate to conduct surveys or structured interviews.

7.4. Applying knowledge: community adaptive strategies

Throughout the research, and in the days that followed the community meeting, islanders would often talk about future eruptive scenarios, their perceptions and likely responses. Many were keen to share that they had prepared their emergency home kit. These rapid small-scale measures to reduce risk were positive, but long-term, sustained risk reduction measures are often challenging to implement and difficult to maintain. Nevertheless, the communications initiated or enhanced three risk reduction strategies: the disaster management plan, construction of an evacuation centre and the completion of an evacuation drill. These are outlined in the following sections.

It will be imperative in subsequent years that the disaster management plan is updated in light of new data and social change, that the evacuation centre is maintained and respected by the community, and that future evacuation drills are conducted periodically (perhaps annually) with full support from the community.

7.4.1. Tristan disaster management plan

The Tristan disaster management plan details several broad evacuation plans (full; full off-island; partial); the roles and responsibilities of those islanders belonging to the Emergency Policy Group, and other information regarding consular assistance, press response and business continuity. The plan is designed to outline response to any disaster, but the major events considered 'most likely' to occur are:

- Deterioration of conditions rendering normal life on the island unsustainable e.g., collapse of harbour wall;
- Volcanic activity without forewarning, or receipt of scientific advice that major volcanic activity is likely;
- A major destructive event with numerous casualties

Following the scenario planning workshop, several amendments were made to the plan, including a record of all possible boat-landing sites on the island and a full list of up-to-date contact numbers for islanders and key personnel in the UK.

7.4.2. Evacuation centre

In discussion with FCO officials at the project outset, it was explained that there were plans to build an evacuation centre on Tristan, as part of disaster management improvements. This investment was a clear message that UK-based officials were taking disaster management seriously.

Design and construction of the centre was to be managed and implemented by islanders, and a site was selected to the west of the Patches. This site was deemed optimum as: a) the nearest gulches are not main tributaries; b) there is easy access to the shore with adequate boat launching positions; c) the terrain is relatively flat and suitable for helicopter landing; d) the centre is close to the camping huts and, e) a natural spring is nearby. In terms of facilities, the centre will have a medical ward and medical supply room, food and equipment storage, a sleeping area for expatriates, a kitchen and toilet facilities. Every six months the food stores will be exchanged with supplies from the supermarket.

As a result of the scenario planning workshop, design recommendations for the evacuation centre were suggested. These included the provision of emergency access and communications capability if the road to the Patches became obstructed and people at the Patches were disconnected from the Settlement. As of May 2012, the main structure of the evacuation centre has been erected and is hoped to be fully functional by end 2012.

7.4.3. Evacuation drill

Following the community presentation, an evacuation drill was conducted. Preparations for the drill had been discussed and refined during the first council meeting. Notices for the drill had been posted around the Settlement for a week prior (Appendix 13) and, as arranged, the administrator ‘rang the gong’ which signalled the heads of families to gather at the village hall (Plate 7.9 and 7.10). The administrator briefly outlined an eruption scenario and instructed people to return home to meet family members and drive to the evacuation site. On the way through Hottentot Gulch, the only driveable exit from the Settlement, names were marked off a list (Plate 7.11). A further roll-call was conducted at the entrance to the evacuation site (Plate 7.12). Except those islanders who were required to work on the harbour project or were ill or infirm, all islanders and expatriates participated in the drill.

In general, feedback from the islanders was positive, although a vociferous minority were dissatisfied with the drill and failed to understand its purpose (especially as the evacuation centre was incomplete). As expected, the exercise highlighted a number of defects in the evacuation plan. These were discussed informally with members of the community and, subsequently, at length with the Island Council following the scenario planning workshop. Several improvements were suggested and many were immediately implemented in a revised version of the plan. Council members suggested that a drill be conducted every year, and that each exercise should be modified to account for a different disaster scenario. Varying the drills in this way prevents complacency, and acts as a reminder that natural events (and responses to them) are often unpredictable and atypical.

Plate 7.9. Administrator Sean Burns ‘ringing the gong’ to alert heads of families to the village hall.

Plate 7.10. Administrator relaying news about the eruption and instructing a complete evacuation to the evacuation site near the Patches.

Plate 7.11. Traffic moving through the check point at Hottentot Gulch.

Plate 7.12. Community gathering at the evacuation site.

7.5. Conclusions

This component of the research aimed to synthesize findings presented in earlier chapters, and to apply social and decision science methods to design effective communication devices tailored for the message and the audience.

There were four 'formal' exchanges with the community, via outreach activities; an Island Council meeting; a community presentation and a participatory scenario planning workshop with the Island Council. The scenario planning workshop formed the focus of the communication strategy and aimed to engage and encourage the Tristan Island Council to consider existing facts within the current context, and reflect on plausible future eruptive scenarios, likely responses and coping strategies. A number of recommendations were produced as a result, including an updated disaster management plan and design changes to the evacuation centre, which is presently being constructed to the west of the Patches. Longer-term adaptations were suggested, such as changes to protocol and infrastructure. The Island Council recommended an evacuation drill to be conducted annually, with regular modification to the hazard, scenario and evacuation strategy (even off-island evacuations plan to be conducted). The evacuation drill itself was successful in terms of assembling the entire population and by initiating rapid, small-scale adaptations in the home (e.g., assembling emergency kits). It is noted, however, that a small, vociferous minority did not agree with (or understand) the reasons for the drill. While this may not be a failing of the communication efforts, it does reflect the challenges of fully connecting with heterogeneous communities (e.g., Bergmans, 2008; Haynes et al., 2008a).

Other structured communication strategies also achieved their aims. Outreach activities with the school children gave them an opportunity to visit and learn about particular volcanic features. As a result, amendments have been made to the school curriculum amendments and geology-focussed field trips will be repeated in future. The film project provided a rare opportunity to engage with elderly islanders who recalled the events of the 1961 eruption. This helped preserve social memory of the eruption itself and the responses to it, which is advantageous given the infrequency of eruptions on Tristan. The community presentation was well-attended, although little evaluation of success was possible at the time, other than the excellent turnout at the subsequent evacuation drill.

On a more informal basis, there was regular interaction with other members of the community to discuss the research, local judgements, beliefs and concerns about the volcano. These casual meetings were particularly useful to connect with the ‘hard-to-reach’ islanders.

Therefore, in summary, to be successful, volcanic risk communication strategies require the integration of three broad areas of expertise: current volcanological knowledge; an ability to identify and summarise uncertainty; and knowledge of social science methods to access and identify community beliefs and values, vulnerabilities and capacities, coupled with an understanding of the social, political and economic context of the community.

CHAPTER EIGHT: Conclusions

This chapter summarises the thesis and draws together the research conclusions. However, given the complexity of this interdisciplinary approach, it is desirable to place it in the wider framework of volcanological research, risk reduction and interdisciplinarity. Therefore, the chapter begins with a short summary of the research context.

8.1. The story so far: a summary of the research context

Traditionally, natural hazards research has focussed on the physical characteristics and drivers of the hazard. Yet, improved knowledge of natural phenomena has failed to reduce the risk posed by geophysical hazards, and losses from natural disasters continue to rise (UNISDR, 2012). Compared to other geophysical hazards, particularly earthquakes, large-scale loss of life from volcanic eruptions is relatively infrequent. However, the paucity of eruptions, in conjunction with their diversity, complexity and unpredictability, often means that the greatest losses generally occur at volcanoes where people are not accustomed to dealing with eruptive phenomena (Peterson, 1988). Furthermore, retrospective accounts of recent volcanic disasters often bear witness to the strong role played by failed communication, and misunderstanding of the nature of social vulnerability, along with the prediction and direct impacts of the volcanic hazards themselves (e.g., Voight, 1990; Tilling, 2009).

Nearly twenty years ago, Tilling and Lipman (1993) reflected on the lessons learned in volcanology, and expressed disappointment at the slow progress (to date) made by the Decade Volcanoes[22] project, created during the International Decade for Natural Disaster Reduction (IDNDR). They concluded that volcanic risk reduction relies upon: a) improvements and increasing numbers of real time monitoring systems; b) comprehensive study of more volcanoes; c) more effective international cooperation, and d) more effective interaction between scientists, authorities and the public (Tilling and Lipman, 1993). Since

[22] The Decade Volcanoes project (1990-2000) was one of the IAVCEI contributions to the IDNDR. The aim of the project was to direct attention to 16 active volcanoes world-wide and to encourage the establishment of a range of research and public-awareness activities aimed at enhancing an understanding of the volcanoes and the hazards posed by them. The project had a few successes, but was hampered by the eruption of the heavily monitored Mount Unzen in Japan (which killed 43) and Galeras in Colombia (which killed nine) as well as civil unrest near Santa Maria (Guatemala) and Nyiragongo (Democratic Republic of the Congo) (Yamamoto et al., 1993; Newhall, 1996; Baxter and Gresham, 1997).

then, significant advances in satellite and ground-based monitoring methods, petrological and geochronological techniques have been made (particularly driven by the ongoing eruption of Soufrière Hills, Montserrat[23]). While tragedies still occur, increasing knowledge of volcanoes and volcanic risk reduction has also led to successful, life-saving evacuations (Siebert et al., 2010). However, the challenge of reducing risk is far from complete. As populations expand and develop, and vulnerabilities and capacities fluctuate and adjust with change, risk reduction strategies necessarily require revision and innovation. Recently, researchers addressing this topic have recognised the role that social vulnerability plays in creating disaster. Complex and dynamic social, political and economic drivers are as important to characterise and understand as the hazard itself. Further, lessons learned from successful preparation, response to and recovery from natural events, have highlighted the important role that the concept of resilience can play. Resilient communities often possess heightened capacity to cope with, and recover from, the impact of natural phenomena (Gaillard, 2007). Therefore, modern approaches to natural hazards research and risk reduction tend towards holism. Disaster risk reduction (DRR) should aim to systematically identify, analyse and reduce the causal factors of disasters (UNISDR, 2004), and this holistic approach necessarily requires integration of methods from diverse disciplines.

This broadening of focus invites contributions, from both social and decision sciences, to the risk reduction sphere. However, interdisciplinary projects integrating knowledge from the physical and social sciences are challenging, and there are often barriers to achieving a successful output. Obstacles are rooted in the tension between the disciplinary organisation of the sciences (e.g., Darnell and Barclay, 2009), specifically, a perceived low status of the social sciences and fundamental epistemological differences. It is common that science subjects requiring more quantitative approaches are perceived (by natural scientists) as more rigorous than those that require less (with physics and mathematics at the top of the hierarchy). Consequently, social sciences are seen as easier and less quantitative that the natural sciences (e.g., Heberlein, 1988; Bauer, 1990). Although rarely acknowledged, it is often the case that social science can be, in a sense, more challenging than natural sciences in

[23] Soufrière Hills Volcano (Montserrat, West Indies, 16.7°N, 62.2°W) is an active volcanic system that originally presented as a crisis (in 1995) and developed into a protracted eruption, with periods of lava dome growth and eruptive phases punctuated by pauses in activity lasting a few days to several months (Kokelaar, 2002). The longevity of the eruption, with continued volcanic events (e.g., pyroclastic flows and surges, sector collapse and tephra fall), provides a suite of volcanic hazard management challenges. These difficulties have been historically exacerbated on Montserrat by communication issues between (and amongst) scientists, decision-makers and the local population (Haynes et al., 2008a).

terms of conceptualisation, and the challenges involved in measuring human behaviour (Heberlein, 1988).

Nonetheless, these challenges are being confronted in many fields (e.g., Bronstein, 2003; Morillo et al., 2003; Sillitoe, 2004; Meagher and Lyall, 2005; Bracken and Oughton, 2006; Barclay et al., 2008; Darnell and Barclay, 2009), and other barriers, particularly funding options and publication outlets, are beginning to break down. It is now recognised that social science methodologies need to be integrated at the outset of research, rather than being 'bolted on' at the end of a physical science study, for example, to facilitate the communication of results. Further, opportunities for early career scientists to undertake exciting and innovative interdisciplinary research are expanding. This particular project provides an example.

Notwithstanding the above, new challenges arising from interdisciplinary studies are emphasised by small-scale or individual research projects such as this. For example, while the issues of communicating between differing disciplinary groups are isolated, they are replaced by challenges of: a) learning a 'new' science and singly appreciating, and working by, different epistemological positions; b) acquiring enough knowledge to appraise the most appropriate method(s) to apply to the problem, and c) preserving scientific rigour throughout. In particular, constraints of time and resources require a delicate balance between producing rigorous science and carefully selecting appropriate methodologies. This feature reflects a general feeling that particular methods and concepts are being used as 'cure all' options for interdisciplinary, issue-driven research; thus revealing an apparent defensiveness that comes with perceived disciplinary ownership of a method, or set of methods.

Therefore, one of the critical roles of an interdisciplinary perspective here is to: a) frame the problem well; b) identify which components of that problem can most effectively be tackled within that frame; c) ensure that correct and robust methods are chosen to tackle the problem, and d) ensure that they are conducted in a robust way. By framing the problem in a way that satisfies the scientific requirements of different disciplines, it is reasonable to reach into a broad methodological toolkit. Yet, this can only be successful if individuals or research groups understand the method, its advantages and limitations in that particular context, and apply it in a scientifically robust way.

This project was undertaken with an understanding of the aforementioned issues. A useful component of this thesis will be to reflect, post-hoc, on the appropriateness of the choices made around the components of this study chosen; the robustness of the methods chosen, and their applicability in settings other than Tristan da Cunha. The remainder of this chapter summarises and discusses the results of this research in relation to the original objectives (see Table 8.1), theory, and wider literature reviewed. The results have already been integrated and applied in Chapter 7. Given the findings from this research, recommendations for further research in interdisciplinary approaches to volcanic risk reduction are presented.

8.2. Research conclusions

This research adopts an integrated, interdisciplinary approach to reducing volcanic risk on Tristan da Cunha. Methodologies from the physical, social and decision-making sciences were integrated, and research components informed another in an iterative manner. While there was considerable overlap between these research components and the application of particular methods, disciplinary 'labels' have been applied in order to assist evaluation of the approach:

This research has two physical science components:

- Using geological techniques to improve knowledge of Tristan volcanology (Chapter 2)
- Constraining recent eruptive behaviour using the $^{40}Ar/^{39}Ar$ technique (Chapter 3)

One decision science component:

- Quantifying uncertainty of future eruptive scenarios using the 'Classical Model' of expert elicitation (Chapter 4)

Two social science components:

- Understanding the present day social, political and economic context, and the history of settlement on Tristan (Chapter 5)
- Using ethnographic methods and tools from disasters, and social-ecological systems (SESs) research, to characterise vulnerability and resilience in the Tristan community (Chapter 6)

All of these components, although themselves interdisciplinary (in that they informed one another), were integrated into an overarching interdisciplinary endeavour. The aim of this venture was to design and implement a variety of risk communication strategies on Tristan, tailored for different audiences with varied knowledge and needs. The communication was focussed around a participatory scenario planning workshop which resulted in a population-wide simulation exercise (Chapter 7).

The broad conclusions from each research component are summarised below, and original objectives are stated, with reference to evidence, in Table 8.1.

Improving knowledge of Tristan volcanology

This research provides an overview of the volcanological and physiographical knowledge of Tristan through new observations, and via the synthesis of data from other authors (see Chapter 2). Tristan has a moderately large edifice (40% of the 5,060m edifice is sub-aerial) which is steep at higher elevations (~30°) and gradually slopes down to a shallower gradient (~8°) at the edge of the high, sheer cliffs which truncate the island. Numerous parasitic centres, considered to be post-shield volcanism, are scattered across the flanks; many of which are breached. Young, low-lying coastal strips flank the north-western and southern margins of the island. Tristan is part of an exclusive group of ocean island volcanoes devoid of a caldera, although collapse has occurred in the past in the form of large scale flank failure. Evidence of collapse is preserved as a significant amphitheatre carved into the north-west sector of the island, and debris avalanche deposits on the seafloor (Holcomb and Searle, 1991).

Mapped eruptive deposits on Tristan demonstrate strong heterogeneity in composition, volume and eruptive style. Sub-aerial deposits are generally silica under-saturated volcanic rocks, spanning a compositional sequence from basanite to phonolite (Le Roex et al., 1990) (wt% K_2O 0.76–6.52). The earliest sub-aerial eruptions appear to represent a shield-building stage; now manifest as well-stratified basanitic and tephritic lava flows, intercalated with localized pyroclastic deposits. The main, gently sloping, shield sequence is succeeded by steeply dipping lavas and pyroclastics, intruded by radial tephritic dykes and trachytic plugs. Recent summit-centred lavas display wider compositional heterogeneity, including small volume phonolitic flows. Styles of activity at the summit have varied, although effusion dominates, with lavas radiating seaward from the central summit vent. The two most recent sub-aerial eruptions (1961-62 eruption; Stony Hill) were low volume leaks of tephri-phonolitic lava, manifest as domes and flows. In 2004, a nearby submarine eruption produced phonolitic pumice rafts which washed up on Tristan beaches.

Geochemical and isotopic studies of Tristan rocks suggest that lavas are tapped by the melting of a heterogeneous source at depth, forming basanitic magma bodies that undergo fractionation and mixing in shallow conduits and transient chambers (Le Roex et al., 1990). Isotopic analyses on the 2004 phonolitic pumice indicate that it was generated by rapid, extensive fractionation of a small parental magma body, unrelated to the 1961 tephri-phonolitic magma (Reagan et al., 2008). This provides some additional evidence that magmatism is not dominated by one large storage region but, rather, smaller individual pockets of magma that source rapidly from depth (see Stroncik et al., 2009, for similarities with El Hierro, Canary Islands).

The overview of the volcanology presented here, and in more depth in Chapter 2, provides a useful summary of the pertinent literature to date, as well as a contribution to new knowledge. It also emphasizes the need to appraise the past eruptive phases of Tristan, and to characterise past magmatic processes, in an attempt to inform future eruptive scenarios. However, due to the wide dispersal of morphologically young (sub-50 ka) parasitic vents and the broad compositional range (medium to low-K) represented within erupted material, this is particularly challenging.

Constraining recent eruptive behaviour using the $^{40}Ar/^{39}Ar$ technique

In an attempt to constrain recent eruptive behaviour and provide insights into the manner in which the volcanic edifice was constructed, new $^{40}Ar/^{39}Ar$ ages were measured on 15 samples selected to reflect possible temporal correlations between eruptive style, composition, or vent location (see Chapter 3). The focus was on the stratigraphically and morphologically younger deposits (usually parasitic centres) in order to bracket age ranges for recent summit and flank activity, and the flank collapse.

Reflecting meticulous sample preparation and state-of-the-art analytical techniques, all 15 samples sites were precisely dated. On Tristan, no spatio-temporal pattern to parasitic centre activity was found, and recent volcanism from these centres varies in style, volume, and composition with time. Timing of the large-scale sector collapse in the north-west was constrained to a 14 ka window, and ages showed that the northern sector of the edifice was built very rapidly (~50 ka). It seems likely that the entire edifice was constructed piecemeal, and has a far more complex evolution than previously assumed. Of particular significance to hazard assessment is the discovery that the summit was active within the same timeframe as recent parasitic centre activity on the flanks and coastal strips. These findings demonstrated the variability of eruption style, volume, composition and location, and present significant uncertainty in terms of anticipating future eruptive scenarios (Hicks et al., 2012).

Quantifying uncertainty of future eruptive scenarios

In an attempt to address this uncertainty, an expert elicitation exercise was conducted (see Chapter 4). Structured expert elicitations such as the 'Classical Model' (CM) (Cooke and Goossens, 1999) have been used successfully to quantify uncertainty in many volcanic settings e.g., Soufriere Hills (Montserrat) (Aspinall and Cooke, 1998) and Vesuvius (Italy) (Baxter et al., 2008), but applications and experts are often informed by monitoring data and comprehensive geochronological records. Given the paucity of eruptions on Tristan and a lack of monitoring records, this exercise was also a test of the effectiveness of this approach to a data-impoverished setting. The content of this elicitation was informed by data collected from the two physical science components (see above, plus Chapters 2 and 3) and information about the social context.

