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

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An interdisciplinary approach to volcanic risk reduction on Tristan da Cunha

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Abstract

This research project adopted an interdisciplinary approach to volcanic risk reduction on the remote volcanic island of Tristan da Cunha (South Atlantic). New data were produced that: (1) established no spatio-temporal pattern to recent volcanic activity; (2) quantified the high degree of scientific uncertainty around future eruptive scenarios; (3) analysed the physical vulnerability of the community as a consequence of their geographical isolation and exposure to volcanic hazards; (4) evaluated social and cultural influences on vulnerability and resilience. Despite their isolation and prolonged periods of hardship, islanders have demonstrated an ability to cope with and recover from adverse events. This resilience is likely a function of remoteness, strong kinship ties, bonding social capital, and persistence of shared values and principles established at community inception.

While there is good knowledge of the styles of volcanic activity on Tristan, given the high degree of scientific uncertainty about the timing, size and location of future volcanism, a qualitative scenario planning approach was used as a vehicle to convey this information to the islanders. This deliberative, anticipatory method allowed on-island decision makers to take ownership of risk identification, management and capacity building within their community.

This paper demonstrates the value of integrating social and physical sciences with development of effective, tailored communication strategies in volcanic risk reduction.

1 Introduction

It is now relatively widely acknowledged that advances in volcanic risk reduction research are contingent on the integration of social and physical science-based knowledge and approaches, and tailored communication methods (e.g., Barclay et al., 2008). There have been innovative multi-disciplinary studies oriented towards the reduction and mitigation of volcanic risk, by advancing understanding of important

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component challenges; for example, heterogeneous risk perceptions (Gregg et al., 2004; Gaillard, 2008; Haynes et al., 2008b; Paton et al., 2008); incorporation of traditional beliefs and knowledge, (Cronin et al., 2004; Mercer et al., 2007; Donovan, 2010); the role of religion (Chester, 2005; Chester et al., 2008); effective risk and hazard communication (Haynes et al., 2007, 2008a); strategies to increase community resilience (e.g. Paton et al., 2001); and building sustainable livelihoods (Kelman and Mather, 2008). There are however few examples of single studies that adopt an integrated interdisciplinary approach to volcanic risk reduction.

This study developed an interdisciplinary approach that was applied on the island of Tristan da Cunha to collect new data on physical and social components of risk, and to integrate and present this knowledge using community-centred strategies. The aims of this study were: (i) to improve knowledge of the recent eruptive history and quantify uncertainty around future eruptive scenarios; (ii) to identify and understand the salient components of risk that would contribute to vulnerability and resilience, during and after a volcanic crisis; (iii) to enable a population at risk to consider and adopt both short and long-term strategies that might reduce their risk from volcanic activity, and (iv) to monitor community response to this interdisciplinary approach and make empirical observations of change.

2 Case study: Tristan da Cunha

Tristan da Cunha (Tristan) is a remote, active volcanic island in the South Atlantic. It is one of fourteen Overseas Territories of the UK, and is home to a small population of 264[1] people who reside in the north of the island as a single community (the Settlement; Fig. 1).

There were several reasons for choosing to focus on Tristan: (i) it is an active volcano, typical of many small island volcanic settings, with the last eruption occurring within

[1] Population correct as of December 2013.

living memory (1961–1962) (Baker et al., 1964); (ii) the morphological evolution of the island and the eruptive history are not fully understood, so working on Tristan offered an opportunity to better define the eruptive history to refine future eruptive scenarios; (iii) it presented a case that was physically and socially well bounded, greatly simplifying analysis of the social processes and the communication of risk; and (iv) the relatively rich account of Tristan's short, yet eventful, history of settlement (< 200 yr) (e.g., Brander, 1940) permitted analysis of how present day vulnerabilities may reflect historic events and developments, and how current societal processes, community development, activities and new policies may affect vulnerability in the future (Lewis, 2009). It was important to analyse not only those characteristics that increase vulnerability to natural hazards, but also those that contribute to resilience. 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 elsewhere (e.g., Pelling and Uitto, 2001; Gaillard, 2007; Kelman, 2007). Therefore, a final aim was: (v) to identify and analyse characteristics of resilience of Tristan islanders. Tristan is often mentioned as an example of small island resilience, in light of the islanders' return to Tristan following a two-year evacuation initiated by the 1961–1962 eruption; however the literature is under-developed thus far (Gaillard, 2007; Dibben and Chester, 1999).

The remainder of this section will provide a more in depth description of Tristan's physical vulnerabilities, both to establish the problem and the importance of developing risk reduction measures on the island.

Situated over 2800 km WSW from Cape Town and over 3350 km from Rio de Janeiro, Tristan islanders are considered to be the most isolated population in the world. 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. These threats can be amplified by 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

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evacuation if the Settlement were to be threatened directly. As a high, steep mountain, Tristan's slopes rapidly transport material (e.g., water, rock, eruptive products) downhill, normally channelled via deeply incised gulches (canyons). 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 slopes of the volcano. 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.