Results showed that experts are highly uncertain about whether unrest would lead to an eruption, and the likely location of future eruptions. 'Rational' consensus was reached via a synthetic 'decision maker', which considered the most likely location of the next eruption to be the coastal strips. This has hazard implications for the islanders who reside on these low lying areas (the Settlement). However, the associated uncertainty around each scenario was very large (between 73-86%).

A paired comparison exercise confirmed that experts were more certain, and in fair agreement on the ranked likelihood of particular hazards occurring, and the likelihood of hazards impacting the Settlement. In the event of an eruption at the summit, on the flanks, on the coastal strips, or from a submarine vent, experts agreed that the hazards most likely to occur, and to impact the Settlement, were earthquakes and rockfalls. This has implications for the Settlement in terms of damage to homes and risk to inhabitants, as buildings were not constructed to withstand seismic activity[24]. Pyroclastic density currents and base surges were considered least likely, probably given the apparent lack of ash flow deposits in the stratigraphy.

Although this elicitation acknowledged extensive uncertainties, it did not indicate a failure of the exercise but, rather, offered an objective expression of the existence and significance of

[24] It is noted that the Tristan buildings were damaged by seismic activity associated with the 1961 eruption (approximately $M \leq 6$) but did not suffer damage from the $M = 4.8$ activity in 2004.

that uncertainty. The results demonstrate the need for broader and deeper understandings of incomplete knowledge, requiring different approaches that complement quantitative risk analysis such as, for example, participatory and deliberative procedures (e.g., Stirling, 2006; Stirling, 2010).

Further, appraisal of the procedure itself highlighted some important considerations for future application of expert elicitation to volcanological problems elsewhere. Particularly in terms of the CM calibration process which rewards experts for good statistical distribution characterization over a set of seed items, at the expense of precision of knowledge. Other expert weighting methods exist. However, the choice of approach is dependent upon a needs assessment of the decision maker, in terms of whether they want experts that are skilled in assessing the degree of uncertainty within their knowledge domain, or experts with knowledge that is best reflected by precise answers (Flandoli et al., 2011).

Defining the social context and characterising vulnerability and resilience

Acknowledging the social dimensions of vulnerability and resilience are crucial for successful risk reduction efforts. On Tristan, information about the social context was gathered from off-island sources, and during two long fieldwork periods on the island (see Chapter 5). By adopting an ethnographic approach to data gathering, information about community characteristics, interactions and social structure were recorded. When examined through a lens of vulnerability and resilience, their dynamic nature became apparent and reflected changing social, economic and political conditions within the community. By reviewing the history of the community, it was possible to take a longer-term view of vulnerability and resilience as inherent in antecedent conditions (e.g., Bankoff et al., 2004) (see Chapter 6).

Cultural changes that resulted from system shocks (e.g., 1961 evacuation), and other slightly slower drivers (e.g., the recent introduction of modern media and communications), have acted to alter vulnerability and resilience. While some changes appeared to strengthen resilience, e.g. the development of a collective identity during the UK sojourn initiating action to return, others appear to erode it, e.g. the detaching effects (from collectivism to individualism) of modern media. Acknowledging the dynamics and drivers of resilience and vulnerability, and their trade-off(s), is thus important in the practical application of disaster management strategies that take account of present day capabilities, and potential community trajectories.

Integrating and communicating results

Long fieldwork seasons were intentionally arranged to invest time for involvement in community activities, and to build relationships with islanders. This had shared benefits for the study aims, the islanders and the researcher. Communicating with the islanders offered an opportunity to make known the research intentions, and to open two-way communication channels about knowledge and perceptions of volcanic hazards and risk. This needs and knowledge assessment of the community was essential for the design of a variety of communication strategies appropriate to different groups. In parallel, time spent with islanders helped foster trust and credibility, mostly through recognition of shared values. In turn, these unforced associations cultivated mutual empathy, sensitivity and reciprocity, and helped establish life-long friendships.

Communication strategies were designed to fit into the Tristan context, and aimed to identify feasible adaptation strategies in order to strengthen existing development plans for the community. Outreach activities were performed with school pupils, one-to-one discussions were regularly conducted, and an informal community meeting was held to discuss results. The main communication strategy was a scenario planning workshop with the Island Council and Administrator. This was an opportunity to present and discuss results from the research while, simultaneously, persuading the participants to consider responses to possible eruptive scenarios. By considering three different eruptive scenarios and a range of possible external factors (e.g., time of day and weather), the workshop encouraged participants to design mitigation measures, make appropriate changes to disaster management strategies, and conduct an annual evacuation drill (see Chapter 7).

Table 8.1 Summary of objectives and evidence of attainment.

Objectives		Evidence
1	To examine the volcanology of Tristan and make relevant field observations to inform a volcanic hazard assessment	Chapter 2
2	To determine high precision $^{40}Ar/^{39}Ar$ ages of rock samples from key locations to test several hypotheses relating to spatio-temporal trends and styles of volcanism	Chapter 3
3	To design and conduct an expert elicitation procedure in order to synthesise expert judgements of possible future eruptive style and location on Tristan	Chapter 4
4	To map local perspectives on volcanic hazards and on their importance relative to other natural hazards	Chapter 6
5	To explore the history of settlement on the island and the present day social,	Chapter 5

	political and economic context	
6	To identify and explore patterns of social organisation, activity and adjustments that have, and may, contribute to resilience and vulnerability	Chapters 5 & 6
7	To identify existing communication networks, both formal and informal, particularly in relation to natural hazards and to the communication of uncertainty	Chapter 6
8	To develop and implement risk and uncertainty communication strategies appropriate to the local context	Chapter 7
9	To test and evaluate the contribution of the context-specific communication methods to support an island risk reduction strategy	Chapter 7
10	To support the community in their mitigation endeavours	Chapter 7

8.3. Further work

Tristan da Cunha is the youngest subaerial active volcanic system on the Walvis Ridge and the latest subaerial manifestation of the Tristan hotspot. This research has shown clear evidence for several differing stages of edifice construction of this young volcano but, to obtain better understanding of edifice construction and insights into rates and changing styles of magmatism - as they relate to this particular intraplate setting - stratigraphically controlled sampling would be necessary. This could address the manner and rate of construction of the volcano. When combined with data from Chapter 3 and those presented in Hicks et al., (2012), further dating of other parasitic centres and coastal strip lavas would provide a relatively complete representation of the eruptive history. Work by other authors suggests that the magmatic plumbing system beneath Tristan is characterised by small pockets of magma that sometimes undergo rapid fractionation at shallow levels (Le Roex et al., 1990; Reagan et al., 2008). Given the lack of monitoring capability on the island and the challenges of evacuation, the onset of a volcanic eruption, with little or no warning time or period of detectable unrest, is a significant concern. Therefore, it would be desirable to conduct further studies of magma petrogenesis and storage to improve our knowledge of magma storage regions, and to uncover petrological evidence for changes that might act to trigger eruptions and the timescales over which they occur. These data, and a more comprehensive geochronology, may help to reduce the uncertainty about future eruptive scenarios.

As part of the support for decision-making processes around volcanic risk, the quantification of uncertainty and tools to achieve consensus between experts have great potential, both in terms of presenting unified forecasts from a team of scientists, but also providing the best possible scientific advice to decision makers during volcanic crises. However, the conclusions from Chapters 4 and 7 demonstrate that, in data-poor volcanic settings, there can be limits to the value of this approach. Nonetheless, this thesis does not provide comprehensive evidence for which strategies and methods work best in which situation, beyond the empirical observation that scenario planning (and other communication techniques) worked best in this instance (i.e. at a volcano where defining probabilities is difficult and where possible outcomes are unclear). Further practical and experimental strategies to test and compare differing types of risk knowledge (i.e. not just risk, but also uncertainty, ambiguity and ignorance) (Stirling, 2003), and the most appropriate ways to communicate and cope with them are required. In Chapter 4, evidence was provided for the ways in which expertise can be ranked and weighted using elicitation techniques. It shows that differing 'types' of expert, and their relative weighting, can impact on both the median value and the distribution of the uncertainty around that answer. Further research is required to explore this.

The research presented in Chapters 5 and 6 demonstrates that the social dimensions of risk are also dynamic. Analysis of the Tristan community has shown that external factors can act to initiate cultural change, thus altering vulnerability of individual members and the society as a whole. Leading on from this, it would be useful to reflect on the value of developing a range of indicators of critical components of this vulnerability, to develop a way in which this might be monitored and evaluated in much the same way as the physical threat.

The best possible science is likely to be ineffective at reducing risk without investing time and effort in the design, implementation and evaluation of communication strategies. These need to be designed in collaboration with the communities at risk, but need not be complex. Strategic listening (Pidgeon and Fischhoff, 2011), for example, can help produce a needs assessment of those at risk, and thus determine the content of the communication rather than just conveying what scientists deem to be important. This thesis provides empirical evidence for the value of this approach, having uncovered evidence of the ways in which the risk messages were to be received. Follow on evaluation would test the enduring nature of these risk messages, and the ways in which they have been incorporated to everyday risk and planning processes.

8.4. *Reflections on the value of an interdisciplinary study*

This research is one of few studies in volcanology that is truly interdisciplinary. It integrates methodologies from the physical, social and decision sciences in an attempt to help reduce risk to volcanic hazards on the island of Tristan da Cunha. In order to produce tailored communication strategies for volcanic risk reduction, new field observations and original geochronological data were integrated with an assessment of the uncertainty of future eruptive scenarios, and with data regarding the unique social context of Tristan, the characteristics and drivers of vulnerability and resilience on the island.

Intriguingly, the research conducted on the chronology of the most recent volcanism in this study resulted in an apparent increase in the degree of uncertainty in anticipating future volcanic activity. Nonetheless, it can be argued that this has improved the understanding of the Tristan volcanic system and, therefore, the accuracy with which the range of potential volcanic activity can be considered has increased. Geochronological and volcanological studies of this type have an important role to play in informing populations about relatively poorly understood systems (e.g., Tilling and Lipman, 1993; Hicks et al., 2012), particularly in the absence of baseline monitoring data. The evidence from this study is that, in this type of data environment, the best means with which to explore risk information is via participatory approaches such as scenario planning. By combining these methods with ethnographic analysis and communication, of which this study has demonstrated the value, this new information can be more effectively used to inform the decision-making processes.

Each component of the study acted to inform the research pathway of the other to maximise the impact of the science. Arguably, single focus on one topic could have produced a more complete analysis – particularly a more comprehensive geochronology. However, conversely, one could argue that a detailed geochronology would not have been embedded within a risk assessment without knowledge of communication processes; its relevance to the development of disaster reduction strategies, and to the Tristan community. In this way, there was value in doing a single person, interdisciplinary study of this type in such a restricted setting.

In choosing approaches, this thesis demonstrates the necessity, *at the project outset*, of taking time to understand the unique social context and dynamics, and integrating this knowledge with information about the volcanic system. Ideally, the type of expertise required for effective interdisciplinary approaches to volcanic risk reduction include subject matter experts (volcanologists), decision scientists who can identify and quantify uncertainties, and social scientists who apply a range of methods to access the public at risk and understand their values, beliefs and knowledge. Communication strategies need to be tailored for the particular social and hazard context and, ideally, need to be designed in collaboration with those at risk. This requires the right type of the communicator (a trusted, credible source) who is able to integrate the science components, successfully deliver messages and evaluate the effectiveness of communications.

If supported by the volcanological community, increasing application of interdisciplinary approaches to volcanic risk reduction will encourage rapid transfer and adjustment of lessons learned at a wide range of volcanic settings.

8.5. Reflections on the transferability of the case study

Whilst this work has been broad in scope, the focus on a very small island population necessarily requires a brief discussion of how to scale up this research to larger volcanoes and populations at risk. Some of the uncertainty around this is due to the need for ideas about behaviour of intraplate volcanoes in this context. However, it is the author's view that this research provides a template for a larger scale, longer duration, multi-researcher study that is still interdisciplinary in scope. This study demonstrates the strength of interdisciplinary research and, whilst challenging, if carefully conducted can achieve its aims.

APPENDIX 1: Data summary from parasitic centres

These data are compiled from work by previous authors and from new measurements. The secondary centres are listed in approximate chronological order (oldest first), based on degree of degradation and, where possible, precise geochronology.

Secondary Centre	Location	$^{40}Ar/^{39}Ar$ age (where known)	No of Vents	Degree of erosion	Est. current volume of cone (assuming circular cone)	Lava Field	Other Info.
Franks Hill	Base	118 ± 4 ka	1	Major	0.0006 km^3	Yes	-
Blackenole	Peak		3	Substantial	0.05 km^3	No	Elongated downslope
Nellie's Hump	Base		Unknown (U/K)	Substantial	U/K	U/K	Over half mound removed by junction with Main Cliffs (collapse)
Stone Castles	Peak		U/K	Substantial	0.026 km^3	U/K	Eroded into prominent pinnacles
Big Gulch Cinder Centres	Base		2	Major	~ 0.05 km^3	U/K	-
Long Ridge & Long Ridge Pinnacles	Base/Peak		U/K	Minor	0.002 km^3	Yes	Pinnacles are from crater wall of centre
Gipsy's Hill	Base		1	Major	0.003 km^3	No	-
Cave Gulch Hill	Base		3	Major	0.006 km^3	U/K	3 centres in a N-S direction; neck exposed in cliffs where centres abruptly stop; probably a maar.
The Knobs	Base/Peak		U/K	Minor	0.007 km^3	Yes (unless collapse)	-
Washout Gulch Cinder Centre	Base		1	Minor	0.002 km^3	No	-
Blineye	Southern Coastal Strip	75 ± 9 ka	2	Substantial	~0.005 km^3 (ERODED)	Yes (but now covered with Stony Hill, Little Hill and Kipuka Hill lavas and Cave Gulch detritus)	Elongate crater rim; 23 m wide feeder dyke

Secondary Centre	Location	$^{40}Ar/^{39}Ar$ age (where known)	No of Vents	Degree of erosion	Est. current volume of cone (assuming circular cone)	Lava Field	Other Info.
Red Hill	Base		1	Minor	0.015 km^3	U/K	-
Ponds Cinder Centre	Base		1	Major	1,590 m^3	U/K	Could have been breached as crater wall on downhill side is only 1m high
Green Hill	Base	44 ± 4 ka	1	Limited	0.012 km^3	Yes	Lava ridge built up seaward side of centre 15m high 30m long
Round Hill	Base		1	Limited	0.008 km^3	Yes	Narrow tongue of hummocky ground from centre of cone
Mate's Hill	Base		1	Limited	0.0006 km^3	Yes	-
Burntwood	Northern Coastal Strip	30 ± 3 ka	U/K	Substantial	~0.118 km^3 (ERODED)	U/K	Heavily marine eroded
Hackel Hill	Southern Coastal Strip	29 ± 4 ka	1	Limited	0.0004 km^3	Yes	-
Big Green Hill	Base	15 ± 1.9 ka	1	Limited	0.005 km^3	No	-
Little Green Hill	Base		1	Limited	0.0003 km^3	Yes	-
Stony Beach Hills	Base		U/K	Substantial	U/K	Yes	Several small centres; cliff eroded
Hillpiece-Burnthill Complex	Northern Coastal Strip	26 ± 5 ka - 2.6 ± 0.9 ka	5	Substantial	0.022 km^3 (not incl. coastal strip)	Yes	At least 2 flows built coastal plain
Little Hill (Hill-with-a-hole-in)	Southern Coastal Strip		2	Limited	0.0005 km^3	Yes	37 m deep vent; no open breach - lava likely issued from base
Kipuka Hill	Southern Coastal Strip		2	Limited	0.0001 km^3	Yes	Extensive aa flow
Stony Hill	Southern Coastal Strip		1	Very limited	0.0023 km^3 (dome only)	Yes	Blocky lava tholoid; 12 m lava spine at summit
1961 Flow	Northern Coastal Strip		1	Very limited	Present dome only-0.0038 km^3; initial tholoid before collapse ~ 0.007 km^3	Yes	-

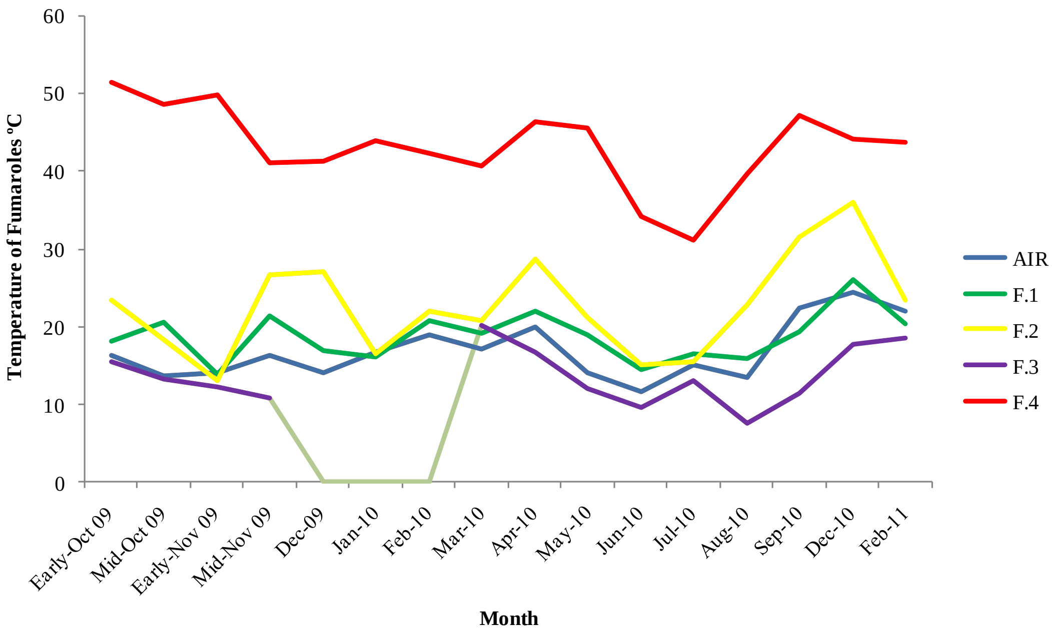
APPENDIX 2: Qualitative and quantitative records of the residual thermal activity from the 1961-62 dome complex (October 2009 – February 2011).

Present day thermal activity on Tristan is confined to the 1961 dome-tholoid complex. Activity is minimal, limited to several fumaroles in the form of small vents and steam seepages from cracks and crevices. Several fumaroles are evident on or near the peripheral crater rim, two of which are persistently active. Other vents around the peripheral crater region show no signs of activity (see fumarole 3 in the table below), and there are other areas where no obvious vents can be detected, but show evidence of minor hydrothermal alteration. The most ‘active’ vent is fumarole 4, situated on the ‘pinnacle’ on the western rim of the original dome-tholoid complex. The pinnacle itself is warm to touch in many areas and displays hydrothermal alteration in the form of white and yellow sulphate encrustations and staining. On calm days, a very slight, almost imperceptible odour of hydrogen sulphide can be detected. Fumarole 4 measured 20 by 30 cm in diameter in October 2009, but was slightly smaller in February 2011. A small amount of steam is visible at close range, and the maximum recorded temperature in the vent entrance reached 51.4°C. A metre or two below the vent is an area of very warm ground reaching similar temperatures to the vent and which occasionally emits diffuse wisps of steam. No audible noise is detectable at any of the fumaroles. Vegetation is limited around the vents, especially fumarole 4. The other vents exhibit grasses, small ferns and mosses. Fumarolic activity also occurs on the dome in the form of north-south trending cracks and crevices. The warm, wet environment promotes the growth of ferns and other vegetation, but steam is visible from some crevices under calm conditions.

During fieldwork seasons, steam seepages were never intense enough to be observed from the Settlement. Hards (2004) field report and interviews with islanders confirmed that steam had not been observed for nearly two years. The unpublished field report of Dunkley (2002) did not make any observation as to the presence or absence of steam visible from the Settlement. Personal communication with the 1991 island ex-patriate doctor confirms that she regularly saw steam emissions from the *volcano* from her house next to the hospital.

Hards (2004) visited the fumaroles during her 3 week visit to Tristan in September 2004 and reported that none showed any visible sign of current activity. Initially it was of concern to the author that the fumaroles were showing signs of renewed activity, but subsequent communication with Hards confirmed that temperature readings were not taken from the hottest fumarole (4). Nevertheless, her records confirm that fumarole 3 was at 9.6°C and temperatures of 34.1°C and 31.6°C were recorded in areas around fumaroles 1 & 2, though it is noted these were recorded by digging down to a depth of 40cm.