The only access to the island is by ship (a 7–10 day journey from Cape Town). This means that Tristan has very restricted access to aid resources and emergency healthcare. Further, dependence on one mode of transportation to and from Tristan controls speed of access. In the event of a rapid-onset eruption, assistance could take many days to arrive, even if mobilised immediately. Rapid crisis response by either the Royal Navy or South African Navy would depend largely on location of available vessels. 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, ability to evacuate possibly the entire population, and the lack of direct access to Tristan's small harbour. Ships have to anchor offshore and dispatch inflatable boats for transferral of cargo and passengers. As the Settlement's position is exposed to the prevailing north-west winds, this makes it vulnerable to frequent bad weather, preventing all but the most high-powered boats from leaving and accessing the island. Even if a ship could arrive in 2–3 days, access to Tristan is not guaranteed.

Location currently restricts Tristan from diversifying its economy. Since the fishing industry was established in 1949, Tristan has been exporting crayfish to US, European and Japanese markets, and approximately 78 % of the economy depends on this single resource (E. Mackenzie, personal communication, 2009). Additional revenue is created

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through tourism and philatelic services, but there are limited options for livelihood diversification.

In terms of infrastructure vulnerability, the island's fish factory is the only building 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 infrequency of volcanic eruptions and seismic activity, no other 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 near to the Settlement. For example, flat 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, 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. Most new buildings are created around a timber frame, set with concrete, but a few retain their thick gable ends which provide resistance to the strong westerly winds. There is one hospital on the island, built in 1971 (and refurbished in 2001 following damage from a severe storm). It 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. Many islanders (> 50 %) are dependent on medication to alleviate symptoms of asthma and other bronchial conditions; genetic disorders which are thought to have afflicted five of the original settlers (Zamel et al., 1996; Slutsky et al., 1997). The hospital does not have the facilities to cope in the event of mass casualties.

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Tristan has many natural springs so water is plentiful. However, 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 tectonic or magmatic activity which could affect water supply.

3 Research design and methodologies

This study was designed from the outset to be interdisciplinary, combining both physical and social science methodologies. It was carried out as a PhD project by the first author (Hicks), who was responsible for conducting all data gathering activities in the field and in the UK. Figure 2 summarises the components of research, and their relationships. Three strands of data were collected: (i) geological (volcanic stratigraphy and timing of volcanic events); (ii) probabilistic (quantification of the uncertainty of possible eruptive scenarios); and (iii) social (physical vulnerabilities and social and cultural influences on vulnerability and resilience). An extended field campaign was designed around two fifteen-week seasons (referred to hereafter as "phases"). The primary objectives of the first phase were to establish trust with decision makers and other community members, make observations of community behaviours and volcanic activity, data gathering (physical and social) and sample collection. The integration of datasets occurred in the second, "action research" phase, which was focussed around the dissemination, debate and presentation of the results of the study, primarily using scenario planning as a vehicle. This paper has been structured to present results from each phase chronologically.

To achieve the research aims required engagement largely with those responsible for making decisions and taking action in the face of a volcanic crisis. At the project outset, contact was made with the on-island Administrator (a representative of the Foreign and Commonwealth Office, FCO), the Tristan Island Council and UK-based FCO officials,

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in order to discuss project objectives and outputs, to identify their requirements and to map out the decision making and implementation processes.

During phase one, volcanological data gathering involved field mapping, geological sampling and analysis via $^{40}Ar/^{39}Ar$ geochronology, refining views about timing, style, location and likely patterns of activity (Hicks et al., 2000). Scientific uncertainty was quantified using an established structured elicitation technique[2] (Cooke and Goossens, 2000); using volcanological data collected in phase one. The focus of the elicitation was on the likely location of a future eruption on Tristan, given unrest. Eighteen UK-based volcanologists, many of whom have experience providing scientific advice to decision makers, were elicited individually or in small groups (2–5 people). The integration of these two research components guided the design of the scenarios for the planning workshop in the action research phase.

Ethnographic reconnaissance approaches were also employed during this initial data-gathering phase, particularly participant observation, purposeful conversations and semi-structured interviews with islanders and island administrators (e.g., Wolcott, 1999). 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 as well as the engagement of decision makers to foster trust and gain access to information about social and cultural vulnerabilities. Given the cautiousness which many islanders exhibit towards “outsiders” (particularly those that are seeking information from them), gathering this information required considerable time spent learning and contributing to routine daily activities on-island. “Strategic” conversations were held when appropriate, almost always under informal circumstances and often within homes as one-to-one discussions, or at the local social hub with a larger group. Astute questioning and reflective listening enabled identification of current knowledge and perceptions of

[2]Expert elicitation is a formalized quantitative method for quantifying uncertainty by weighting expert judgments using mathematical scoring rules to determine performance-based metrics.

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volcanic risk. No one particular person or viewpoint was relied upon more than another and data sources were triangulated to cross-check accounts that were given.

Several methodologies were used to analyse and refine data gathered in the field following phase one. Community vulnerability and resilience were characterised within a simple capacities and vulnerabilities matrix (Anderson and Woodrow, 1989), which focusses on three broad, interrelated areas: physical/material, social/organisational and motivational/attitudinal. While a descriptive, rather than analytical tool, this matrix provides a practical approach to systematically and comprehensively assess community characteristics, with an aim to inform mitigation measures and disaster preparedness (Twigg, 2001). The spatial and temporal component of Holling's (2001) adaptive cycle enabled an analysis of the changes within the community over time, as well as an indication of how those changes may have altered levels of resilience to risk. These analyses, integrated with interview and observational data, guided choices of the action research phase and informed content of communication strategies.