Repeat measurements made during the second field season (November 2010 – February 2011) show no major temperature alterations. The figure below shows the apparent correlation between ambient air temperature and fumarole temperature which probably explains the recorded fluctuations. Fumarole 2 recorded the largest fluctuation, reading a minimum temperature of 13.1°C in November 2009 and a maximum temperature of 36.1°C in December 2010. In the authors opinion, these fluctuations can be explained by diverse weather conditions and heating of the rocks by the sun. The lack of sulphurous gases and precipitates indicates that fumarolic activity in general can be attested to residual heat within the dome-tholoid complex heating meteoric water. Note the absence of data for fumaroles 3 between December 2009 and February 2010.



The following table records fumarolic activity from 7th October 2009-14th February 2011. Measurements were recorded with an Omega HH22 Handheld Microprocessor Thermometer and Type K 1m Thermocouple. Measurements from January 2010 to September 2010 were recorded by Leon Glass; all other measurements were recorded by the author.

			Fumarole Temperature (°C)					
Date	**Ambient Temp. °C**	**Weather**	**1**	**2**	**3**	**4**	**5**	**Comments**
07/10/09	16.2	Sunny, slight cool breeze	18.1	23.4	15.4	51.4	N/A	Visible steam emissions from fumarole (4), faint traces of H_2S at fumarole (1), stronger at (4). Fumarole (2) quite vegetated with moss and grasses. (1) grass at fumarole entrance is dead. Very little vegetation (some moss) at (4)
16/10/09	13.6	Moderate wind, drizzly rain	20.5	18.3	13.2	48.6	N/A	Steam barely visible from (4), H_2S at (4), none smelt at (1). (3) is confirmed to be inactive.
18/11/09	14	Cloudy, dry	13.8	13.1	12.3	49.9	15.1	No steam visible from (4). No steam visible from (5), though had been sighted in days previous. Dome crack contains rich vegetation owing to warm, dark, damp environment.
24/11/09	16.3	Partly cloudy, warm	21.4	26.6	10.8	41.1	N/A	Area to the North of (4) lower down on the pinnacle showed slightly hotter temperatures
02/12/09	14	Partly cloudy, moderate winds	17	27	N/A	41.4	N/A	Area to the North of (4) measured highest temperature of 47.2°C. No further changes in vegetation since initial readings. Dome crack showed no obvious thermal emissions. (3) not measured as has showed no comparative increase to ambient temperature.
11/01/10	16.7	N/A	16.0	16.6	N/A	44.0	N/A	N/A
09/02/10	19	N/A	20.7	22.0	N/A	42.3	N/A	N/A
02/03/10	17.1	N/A	19.2	20.7	20.2	40.7	N/A	N/A
28/04/10	20.0	N/A	22.0	28.8	16.8	46.5	N/A	N/A
28/05/10	14.1	Cold wind	19.0	21.2	12.1	45.5	N/A	Steam visible from fumarole 4
24/06/10	11.7	N/A	14.4	15.0	9.5	34.1	N/A	N/A
16/07/10	15.0	N/A	16.6	15.5	13.1	31.1	N/A	N/A
21/08/10	13.4	N/A	15.8	22.9	7.5	39.6	N/A	N/A
15/09/10	22.5	N/A	19.3	31.6	11.5	47.3	N/A	N/A
09/12/10	24.4	Clear, dry	26.1	36.1	17.7	44.1	N/A	Slight steam perceptible from fumarole 2, slight odour for fumarole 4
14/02/11	22.0	Clear, warm & humid	20.3	23.5	18.5	43.8	N/A	Slight steam and odour from (4)

APPENDIX 3: Analytical procedures and results from XRF

Jaw crushed material was powdered in a Tema agate mill and thin sections were made for petrographic analysis. Majors and traces were analysed at the University of East Anglia, UK. Major elements were analysed in glass beads of lithium tetraborate and rock powder. Trace elements were analysed in pressed powder pellets by a Bruker S4 Pioneer wavelength dispersive X-ray fluorescence spectrometer. The rock powder was heated to 1050°C in ceramic crucibles to determine loss on ignition. Calibration was performed using International Standards listed in Appendix 4.

The following table shows major and trace element analyses for 35 representative samples from Tristan da Cunha. Major element content is in wt.% and trace element content is in ppm.

Rock Type	*ankaramitic basanite*	*basanite*	*basanite*	*basanite*	*basanite*	*basanite*	*basanite*	*basanite*	*tephrite*	*tephrite*	*tephrite*	*tephrite*	*tephrite*	*tephrite*	*tephrite*	*tephrite*	*tephrite*	*tephrite*	*tephrite*	
Location	Main Cliffs	Hillpiece	Peak NW	Peak NE	Green Hill	Green Hill	B.Green Hill	B.Green Hill	Blineye	Hottentot	Big Point	Burntwood	Franks Hill	Spring Ridge	J.Watron	J.Watron	Burnthill	Top of Base	Pillows	
Sample No.	**001**	**003**	**041A**	**046**	**052**	**053**	**086**	**092**	**022A**	**007A**	**009A**	**014A**	**054/55A**	**058A**	**068**	**070**	**085A**	**089**	**100**	
MgO	8.21	3.45	5.2	4.73	4.4	4.32	2.68	6.83	4.26	4.48	4.01	4.87	4.14	5.48	0.36	0.43	4.46	3.77	4.44	
Al_2O_3	13.5	16.4	15.92	16.43	17.91	17.59	19.52	14.73	16.46	16.33	17.41	15.93	17.38	16.16	23.55	23.2	16.45	17.38	16.4	
SiO_2	40.6	44.9	44.49	44.68	44.68	42.19	43.95	43.02	43.09	45.98	45.65	45.02	46.04	46	47.4	48.1	46.08	45.91	45.4	
P_2O_5	0.7	1.03	0.73	0.76	1.15	1	0.74	0.71	1.12	0.95	0.97	0.85	1.2	0.74	1.02	0.53	0.93	1.15	0.95	
CaO	11.67	7.8	9.94	9.27	9.03	8.64	6.2	10.61	9.03	9.06	9.09	9.51	8.4	9.52	0.67	0.74	9.04	9.03	9.1	
TiO_2	4.2	2.73	3.63	3.48	2.82	3.22	2.48	3.78	3.19	3.22	3.28	3.31	3.08	3.35	0.66	0.71	3.23	3.3	3.21	
MnO	0.15	0.17	0.19	0.17	0.19	0.17	0.18	0.16	0.27	0.18	0.16	0.18	0.16	0.16	0.05	0.1	0.18	0.18	0.18	
K_2O	1.56	3.31	2.67	2.51	2.42	2.22	3.24	0.76	2.56	3.02	2.95	1.25	3.38	2.66	4.03	4.12	3.2	1.03	3.04	
Fe_2O_3	15.78	9.94	12.15	11.52	10.07	11.68	8.54	13.68	12.54	11.58	11.11	12.34	10.11	12.39	1.17	3.23	11.68	10.5	11.76	
Na_2O	2.42	5.26	3.64	3.78	3.17	3.08	3.98	3.91	3.67	4.2	4.02	5.19	4.21	3.71	3.29	3.23	3.96	5.36	3.96	
Total	98.72	95.04	98.56	97.33	95.84	94.11	91.51	98.19	96.19	99	98.65	98.45	98.1	100.17	82.2	84.39	99.21	97.61	98.41	
% LOI at 1050°C	*1.28*	*3.38*	*-0.15*	*1.46*	*3.94*	*5.04*	*7.76*	*0.39*	*2.42*	*-0.22*	*0.18*	*0.7*	*0.52*	*-0.06*	*18.47*	*15.46*	*-0.29*	*1.18*	*-0.19*	
Total	**100.0**	**98.4**	**98.4**	**98.8**	**99.8**	**99.2**	**99.3**	**98.6**	**98.6**	**98.8**	**98.8**	**99.2**	**98.6**	**100.1**	**100.7**	**99.9**	**98.9**	**98.8**	**98.2**	
																				M'ment Err.+/-
Sc	23	10	14	14	10	10	<10	22	12	12	<10	12	10	16	<10	<10	12	10	10	4
V	414	159	267	238	187	219	137	336	210	195	182	259	198	250	58	109	196	202	198	15
Cr	79	<20	<20	<20	<20	<20	<20	70	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	15
Ni	71	<10	14	<10	14	<10	<10	57	19	<10	12	<10	<10	24	<10	<10	<10	<10	<10	5
Cu	55	<10	16	<10	29	17	<10	31	50	13	<10	16	<10	57	<10	<10	<10	<10	28	5
Zn	98	113	97	104	97	106	107	100	113	100	94	111	107	82	42	73	108	100	111	10
As	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	13	11	<10	<10	<10	3
Rb	41	77	70	74	55	43	74	49	56	72	68	73	71	71	70	82	73	72	67	6
Sr	897	1187	1112	1137	1243	1183	1206	1019	1184	1208	1264	1181	1459	1041	104	198	1197	1442	1243	8
Y	21	27	27	26	29	27	33	25	29	29	29	26	29	25	17	21	29	29	28	5
Zr	219	373	302	311	322	348	410	261	338	343	321	346	350	307	997	968	349	320	341	5
Nb	44	84	66	71	70	75	93	58	76	76	73	78	90	62	228	213	79	77	76	20
Mo	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	3
Ba	393	716	688	711	818	838	950	555	720	742	725	781	825	662	121	289	726	886	747	15
La	38	83	70	70	77	73	117	60	84	77	74	82	96	61	127	178	73	75	80	5
Ce	110	203	165	184	212	207	263	157	214	196	190	205	226	167	220	259	184	214	191	10
Pb	<10	<10	<10	<10	<10	11	<10	<10	10	<10	<10	<10	<10	<10	23	23	<10	<10	<10	6
Th	<10	12	11	12	12	12	15	<10	11	11	12	13	13	11	32	34	13	11	12	4
U	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	

Rock Type	*phono tephrite*	*phono tephrite*	*phono tephrite*	*phono tephrite*	*phono tephrite*	*phono tephrite*	*phono tephrite*	*phono tephrite*	*phono tephrite*	*basaltic trachyandesite*	*tephi phonolite*	*tephi phonolite*	*tephi phonolite*	*tephi phonolite*	*phonolite*	*phonolite*	
Location	Blineye	Kipuka Hill	Little Hill	Peak SE	Base BGH	Hackel Hill	Hackel Hill	Peak SE	Peak Crater	Caves	Stony Hill	Peak Plug	1961 Dome	1961 Dome	J.Watron	S.Bay Pumice	
Sample No.	**019**	**020**	**021A**	**040**	**087**	**025**	**033**	**044**	**050**	**024B**	**023A**	**035-038**	**095**	**097A**	**062A**	**034**	
MgO	3.31	1.64	1.57	2.25	2.54	1.96	2.14	2.31	2.4	1.94	1.65	0.67	0.96	1.44	0.3	0.35	
Al_2O_3	17.26	18.97	19.02	19.17	18.63	18.82	18.6	19.06	18.97	18.59	18.97	20.18	19.0	19.24	19.66	17.9	
SiO_2	47.77	52.89	53.2	51.84	50.35	51.26	50.8	49.25	50.05	51.78	53.45	57.27	56.4	54.96	60.02	61.4	
P_2O_5	1.05	0.48	0.45	0.76	0.74	0.87	0.66	0.76	0.7	0.65	0.49	0.14	0.24	0.38	0.06	0.06	
CaO	8.26	5.82	5.63	5.89	6.5	6.37	6.59	5.98	6.54	6.45	5.74	3.08	4.08	5.46	1.22	1.24	
TiO_2	2.69	1.71	1.68	2.29	2.35	1.95	1.97	2.29	2.28	1.86	1.7	1.04	1.26	1.65	0.5	0.46	
MnO	0.18	0.18	0.18	0.15	0.17	0.17	0.18	0.17	0.17	0.18	0.18	0.12	0.17	0.18	0.23	0.12	
K_2O	3.22	4.41	4.45	4.2	4.12	4.06	3.92	3.19	3.86	2.68	4.51	5.4	4.96	4.67	6.75	6.52	
Fe_2O_3	10.18	6.58	6.37	6.7	7.88	7.37	7.54	7.56	7.76	7.15	6.55	3.28	4.68	5.89	2.29	2.13	
Na_2O	4.64	4.95	5.14	5.31	4.86	4.86	4.88	5.16	4.91	5.96	5.3	6	6.13	5.72	5.68	6.91	
Total	98.56	97.63	97.69	98.56	98.14	97.69	97.22	95.73	97.64	97.24	98.54	97.18	97.85	99.59	96.71	97.1	
% LOI at 1050 °C	*-0.1*	*1.2*	*1.28*	*1.02*	*0.79*	*1.28*	*1.51*	*3.06*	*1.44*	*1.46*	*0.74*	*1.74*	*0.86*	*0.4*	*2.85*	*2.33*	
Total	**98.5**	**98.8**	**99.0**	**99.6**	**98.9**	**99.0**	**98.7**	**98.8**	**99.1**	**98.7**	**99.3**	**98.9**	**98.7**	**100.0**	**99.6**	**99.4**	
																	M'ment Err.+/-
Sc	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	4
V	164	75	75	131	130	92	96	85	115	90	69	55	59	68	12	18	15
Cr	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	15
Ni	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	5
Cu	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	5
Zn	108	102	102	95	106	104	111	102	101	96	95	63	90	93	81	74	10
As	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	12	3
Rb	84	101	101	107	96	90	88	117	96	93	104	155	121	112	173	161	6
Sr	1292	1389	1373	1416	1320	1414	1420	1447	1365	1453	1390	920	1289	1408	77	79	8
Y	29	27	29	27	28	28	29	27	28	27	29	22	31	31	24	14	5
Zr	394	474	478	397	412	463	436	398	432	423	475	530	530	473	799	720	5
Nb	87	105	105	97	95	103	98	98	98	95	104	106	127	113	172	120	20
Mo	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	3
Ba	805	1170	1160	1147	985	1170	1085	1184	1027	1166	1172	1308	1487	1289	<20	51	15
La	88	115	113	97	95	106	108	107	102	114	109	99	126	120	165	119	5
Ce	218	240	250	219	219	241	240	233	228	256	239	191	249	255	223	156	10
Pb	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	13	11	<10	21	25	6
Th	13	15	16	15	14	15	14	15	16	15	16	20	19	17	28	24	4
U	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	

APPENDIX 4: Calibration, precisions and quantification limits for the Bruker S4 Pioneer wavelength dispersive X-ray fluorescence spectrometer.

The calibration for major elements (Na, Mg, Al, Si, P, K, Ca, Ti, Mn, Fe) was made with a set of certified geological standards:

1c, Argillaceous limestone, USNBS
368, Dolomite, BCS
376, Potash Feldspar, BCS
AC-E, Granite, CNRS
AGV-1, Andesite, USGS
BCR-2, Basalt, USGS
BE-N, Basalt, CNRS
BX-N, Bauxite, CNRS
DTS-1, Dunite, USGS
DTS-1, Dunite, USGS
G-2, Granite, USGS
GS-N, Granite, CNRS
GXR-1, Drum Mountains, Utah, USGS
GXR-2, Park City, Utah, USGS
GXR-3, Humbolt County, Nevada, USGS
LKSD-3, Lake sediments, NRC
MRG-1, Mont Royal Grabbo, NRC
SARM-2, Syenite, SABS
STSD-1, Stream sediments, NRC
UB-N, Serpentine, CNRS

The precisions are:
Na2O: +/- 0.10% up to 0.50% and +/- 0.20% up to 4%
MgO: +/- 0.10%
Al2O3: +/- 0.25%
SiO2: +/- 0.60%
P2O5: +/- 0.03%
K2O: +/- 0.05%
CaO: +/- 0.04% up to 2%, +/- 0.15% up to 10% and +/- 0.6% above 10%
TiO2: +/- 0.04%
MnO2: +/- 0.02%
Fe2O3; +/- 0.10% up to 5% and +/-0.20% up to 10%

The quantification limits (limits below which no concentration is given) are:
Na2O: 0.20%
MgO: 0.20%
Al2O3: 0.50%
SiO2: 1.0%
P2O5: 0.05%
K2O: 0.10%
CaO: 0.10%
TiO2: 0.05%
MnO: 0.03%
Fe2O3: 0.12%

APPENDIX 5: Sampling sites and sample descriptions.

Sample number	Sample type	GPS data	Location description	Sample/deposit description
TDCAH001	Lava		Rockfall from Old Burnt, near Big Sandy Gulch	Samples collected from base of slope; fresh surfaces; boulders between 30cm-2m in size; rolled up to 40m from base of slope; numerous indentations on vegetated cliff face; fall originated from high up (~300m) in the tree-lined zone of the cliff; highly porphyritic ankaramitic basanites.
002	Lava		Rockfall from Old Burnt, near Big Sandy Gulch	
003	Small pumiceous scoria (almost reticulite)		Hottentot Beach (washed up). Originally from Hillpiece	Hottentot Beach due east of Hillpiece where fresh rockfall occurred 1-2 days prior to washed up deposits; high ‘tide’ is marked by numerous small (~10mm) green/yellow rounded pumiceous fragments.
004	Scoria		Hottentot Beach (washed up). Originally from Hillpiece	Same location as 003; scoria blocks between 7-60cm diameter; red/black; moderately rounded.
005	Peat	738522 5894187	Hottentot Gulch	Thin layer (~3cm) of clayey peat. Part of succession of lavas, alluvium, sand and gravel layers.
006	Lava		Hottentot Gulch	Samples taken from relatively un-weathered section of the uppermost of two thick lava flows that comprise the Settlement coastal strip; fine, mid grey aphyric lava with small vesicles; spheroidal weathering common in both flows generally, though rare in these samples.
007	Lava	738481 5894402	Hottentot Gulch	
008	Lava		Hottentot Gulch	
009	Lava	741764 5894788	Big Point	Rockfall west of Big Point from 3rd lava flow outcropping in Main Cliffs; flow ~20m in width with rubbly top and bottom; some columnar jointing though not as pronounced as lower flows. Massive flows. Mafic (tephritic/basanitic). Aphyric.
010	Lava		Big Point	

011	Lava fragments/bombs	740712 5893765	Burntwood	Uppermost layer of scoria cone; fragments taken from spatter/bomb on ridge. Highly vesicular.
012	Lava fragments/bombs		Burntwood	
013	Lava fragments/bombs		Burntwood	
014	Lava fragments/bombs		Burntwood	
015	Bomb		Burntwood	Uppermost layer of Burntwood 'red' layer.
016	Bomb		Burntwood	Taken from scree slope at base of Burntwood.
017	Bomb		Burntwood	
018	Lava	742445 5883636	Blineye	Leucitic Basanite?? Rounded lava sample from base of thick plug (~20m diameter) to the east of Blineye.
019	Lava			
020	Lava	741758 5883247	Kipuka Hill	Taken from lobe of lava on northern slope of Kipuka Hill. Small lobe (5-6m in length) emerging from crater rim; highly vesicular; v.fine grained; glassy in places; almost aphanitic.
021	Bomb/fragments	741673 5883549	Little Hill	Samples taken from crater rim; spindle bombs and lava fragments; light grey; very fine grained; rare feldspar.
022	Bomb/fragments	742345 5883298	Blineye	Samples taken from southern crater rim, east of breach; occasional bombs (spindle) and lava fragments; samples were part of large bomb/spatter.
023	Lava	742100 5883223	Stony Hill	Sample taken from top of arch of blocky flow south-east of Stony Hill summit; columnar jointed flow; mid grey; some feldspars visible in hand specimen.
024	Lava	738244 5883792	Caves	Bottom-most lava flow; sample taken from recent small rockfall from middle of flow; relatively unweathered compared to rest of flow. Spheroidal weathering common in these flows.

025	Lava	738442 5883997	Hackel Hill Flow at Seal Bay	Top of flow from Hackel Hill forming uppermost (and only) flow outcropped at Seal Bay.
026	Lava		Seal Bay	Sample of lava from alluvium around Seal Bay. Highly porphyritic.
027	Lava			
028	Breccia		Bull Point	Fallen block from distinct layer half way up cliff face (~250m). Highly porphyritic..
029	Lava		Hackel Hill	Sample from weathered boulders in alluvium around Hackel Hill. Highly porphyritic.
030	Lava			
031	Lava			
032	Lava			
033	Lava (Hornito)	737819 5884713	Hackel Hill	
034	Pumice		Seal Bay	Weathered pumice washed up on Seal Bay; well rounded; likely a remnant of the 2004 submarine eruption.
035	Lava (Plug)	740894 5889802	Peak summit crater wall	Light grey lava; very fine grained; dense; frost shattered; phonolitic?? Feldspar phenocrysts visible in hand specimen.
036	Lava (Plug)			
037	Lava (Plug)			
038	Lava (Plug)			
039	Sulphurous deposits		Peak E side	Slightly north of summit is a small area of yellow/white stained powdery deposits; no gas, elevated temperature or sulphur crystals.
040	Lava	741901 5889734	Peak E side	Light grey, platy lava flow; heavily frost shattered. Low volume flow on upper slopes, but could possible extend to the east capping ridge...difficult to confirm.
041	Lava	740367 5890268	Peak NW side	Thin, light grey platy flow capping ridges, frost shattered, some phenocrysts
042	Lava			
043	Lava	740923 5889259	Peak E side	3m thick weathered brown flow emerging from summit (is this lava or solifluxion deps????); occasional phenocrysts; very sandy.
044	Lava			

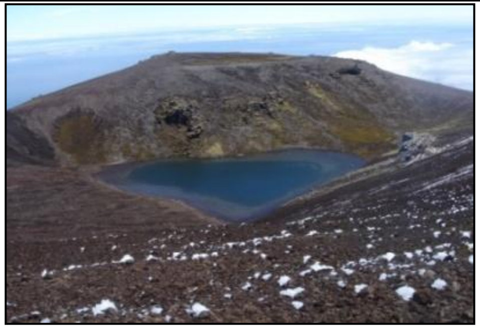
045	Lava		NE rim of Peak summit	Alkali feldspar rich lava; weathered; thick deps in places, may have been large flow but eroded in most places now to leave sparse pink deposits.
046	Lava			
047	Bomb/lava fragments	740812 5889499	Peak crater rim	Spindle bombs and various other types collected from crater rim; show very little signs of weathering.
048	Bomb/lava fragments			
049	Bomb/lava fragments			
050	Bomb/lava fragments			
051	Lava	738986 5887187	Green Hill	Sample from north of crater rim, red vesicular lava. Pyroxenes and amphiboles visible in hand specimen.
052	Lava			
053	Lava	738800 5886902	Green Hill – central lava ridge	Sample of black lava from top of ridge section (south of crater)
054	Lava frags/bombs/scoria	736615 5887545	Franks Hill	Samples collected from seaward side, just above embayment. Only obvious outcrop of large blocks and bombs on otherwise red/black scoria cone. Blocks of black vesicular lava 30cm-100cm. Aphyric.
055	Lava frags/bombs			
056	Lava frags/bombs			
057	Lava frags/bombs			
058	Plug	737008 5890726	Spring Ridge	Plug extends vertically for entire height of cliff face (~ 600m); light grey; fine grained; leucitic?; few phenocrysts, NW facing, section has some cavities with what appears to be secondary injection of magma; few rockfalls to base of plug, majority of erosion seems to be to the west of the plug with scree accumulating in small gully, plug quite well fractured, whole area slightly vegetated.
059	Plug			
060	Plug			
061	Plug			
062	Lava		Jenny's Watron	Lavas sitting unconformably beneath 067-071. Pale grey/pink, alkali feldspar – probably volcanic neck/plug eroded prior to deposition of 067-071.
063	Lava			
064	Lava			

065	Lava			
066	Lava			
067	Sub-aqueous Deps		Jenny's Watron	Light coloured tuffs capping 069-071.
068	Sub-aqueous Deps			
069	Sub-aqueous Deps			
070	Sub-aqueous Deps		Jenny's Watron	Coarse yellow agglomerates with lava fragments
071	Sub-aqueous Deps			
072	Lava/Scoria		Patches	
073	Lava/Scoria		Patches	
074	Lava/Scoria		Patches	
075	Lava (Hornito)		Patches	
076	Lava		Patches	
077	Lava/bomb		Patches	
078	Lava/bomb		Patches	
079	Lava		Patches	
080	Lava		Patches	
081	Bomb		Hillpiece	Small crater to the W of Hillpiece – probably last to form in the whole complex. Sample taken from crater rim.
082	Lava		Hillpiece	Found on crater rim, but a discrete outcrop – looks similar to heavily weathered boulders at Hackel Hill alluvial plain. From elsewhere??
083	Lava		Hillpiece	Small crater to the W of Hillpiece – probably last to form in the whole complex. Sample taken from crater rim.
084	Lava/scoria		Burnthill	Samples collected from base of outcrop to the west of Burnthill (Burnthill younger than Hillpiece). Lava samples from discrete layers, set in no particular arrangement, amongst the unconsolidated scoria.
085	Lava/scoria	737979 5892401	Burnthill	
086	Cinder		Big Green Hill	Sample gathered from the western outer slope from one outcrop on an otherwise completely vegetated scoria cone.

087	Lava		W of Councils Gulch/Main Cliffs – at landslide	Very thin (~2cm), reddish layer outcropping on the very surface of the Base. Could only trace for 2-3 m.
088	Lava		W of Councils Gulch/Main Cliffs	Uppermost flow on the Base (collapse constraint?). Some apparent variations with 092 and 093, but in the field could be same flow, or at least same pulse. Phenocrysts of pyroxene and amphibole visible in hand specimen.
089	Lava	740712 5893765	W of Councils Gulch/Main Cliffs	
090	Agglomerate?		Councils Gulch/BGH	Samples gathered from base of Big Green Hill
091	Agglomerate?		Councils Gulch/BGH	
092	Lava		Councils Gulch/BGH	Lava immediately underlying Big Green Hill and, if in line with carbon dating from the 60's should be ~12,000 B.P. Sample taken from flow that also happens to be one of the uppermost flows on the Base (see 089), so also can constrain collapse??
093	Lava	741578 5893723	Councils Gulch/BGH	
094	Stained lava		1961 fumarole	
095	Lava		1961 pinnacle	
096	Lava		1961 dome	
097	Lava		1961 dome	
098	Lava		Burntwood	Sample taken from base of slope
099	Agglomerate /Agglutinate?		Burntwood	Sample taken from base of slope
100	Lava	738788 5894850	Harbour Pillows	Leon Glass collected from pillow lavas at intertidal zone near Harbour. Aphyric flows. Highly vesicular.

APPENDIX 6: Summary of specific sampling locations and deposits used for $^{40}Ar/^{39}Ar$ dating (see Chapter 3).

Sample #	Rock type	Deposit	GPS Coordinates (UTM)	Location description	$^{40}Ar/^{39}Ar$ age	Image of sampling site
TDCAH054	Tephrite	Scoria	0736615 5887545	Small scoria cone on SW flank of Base	118 ± 4 ka	
TDCAH010	Tephrite	Lava flow	0741764 5894788	Thick lava flow 5 metres from cliff base in north of the island	81 ± 10 ka	

TDCAH047	Phono-teprhite	Bomb	0740812 5889499	Peak summit crater bomb	81 ± 8 ka	
TDCAH022	Tephrite	Scoria cone	0742345 5883298	Large scoria cone dissecting south flank and coastal strip	75 ± 9 ka	
TDCAH052	Tephrite	Scoria	0738986 5887187	Large scoria cone on the south-west flank	44 ± 4 ka	

TDCAH038	Trachyte	Volcanic plug	0740894 5889802	Volcanic plug within summit crater	42 ± 6 ka	
TDCAH089	Tephrite	Lava flow	0740712 5893765	Surface lava flow on northern flank	34 ± 1 ka	
TDCAH011	Tephrite	Scoria	0736087 5889692	Large scoria cone on the western coastal strip/Base	30 ± 3 ka	

TDCAH024	Basaltic trachyandesite	Lava flow	0738244 5883792	Lava flow on southern coastal strip	29 ± 4 ka	
TDCAH007	Tephrite	Lava flow	0738481 5894402	Thick lava flow on northern coastal strip	26 ± 5 ka	
TDCAH100	Tephrite	Lava flow	0738788 5894850	Pillow lavas on northern coastal strip	16 ± 6 ka	

TDCAH041	Tephrite	Lava flow	0740367 5890268	Small lava flow on north-western Peak	16 ± 3 ka	
TDCAH093	Basanite	Scoria	0741578 5893723	Small scoria cone on northern flank	15 ± 2 ka	
TDCAH040	Tephri-phonolite	Lava flow	0741901 5889734	Low volume lava flow on eastern Peak	5 ± 1 ka	

TDCAH085	Tephrite	Scoria	0737979 5892401	Large scoria cone on north-west coastal strip	3 ± 1 ka	

APPENDIX 7: Details of separated samples for $^{40}Ar/^{39}Ar$ analysis.

The following table records the details of separated samples for $^{40}Ar/^{39}Ar$ analysis. Sizes represent mesh size of sieves. Note that sample NGTAH006 was analysed but ages were not discussed in the chapter or in Hicks et al., 2012.

Sample number	Mineral separate	Size(s) of separate (μm)	Picked weight (g)
TDCAH007	Groundmass	500-1000	1.05
TDCAH089	Groundmass	500-1000	1.00
TDCAH093	Groundmass	500-1000	0.91
TDCAH100	Groundmass	500-1000	1.94
TDCAH047	Hornblende	250-500 & 500-1000	0.20
TDCAH041	Groundmass	500-1000	0.85
TDCAH040	Groundmass	500-1000	1.05
TDCAH038	Groundmass	500-1000	2.28
TDCAH085	Groundmass	500-1000	1.10
TDCAH052	Hornblende	250-500	0.98
TDCAH011	Groundmass	500-1000	0.96
TDCAH054	Groundmass	500-1000	1.14
TDCAH022	Hornblende	250-500 & 500-1000	1.18
TDCAH024	Hornblende	250-500 & 500-1000	1.17
TDCAH010	Groundmass	500-1000	1.00
NGTAH006	Hornblende	500-1000	0.48

APPENDIX 8: Raw data from $^{40}Ar/^{39}Ar$ analyses; blank discrimination and constant and standard details.

Lab ID#	%	Plateau	J (X 10^{-3})	±1s (X 10^{-3})	^{40}Ar (10^{-2} V)	±1s	^{39}Ar (10^{-2} V)	±1s	^{38}Ar (10^{-2} V)	±1s	^{37}Ar (10^{-2} V)	±1s	^{36}Ar (10^{-2} V)	±1s
TDCAH007, groundmass, 150 mg, PKT 91, EK61														
50449-1	5		0.013100	0.000026	219.5150	1.1000	4.1687	0.0441	0.2011	0.0178	12.1774	0.2223	0.6347	0.0029
50449-2	15		0.013100	0.000026	176.7063	0.7200	4.6815	0.0301	0.2821	0.0178	8.4959	0.1673	0.5199	0.0028
50449-3	25		0.013100	0.000026	225.8203	0.5000	6.3451	0.0391	0.3609	0.0178	9.2645	0.1631	0.7011	0.0033
50449-4	30	x	0.013100	0.000026	167.2643	1.2000	5.6151	0.0421	0.8693	0.0386	9.7299	0.1565	0.5597	0.00774
50449-5	35	x	0.013100	0.000026	287.6141	2.2000	8.7382	0.0631	0.9498	0.0320	11.4578	0.2098	0.9548	0.0033
50449-6	45	x	0.013100	0.000026	277.3121	1.1000	8.8196	0.0611	0.6391	0.0273	10.2495	0.1649	0.8969	0.0039
50449-7	60	x	0.013100	0.000026	260.6948	0.8500	7.7178	0.0271	0.5396	0.0367	9.6237	0.1774	0.8525	0.0028
TDCAH010, groundmass, 175 mg, PKT 78, EK61														
50327-1	5	x	0.013300	0.000027	620.7915	0.9600	4.9945	0.0231	0.4869	0.0130	3.8063	0.1369	2.0512	0.0048
50327-2	15	x	0.013300	0.000027	1609.0300	3.1000	12.5730	0.0631	1.3285	0.0140	8.1299	0.1523	5.2841	0.0085
50327-3	25	x	0.013300	0.000027	2625.0360	3.4000	19.3039	0.0521	2.0198	0.0200	11.0692	0.1755	8.6519	0.01
50327-4	30	x	0.013300	0.000027	2447.6290	6.7000	16.7128	0.0681	1.9745	0.0300	9.5055	0.1654	8.1158	0.013
50327-5	35	x	0.013300	0.000027	2116.4030	4.2000	13.7754	0.0621	1.7121	0.0270	8.5891	0.1635	6.9912	0.01
50327-6	40	x	0.013300	0.000027	1993.7760	3.5000	11.9702	0.0571	1.5201	0.0150	8.4928	0.1866	6.6027	0.0094
50327-7	50	x	0.013300	0.000027	1959.7930	5.2000	10.5284	0.0441	1.4450	0.0160	8.6962	0.1466	6.5236	0.011
50327-8	60	x	0.013300	0.000027	2385.2810	7.9000	12.8641	0.0621	1.7644	0.0210	12.0836	0.2091	7.9606	0.014
TDCAH011, groundmass, 150 mg, PKT 74, EK61														
50711-1	5	x	0.013900	0.000028	66.0868	0.7600	3.1647	0.0281	0.4302	0.0246	5.0182	0.1362	0.2106	0.00723
50711-2	15	x	0.013900	0.000028	167.2643	1.2000	6.5035	0.0421	0.8693	0.0386	7.4994	0.1206	0.5397	0.00774
50711-3	25	x	0.013900	0.000028	287.6141	2.2000	9.6263	0.0631	0.9498	0.0320	8.8313	0.1617	0.9448	0.0033
50711-4	30	x	0.013900	0.000028	277.3121	1.1000	8.6909	0.0611	0.6391	0.0273	7.9000	0.1271	0.9069	0.0039
50711-5	35	x	0.013900	0.000028	260.6948	0.8500	7.5893	0.0271	0.5396	0.0367	7.4176	0.1367	0.8625	0.0028
50711-6	40	x	0.013900	0.000028	225.8203	0.5000	6.2167	0.0391	0.3609	0.0178	7.1407	0.1257	0.7311	0.0033
50711-7	50	x	0.013900	0.000028	176.7063	0.7200	4.5532	0.0301	0.2821	0.0178	6.5483	0.1289	0.5799	0.0028
50711-8	60	x	0.013900	0.000028	219.5150	1.1000	4.0405	0.0441	0.2011	0.0178	9.3859	0.1713	0.7247	0.0029

^{39}Ar Moles	^{39}Ar % of total	%(^{36}Ar)$_{Ca}$	Ca/K	±1s	%^{40}Ar*	Age (Ma)	±1s	w/±*J* ±1s	^{36}Ar/^{40}Ar	±%1s	^{39}Ar/^{40}Ar	±%1s	^{36}Ar/^{39}Ar Er. Corr.
4.7E-15	9.0	0.5	5.73	0.12	15.0	0.1869	0.0121	0.0121	0.0029	1.0508	0.0190	1.1902	0.5510
5.3E-15	10.2	0.4	3.56	0.07	13.4	0.1199	0.0085	0.0085	0.0029	1.0490	0.0265	0.7883	0.6119
7.2E-15	13.8	0.3	2.86	0.05	8.6	0.0722	0.0075	0.0075	0.0031	0.9557	0.0281	0.6856	0.6036
6.3E-15	12.2	0.5	3.40	0.06	1.6	0.0111	0.0122	0.0122	0.0033	1.7575	0.0335	1.0585	0.4564
9.9E-15	19.0	0.3	2.57	0.05	2.2	0.0172	0.0090	0.0090	0.0033	1.1610	0.0304	1.0724	0.7277
1.0E-14	19.1	0.3	2.28	0.04	4.7	0.0349	0.0072	0.0072	0.0032	0.9944	0.0318	0.8242	0.6271
8.7E-15	16.7	0.3	2.44	0.05	3.6	0.0291	0.0072	0.0072	0.0033	0.9252	0.0296	0.5199	0.7279
	100.0		**2.77**	**0.02**		**0.0597**	**0.0032**	**0.0032**					
5.6E-15	4.9	0.0489887	1.49	0.05	2.4	0.0718	0.0249	0.0249	0.0033	0.8478	0.0080	0.5278	0.7038
1.4E-14	12.2	0.040618	1.27	0.02	3.0	0.0920	0.0252	0.0252	0.0033	0.8384	0.0078	0.5741	0.7113
2.2E-14	18.8	0.0337763	1.12	0.02	2.6	0.0861	0.0262	0.0262	0.0033	0.8185	0.0074	0.3602	0.7686
1.9E-14	16.3	0.0309206	1.11	0.02	2.0	0.0720	0.0299	0.0299	0.0033	0.8606	0.0068	0.5305	0.7458
1.6E-14	13.4	0.032434	1.22	0.02	2.4	0.0891	0.0304	0.0304	0.0033	0.8365	0.0065	0.5321	0.7285
1.4E-14	11.7	0.0339573	1.39	0.03	2.2	0.0868	0.0328	0.0328	0.0033	0.8312	0.0060	0.5467	0.7193
1.2E-14	10.2	0.0351921	1.62	0.03	1.7	0.0746	0.0380	0.0380	0.0033	0.8595	0.0054	0.5351	0.7404
1.5E-14	12.5	0.0400733	1.84	0.03	1.4	0.0631	0.0390	0.0390	0.0033	0.8836	0.0054	0.6193	0.7322
	100.0		**1.29**	**0.01**		**0.0808**	**0.0105**	**0.0105**					
3.6E-15	6.3	0.6290343	3.11	0.09	6.4	0.0337	0.0185	0.0185	0.0032	3.7291	0.0479	1.4691	0.2988
7.3E-15	12.9	0.3668496	2.26	0.04	5.0	0.0323	0.0112	0.0112	0.0032	1.7973	0.0389	0.9882	0.4626
1.1E-14	19.1	0.2467805	1.80	0.04	3.2	0.0237	0.0086	0.0086	0.0033	1.1619	0.0335	1.0284	0.7436
9.8E-15	17.2	0.2299619	1.78	0.03	3.6	0.0286	0.0078	0.0078	0.0033	0.9921	0.0313	0.8327	0.6259
8.6E-15	15.1	0.2270385	1.92	0.04	2.4	0.0210	0.0078	0.0078	0.0033	0.9236	0.0291	0.5239	0.7279
7.0E-15	12.3	0.2578694	2.25	0.04	4.6	0.0417	0.0083	0.0083	0.0032	0.9459	0.0275	0.6970	0.6065
5.1E-15	9.0	0.2980974	2.82	0.06	3.3	0.0321	0.0097	0.0097	0.0033	1.0207	0.0257	0.8030	0.6241
4.6E-15	8.0	0.3419308	4.55	0.10	2.8	0.0378	0.0138	0.0138	0.0033	1.0266	0.0184	1.2198	0.5556
	100.0		**2.12**	**0.02**		**0.0301**	**0.0034**	**0.0034**					