During the action research phase, tailored communication processes culminated in a scenario planning workshop, school outreach and a town hall event. The scenario planning workshop was a strategy designed to both communicate research results and to encourage on-island decision makers (Administrator and Island Council) to identify feasible adaptation strategies in order to strengthen existing risk reduction and island development plans. Three different eruption scenarios were "played out" and the impact of dynamic external factors (e.g., time of day and weather) were discussed. Further, outreach activities were conducted with school pupils, including field trips and eruption analogy experiments. A film project about the 1961 eruption was designed to give students an opportunity to interview their grandparents to learn first-hand what happened during that time, thus helping to retain social memory of the events. A town hall meeting, held with islanders towards the end of phase two, enabled discussion of research results and offered a platform for the community to raise questions.

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4 Analysis of factors contributing to risk

The following three sections present a short summary of results from the geological, geochronological and probabilistic research components, and a longer analysis of the findings from the social science component.

4.1 Physiography of Tristan and timing of volcanic events

Volcanic activity on Tristan is attributed to an intra-plate melting anomaly, known as the Tristan hotspot, rather than partial melting from the Mid Atlantic Ridge, approximately 350 km eastward (Sleep, 1990). The Tristan hotspot 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 melting anomaly.

Tristan has a roughly conical edifice, with a maximum diameter of 1200 m and rises ∼ 5500 m from the sea floor. The uppermost 2060 m is exposed sub-aerially and is composed of summit-sourced lavas and intercalated pyroclastics. Numerous parasitic cones, considered to be post-shield volcanism, are scattered across the flanks; many of which are breached by lava flows. The island is almost entirely volcanic, comprising mainly silica under-saturated basanites to phonolites, and probably emplaced within the last ∼ 200 ka (Hicks et al., 2012; Dunkley, 2002; McDougall and Ollier, 1982). Young, low-lying coastal strips flank the north-western and southern margins of the island. Situated on these strips are the two most recent sub-aerial eruptions (1961–1962 eruption and Stony Hill; Fig. 1), which were low volume leaks of tephri-phonolitic lava, manifest as domes and flows (Dunkley, 2002). A large sector collapse scar is evident in the north-west of the island, and was inferred by Holcomb and Searle (1991) to have an associated submarine avalanche of ∼ 150 km^3.

Geochemical and isotopic studies of Tristan rocks suggest that lavas are derived from melting of a deep, heterogeneous source, forming basanitic magma bodies that undergo fractionation and mixing in shallow conduits and transitory chambers (Le Roex

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et al., 1990). Isotopic analyses of phonolitic pumice that erupted from a submarine vent in 2004 (O'Mongain et al., 2005) 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 further suggests that, rather than being dominated by one large chamber, magma is sourced rapidly from depth and siphons off into smaller, discrete, magma pockets nearer the surface. Given this style of magmatism and the spatial heterogeneity of eruptive centres (Fig. 1), it was important to appraise the past eruptive phases of Tristan and to constrain the relative timings of the differing styles of volcanism in an attempt to forecast future eruption scenarios.

The $^{40}Ar/^{39}Ar$ method (Renne et al., 1997; Lanphere et al., 2007) was applied to 15 well-defined eruptions on Tristan (Hicks et al., 2012). The aim of the new geochronology was to ascertain spatio–temporal relationships of recent volcanism; explore relative timings and frequency of eruptions, and to establish if the most recent summit activity post-dated eruptions from the parasitic centres lower on the flanks. For detailed methodology and results, see Hicks et al. (2012).

From the new dates no spatio-temporal pattern to parasitic cone activity was found, and recent volcanism from these sites varied in style, volume and composition with time, unlike recent activity from other well-dated ocean island systems. The northern sector of the island was built rapidly (81 ± 10 ka to 34 ± 1 ka) with the sector collapse occurring within a 14 kyr period (34 ± 1 ka–26 ± 5 ka); however the southern sector and summit cone appeared to have a longer evolution (118 ± 4 ka and 81 ± 8 ka, respectively). Therefore it is likely that the construction of the edifice was piecemeal, evolving with more spatial and temporal complexity than previously suggested. Activity at the summit was concurrent with recent parasitic centre activity on the flanks and coastal strips between 81 ± 8 ka and 5.2 ± 1.1 ka. Given that the summit slopes are very steep, and the channelising nature of the gulches, the consequences of a summit eruption for the island's Settlement are different than an eruption on lower-lying areas. Although the two most recent eruptions occurred on low-lying coastal strips (1961–1962 dome and flows; Stony Hill dome and flows, ∼ 200–300 yr BP), the new temporal

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framework revealed that future eruption on the flanks, or from the summit, cannot be discounted (Hicks et al., 2012).