Lab ID#	%	Plateau	*J* (X 10^{-3})	±*1s* (X 10^{-3})	^{40}Ar (10^{-2} V)	±1s	^{39}Ar (10^{-2} V)	±1s	^{38}Ar (10^{-2} V)	±1s	^{37}Ar (10^{-2} V)	±1s	^{36}Ar (10^{-2} V)	±1s
TDCAH022, hornblende, 100 mg, PKT 93, EK61														
50454-1	5	x	0.013600	0.000027	77.0697	0.4130	0.1430	0.0172	0.0385	0.0348	0.6730	0.0893	0.2596	0.00171
50454-2	15	x	0.013600	0.000027	100.9048	0.5622	0.7075	0.0180	0.2471	0.0366	1.9337	0.1022	0.3362	0.00191
50454-3	25	x	0.013600	0.000027	155.2303	1.2010	1.6121	0.0288	0.5962	0.0429	4.0610	0.1309	0.5126	0.00251
50454-4	35	x	0.013600	0.000027	201.4313	2.0006	3.0975	0.0413	1.3694	0.0773	7.4766	0.1279	0.6492	0.00331
50454-5	40	x	0.013600	0.000027	193.9253	2.5005	3.2360	0.0510	1.3041	0.1444	9.4261	0.1890	0.6387	0.0046
50454-6	50	x	0.013600	0.000027	296.5648	4.0003	6.1211	0.0619	2.5361	0.1347	14.4955	0.2019	0.9534	0.0045
50454-7	60	x	0.013600	0.000027	105.6748	0.9513	2.0197	0.0251	0.4617	0.0620	7.3982	0.1398	0.3299	0.00328
TDCAH024, hornblende, 150 mg, PKT 100, EK61														
50374-1	5	x	0.013000	0.000026	101.2257	0.2979	0.2095	0.0211	0.0742	0.0056	0.6162	0.0248	0.3415	0.0022
50374-2	10	x	0.013000	0.000026	82.8103	0.4749	0.9562	0.0269	0.2147	0.0122	3.2721	0.0663	0.2733	0.00228
50374-3	15	x	0.013000	0.000026	93.0122	0.6038	1.5433	0.0276	0.4062	0.0172	5.7217	0.0881	0.3103	0.00244
50374-4	20	x	0.013000	0.000026	55.9581	0.4551	2.1418	0.0314	0.4843	0.0172	7.9173	0.1463	0.1849	0.00228
50374-5	25	x	0.013000	0.000026	67.2442	0.7332	2.7450	0.0347	0.5884	0.0271	10.0451	0.1173	0.2193	0.00228
50374-6	30	x	0.013000	0.000026	75.0695	0.8415	2.9571	0.0453	0.8020	0.0313	11.0805	0.1550	0.2433	0.00261
50374-7	35	x	0.013000	0.000026	74.1943	1.1022	3.3830	0.0394	0.7800	0.0327	12.8118	0.2133	0.2385	0.00252
50374-8	40	x	0.013000	0.000026	61.7452	0.9627	2.8761	0.0375	0.7443	0.0357	11.2634	0.1122	0.1971	0.00244
50374-9	45	x	0.013000	0.000026	25.0461	0.3680	1.2372	0.0192	0.2408	0.0242	5.8854	0.0640	0.0840	0.00191
TDCAH038, groundmass, 100 mg, PKT 84, EK61														
50350-1	5	x	0.013900	0.000036	290.1481	0.7800	2.9225	0.0251	0.2928	0.0124	3.0550	0.1248	0.9647	0.0036
50350-2	15	x	0.013900	0.000036	675.7370	0.7900	8.7699	0.0271	0.7855	0.0242	7.2919	0.1354	2.2196	0.0046
50350-3	25	x	0.013900	0.000036	1257.6150	3.8000	17.3687	0.0751	1.4609	0.0256	11.3335	0.1749	4.1658	0.0089
50350-4	30	x	0.013900	0.000036	1399.5170	4.3000	18.6154	0.0851	1.4407	0.0267	11.1980	0.1658	4.6688	0.0094
50350-5	35	x	0.013900	0.000036	1342.0510	1.8000	17.9814	0.0441	1.4419	0.0355	11.0258	0.1848	4.4715	0.0071
50350-6	40	x	0.013900	0.000036	1147.9520	3.6000	15.8987	0.0691	1.1363	0.0167	10.8453	0.1947	3.7980	0.0077
50350-7	50	x	0.013900	0.000036	890.0019	2.2000	12.2691	0.0461	0.8868	0.0285	9.9641	0.1336	2.9248	0.007
50350-8	60		0.013900	0.000036	906.5497	2.2000	11.3332	0.0701	0.7181	0.0171	12.0823	0.2048	2.8941	0.0065
TDCAH040, groundmass, 150 mg, PKT 79, EK61														
50325-1	5		0.013700	0.000027	66.1868	0.6200	3.2883	0.0311	0.4030	0.0185	2.0792	0.1267	0.2119	0.00201
50325-2	15	x	0.013700	0.000027	104.3104	1.0000	8.5738	0.0621	0.8294	0.0368	5.2855	0.1406	0.3488	0.00261
50325-3	20	x	0.013700	0.000027	125.1883	0.9900	13.6852	0.0621	0.7590	0.0319	6.9628	0.1499	0.4128	0.00271
50325-4	25	x	0.013700	0.000027	107.3816	1.1000	13.0371	0.0691	0.6471	0.0299	6.1244	0.1538	0.3511	0.00251
50325-5	30	x	0.013700	0.000027	87.1683	0.4800	10.7481	0.0621	0.2861	0.0172	5.6425	0.1598	0.2902	0.00221
50325-6	35	x	0.013700	0.000027	87.2604	0.2801	9.9540	0.0431	0.1909	0.0155	6.0248	0.1679	0.2911	0.00171
50325-7	40	x	0.013700	0.000027	72.7836	0.4100	7.7533	0.0461	0.1574	0.0119	5.1430	0.1631	0.2430	0.00191
50325-8	60	x	0.013700	0.000027	86.4347	0.2401	7.4601	0.0301	0.1585	0.0107	6.6266	0.1573	0.2864	0.00435

^{39}Ar Moles	^{39}Ar % of total	$\%(^{36}Ar)_{Ca}$	Ca/K	±1s	$\%^{40}Ar^{*}$	Age (Ma)	±1s	w/±J ±1s	$^{36}Ar/^{40}Ar$	±%1s	$^{39}Ar/^{40}Ar$	±%1s	$^{36}Ar/^{39}Ar$ Er. Corr.
1.6E-16	0.8	0.0684295	9.23	1.65	0.5	0.0683	0.1548	0.1548	0.0034	1.1675	0.0018	12.1073	0.0655
8.0E-16	4.2	0.1518264	5.36	0.31	1.7	0.0594	0.0393	0.0393	0.0033	1.1294	0.0070	2.6253	0.3008
1.8E-15	9.5	0.2091566	4.94	0.18	2.6	0.0627	0.0285	0.0285	0.0033	1.2171	0.0104	1.9627	0.4647
3.5E-15	18.3	0.3040316	4.73	0.10	5.1	0.0814	0.0216	0.0216	0.0032	1.3752	0.0154	1.6773	0.6100
3.7E-15	19.1	0.3896097	5.71	0.15	3.1	0.0455	0.0246	0.0246	0.0033	1.6830	0.0167	2.0515	0.6031
6.9E-15	36.1	0.4013994	4.64	0.08	5.4	0.0647	0.0193	0.0193	0.0032	1.6405	0.0206	1.7003	0.7656
2.3E-15	11.9	0.5920183	7.18	0.16	8.3	0.1070	0.0192	0.0192	0.0031	1.5671	0.0191	1.5517	0.5054
	100.0		**5.10**	**0.05**		**0.0748**	**0.0095**	**0.0095**					
2.4E-15	1.2	0.0476432	5.76	0.63	0.4	0.0416	0.1211	0.1211	0.0034	1.0691	0.0021	10.1162	0.0670
1.1E-14	5.3	0.3161187	6.71	0.23	2.8	0.0570	0.0258	0.0258	0.0033	1.2929	0.0115	2.8858	0.2464
1.7E-14	8.6	0.4867354	7.27	0.17	1.9	0.0268	0.0182	0.0182	0.0033	1.2997	0.0166	1.9193	0.3797
2.4E-14	11.9	1.13062	7.25	0.17	3.5	0.0214	0.0101	0.0101	0.0033	1.6928	0.0382	1.6944	0.3939
3.1E-14	15.2	1.209043	7.17	0.12	4.8	0.0276	0.0096	0.0096	0.0032	1.7161	0.0407	1.6855	0.5481
3.3E-14	16.4	1.20232	7.34	0.15	5.4	0.0323	0.0102	0.0102	0.0032	1.7559	0.0393	1.9129	0.5040
3.8E-14	18.7	1.417924	7.42	0.15	6.4	0.0328	0.0101	0.0101	0.0032	2.0031	0.0455	1.9017	0.6664
3.2E-14	15.9	1.508647	7.68	0.13	7.1	0.0359	0.0106	0.0106	0.0031	2.1605	0.0465	2.0462	0.6284
1.4E-14	6.9	1.849698	9.32	0.18	2.7	0.0130	0.0134	0.0134	0.0033	2.8615	0.0493	2.1517	0.4150
	100.0		**7.51**	**0.05**		**0.0288**	**0.0041**	**0.0041**					
3.3E-15	2.8	0.0836041	2.05	0.09	1.8	0.0456	0.0227	0.0227	0.0033	0.9230	0.0101	0.9233	0.5736
9.9E-15	8.3	0.0867291	1.63	0.03	3.0	0.0584	0.0158	0.0158	0.0033	0.8347	0.0130	0.3865	0.7436
2.0E-14	16.5	0.0718237	1.28	0.02	2.2	0.0396	0.0158	0.0158	0.0033	0.8816	0.0138	0.5647	0.7338
2.1E-14	17.7	0.0633197	1.18	0.02	1.5	0.0279	0.0165	0.0165	0.0033	0.8804	0.0133	0.5866	0.7307
2.0E-14	17.1	0.0650972	1.20	0.02	1.6	0.0300	0.0153	0.0153	0.0033	0.8266	0.0134	0.3438	0.7667
1.8E-14	15.1	0.0753855	1.34	0.02	2.3	0.0417	0.0158	0.0158	0.0033	0.8830	0.0138	0.5726	0.7371
1.4E-14	11.7	0.0899398	1.59	0.02	3.0	0.0541	0.0156	0.0156	0.0033	0.8710	0.0138	0.4926	0.7342
1.3E-14	10.8	0.1102156	2.09	0.04	5.8	0.1158	0.0167	0.0167	0.0032	0.8658	0.0125	0.6947	0.6723
	100.0		**1.38**	**0.01**		**0.0512**	**0.0058**	**0.0058**					
3.7E-15	4.4	0.2590615	1.24	0.08	5.6	0.0280	0.0075	0.0075	0.0032	1.5578	0.0497	1.3481	0.5860
9.7E-15	11.5	0.4001088	1.21	0.03	1.6	0.0047	0.0043	0.0043	0.0033	1.4589	0.0822	1.2202	0.6849
1.5E-14	18.4	0.4453059	1.00	0.02	2.9	0.0066	0.0029	0.0029	0.0033	1.3054	0.1094	0.9353	0.7178
1.5E-14	17.5	0.4605052	0.92	0.02	3.8	0.0076	0.0030	0.0030	0.0033	1.4870	0.1215	1.1731	0.7459
1.2E-14	14.4	0.5133779	1.03	0.03	2.0	0.0041	0.0024	0.0024	0.0033	1.2379	0.1234	0.8245	0.5969
1.1E-14	13.4	0.54645	1.19	0.03	1.9	0.0041	0.0022	0.0022	0.0033	1.0465	0.1141	0.5759	0.6263
8.8E-15	10.4	0.5587171	1.30	0.04	1.8	0.0042	0.0029	0.0029	0.0033	1.2593	0.1066	0.8447	0.5894
8.4E-15	10.0	0.6108964	1.74	0.04	2.6	0.0075	0.0049	0.0049	0.0033	1.7469	0.0863	0.5299	0.3693
	100.0		**1.11**	**0.01**		**0.0057**	**0.0011**	**0.0011**					

Lab ID#	%	Plateau	*J* (X 10^{-3})	±*1s* (X 10^{-3})	^{40}Ar (10^{-2} V)	±1s	^{39}Ar (10^{-2} V)	±1s	^{38}Ar (10^{-2} V)	±1s	^{37}Ar (10^{-2} V)	±1s	^{36}Ar (10^{-2} V)	±1s
TDCAH041, groundmass, 175 mg, PKT 82, EK61														
50332-1	5	x	0.013400	0.000027	163.4232	0.3901	4.5723	0.0191	0.1869	0.0237	5.2245	0.1376	0.5332	0.00452
50332-2	15	x	0.013400	0.000027	251.5788	1.3000	9.5032	0.0581	0.4318	0.0284	8.9998	0.1700	0.8345	0.005
50332-3	20	x	0.013400	0.000027	298.5431	1.1000	12.5780	0.0591	0.5532	0.0266	9.3228	0.1702	0.9801	0.00525
50332-4	25	x	0.013400	0.000027	251.6582	1.2000	10.3515	0.0671	0.5712	0.0297	7.9014	0.1809	0.8339	0.00545
50332-5	30	x	0.013400	0.000027	219.1512	0.8500	8.5994	0.0641	0.3087	0.0266	7.0448	0.1501	0.7209	0.00506
50332-6	35	x	0.013400	0.000027	235.6000	0.7800	8.4233	0.0491	0.4014	0.0256	8.1139	0.1817	0.7964	0.00519
50332-7	40	x	0.013400	0.000027	236.0537	0.7000	6.9751	0.0461	0.3191	0.0246	8.3976	0.1692	0.7782	0.00512
50332-8	60	x	0.013400	0.000027	280.5992	0.8500	6.9048	0.0401	0.3212	0.0261	10.8997	0.2042	0.9422	0.00525
TDCAH047, hornblende, 150 mg, PKT 99, EK61														
50355-1	5	x	0.015000	0.000035	47.5703	0.4965	0.9217	0.0347	0.1075	0.0189	1.5356	0.0798	0.1513	0.00262
50355-2	15	x	0.015000	0.000035	97.5143	1.2106	2.0712	0.0407	0.8990	0.0461	3.6525	0.0925	0.3104	0.00344
50355-3	25	x	0.015000	0.000035	117.8179	2.2058	3.2501	0.0472	1.3485	0.0876	5.8936	0.1576	0.3644	0.00386
50355-4	34	x	0.015000	0.000035	123.0740	2.7047	4.4979	0.0763	1.8760	0.0945	9.6884	0.1862	0.3749	0.00474
50355-5	45	x	0.015000	0.000035	129.0709	2.8046	5.1081	0.0725	2.5253	0.1503	10.6836	0.1437	0.4000	0.00576
50355-6	50	x	0.015000	0.000035	180.8611	3.7035	6.6678	0.1032	3.0165	0.1603	15.5979	0.2150	0.5486	0.00576
50355-7	60	x	0.015000	0.000035	81.4146	2.4515	3.8261	0.0587	2.0900	0.1304	7.5543	0.1581	0.2313	0.00465
TDCAH052, hornblende, 100 mg, PKT 95, EK61														
50371-1	5	x	0.013600	0.000026	2.7791	0.0454	0.1106	0.0102	0.0078	0.0088	0.0417	0.0631	0.0083	0.000830241
50371-2	15	x	0.013600	0.000026	167.9758	0.6400	1.6833	0.0221	0.2784	0.0125	6.4757	0.1334	0.5617	0.0025
50371-3	25	x	0.013600	0.000026	137.0920	0.5100	2.7859	0.0191	0.3000	0.0199	13.1863	0.0956	0.4490	0.0022
50371-4	30	x	0.013600	0.000026	100.4884	0.4800	2.7430	0.0241	0.3007	0.0180	13.2004	0.1336	0.3272	0.0021
50371-5	35	x	0.013600	0.000026	91.3598	0.4700	2.9567	0.0271	0.2518	0.0125	13.1951	0.2537	0.2927	0.0021
50371-6	40	x	0.013600	0.000026	68.7064	0.3401	2.4001	0.0211	0.1066	0.0069	12.5990	0.1413	0.2187	0.0017
50371-7	50	x	0.013600	0.000026	86.3930	0.3901	3.2416	0.0291	0.1439	0.0072	18.0592	0.2683	0.2806	0.0019
50371-8	60	x	0.013600	0.000026	70.8559	0.3401	2.3964	0.0231	0.1471	0.0109	12.1585	0.1852	0.2294	0.0016
TDCAH054, groundmass, 175 mg, PKT 85, EK61														
50439-1	5	x	0.014400	0.000029	11.0558	0.2001	0.3840	0.0142	0.0494	0.0156	0.8229	0.0886	0.0328	0.00709
50439-2	15	x	0.014400	0.000029	58.5230	0.6200	2.7926	0.0191	0.3146	0.0320	4.6295	0.0970	0.1619	0.00728
50439-3	20	x	0.014400	0.000029	157.6972	0.8500	5.9342	0.0381	0.6471	0.0581	7.3228	0.0988	0.4440	0.00758
50439-4	25	x	0.014400	0.000029	290.4374	1.1000	9.2867	0.0621	0.9027	0.0405	8.8512	0.1902	0.8612	0.00806
50439-5	30	x	0.014400	0.000029	291.1672	0.6500	8.3960	0.0341	0.5326	0.0255	8.0738	0.1379	0.8477	0.00762
50439-6	35	x	0.014400	0.000029	271.4453	1.1000	7.5264	0.0521	0.6291	0.0301	8.3955	0.1725	0.7885	0.00796
50439-7	40	x	0.014400	0.000029	212.9093	0.6300	5.5222	0.0381	0.1767	0.0140	7.6619	0.1402	0.6438	0.00754
50439-8	50	x	0.014400	0.000029	172.2771	0.5800	4.1176	0.0321	0.1316	0.0131	7.7662	0.1281	0.5213	0.0074
50439-9	60	x	0.014400	0.000029	172.7677	0.7200	3.6695	0.0351	0.1319	0.0141	10.8021	0.1940	0.5271	0.00743

^{39}Ar Moles	^{39}Ar % of total	%(^{36}Ar)$_{Ca}$	Ca/K	±1s	%^{40}Ar*	Age (Ma)	±1s	w/±J ±1s	^{36}Ar/^{40}Ar	±%1s	^{39}Ar/^{40}Ar	±%1s	^{36}Ar/^{39}Ar Er. Corr.
5.2E-15	6.7	0.2587028	2.24	0.06	3.8	0.0331	0.0100	0.0100	0.0033	1.1915	0.0280	0.5221	0.5274
1.1E-14	14.0	0.2847143	1.86	0.04	2.2	0.0143	0.0071	0.0071	0.0033	1.1268	0.0378	0.8263	0.6290
1.4E-14	18.5	0.2511307	1.45	0.03	3.2	0.0184	0.0058	0.0058	0.0033	1.0321	0.0421	0.6305	0.6459
1.2E-14	15.2	0.2501456	1.50	0.04	2.3	0.0135	0.0066	0.0066	0.0033	1.1393	0.0411	0.8304	0.5937
9.7E-15	12.7	0.257988	1.61	0.04	3.0	0.0186	0.0068	0.0068	0.0033	1.1344	0.0392	0.8650	0.5340
9.5E-15	12.4	0.2689539	1.89	0.04	0.4	0.0024	0.0073	0.0073	0.0034	1.0849	0.0357	0.7005	0.5744
7.9E-15	10.3	0.2848967	2.36	0.05	2.8	0.0233	0.0086	0.0086	0.0033	1.0792	0.0295	0.7525	0.5466
7.8E-15	10.2	0.3054071	3.09	0.06	1.1	0.0104	0.0100	0.0100	0.0033	1.0223	0.0246	0.6858	0.5991
	100.0		**1.79**	**0.01**		**0.0160**	**0.0026**	**0.0026**					
1.0E-15	3.5	0.2680277	3.27	0.21	6.3	0.0880	0.0293	0.0293	0.0032	2.1822	0.0194	3.9188	0.1967
2.3E-15	7.9	0.3106631	3.46	0.11	6.3	0.0801	0.0229	0.0229	0.0032	1.8507	0.0212	2.3353	0.4665
3.7E-15	12.3	0.4270136	3.55	0.11	9.1	0.0890	0.0220	0.0220	0.0031	2.3001	0.0276	2.3822	0.7015
5.1E-15	17.1	0.6821745	4.22	0.11	10.7	0.0791	0.0192	0.0192	0.0030	2.6670	0.0365	2.7884	0.6959
5.8E-15	19.4	0.7051515	4.10	0.08	9.2	0.0629	0.0182	0.0182	0.0031	2.7365	0.0395	2.6079	0.7053
7.5E-15	25.3	0.7506761	4.59	0.10	11.1	0.0819	0.0175	0.0175	0.0030	2.4435	0.0368	2.5793	0.7190
4.3E-15	14.5	0.8621896	3.87	0.10	16.9	0.0976	0.0204	0.0204	0.0028	3.7250	0.0470	3.3908	0.7407
	100.0		**3.98**	**0.04**		**0.0814**	**0.0078**	**0.0078**					
1.2E-16	0.6	0.1328495	0.74	1.12	11.9	0.0736	0.0560	0.0560	0.0030	10.1923	0.0398	9.3903	0.0345
1.9E-15	9.2	0.3043624	7.54	0.18	1.5	0.0365	0.0241	0.0241	0.0033	0.9928	0.0100	1.3863	0.4664
3.1E-15	15.2	0.7752517	9.28	0.09	4.0	0.0479	0.0119	0.0119	0.0033	1.0124	0.0203	0.8082	0.6062
3.1E-15	15.0	1.065101	9.43	0.13	4.8	0.0433	0.0099	0.0099	0.0032	1.1372	0.0272	1.0232	0.5400
3.3E-15	16.1	1.19001	8.75	0.19	6.4	0.0489	0.0087	0.0087	0.0032	1.1987	0.0323	1.0731	0.5206
2.7E-15	13.1	1.520663	10.29	0.15	7.3	0.0517	0.0082	0.0082	0.0031	1.2303	0.0348	1.0324	0.5066
3.7E-15	17.7	1.699148	10.92	0.19	5.6	0.0370	0.0073	0.0073	0.0032	1.1511	0.0374	1.0281	0.5176
2.7E-15	13.1	1.39905	9.94	0.18	5.6	0.0410	0.0082	0.0082	0.0032	1.1731	0.0337	1.0993	0.5051
	100.0		**9.42**	**0.05**		**0.0442**	**0.0035**	**0.0035**					
4.3E-16	0.8	0.6621447	4.20	0.48	12.9	0.0966	0.1429	0.1429	0.0029	21.8380	0.0347	4.1212	0.0425
3.2E-15	5.9	0.7548048	3.25	0.07	18.9	0.1029	0.0212	0.0212	0.0027	4.7233	0.0477	1.2794	0.2321
6.7E-15	12.5	0.4354015	2.42	0.04	17.2	0.1187	0.0116	0.0116	0.0028	1.9678	0.0376	0.8630	0.3629
1.0E-14	19.5	0.2713221	1.87	0.04	12.6	0.1026	0.0095	0.0095	0.0030	1.2908	0.0320	0.7952	0.4817
9.5E-15	17.6	0.2514591	1.88	0.03	14.2	0.1279	0.0097	0.0097	0.0029	1.2256	0.0288	0.5053	0.5111
8.5E-15	15.8	0.2810812	2.19	0.05	14.4	0.1351	0.0113	0.0113	0.0029	1.3534	0.0277	0.8277	0.4640
6.2E-15	11.6	0.3142126	2.72	0.05	10.9	0.1095	0.0132	0.0132	0.0030	1.4522	0.0259	0.7779	0.4010
4.7E-15	8.6	0.3932933	3.70	0.07	10.9	0.1189	0.0164	0.0164	0.0030	1.6691	0.0239	0.8738	0.3443
4.1E-15	7.7	0.5410657	5.77	0.12	10.3	0.1267	0.0188	0.0188	0.0030	1.6812	0.0212	1.0647	0.3350
	100.0		**2.39**	**0.02**		**0.1183**	**0.0044**	**0.0044**					

Lab ID#	%	Plateau	*J* (X 10^{-3})	±*1s* (X 10^{-3})	^{40}Ar (10^{-2} V)	±1s	^{39}Ar (10^{-2} V)	±1s	^{38}Ar (10^{-2} V)	±1s	^{37}Ar (10^{-2} V)	±1s	^{36}Ar (10^{-2} V)	±1s
TDCAH085, groundmass, 200 mg, PKT 89, EK61														
50364-1	5		0.013400	0.000027	104.7867	0.7400	7.7698	0.0531	0.5538	0.0456	6.9790	0.1487	0.3299	0.0023
50364-2	15	x	0.013400	0.000027	133.3900	1.1000	16.4537	0.0821	0.9548	0.0569	10.5686	0.1393	0.4501	0.0028
50364-3	25	x	0.013400	0.000027	160.5014	1.4000	24.3435	0.2102	1.4494	0.0556	11.8393	0.1766	0.5302	0.003
50364-4	35	x	0.013400	0.000027	122.1709	0.7900	20.1724	0.1602	0.9071	0.0527	9.1526	0.2061	0.4111	0.0027
50364-5	40	x	0.013400	0.000027	108.0926	0.8300	16.3544	0.0731	0.7616	0.0511	8.1633	0.1770	0.3580	0.0025
50364-6	45	x	0.013400	0.000027	96.2859	0.5300	12.3810	0.0921	0.4221	0.0472	7.9043	0.1373	0.3257	0.002
50364-7	50	x	0.013400	0.000027	77.4169	0.4300	8.1839	0.0491	0.2220	0.0456	7.6153	0.1495	0.2616	0.0019
50364-8	60		0.013400	0.000027	71.1416	0.2901	6.0995	0.0431	0.1326	0.0447	8.1782	0.1497	0.2289	0.0017
TDCAH089, groundmass, 200 mg, PKT 80, EK61														
50164-1	5	x	0.013600	0.000027	44.4116	0.3801	1.3012	0.0181	0.1559	0.0456	1.6322	0.1001	0.1438	0.0016
50164-2	15	x	0.013600	0.000027	120.8254	1.1000	11.4535	0.0741	0.9797	0.0581	9.1262	0.1685	0.3589	0.0029
50164-3	25	x	0.013600	0.000027	147.3662	1.3000	22.8876	0.1501	1.4369	0.0674	13.4182	0.2175	0.3910	0.0032
50164-4	30	x	0.013600	0.000027	153.4032	1.5000	28.8038	0.2002	1.3275	0.0681	13.0722	0.1688	0.3890	0.0028
50164-5	35	x	0.013600	0.000027	133.4200	1.3000	22.7123	0.1501	1.1989	0.0666	9.8416	0.1399	0.3526	0.0026
50164-6	40		0.013600	0.000027	107.5119	0.8800	15.9489	0.0911	0.5923	0.0492	4.7179	0.1884	0.3452	0.0023
50164-7	45		0.013600	0.000027	98.0319	0.3901	11.4584	0.0591	0.3654	0.0465	4.3701	0.1600	0.2920	0.0021
50164-8	50		0.013600	0.000027	74.9230	0.4500	7.5793	0.0491	0.1887	0.0447	3.3523	0.1509	0.2428	0.002
50164-9	60		0.013600	0.000027	75.1833	0.4300	6.1593	0.0401	0.1487	0.0451	4.3916	0.1354	0.2386	0.0016
TDCAH093, groundmass, 175 mg, PKT 77, EK61														
50329-1	5	x	0.013500	0.000027	33.4358	0.2501	1.8282	0.0221	0.1154	0.0235	4.3903	0.1341	0.1099	0.00141
50329-2	15	x	0.013500	0.000027	49.0450	0.5900	5.8951	0.0261	0.4406	0.0402	10.0826	0.1627	0.1573	0.00191
50329-3	20	x	0.013500	0.000027	77.1777	1.4000	8.1707	0.0541	1.0435	0.0648	10.0187	0.2215	0.2514	0.00281
50329-4	25	x	0.013500	0.000027	60.2680	1.0000	5.8797	0.0411	0.7673	0.0438	6.4090	0.1494	0.1895	0.00241
50329-5	30	x	0.013500	0.000027	44.5618	0.4700	4.2325	0.0351	0.3417	0.0295	4.9038	0.1322	0.1436	0.00181
50329-6	40	x	0.013500	0.000027	51.7491	0.7200	3.6181	0.0361	0.4095	0.0315	5.1578	0.1389	0.1693	0.00201
50329-7	50	x	0.013500	0.000027	45.7151	0.4400	2.6065	0.0271	0.1270	0.0231	5.0197	0.1480	0.1459	0.00151
50329-8	60	x	0.013500	0.000027	63.7801	0.3601	2.7988	0.0301	0.1038	0.0231	7.9414	0.1888	0.2160	0.00181
TDCAH100, groundmass, 100 mg, PKT 84, EK61														
50320-1	5	x	0.013800	0.000035	396.4005	1.2000	5.1471	0.0311	0.3146	0.0119	5.1640	0.1013	1.3092	0.0044
50320-2	15	x	0.013800	0.000035	998.4799	2.6000	14.2566	0.0661	0.9881	0.0107	10.1485	0.1369	3.3526	0.0065
50320-3	25	x	0.013800	0.000035	1553.7750	2.9000	22.4352	0.1401	1.5541	0.0215	12.4186	0.1456	5.2154	0.0089
50320-4	30	x	0.013800	0.000035	1424.2750	3.5000	20.3913	0.0711	1.4387	0.0244	11.7036	0.2013	4.8024	0.0093
50320-5	35	x	0.013800	0.000035	1186.4980	2.6000	17.0485	0.0871	1.2828	0.0303	10.4971	0.1546	3.9811	0.0072
50320-6	40	x	0.013800	0.000035	934.8560	2.8000	12.6378	0.0641	0.8444	0.0166	10.2419	0.1549	3.1394	0.0057
50320-7	50	x	0.013800	0.000035	759.7726	1.8000	9.6888	0.0521	0.6497	0.0156	9.7843	0.1463	2.5474	0.0067
50320-8	60	x	0.013800	0.000035	861.6510	1.8000	10.4427	0.0591	0.6824	0.0147	12.5943	0.2021	2.9200	0.006

^{39}Ar Moles	^{39}Ar % of total	%(^{36}Ar)$_{Ca}$	Ca/K	±1s	%$^{40}Ar^{*}$	Age (Ma)	±1s	w/±*J* ±1s	$^{36}Ar/^{40}Ar$	±%1s	$^{39}Ar/^{40}Ar$	±%1s	$^{36}Ar/^{39}Ar$ Er. Corr.
8.8E-15	7.0	0.5584737	1.76	0.04	7.5	0.0244	0.0040	0.0040	0.0031	1.2784	0.0742	1.0046	0.6365
1.9E-14	14.7	0.6198867	1.26	0.02	0.8	0.0017	0.0026	0.0026	0.0034	1.3105	0.1234	0.9865	0.7269
2.8E-14	21.8	0.5895622	0.95	0.02	2.9	0.0046	0.0021	0.0021	0.0033	1.3158	0.1518	1.2465	0.6743
2.3E-14	18.0	0.5877352	0.89	0.02	1.0	0.0015	0.0018	0.0018	0.0033	1.2245	0.1653	1.0459	0.6055
1.8E-14	14.6	0.6020004	0.98	0.02	2.6	0.0042	0.0021	0.0021	0.0033	1.3149	0.1514	0.9128	0.7009
1.4E-14	11.1	0.6406533	1.25	0.02	0.6	0.0011	0.0022	0.0022	0.0034	1.1527	0.1287	0.9489	0.6019
9.2E-15	7.3	0.7686609	1.82	0.04	0.9	0.0020	0.0028	0.0028	0.0034	1.2201	0.1057	0.8433	0.6032
6.9E-15	5.5	0.9432663	2.63	0.05	5.8	0.0163	0.0032	0.0032	0.0032	1.1715	0.0857	0.8415	0.5344
	100.0		**1.17**	**0.01**		**0.0045**	**0.0008**	**0.0008**					
1.5E-15	1.0	0.2997604	2.46	0.15	4.6	0.0389	0.0132	0.0132	0.0032	1.6195	0.0293	1.6500	0.4426
1.3E-14	8.9	0.6713414	1.56	0.03	12.8	0.0331	0.0035	0.0035	0.0030	1.4620	0.0948	1.1368	0.6716
2.6E-14	17.8	0.9060768	1.15	0.02	22.3	0.0352	0.0020	0.0020	0.0026	1.4522	0.1555	1.1201	0.6591
3.3E-14	22.4	0.8870726	0.89	0.01	25.6	0.0335	0.0017	0.0017	0.0025	1.4605	0.1880	1.2195	0.7021
2.6E-14	17.7	0.7368456	0.85	0.01	22.4	0.0323	0.0019	0.0019	0.0026	1.4662	0.1704	1.1974	0.7038
1.8E-14	12.4	0.3608439	0.58	0.02	5.4	0.0089	0.0021	0.0021	0.0032	1.3275	0.1485	1.0203	0.7001
1.3E-14	8.9	0.3951603	0.75	0.03	12.3	0.0257	0.0022	0.0022	0.0030	1.1499	0.1170	0.6827	0.5829
8.6E-15	5.9	0.3645182	0.87	0.04	4.5	0.0110	0.0031	0.0031	0.0032	1.2990	0.1012	0.9074	0.5785
7.0E-15	4.8	0.4858851	1.40	0.04	6.6	0.0198	0.0034	0.0034	0.0032	1.1934	0.0819	0.8909	0.6135
	100.0		**0.93**	**0.01**		**0.0268**	**0.0008**	**0.0008**					
2.1E-15	5.2	1.055005	4.71	0.15	3.9	0.0174	0.0074	0.0074	0.0033	1.7026	0.0546	1.4395	0.4057
6.7E-15	16.8	1.691962	3.35	0.06	6.8	0.0137	0.0037	0.0037	0.0032	1.9048	0.1202	1.3003	0.6758
9.2E-15	23.3	1.05208	2.40	0.06	4.8	0.0109	0.0052	0.0052	0.0032	2.2858	0.1059	1.9454	0.7926
6.6E-15	16.8	0.8927242	2.14	0.05	7.9	0.0197	0.0054	0.0054	0.0031	2.2484	0.0976	1.8152	0.7344
4.8E-15	12.1	0.9016536	2.27	0.06	5.6	0.0144	0.0045	0.0045	0.0032	1.8392	0.0950	1.3593	0.5707
4.1E-15	10.3	0.8042847	2.79	0.08	4.1	0.0142	0.0068	0.0068	0.0032	2.0050	0.0699	1.7269	0.6492
2.9E-15	7.4	0.9083627	3.77	0.12	6.5	0.0278	0.0067	0.0067	0.0032	1.6338	0.0570	1.4339	0.5537
3.2E-15	8.0	0.9707967	5.56	0.15	0.9	0.0049	0.0071	0.0071	0.0034	1.2963	0.0438	1.2340	0.4706
	100.0		**2.77**	**0.03**		**0.0150**	**0.0019**	**0.0019**					
5.8E-15	4.6	0.1041278	1.97	0.04	2.5	0.0480	0.0174	0.0174	0.0033	0.9193	0.0130	0.7056	0.6595
1.6E-14	12.7	0.0799136	1.40	0.02	0.8	0.0148	0.0150	0.0150	0.0034	0.8635	0.0143	0.5687	0.7238
2.5E-14	20.0	0.0628623	1.08	0.01	0.9	0.0150	0.0144	0.0144	0.0034	0.8390	0.0144	0.6827	0.6738
2.3E-14	18.2	0.0643385	1.12	0.02	0.4	0.0073	0.0149	0.0149	0.0034	0.8591	0.0143	0.4715	0.7500
1.9E-14	15.2	0.0696104	1.21	0.02	0.9	0.0158	0.0147	0.0147	0.0034	0.8490	0.0144	0.5914	0.7083
1.4E-14	11.3	0.086126	1.59	0.03	0.8	0.0155	0.0160	0.0160	0.0034	0.8735	0.0135	0.6227	0.7199
1.1E-14	8.6	0.1014007	1.98	0.03	1.0	0.0199	0.0170	0.0170	0.0033	0.8750	0.0127	0.6213	0.6860
1.2E-14	9.3	0.1138666	2.36	0.04	0.0	0.0000	0.0176	0.0176	0.0034	0.8521	0.0121	0.6363	0.6869
	100.0		**1.34**	**0.01**		**0.0165**	**0.0056**	**0.0056**					

Full system blanks, standard deviations taken from entire run sequence (encompassing all sample runs), *n* = 66

^{40}Ar (V)	±1s	^{39}Ar (V)	±1s	^{38}Ar (V)	±1s	^{37}Ar (V)	±1s	^{36}Ar (V)	±1s
0.009026549	0.000321	0.000274336	0.00002	0.000168142	0.000025	0.00069469	0.000019	0.000122124	0.00001

Air calibrations (monitor mass discrimination), average ± standard deviation (encompassing all sample runs), n = 21

^{40}Ar/^{36}Ar	±1s	D ^{40}Ar/^{36}Ar	D ±1s
288.3	0.6	1.0088	0.0005

NOTES:
Samples were irradiated for 5 minutes in the Cd-lined facility at McMaster. Sanidine from the Alder Creek Tuff was used as the neutron fluence monitor with a reference age of 1.193 ± 0.001 Ma (Nomade *et al.*, 2005).

Nucleogenic production ratios:

$(^{36}Ar/^{37}Ar)_{Ca}$	2.64		$\times 10^{-4}$
$(^{39}Ar/^{37}Ar)_{Ca}$	6.5		$\times 10^{-4}$
$(^{38}Ar/^{37}Ar)_{Ca}$	0.196	± 0.00816	$\times 10^{-4}$
$(^{40}Ar/^{39}Ar)_{K}$	85		$\times 10^{-4}$
$(^{38}Ar/^{39}Ar)_{K}$	1.22	± 0.0027	$\times 10^{-2}$
$(^{36}Ar/^{38}Ar)_{Cl}$	3.2		$\times 10^{2}$
$^{37}Ar/^{39}Ar$ to Ca/K	1.96		

Isotopic constants and decay rates:

$\lambda(^{40}K_{\varepsilon})$ /yr	5.81	± 0.04	$\times 10^{-11}$
$\lambda(^{40}K_{\beta-})$ /yr	4.962	± 0.00043	$\times 10^{-10}$
$\lambda(^{37}Ar)$ /d	1.975		$\times 10^{-2}$
$\lambda(^{39}Ar)$ /d	7.068		$\times 10^{-6}$
$\lambda(^{36}Cl)$ /d	6.308		$\times 10^{-9}$
$(^{40}Ar/^{36}Ar)_{Atm}$	295.5	± 0.5	
$(^{40}Ar/^{38}Ar)_{Atm}$	1575	± 2	
$^{40}K/K_{Total}$	0.01167		

APPENDIX 9: Seed questions

<u>Instructions</u>

These are the 'seed' questions for calibrating individual expert's inputs and 'informativeness' in order to produce weightings for pooling responses in the elicitation of Event Tree and Paired Comparison target items.

Please provide both your 'credible range' of uncertainty (low value <-> high value), and your 'central' estimate of the median value. The credible range should indicate the lowest and highest values you believe must encompass the 'true' answer with about 90% confidence (i.e. there is only a 5% chance the value falls below your lower value, and only a 5% chance it is higher than your upper value).

Your 'central' estimate should represent the median (50%ile) value of the uncertainty distribution - i.e. the value at which you judge there is an equal likelihood that the true realization (answer) will be above or below this value (this is not the mode, or most likely value; the two will be close but depend on skewness).

The distribution shape of your credible range need not be symmetric about the median.

We recommend that you assign your extreme values (5%ile and 95%ile) first to help prevent anchoring around the median.

Please be careful to note the units in which your 'answers' should be expressed.