4.2 Using expert judgement to constrain uncertainty

The variability in volcanism on Tristan presents significant uncertainty in terms of anticipating future eruptive scenarios on Tristan. In an attempt to address this uncertainty, an expert elicitation exercise was conducted. Using the eruption record and results from field mapping, 18 volcanic experts were elicited on the likelihood of progression through an event tree which considered an eruption following unrest, the likelihood of an eruption and then the likely location of eruption. Opinions on the likely hazard and their impacts were elicited using a paired comparison analysis[3]. Given that Tristan is a relatively data-impoverished setting, a paired comparison analysis was more appropriate than extending the event tree to assign absolute probabilities to a multitude of uncertain eruptive scenarios (Hicks et al., 2013).

By using the structured elicitation and asking experts to provide their confidence limits on probabilistic estimates, we were able to use the Classical Model to quantify expert uncertainty. This method weights expert judgements by using mathematical scoring rules to determine performance-based metrics (Cooke, 1991). By pooling weighted expert opinion, a representative group distribution is produced. This emergent consensus is seen as invaluable for decision support and encourages the creation of "one voice" (Newhall et al., 1999; Aspinall and Cooke, 1998)[4].

[3]Paired comparison is a technique used to produce a rank of preference by comparing pairwise sets of alternatives according to particular criteria. For the Tristan exercise, experts were asked to rank particular volcanic hazards in terms of likelihood of occurrence and likelihood of impact.

[4]The appeal for transparent handling of uncertainty in quantitative decision making support is persistent and the CM – amongst other structured methods for obtaining and combining expert judgement – provides tools for doing so. A special issue of *Reliability Engineering and*

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Results indicated that the experts were extremely uncertain about whether unrest would lead to an eruption, and the location of future eruptions on Tristan. Table 1 shows the group distribution; presenting the median values and the spread of uncertainty (5th and 95th percentile) for each question posed. However, this severe uncertainty was not unexpected with the available information, given that Tristan has not evolved a dominant central vent preference. In the event of an eruption, the emergent consensus of the expert group was that the most likely broad location of eruption to be the coastal strips and the least likely location to be the summit. However, when presented with the new geochronological evidence proving that the summit had been active very recently (see Sect. 4.1), many experts expressed *greater* uncertainty about future eruptive scenarios on the island. The paired comparison exercise confirmed that experts were in agreement that earthquakes and rockfalls were the hazards most likely to impact the Settlement, whether the eruption was at the summit, on the flanks, on the coastal strips, or from a submarine vent. This has implications for the Settlement in terms of damage to homes and risk to inhabitants, as buildings were not constructed to withstand all seismic activity. Pyroclastic density currents and base surges were considered least likely, probably given the apparent lack of those deposits in the stratigraphic record.

For Tristan, this level of uncertainty presented a further challenge in effective risk communication during the action research phase. Lack of certainty can be misinterpreted as a lack of confidence or ability, possibly exacerbated in this instance by compiling the findings of unknowable and unseen "experts". Nonetheless, the description of this uncertainty was a necessary step in establishing openness, transparency and long-term trust (Poortinga and Pidgeon, 2003).

System Safety on expert judgement provides a comprehensive collection of state-of-the-art methodologies (Cooke, 2008).

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4.3 Social and cultural influences on vulnerability and resilience

Here we refer to vulnerability and resilience as the characteristics of a person, group and/or their situation which negatively or positively influence resistance, coping capacity and recovery. On Tristan, both vulnerability and resilience to natural hazards are influenced by a complex network of social interaction and behaviours, some of which can be traced to recent developments within the community, and others which have historical roots. These are summarised in Table 2. The following three sections present evidence from the literature and new results from the ethnographic reconnaissance, conducted in phase one of the research.

4.3.1 An evolving economic and political landscape (1816–1961)

Tristan was first discovered by Portuguese explorer Tristaõ d'Acunha in 1506 (e.g., Brander, 1940, and references therein) although the island was not permanently inhabited until the withdrawal of a British garrison in 1816. Those few that chose to remain on Tristan created a community based on principles of communal ownership, integrity, and equality. There was no chain of command or official leaders, and all produce and profits were shared equally. This founding vision is a significant marker in Tristan's history as the cultural homogeneity that accompanied these established values and principles has helped to generate plentiful stocks of social capital (a concept that brings attention to the role of social interactions in explaining individual and collective outcomes), mainly founded on strong community bonds and reciprocal behaviour (Table 2).

From 1890, the whaling industry declined, and the shortage of passing ships forced the islanders to modify their barter economy to one of subsistence (and increased independence), in order to cope (Table 2). There were several decades of hardship, until the British Royal Navy established a garrison on Tristan during World War II, bringing with it a cash economy, new jobs, infrastructure (e.g., school, shop, hospital) and permanent contact with the outside world (wireless station). These transformations

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began to erode the anarchist form of social organisation and was replaced by a more formal and structured system (British Administration; Table 2). The first contracted resident British Administrator became the head of government on Tristan in 1950, followed shortly by the creation of the first Island Council (the first Chief Islander was not appointed until 1970). While outside support strengthened resilience in some ways, the de-traditionalisation and introduction of hierarchy may have weakened it.