Example

In a recent work modelling the magma dynamics and collapse mechanisms during four well-known historic caldera-forming events, one model input was the time duration of magma evacuation before the caldera block began to subside. Based on previously reported data, what value, **<u>in hours</u>**, was used for this duration in the case of Katmai 1912?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 1

4600 years ago, Mount Fogo on the island of Sao Miguel (Azores) erupted one of its largest Plinian eruptions. The volume of the eruption was 0.6 - 0.7km^3 (DRE) and was composed mostly of coarse-grained homogeneous pumice breccias. **In km**, what was the distance thrown from the vent of a 27cm lithic block weighing 6.4kg?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 2

What was the greatest distance, **in km,** traversed by the base surge at Taal (Philippines) in 1965?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 3

Over a period of 8 months following the 1783-1784 eruption of Laki (Iceland), what was the total accumulative atmospheric mass loading, **in Mt (or Tg),** of sulphur dioxide?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 4

During the same Laki eruption, what was the total volume, in **km^3**, of erupted lava?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 5

What was the column height, **in km**, of the dacitic plinian eruption plume of Santa Maria (Guatemala) in 1902?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 6

Over **how many hours** did the plinian fall occur?

low end value (5%ile)	median (50%ile)	high end value (95%ile)

QUESTION 7

On 20 November 1998, a new andesitic lava dome began growing inside the 1994 summit dome crater of Volcan de Colima (Mexico). At what rate, **in m^3/s**, did the new block-lava dome grow before it collapsed 24 hours later?

low end value (5%ile)	median (50%ile)	high end value (95%ile)

QUESTION 8

The major control determining the relative proportions of lavas and volcaniclastic deposits in the growth of a submarine volcano is hydrostatic pressure. As such, during submarine eruptions the explosive release of volatiles is limited at certain water depths and depends largely on the volatile content of the magma. **In metres**, what is the maximum water depth at which hydromagmatic explosivity occurs in alkali magmas?

low end value (5%ile)	median (50%ile)	high end value (95%ile)

QUESTION 9

What is the mean collapse load, **in kPa**, that tephra can exert on a sloping reinforced concrete roof?

low end value (5%ile)	median (50%ile)	high end value (95%ile)

QUESTION 10

In **km^3 per year**, what is the total melt production rate beneath mid-ocean ridges?

low end value (5%ile)	median (50%ile)	high end value (95%ile)

QUESTION 11

In km^3, what was the proposed volume loss of the entire El Hierro (Canary Islands) edifice following the debris avalanche which is thought to have created the Julan embayment?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 12

A statistically significant relationship exists between average daily scoria cone construction rate and ultimate cone volume. The final volume of a scoria cone equals approximately **how many times** the average daily construction rate?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 13

In m^3/s, what was the average effusion rate at Piton de la Fournaise (La Réunion) during the May-July 2003 eruption?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 14

In km, how long was the andesite lava flow that erupted from Lonquimay (Chile) between 1988-1990?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 15

In **km^3 per year**, what is the melt production rate (volcanic and plutonic) for the Hawaiian Chain?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 16

The 1991 eruption of Hekla (Iceland) was unexpected as there had been no long-term precursory seismic activity. The first related seismic events occurred just half an hour before eruption onset, which itself was accompanied by intensive earthquakes and tremor. **How many events** up to Mt. magnitude 2.5 were recorded during the first few hours of the eruption?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

QUESTION 17

During the eruption of Mount Asama (Japan) in 1958, what was the maximum recorded distance from the crater, **in km**, that window damage was reported?

low end value (5%ile)	**median (50%ile)**	**high end value (95%ile)**

APPENDIX 10: Range graphs for seed questions and target variables (itemwise).

```
Range graph of input data
Item no.:   1 Item name: Fogo Lithic Scale: UNI
Experts
  1     [---------*-------------------]
  2 [-*------]
  3 [---*----------------------------------]
  4 [-*-]
  5   [-*-------------------]
  6   [-*----]
  7 [---*-------------------]
  8     [---------*----------------------------------]
  9     [-------------------*------------------------]
 10     [--*-----------]
 11          [---------*-----------------------------]
 12 [--------*--------------]
 13     [-------*-----------]
 14        [---------*-----------]
 15     [----*---------]
 16     [------------------------*-------------------]
 17                    [----*--------------]
 18                              [--------------*-----------------------------]
DMaker 1 [============*============================]
Real:::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::
                                  6
    1E-005                                                                  15
```

```
Item no.:   2 Item name: Taal Surge Scale: UNI
Experts
  1 [*-----]
  2 [---*-----------------]
  3       [-----------------------------*------------------------------------]
  4  [-*----]
  5 [*-]
  6       [-----------------------------*------------------------------------]
  7   [---------------*----------]
  8               [-------*------]
  9 [*-]
 10   [*-]
 11    [------*-----------]
 12               [--------------*--------------------------------------------]
 13  [--*---------]
 14   [-----*-------]
 15  [*--]
 16   [-*---------------------]
 17     [--*--]
 18       [------*-----------]
DMa [======*=================]
Real::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
         6
    0.5                                                                    100
```

```
Item no.:   3 Item name: Laki SO2 Scale: LOG
Experts
  1                                                    [*-]
  2                                            [---*---------------]
  3                [-------------------------------*---------------]
  4                                [---------------*-----------]
  5 [------*---]
  6            [-------------*--]
  7                [---------------*---------------]
  8                                     [---------*-----]
  9                                [-----------*---]
 10                                                 []
 11     [--------------------------*---------------]
 12                            [-------------------*-----------]
 13                                                     [----------*----]
 14                                     [--------*----]
 15                                [---------------*---------------]
 16                       [--------------------*------------------------------]
 17                                [------*----]
 18                        [---------*------]
DMaker 1                   [======================*=====================]
Real:::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::
                                                     122
    0.1                                                                   5000


Item no.:   4 Item name: Laki Lava Scale: LOG
Experts
  1                                             [*-]
  2                      [---------------------------*--------------]
  3                [---------------*-----------]
  4                                     [------*--------------]
  5                                            [-------*------]
  6                             [-------*----------------]
  7                      [--------------*------]
  8                                          [--*----]
  9 [--------------*-----]
 10                                            [--*]
 11                                            [*---]
 12                                                           [*--------]
 13                      [------------------------*---------------]
 14                                            [*---]
 15                                                           [-----*---------]
 16                      [---------------------*--------------------]
 17                                            [--*-----------]
 18                                            [-----*---]
DMaker 1                    [=====================*==============]
Real::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::
                                                 14.7
    0.1                                                                    300
```

```
Item no.:   5 Item name: Santa Maria Co Scale: UNI
Experts
  1                              [------*--------------------]
  2          [-----*----]
  3             [-----------------------*---------------]
  4                      [-------*--------------]
  5     [------------------------*------]
  6             [----------------*------]
  7                          [----------*---------------]
  8 [------*---------------------]
  9             [-----*----------]
 10                                     [----------*----]
 11                      [----------*-----------]
 12             [----------------*--------------]
 13                      [----------*-------------------]
 14                                         [-----------*----------]
 15             [-------------------------------*---------------]
 16          [------------*-------------]
 17                              [--------------*-------------------------------]
 18                                     [---------------*----------------]
DMaker 1        [=================================*================]
Real::::::::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::
                                                      34
     2                                                                       50
```

```
Item no.:   6 Item name: S. Maria Fall Scale: UNI
Experts
  1 [-*--]
  2   [-*-------------------------------]
  3      [------------------*---------------------------------------------------]
  4 [---*----]
  5   [--------*-------------]
  6 [-*]
  7 [--*-----]
  8     [-------*------]
  9  [--*----]
 10            [-----*------------------]
 11   [----*-]
 12   [-----*--------]
 13     [--*------]
 14   [--------*-------------]
 15   [-*----]
 16 [*---------------]
 17  *]
 18   [--------------*------------]
DMa [=======*================]
Real:::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
                    35.1
     1                                                                      150
```

```
Item no.:   7 Item name: Colima Dome Scale: LOG
Experts
  1                            [--------------*------------]
  2                                   [-------*------------]
  3                            [--------------*------------]
  4                            [---------------------*-----]
  5       [--------------------*----------]
  6       [-----*--------]
  7       [----------------------------------------*-------]
  8                                                               [-------*---]
  9                                       [----------*---------]
 10                                           [----*--]
 11       [-----------------------------------*----------]
 12             [--------*---------------------------]
 13             [-------------------------------*----------]
 14                            [---------------------*---------]
 15 [--------------------------*--------------]
 16               [--------------------------------------*--------------------]
 17                                                  [*----]
 18                                   [---------*--------]
DMaker 1             [==============================*=====================]
Real:::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::
                                             4.4
    0.05                                                                   160
```

```
Item no.:   8 Item name: Submarine erup Scale: LOG
Experts
  1                                             [*--]
  2                       [-----------*--]
  3                                            [---*-------]
  4                       [------*----------]
  5                          [--------*--------]
  6                              [----*-----]
  7                                              [------*---------------------]
  8                                         [--*-]
  9 [-----------*-]
 10                                      [--*-----]
 11                                      [--*--]
 12                       [--*--------]
 13                                                        [-*---]
 14                                         [-----------*-------]
 15                                   [------------*---------]
 16                         [----------------------*-----------]
 17                                        [--*]
 18                                   [------*---]
DMaker 1                      [=====================*===========]
Real::::::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::
                                                       1000
     1                                                                   2E004
```

```
Item no.:   9 Item name: Collapse load Scale: LOG
Experts
  1                                                          [---*------------]
  2 [------*---]
  3            [--------*------]
  4    [-------*--------]
  5                            [------*-----]
  6                 [---*---]
  7                 [---*---]
  8                 [---*------]
  9              [------*------]
 10                  [-*---]
 11        [------------*-------------]
 12        [---*------------------]
 13        [--------*----------]
 14          [---*-----]
 15                               [------------*-------]
 16              [-------------*--------------------------]
 17              [------*---------]
 18                        [---*------]
DMaker 1     [======*==================================================]
Real:::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
                   4.5
    0.3                                                                  1E005
```

```
Item no.:  10 Item name: Melt Prod Rate Scale: LOG
Experts
  1             [*]
  2              [--------------*-------------]
  3                   [-----------*----]
  4                                           [---------------------*---------]
  5        [-----*---]
  6           [-------*---------]
  7 [---------*----------]
  8              [---*------]
  9                      [----------*------]
 10           [--*---]
 11 [---------*----------]
 12                                        [-------------*-------]
 13                                    [------*------]
 14    [------*----]
 15        [----------*--]
 16                   [---------*---------------------]
 17                      [---*------]
 18                      [----*-----]
DMaker [========*=================================]
Real:::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
                 20
     1                                                                   1E007
```

```
Item no.:  11 Item name: Hierro Scale: LOG
Experts
  1                           [---------*--------]
  2                                     [---------*----------------------------]
  3                 [---------*------]
  4                    [------*---------]
  5                    [------*--]
  6                           [---*--]
  7                 [------*--]
  8                           [---*-]
  9                    [---*--]
 10            [-*----]
 11                           [------*--]
 12                                    [-*----]
 13                                  [---*--]
 14                              [--------*------]
 15                        [-----*------]
 16 [------------------*-----------------------------]
 17                        [-*------]
 18                           [---*----]
DMaker 1 [==============================*===========]
Real::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::
                                        100
    0.02                                                                 1E006
```

```
Item no.:  12 Item name: Scoria cone Scale: LOG
Experts
  1                    [------------*----------------]
  2         [------------------*-------------------]
  3                                          [-------------*------------------]
  4                            [-------------*-------------]
  5                    [----------------*----------]
  6                                                                [----*-----]
  7 [-----------------------------------*------------------]
  8         [------------------*-------------------]
  9         [------------------*-------------]
 10              [-------*-----]
 11                    [-------*--------]
 12 [-------*----------]
 13                                                [-------*----------]
 14              [-----------*----------------------------------]
 15 [------------------*-------]
 16             [------*-----------------------------------]
 17         [----*-------------]
 18                      [----------*------------]
DMaker 1        [=============*=================================]
Real:::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::
                                 12
     1                                                                     500
```

```
Item no.:  13 Item name: Effusion rate Scale: LOG
Experts
  1                                    [-------*--------]
  2                           [---------*------]
  3                                                 [------------*------------]
  4                                        [--------*-------]
  5                                                 [---------*--]
  6                                        [-----*--]
  7                           [--------*-------]
  8                                                [------*-]
  9                                 [------*-----]
 10                               [-------*-]
 11                               [----*-------]
 12                               [---*------]
 13                           [------------------*------]
 14                           [------------------*---------------]
 15              [----------------*------------]
 16 [----------------*-----------------]
 17                                    [-*--]
 18                                    [-----*----]
DMaker  [===================================*====================]
Real:::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::
                               1.2
    0.01                                                                  5000
```

```
Item no.:  14 Item name: Lava Flow Leng Scale: UNI
Experts
  1    [-*--------]
  2    [---*-----------------------------]
  3 [*------]
  4 [*-]
  5 [--*---]
  6    [*--]
  7 [------*----------]
  8  [*----]
  9  [-*---]
 10 [-*]
 11    [---*----------]
 12    [----------*-------]
 13 [-*-]
 14         [-*--]
 15  [-*-------]
 16  [----------------*-------------------------------------------------------]
 17   [--*--]
 18      [-*---]
DMake [=======*================================================]
Real:::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
          10.2
    0.3                                                                    100
```

```
Item no.:  15 Item name: Melt Prod Hawa Scale: LOG
Experts
  1          [---*-------------]
  2                        [-------*------------------]
  3          [-------------*-----------------]
  4                                          [--------*---]
  5       [------*------]
  6                  [-----------*-]
  7 [--------------------------*-------------]
  8                                              [-----*--]
  9                        [-------*----]
 10                      [--*----]
 11                  [---------*---]
 12                                                       [-------------*-----]
 13                                     [--------*--------]
 14          [----------*------]
 15 [------------*----------------------]
 16                            [-------------*--------------------------]
 17                                                   [---*-----]
 18              [---------*------------]
DMaker 1     [============*======================================]
Real:::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::
                    0.18
    0.01                                                                  3000
```

```
Item no.:  16 Item name: Hekla earthqua Scale: LOG
Experts
  1                                [-----------*---------------]
  2                                       [----*----------]
  3 [----------*---------------]
  4                                [-----------*------------------------------]
  5                                       [--------*------]
  6       [*---]
  7                                       [--------*---------------]
  8            [----------*----]
  9            [-------------------------------*---------------]
 10            [-----------*-------]
 11            [-------------------------------*---------------]
 12                [------*----]
 13                       [-----------*-------]
 14                            [--------------------------*-----------]
 15            [----------*--------]
 16 [------------------------------*---------------]
 17                                                    [--*----]
 18                            [--------*------]
DMaker 1   [=====================================*====================]
Real::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::
                                        380
     2                                                                   1E005
```

```
Item no.:  17 Item name: Window Asama Scale: UNI
Experts
  1    [--*--------------]
  2 [--*--]
  3 [--------------------*----------------------------------------------------]
  4 [-----*-------]
  5 [--*--]
  6   [*--]
  7 [-----*-------]
  8    [----------*----------------------]
  9 [--*--]
 10   [*--]
 11    [------*----------]
 12                      [---------------*------------------------------------]
 13   [---*-----------]
 14 [--*--]
 15 [-----*---]
 16 [---------*--------------]
 17  [-*]
 18       [-----*------------]
DMa [===*===================]
Real::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
              15
     1                                                                      100
```

```
Item no.:  18 Item name: Eruption Scale: UNI
Experts
  1               [----------------------*--------------]
  2                       [--------------*--------------]
  3        [-----------------------------*-----------------------------]
  4    [-------------------------*-----------------------------------------]
  5                                      [---------------------*-------]
  6    [------------------*------------------------------------------------]
  7 [----------------------------------------------------------*--------------]
  8    [------------------------------------------------*------------------]
  9                              [-----------------------------*-------]
 10                                                                    [---*--]
 11                              [----------------------*------]
 12                                             [--------------*-------]
 13 [----*--------]
 14               [-------------------------------------*--------------]
 15    [------------------*------------------------------------]
 16 [----------*-----------------------------------------------]
 17        [------------------------------------*--------------]
 18               [-----------------------------*--------------]
DMake [=======================================*========================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                  100
```

```
Item no.:  19 Item name: No eruption Scale: UNI
Experts
  1               [----------------------*---------------------]
  2                      [--------------*--------------]
  3        [-----------------------------*-----------------------------]
  4    [----------------------------------------*--------------------------]
  5        [------*-------]
  6                                      [--------------*--------------]
  7 [-------------*-----------------------------------------------------------]
  8    [------------------*------------------------------------------------]
  9        [------*-----------------------------]
 10 [--*-------]
 11 [---------------------*--------------]
 12    [----------*--------------]
 13                                      [------------------------------*-----]
 14        [--------------*--------------------------------------------]
 15        [--------------------------------------------*------------------]
 16        [-------------------------------------------------------*---------]
 17        [---------------------*-----------------------------]
 18        [---------------------*-----------------------------]
DMaker 1   [========================*=======================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                 100
```

```
Item no.:  20 Item name: Summit Scale: UNI
Experts
  1 [---*----]
  2     [--------------*-------------------]
  3  [-----------------*-----------------------------]
  4 [---*----]
  5 [---*----]
  6     [----*----]
  7 [---*--------------------------------------------]
  8 [---*--------------]
  9 [--------*---------]
 10 [---*]
 11     [---------*------------------------]
 12 [---*------------------------]
 13     [----*-----------------------------]
 14          [---------*---------]
 15 [---*--------------]
 16  [-------*-------------------------------------------------------]
 17     [--------------*------------------------------------------------------]
 18 [---*------------------------------------------------------]
DMake [=============*====================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                  75
```

```
Item no.:  21 Item name: Flank Scale: UNI
Experts
  1                [------------*-----------]
  2     [-----------*-----------------------]
  3            [-----------------------------*-----------------------------]
  4 [----------------*-------]
  5 [---*---]
  6     [---*---]
  7 [-------*-----------------------------------]
  8 [-------*-------------------------------------------]
  9       [-------*-------]
 10 [---*-------]
 11     [-------*-------------------]
 12     [-------*---------------------------]
 13                [----------------*-----------------------]
 14               [*-------]
 15 [-------*-------------------------------------------]
 16     [-----------------------------------*-----------------------------------]
 17         [-------*---------------------------------------------------]
 18     [-----------*-------------------------------------------------------]
DMaker 1   [===========*==============================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                    90
```

```
Item no.:  22 Item name: Coastal Strip Scale: UNI
Experts
  1                   [-----------*---------------]
  2               [-------*-------------------------------------------------]
  3    [-----------*-----------------------------]
  4        [-------------------*-------------------------]
  5                                [-----------------------*-------]
  6               [-------*---------------]
  7 [-------------------------*-------------------------------------------------]
  8 [-------------------*-----------------------------]
  9                       [-------*---------------]
 10               [---------------*-----------------------]
 11                       [---------------*-----------------------]
 12                       [---------------*-----------------------]
 13        [-------*-----------------------]
 14               [---------------*-------------------------------]
 15    [-------------------------------------------------------*-----------------]
 16  [---------*---------------------------------------]
 17        [---------------*-----------------------]
 18        [-------------------*-----------------------]
DMaker [=========================*================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                    95
```

```
Item no.:  23 Item name: Submarine Scale: UNI
Experts
  1        [------*--------------]
  2               [-------*--------------------------------------------]
  3    [---*-----------------------------]
  4        [---------------------*----------------------]
  5 [------*------]
  6               [----------------------*------]
  7 [----------------------------------------*--------------------------------]
  8 [-------------------------------------------*----------------------]
  9        [--------------*------]
 10               [--------------*-----------------------------]
 11        [------*----------------------]
 12        [--------------*--------------]
 13        [--------------*--------------]
 14        [------*--------------------------------------------]
 15 [----------*-------------------------]
 16   [---------------*------------------------------------------------]
 17        [--------------*---------------------------------]
 18               [--------------*----------------------]
DMaker [============*==============================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                 100
```

```
Item no.:  24 Item name: Proximal Flank Scale: UNI
Experts
  1                [-------*-------]
  2    [---*-------]
  3   [---*----]
  4    [-----------*-------------------------------]
  5 [------*-------]
  6                        [---------------*---------------]
  7    [-----------*---------------]
  8 [------*-------------------------------------------------------]
  9                                        [---------------*-------]
 10    [---*-----------------------]
 11  [-----*---------------]
 12    [-------*-----------]
 13 [*-----]
 14 [--*-------------------]
 15 [--*-----------]
 16 [----------*---------------------------]
 17 [------------------*-------------------]
 18                                                [---------------*----------]
DMa [=====*==============================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                  95
```

```
Item no.:  25 Item name: Distal Flank Scale: UNI
Experts
  1                                      [--------------*--------------]
  2                                                                [---*---]
  3                                                                [----*---]
  4                                      [---------------------*-------]
  5                                      [-----------------------------*------]
  6                              [-------*------]
  7                                                [----------*--------------]
  8 [------------------------------------------------------------------*------]
  9               [-------*--------------]
 10                                                     [--------------*------]
 11                                                         [----------*---]
 12                                                     [----------*---]
 13                                      [-----------------------------------*]
 14                                                     [------------------*--]
 15    [----------*--------------------------------------------]
 16                                                         [----------*------]
 17        [------------------------------------------------*----------]
 18      [--------*----------------------]
DMaker 1                                   [===========================*======]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                 100


Item no.:  26 Item name: Proximal CS Scale: UNI
Experts
  1                        [-------*---------------]
  2                [---------------*-------]
  3                                [---------------*---------------]
  4                [-------------------------------*---------------]
  5                [-----------------------*---------------]
  6                                                                [-------*--]
  7                        [---------------*-----------------------]
  8 [----------------------------------------------*-----------------------]
  9                                        [---------------*-------]
 10                        [-------------------*---]
 11                [-------*-------]
 12                        [-------*-------]
 13 [------*-------]
 14    [---------------------------*-------------------------------]
 15        [-----------------------*---------------------------------------]
 16  [------------------------*----------------------------------------]
 17        [-------------------------------------------------------*----------]
 18                        [-----------------------*-----------------------]
DMaker [==========================*=================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                  95
```

```
Item no.:  27 Item name: Distal CS Scale: UNI
Experts
  1                               [--------------*------]
  2                                      [-------*---------------------]
  3                [--------------*--------------]
  4                [--------------*-----------------------------]
  5                [---------------------*--------------]
  6    [---*-------]
  7                       [--------------*----------------------]
  8 [-----------------------------*------------------------------------]
  9                [------*--------------]
 10                [-----------------*--------------]
 11                                      [--------------*--------------]
 12                               [--------------*--------------]
 13                [---------------------------------------------------*------]
 14                [-----------------------------*-------------------------]
 15    [----------------------*---------------------------------]
 16        [------------------------------------------*-----------------------]
 17 [--------------*---------------------]
 18                   [-----------*-----------------------------]
DMaker 1       [=================================*==========================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                99.5
```

APPENDIX 11: Range graphs for seed questions (expertwise).

```
Range graph of input data
Expert no. :    1     Expert name:  1
Items
  1(U)     [---------*------------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U) [*----]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                                                  [*-]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                            *-]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)                           [-------*------------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U) [-*--]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                           [--------------*-----------]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                                           [*--]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)                                                        [--*------------]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)             [*]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                          [--------*--------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L)                   [------------*---------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                                   [------*--------]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U)    [*---------]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)          [---*------------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)                               [----------*--------------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U)   [---*--------------]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
```

```
Expert no. :    2     Expert name:  2
Items
  1(U) [-*------]
Real   :::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U) [---*-----------------]
Real   :::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                                          [---*---------------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                      [--------------------------*--------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)         [-----*----]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U)  [--*------------------------------]
Real   ::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                                  [--------*-----------]
Real   ::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                       [-----------*--]
Real   :::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L) [-----*---]
Real   :::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)              [-------------*--------------]
Real   :::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                                    [--------*---------------------------]
Real   :::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L)         [------------------*------------------]
Real   :::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                           [---------*-----]
Real   :::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U)    [---*----------------------------]
Real   :::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                        [-------*-----------------]
Real   ::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)                                      [----*----------]
Real   :::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U) [-*---]
Real   ::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
```

```
Expert no. :    3     Expert name:  3
Items
  1(U) [---*---------------------------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U)       [----------------------------*-----------------------------------]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                [-----------------------------*---------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)               [---------------*----------]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)            [----------------------*--------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U)      [----------------*------------------------------------------------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                           [--------------*-----------]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                                          [---*-------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)           [--------*------]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)                  [----------*----]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                [---------*-----]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L)                                        [-------------*-----------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                                               [------------*-----------]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U) [*------]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)          [------------*----------------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L) [---------*---------------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U) [--------------------*-------------------------------------------------]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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```
Expert no. :    4     Expert name:  4
Items
  1(U) [-*-]
Real   ::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::

  2(U)  [-*----]
Real   :::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                               [--------------*----------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                    [-----*-------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)                    [------*--------------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U) [---*----]
Real   ::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                          [--------------------*-----]
Real   :::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::

  8(L)                      [------*---------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)   [-------*--------]
Real   :::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)                                          [--------------------*---------]
Real   :::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                   [------*--------]
Real   ::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::

 12(L)                          [-------------*-------------]
Real   ::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::

 13(L)                                      [--------*-------]
Real   ::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::

 14(U) [*-]
Real   :::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                                        [--------*---]
Real   ::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)                               [-----------*-----------------------------]
Real   ::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::

 17(U) [-----*------]
Real   ::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
```

```
Expert no. :    5     Expert name:  5
Items
  1(U)   [-*------------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U) [*-]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L) [------*--]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                          [-------*-----]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)     [---------------------*-------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U)  [---------*-----------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)       [-------------------*---------]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                         [--------*-------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)                           [-----*------]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)        [-----*--]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                   [------*--]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L)                   [---------------*----------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                                               [---------*--]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U) [--*---]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)       [------*-----]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)                                     [--------*------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U) [-*---]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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```
Expert no. :    6    Expert name:  6
Items
  1(U)   [-*----]
Real   :::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::

  2(U)       [---------------------------*----------------------------------]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)           [------------*--]
Real   :::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                          [--------*--------------]
Real   ::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)            [-------------*-------]
Real   :::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U) [*]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)       [-----*-------]
Real   ::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::

  8(L)                            [----*----]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)                [---*---]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)           [------*--------]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                         [---*-]
Real   :::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::

 12(L)                                                            [----*----]
Real   :::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::

 13(L)                                     [-----*--]
Real   :::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::

 14(U)    [*--]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                 [----------*-]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)       [*--]
Real   :::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::

 17(U)   *---]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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```
Expert no. :    7     Expert name:  7
Items
  1(U) [---*------------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U)   [--------------*----------]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                [--------------*--------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                     [--------------*-----]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)                        [----------*--------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U) [--*-----]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)       [--------------------------------------*-------]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                                            [------*--------------------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)                [---*---]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L) [---------*---------]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                [------*--]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L) [---------------------------------*------------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                          [--------*------]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U) [------*---------]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L) [-------------------------*------------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)                                     [--------*---------------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U) [-----*------]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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```
Expert no. :    8     Expert name:  8
Items
  1(U)      [---------*--------------------------------]
Real    ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U)                [------*------]
Real    :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                                     [--------*-----]
Real    :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                         [---*---]
Real    ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)  [------*-------------------]
Real    :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U)      [------*------]
Real    ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                                                             [-------*---]
Real    :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                                        [--*-]
Real    ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)                 [---*------]
Real    :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)               [--*------]
Real    :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                           [--*-]
Real    ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L)          [-----------------*------------------]
Real    ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                                               [------*-]
Real    ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U)   [*----]
Real    :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                                             [-----*--]
Real    ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)            [----------*----]
Real    ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U)    [----------*---------------------]
Real    ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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```
Expert no. :    9     Expert name:  9
Items
  1(U)     [------------------*-----------------------]
Real   ::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::

  2(U) [*-]
Real   :::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                               [----------*---]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::

  4(L) [-------------*-----]
Real   ::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::

  5(U)            [-----*--------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::

  6(U) [---*----]
Real   ::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                                     [----------*---------]
Real   :::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::

  8(L) [----------*--]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::

  9(L)              [-----*------]
Real   :::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)                     [---------*-------]
Real   :::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                   [---*--]
Real   ::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::

 12(L)         [-----------------*------------]
Real   ::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::

 13(L)                                [-----*-----]
Real   ::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::

 14(U)  [-*---]
Real   :::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                       [-------*----]
Real   ::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)           [------------------------------*--------------]
Real   ::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::

 17(U) [-*---]
Real   ::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
```

```
Expert no. :   10     Expert name:  10
Items
  1(U)     [--*-----------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U)   [*-]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                                               []
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                          [--*]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)                                   [---------*----]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U)            [----*-----------------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                                          [---*--]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                                     [-*-----]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)                 [-*---]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)           [--*--]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)           [--*---]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L)             [-------*-----]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                              [------*-]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U) [*-]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                      [-*----]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)           [-----------*-------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U)   [*-]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
```

```
Expert no. :   11     Expert name:  11
Items
  1(U)          [---------*---------------------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U)    [------*----------]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)     [-------------------------*--------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                          [-*--]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)                    [---------*-----------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U)  [----*--]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)       [----------------------------------*--------]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                                     [-*--]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)       [------------*------------]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L) [---------*---------]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                          [-----*---]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L)                   [-------*-------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                              [----*------]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U)    [---*---------]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                  [--------*---]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)           [------------------------------*--------------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U)   [-------*----------]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
```

```
Expert no. :   12     Expert name:  12
Items
  1(U) [--------*-------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U)               [-------------*------------------------------------------]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                           [------------------*----------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                                        [*--------]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)            [--------------*--------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U)  [------*-------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)             [-------*--------------------------]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                      [--*--------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)       [---*-----------------]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)                                       [------------*------]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                                  [--*----]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L) [-------*---------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                              [--*-------]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U)    [----------*------]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                                                     [------------*-----]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)                [-----*----]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U)                      [-------------*-----------------------------------]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
```

```
Expert no. :   13     Expert name:  13
Items
  1(U)     [------*-----------]
Real   ::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::

  2(U)  [--*---------]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                                                  [---------*----]
Real   ::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::

  4(L)                    [------------------------*-------------]
Real   :::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::

  5(U)                   [---------*-------------------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::

  6(U)     [-*-------]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)             [----------------------------*----------]
Real   ::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::

  8(L)                                                     [-*---]
Real   :::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::

  9(L)       [--------*----------]
Real   ::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)                                 [-------*-----]
Real   ::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                               [----*--]
Real   :::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::

 12(L)                                             [-------*---------]
Real   :::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::

 13(L)                         [-----------------*------]
Real   :::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::

 14(U) [*--]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                                   [-------*--------]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)                     [-----------*------]
Real   :::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::

 17(U)   [---*----------]
Real   :::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
```

```
Expert no. :   14     Expert name:  14
Items
  1(U)        [--------*-----------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U)   [-----*-------]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                                    [-------*----]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                          [-*--]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)                                      [-----------*---------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U)  [---------*-----------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                           [--------------------*---------]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                                       [-----------*-------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)          [---*----]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)    [------*----]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                             [--------*-----]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L)             [-----------*---------------------------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                          [-----------------*---------------]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U)        [-*--]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)          [---------*------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)                           [-------------------------*----------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U) [-*---]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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Expert no. :   15     Expert name:  15
Items
  1(U)     [----*---------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U)  [*--]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                               [--------------*---------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                                        [------*--------]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)            [-----------------------------*--------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U)  [--*----]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L) [-------------------------*--------------]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                                  [-----------*---------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)                             [-------------*------]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)        [---------*--]
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 11(L)                       [-----*-----]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L) [-----------------*-------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)             [----------------*-----------]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U)  [-*------]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L) [------------*---------------------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)           [----------*--------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U) [-----*---]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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Expert no. :   16     Expert name:  16
Items
  1(U)     [-----------------------*------------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U)   [-*-------------------]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                      [-------------------*-----------------------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                     [--------------------*--------------------]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)         [-----------*-------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U) [*--------------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)               [-----------------------------------*--------------------]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                        [---------------------*----------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)              [------------*-------------------------]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)                  [---------*--------------------]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L) [-----------------*----------------------------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L)            [------*-----------------------------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L) [---------------*-----------------]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U)  [---------------*-----------------------------------------------------]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                           [------------*-------------------------]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L) [-----------------------------*--------------]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U) [---------*-------------]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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Expert no. :   17     Expert name:  17
Items
  1(U)                      [---*--------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

  2(U)    [--*---]
Real   :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                                 [-----*----]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                            [---*---------]
Real   ::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)                             [--------------*-----------------------------]
Real   :::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U) [*]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                                                  [*----]
Real   :::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                                      [--*]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)              [-----*---------]
Real   :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)                     [---*-----]
Real   :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                       [-*-----]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 12(L)         [---*-------------]
Real   ::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::

 13(L)                                   [*--]
Real   ::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::

 14(U)   [-*---]
Real   :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)                                                 [---*----]
Real   ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)                                                  [--*---]
Real   ::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::

 17(U)  [*-]
Real   ::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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Expert no. :   18     Expert name:  18
Items
  1(U)                             [---------------*---------------------------]
Real   ::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::

  2(U)       [-------*---------]
Real   :::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                       [--------*------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  4(L)                                               [-----*---]
Real   :::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::

  5(U)                                        [--------------*--------------]
Real   ::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::

  6(U)   [-------------*-----------]
Real   ::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                                        [---------*-------]
Real   ::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::

  8(L)                                         [------*--]
Real   :::::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::

  9(L)                       [---*-----]
Real   :::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)                     [----*----]
Real   :::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)                          [---*----]
Real   ::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::

 12(L)                     [----------*------------]
Real   ::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::

 13(L)                                        [-----*---]
Real   ::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::

 14(U)     [--*---]
Real   :::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)              [--------*------------]
Real   ::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)                           [--------*-----]
Real   ::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::

 17(U)      [------*-----------]
Real   ::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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Expert no. :  DM      Expert name:  DMaker 1
Items
  1(U)      [=============*===========================]
Real    :::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::

  2(U)  [======*================]
Real    :::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  3(L)                        [======================*====================]
Real    ::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::

  4(L)                         [====================*===============]
Real    :::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::

  5(U)             [================================*===============]
Real    ::::::::::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::

  6(U)  [======*===============]
Real    ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  7(L)                  [==============================*====================]
Real    ::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::

  8(L)                           [======================*==========]
Real    :::::::::::::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::

  9(L)           [=====*=================================================]
Real    :::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 10(L)     [========*================================]
Real    :::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 11(L)      [===============================*==========]
Real    :::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::

 12(L)              [============*================================]
Real    :::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::

 13(L)      [==================================*====================]
Real    :::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::

 14(U)    [=======*===============================================]
Real    :::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 15(L)           [===========*======================================]
Real    ::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 16(L)        [=====================================*===================]
Real    :::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::

 17(U)  [===*==================]
Real    ::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
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APPENDIX 12: Scenario 'stages' and selected responses from workshop participants (anonymous).

Scenario summary		Relative 'risk' level	Stage	Selected responses from workshop
8	4 months of earthquakes felt at the Settlement, but a volcano never breaks the surface	Low	It is a normal working day, earthquake is felt in the village and objects move on desks and shelves	"has everyone felt it, or was it only felt in certain places?" "older people would compare it to the 1961 eruption" "immediate assessment on self, family and infrastructure" "what does this mean?" "where would I go to get that information?" "can we access the CTBTO data?" "people would pick up the phone to family and friends abroad – how would we handle the media?" "what happens if it happened at night?"
			The earthquakes increase in frequency over the next 4 months. They can be felt all over the island. There are associated rockfalls and some damage to homes and to the camping huts.	"can we make an assumption that we have experts here by that time?" "would the scientists be in a position to tell us to evacuate?" "during this period, we would have to make sure there was a ship in the vicinity" "because you can feel the earthquakes all over the island, you would never know where it would come up" "someone would need to assess damage to the hospital and the evacuation site" ***N.B. During this point in the workshop, the council decided that, if the experts were not able to provide advice on the most likely course of activity, the population would be evacuated at this stage.***

			The earthquakes suddenly come to a complete stop, none are felt again and no volcano breaks the surface	“it would be a community decision, you would feel which way the community was going” “there would be support in place” “the decision to resettle would be up to the experts” “if you do evacuate and nothing happens, there is going to be disquiet” “support from DfiD and the MOD....would be much better now than in 1961” “it would be an opportunity, because there would be massive media interest. People would want to see the British Government doing it properly” “if people wanted to stay, they would have to be reassured that they would be looked after properly”
7	Scoria cone growth near Hillpiece, erupted without warning	Med	A large crack opens up on the road to the Patches, between the cliff and Hillpiece. Small rocks (scoria) start erupting from the crack and build up a cone. As soon as the eruption starts, earthquakes are felt at the Settlement and at the Patches.	“the first thing you would have to do is check a head count, check who was out at the Patches and in the Settlement, or maybe send a boat out” “would there be a radio at the evacuation centre?” “normally it’s the pensioners that are out” “on their own? On a working day?” “that’s not a good situation at all” “does anyone know they’re there?” “it depends... if they go out on the bus, then yes, but they might walk home on their own” “we need a boat out there, someone with a megaphone” “we need to keep everyone together” “what if the weather is bad?” “if there are pensioners out there, do they know how to use a radio, and can they get into the hut?”

				“we need a sealed glass box with a radio in it and basic instructions for use” “let’s assume the weather is poor” “pensioners could not access the mountain” “in the case of a disaster, we can’t just have certain people having a key... in case they’re trapped...try to think of a solution that it [the hut] can be accessed by anyone in the case of an emergency” “need to make a visit to it [the hut] every so often to make sure...periodic checks” “if the sea is too rough, we could send a team of able-bodied men up on the mountain and come down Burntwood”
			The eruption continues for the next week and a cone is built almost 40 m in height. Ash and rock is blown towards the Settlement.	“wouldn’t we have evacuated off—island at this point?” “the water supply would be affected and we would have to leave anyway” “the [water] tank is not covered” “the water can be shut off, but how long would it last? “it wouldn’t last that long” “we should only be a few days away from evacuating” “what about the water supply down at Pigbite?” “so, for a number of reasons, we obviously need an alternative water supply” “would ash get into it [the tanks] even if it was covered over?” “in the case of earthquakes, no matter where it is, another rockfall can damage the water supply” “means getting it piped or stored...” “[talking about new tanks] don’t plastic give off a certain type of something after a certain time?”

				N.B. Again, at this point in the workshop, the council decided that an off-island evacuation should be conducted "I think the point, is, it's hard to tell whether it's going to be low or high risk....if it was more predictable....we would have a different attitude, but because an eruption is so unpredictable, you never know if it's going to be high, low or medium." "but here we have bits of rock landing on my roof....." "it's not like we can go to the next town...." "do you think islanders would want to come back if the potato patches were cut off?" "probably not" "their livelihood has gone" "without potatoes....we would be nothing" "it would be catastrophic"
6	Explosive eruption from summit, with volcanic bombs reaching the edge of the Base. Ash clouds erupted and ground collapse occurs. 2 weeks of earthquakes	High	Earthquakes increase in intensity and frequency for the next 2 weeks and can be felt all over the island. Rockfalls cause damage to homes and the roads begin to crack and buckle.	"can we get satellite images in this case?" "what if the clouds are over though?" "if you see any sort of activity around the Peak, you have to start preparing people for evacuation" "don't you think we should have a disaster management hut at Nightingale? What if we need to get off and we have to wait for a ship to come?" "we could store tents inside [a hut on Nightingale]" "it's just more difficult not using the longboats now" "see the longboats could be launched from anywhere" "one thing we could look at is the possibility of a fishing ship being around, or one of the

				freighters going through, and contacting them, to be on standby. "let's plan for the worst and hope for the best" "surely in this case, there will be a team of people in London managing this" "how long would it take a Navy ship to come here?" "the media would drive it...." "it could possibly be three or four days, or up to a week" "that's where the idea about Nightingale is very good" "we need to get a stock of tents" "let's establish how many we have" "why don't we use the Agulhas [helicopter] to replenish a container on Nightingale every year" ***N.B. Rest of scenario was abandoned as workshop participants considered that an off-island evacuation would be conducted at this point. Rest of discussion was focussed on coming back to Tristan.***
				"in terms of coming back, it will depend on the damage" "is it sustainable" "the deciding thing would be, where would be people be put [Falkland, Cape Town]. If it's a busy place they probably wouldn't stay" "they would have to learn from 1961, it would have to be somewhere more in tune with life on Tristan"

APPENDIX 13: Evacuation drill poster

EVACUATION DRILL

Instructions

- Monday 21st February (**<u>if it's not a fishing day</u>**)
- Do not go to work in the morning
- Sean will ring the dong (or a siren) to alert heads of families to the hall
- Sean will relay message to all heads of families
- Return home and deliver message to family
- Make your way through Hottentot Gulch where Cynthia will check you off a list
- Drive (or walk, if you are fit and able) to the Evacuation Site between the Bluff and the Patches
- Make sure you have worked out **in advance** which vehicle you will be travelling in and who will be going with you. This is especially important for children and pensioners
- Geraldine will take a roll call at the Evacuation Site
- Do not worry about bringing a supply kit
- Please leave dogs at home

The drill is <u>compulsory</u> for everyone (including ex-pats).
People permitted not to attend are:

Harbour project workers
Hospital patients
House-bound
Suffering from illness

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