The success of the fishery, built in 1948 to exploit the crayfish resource, brought technical and agricultural improvements (e.g., modern sanitation and effective grazing methods). Islanders were able to purchase "luxury" goods and thus raise their standards of living in line with those of the "outside world" (Munch, 1964). However, this came at a cost as greater dependence on imports further affected traditional forms of social and cultural practice and organisation.

4.3.2 Social impact of eruptive activity (1961–1963)

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 9th October, the Administrator decided to evacuate the whole Settlement to the potato patches (known simply as the "Patches") three kilometres westward. Upon being advised that a new volcanic dome was erupting, the Administrator temporarily evacuated the entire population ($n = 264$) to nearby uninhabited Nightingale Island and eventually onwards to England (via South Africa).

The islanders were ultimately moved, as a unit, to an Air Force base in Southampton, UK. They successfully applied for jobs and the children were sent to school (Table 2). Some islanders, especially the younger ones, enjoyed their time in the UK and several were happy to stay and continue the new lifestyles to which they had adapted so rapidly (Table 2). However, during the ethnographic survey, many islanders reflected on the challenges of adjusting to their new lives, particularly crime, probing journalists and medical researchers, poor weather and lack of immunity to common ailments. When eruptive activity on Tristan began to wane in March 1962, the islanders submitted

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a petition to the Colonial Office to return to their home, which remained unanswered. Upon hearing that twelve men had travelled back to Tristan to begin the repair effort, financed solely by the community, the Colonial Office consented for the islanders to return. The move was finally completed in November 1963 when the final 198 islanders departed the UK (51 had already left in March). Eleven islanders remained in England.

During the ethnographic survey, many islanders commented that had the Colonial Office (now the Foreign and Commonwealth Office) not kept the community together in one location, resettlement on Tristan would have been unlikely. By staying together, the community developed stronger bonding ties, and defended much of their cultural identity, although certain changes were inexorable. A longitudinal study by Munch (1964, 1970) postulated that the community had actually become closer as the islanders attempted 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 Colonial Administration they had regarded as absolute, and to use their own initiative and action to defend their culture against the pressures from modern society (Munch, 1964). The UK sojourn engendered a new pride in their will and ability to survive as a community and they reacted against social and cultural subordination. Regardless of being submersed in an unfamiliar, hierarchical society for two years, the islanders retained their original values of equality, mutual aid and selective reciprocity; principles that prevail today.

4.3.3 Recent influences on social and cultural vulnerability and resilience (1963–2013)

At the time of the ethnographic survey[5] the Tristan community was characterised by a small, cohesive population that remains shaped and organised according to kinship. Social solidarity remains strong. For example, small-holding work at the Patches continues and is seen as an important part of Tristan's heritage and an expression

[5]October–December 2009 and December 2010–March 2011.

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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 plots at the Patches are shared out amongst families. Joint ownership (family members and/or friends) of large or expensive items also still exists (e.g., huts at the "Caves" in the south of the island). Further, while many traditional community activities (such as longboat sailing, for example) have been replaced or discontinued, the islanders still maintain unique annual community celebrations (e.g. Queen's Day [village wide sports day, plus other competitions]). These events illustrate the sense of community that the islanders still share. Family bonds and cooperative kinship networks were vital when hardship was most pressing in the past, and these sustained relationships still offer a rich source of social capital and an essential means for communities to absorb stress.

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), *with* declining self-sufficiency (more dependent on imported food). Social capital 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 and others fracture (Coleman, 1990; Putnam, 1993, 2000; Murphy, 2007; Rubin and Rossing, 2012). The implication would be that the erosion of social capital could alter response and recovery to volcanic activity. 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.

The resilient qualities of the islanders and administrative and financial support from the UK government have been essential in overcoming the damaging effects of other natural and accidental events, for example, a severe storm in 2001, a factory fire in 2008, and frequent harbour damage. The UK government's support in the event of a further volcanic crisis is a certainty. Good communication has reduced the perceived

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distance between Tristan and the outside world, which has both positive and negative impacts.

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 (Table 2). Modern communications have had significant consequences for the usage and purpose of social spaces in the Settlement. The advent of television (in 2001) and the introduction of digital entertainment have changed the choice of leisure activities and the type 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 using larger community spaces to socialise 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 to "outsiders", 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, in the face of a volcanic crisis (e.g., Pelling and High, 2005).

Modernisation has adversely affected many customary practices, especially knowledge of traditional crafts and skills such as sailing (longboats) and thatching. While the uptake of modern tools and equipment has improved productivity and efficiency, these often require complex maintenance which cannot always be accomplished by islanders. Faulty machinery may remain idle for months until a technician can be sent to the island to repair it. If this happens to be essential for evacuation, response or recovery, it can weaken resilience. For example, the evacuation in 1961 was only possible by transferring islanders to Nightingale Island in locally-crafted longboats. These could be launched from the beach even in sub-optimal sea conditions. Modern, motorised vessels can only be launched from the harbour; therefore greater dependency on good weather conditions has been introduced.

In terms of resilience to natural hazards, maintaining stocks of social capital on Tristan 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. For this study, working with the Island Council was therefore crucial, as the group brought an innate knowledge of community capacities.

5 Synthesis into scenarios: communicating volcanic risk and uncertainty

Thus far, we have presented the results of physical and social components of the research, and while the separate streams of data were collected synchronously, integration of the outputs of the two sets of analysis was achieved at the scenario design phase and via the planning workshop.

One of the main research aims was to help increase the capacity of the Tristan Island Council, and consequently, the wider community, to act to reduce risk under conditions of uncertainty. While the absence of certainty is central to 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 challenge, not only to volcanology, but also to those engaged in developing and communicating volcanic risk reduction strategies.

To help communicate the high uncertainty of future eruptive scenarios, and to attempt to empower the community to prepare, scenario planning was selected as an appropriate vehicle to disseminate and discuss research results. This choice of method was reinforced by the work of Stirling (2003, 2010), who distinguishes between two ways in which knowledge about risk may be incomplete and examines the consequences for the effectiveness of analytical methods such as quantified risk assessment or expert consensus, identifying methodological options which may be more appropriate to different epistemic conditions (Fig. 3).

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In the case of Tristan, there was limited basis on which to define probabilities of future eruptive scenarios, therefore our knowledge of risk was at the “problematic” end of that axis (Fig. 3). Existing geological knowledge, combined with the new geochronology and field mapping produced by this research, meant that it was possible to present knowledge of a discrete set of outcomes, thus approaching the “unproblematic” end of the “consequences” axis. These conditions suggested, following Stirling’s schema, that a scenario-based methodology would be one of the most appropriate techniques to employ. Other structured communication strategies included: a formal presentation of project results to the Island Council; outreach initiatives with school children and school curriculum updates; a town hall event; and an evacuation drill. A summary of all communication strategies, responses from the community, and adaptations are presented in Table 3.

5.1 Risk communication and scenario planning

Risk communication was focussed around two meetings with the Island Council, firstly a presentation and discussion of results, and secondly a scenario planning workshop. Using this incremental approach was vital in establishing trust between the researcher (Hicks) and the Island Council.

Results from the research were presented in the first meeting to enable discussion around the volcano and the attendant scientific uncertainty, new observations from the current study and their implications for risk management. During the session, 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.

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 style of analysis presents a suitable way of engaging with people and communities who have not considered uncertain and/or seemingly incredible visions of the future, and whose thoughts are rooted in more immediate, everyday concerns.

In this study, Hicks designed and ran the scenario planning exercise. Eight scenarios were produced, given a relative risk level, and presented to the workshop participants (Table 4). The vulnerable and resilient characteristics identified from the phase one analysis (Table 3) were also built into the scenario dialogue as posed as questions at relevant moments (see "question prompts" in Table 5).

The group selected three scenarios to "play out": a best, most likely, and reasonable worst case (Tables 4 and 5). Worst cases are normally taken from the historical record, but due to the short history of Settlement on Tristan, worst cases were taken from the stratigraphic record and knowledge of plausible eruptive behaviour on analogous volcanic ocean islands. This made it clear to the group that the worst can happen with no historic precedent on which to draw.

Each scenario developed as a narrative, enabling participants to imagine responding to particular events. The progress of the scenario was "frozen" at key points to allow the group to discuss assumptions, examine responses and consider measures to reduce risk. The group was able to independently explore many of the physical, economic, cultural and social components of vulnerability and resilience identified earlier in the study. Although "expert" questions were used to prompt this discussion, the analysis was driven by the participants (Table 5).

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 engaged and were keen to participate. Several reflected that the scenario planning framework would be readily transferrable to multi-hazard scenarios and to the identification and mitigation of other natural and man-made risks on Tristan.

Evaluating the effectiveness of the scenario planning approach was conducted qualitatively, by observing the changes made as a result of the workshop. Modifications to behaviour and protocol provided an evidence base for successful communication as the "audience" are required to both understand the message and see it as personally relevant (Walker and Meyer, 1980; Morgan et al., 2002).

5.2 Outcomes and further activities

The Island Council devised a large number of recommendations from the workshop; indicative of the many actions and resources required to plan for an eruptive crisis and mitigate the impacts and risk, should an eruption ensue (Table 3). Recommendations were mainly focussed on the need to reduce uncertainty and to provide effective early warnings by monitoring.

One of the questions raised during stage one of the first scenario (Table 5), following felt earthquakes at the Settlement was simply about who to contact. Until then, no one was sure who to call:

WORKSHOP PARTICIPANT 1. Where would I go to get that information?[6]

As a result, the disaster management plan was updated to include contact details of appropriate personnel at the British Geological Survey (BGS), and the Disaster Management Coordinator on Tristan and Head of Volcanology at BGS made direct contact.

[6] All members of the workshop were island council members, conducted on Tristan da Cunha, February 2011.

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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. As one participant suggested:

WORKSHOP PARTICIPANT 2. Someone would need to assess damage to the hospital and the evacuation site.

During the workshop, the appropriate person was identified and protocol in the DM plan was later amended.

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 and design changes to the disaster management centre. The following is an extract of the discussions between workshop participants, and provides an example of problem identification and a solution; which has since been implemented:

WORKSHOP PARTICIPANT 2. 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.

WORKSHOP PARTICIPANT 3. If there are pensioners out there, do they know how to use a radio, and can they get into the hut (Disaster Management, DM, Centre)?

WORKSHOP PARTICIPANT 4. 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 DM centre) can be accessed by anyone in the case of an emergency.

WORKSHOP PARTICIPANT 5. We need a sealed glass box with a key and radio in it with basic instructions for use.

Other infrastructure recommendations were suggested, including the active exploration of the use of Nightingale Island as a temporary off-island evacuation site (Table 3), illustrated by the following conversation:

WORKSHOP PARTICIPANT 2. 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?

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WORKSHOP PARTICIPANT 6. We could store tents inside (a hut on Nightingale).

WORKSHOP PARTICIPANT 1. It could possibly be three or four days, or up to a week.

WORKSHOP PARTICIPANT 3. That's where the idea about Nightingale is very good.

WORKSHOP PARTICIPANT 4. We need to get a stock of tents; let's establish how many we have.

WORKSHOP PARTICIPANT 7. Why don't we use the Agulhas (supply ship's helicopter) to replenish a container on Nightingale every year.

Following the scenario planning exercise, an evacuation drill was conducted with all islanders and expatriates. Deficiencies in the evacuation plan were discussed informally and improvements were immediately implemented in a revised version. 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.

Since project completion, there is evidence of sustained interest in volcanic risk reduction from island administrators and FCO officials (Table 3). Annual meetings between the authors and FCO officials continue to be held two years post-project to maintain knowledge transfer and help implement recommendations as administrators and FCO officials move roles (there have been three different administrators and desk officers since project commencement in 2009). Sustained links with community members and the UK-based Tristan community have helped to prolong an interest in volcanic risk reduction, although longer-term dialogue on risk and resources will be needed to maintain this. This includes capacity building in terms of monitoring. The British Geological Survey retain responsibility for monitoring and providing initial response to volcanic and tectonic activity affecting Tristan, however, like many island volcanoes, effective monitoring is inadequate (one IRIS seismometer) and resources are limited.

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6 Reflections on the interdisciplinary approach and transferability to other settings

Significant experience shows that decisions by governments and civil society to enhance resilience require scientific knowledge to be credible, salient and legitimate (Cash et al., 2003), and that research evidence and scientific knowledge is only one factor influencing the formulation of strategies to reduce risk.

We reflect that the success of this interdisciplinary approach requires, *at the project outset*, to take time not only to understand the unique social context and dynamics to establish the most salient components, but to integrate 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 engage with the public at risk and understand their values, beliefs and knowledge. This type of expertise can be brought as both a larger interdisciplinary team, or by a lone researcher, as demonstrated here. It is acknowledged that a larger research group was not necessary, or even suitable for a study in this setting, however our approach to this research provides a template for a larger scale, longer duration, multi-researcher study that is still interdisciplinary in scope.

Ultimately, actions to reduce risk are taken and owned by communities at risk. Therefore, 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. Tackling the communication challenges successfully therefore 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 in ways adapted to specific hazard and social contexts (e.g., Stirling, 2010; Pidgeon and Fischhoff, 2011). Further, while features such as functional competence, legitimacy, fairness and openness are known to increase trust

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and thereby the effectiveness of risk communication (e.g., Haynes et al., 2008a), experience on Tristan also highlighted the importance of interpersonal competence (Gabarro, 1978) of the communicator when interacting with small communities, in order to build, for example through empathy, amiability, enthusiasm and readiness to participate, positive interpersonal relationships.

In this study, the scenario planning strategy was well-suited to the integration, deliberation and high degree of scientific uncertainty. 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 an evacuation drill, was encouraged by gradual and steady discussion of both 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 and personal interaction less.

7 Conclusions

In any volcanic setting, it is important to identify and understand the most salient components of risk. This research adopted an integrated, interdisciplinary approach to reducing volcanic risk on Tristan da Cunha. By examining all components concurrently, this approach provides a more complete picture of risk, and made anticipating the relationships between different components clearer. Conclusions from the physical, social and decision-making science components are briefly summarised below.

Understanding the time-size distribution of volcanic eruptions provides an important first step in volcanic hazard assessments. The new field observations from Tristan provided a more precise geochronology of the recent eruptive history (< 80 ka). Results showed that there is no spatio-temporal pattern to parasitic centre activity on Tristan. When combined with geochemical and isotopic evidence (Le Roex et al., 1990; Reagan et al., 2008), this suggests that magmatism is not dominated by one large chamber but, rather, smaller individual pockets of magma that source rapidly from depth. These

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findings demonstrate the variability of eruption style, volume, composition and location, and present significant uncertainty in anticipating future eruptive scenarios.

To quantify this uncertainty, these data were presented in an expert elicitation exercise. Results describe the extent to which experts were uncertain about the likely location of future eruptions and demonstrated that the absence of records of proximal monitoring data, in particular, contributed to great uncertainty as to whether registered "unrest" would lead to an eruption. Nonetheless the consensus, reached via a weighted mean of responses, showed that the consensus view was that the likely location of the next eruption would be the coastal strips. However, the associated uncertainty around each scenario was very large (Table 1).

The results from this exercise demonstrated 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 (Stirling, 2010). In the absence of even a partially-complete data set (lack of monitoring data), a scenario planning approach was selected as the most suitable method for discussing volcanic risk, and evaluating responses on Tristan. Successful design and execution of this approach was contingent on creating a trusting relationship with the community and acknowledging the social dimensions of vulnerability and resilience.

Information about the social context on Tristan was gathered from off-island sources and during two 15-week fieldwork periods on the island. By adopting an ethnographic approach to data gathering, information about community characteristics, interactions and social structure were recorded. Physical vulnerabilities are rooted in the isolation of Tristan.

Results suggested that, while location and seclusion have, on one hand, augmented a vulnerable state (to natural hazards), on the other, they have led to the formation of successful coping mechanisms (Lewis, 1999; Howorth, 2005; Kelman and Mather, 2008). 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

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events (e.g. 1961–1962 eruption). Adjustment to new circumstances has undoubtedly affected the vulnerability-resilience balance (caused by, for example, introduction of formal governance and modern communications). By examining the temporal dynamics of vulnerability and resilience on Tristan, it was possible to guide the scenario planning exercise to allow decision makers to consider community capacity to cope with a future eruptive crisis.

The challenge for Tristan will be to consider and address this changing vulnerability-resilience balance to sustain risk reduction measures. In order to maintain resilience in the face of volcanic 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.

Reducing volcanic risk is a complex and nuanced process. The first step in this process is a more sophisticated understanding of risk and acknowledgement that this can change. This study provides a template for the integration of characteristics of risk and the means to share that understanding with those who need to act.

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Table 1. Results from expert elicitation "event tree" exercise, conducted with 18 UK-based volcanologists. Median values for the group distribution are presented alongside the upper and lower bounds of the group uncertainty.

	Median value	Bounds of uncertainty	
		Lower value	Upper value
Probability of eruption given unrest			
Eruption	55	3	90
No eruption	45	10	96
Probability of eruption at each of four locations			
Summit	17	2	53
Flanks	24	6	79
Coastal strips	38	5	83
Submarine	21	4	83
Probability of flank eruption being proximal or distal to the Settlement			
Proximal	11	0.3	46
Distal	89	26	99
Probability of coastal strip eruption being proximal or distal to the Settlement			
Proximal	40	5	83
Distal	59	13	96

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Table 2. Economic, social and cultural influences on vulnerability (V) and resilience (R), and their dynamics since settlement.

			Time periods		
			Historical (1817–1961)	Eruption & Evacuation (1961–1963)	Post-eruption (1963–2013)
Social and cultural influences	Governance	R	Anarchist until WW2 (formal administration introduced in 1950); creation of the first island council (1951)	Under UK governance	UK links provide source of financial and decision-making support
		V	De-traditionalisation brought about by formal administration		Reliance on support
	Economy	R	Barter (with passing ships) with shared profits; gradually moving to increased subsistence and independence; introduction of cash wages (1942); exploitation of crayfish (1948)	Under UK governance	Crayfish industry excellent cash "crop"; increased revenue from tourism in recent years
		V	Crayfish canning factory destroyed by lava flow (1961)		Effectively a single "crop" economy (crayfish) which itself is susceptible both to fluctuating markets and ecological threats; increase in number of patients requiring medical treatment in Cape Town presents economic burden
	Livelihood diversification	R	Barter (with passing ships), gradually moving towards subsistence	Offered paid work; learned new skills	All maintain Potato Patches; many islanders have multiple roles (as most jobs are weather-dependent)
		V	No options for diversification		Limited options for diversification
	Social capital	R	Development of community based on communal ownership, integrity and equality; community engage in collective action; building trust; determination to remain on Tristan despite hardship	Strengthened cohesion from outside exposure; weakened social subordination to outsiders; increased self-identity and confidence	Strong kinship ties; retained original values of equality, mutual aid and selective reciprocity
		V			Communications and media altering interaction
	Cultural capital	R	"The Agreement" – shared values and principles; community engage in collective action; development of their own, new, culture	Developed greater cultural confidence	Sound sense of place; pride in heritage; maintain traditional annual events
		V			Modernism and modern communication undermining cultural characteristics
	Health & Well-being	R	Initially very good; plentiful food (until end-19th C); illness rare due to lack of visitors	Access to good medical facilities	All islanders frequently work at the Patches; fishing and building is labour-intensive
		V	Regularly in a state of privation from end-19thC to WW2	No immunity; illnesses common	Most have asthma or other bronchial conditions; weakened immune systems from common infections; high level of diabetes; importing more food; increase in sedentary jobs; increase in motor vehicles; aging population

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Table 2. Continued.

		Time periods		
		Historical (1817–1961)	Eruption & Evacuation (1961–1963)	Post-eruption (1963–2013)
Marginalisation	R	Isolation also positive (improved coping strategies); became less marginalised during WW2	Many adapted rapidly to a new way of life	Annual visit from Gough Island relief vessel (1980's onwards); increase in shipping; more tourism; better links with outside world
	V	Extremely isolated – almost no assistance available; risks taken to meet with passing ships	Thrust into public eye; probing journalists and researchers; experienced crime; kept a degree of marginalisation as lived together on an army base.	Declining self-sufficiency
Infrastructure & Resources	R	Arrival of shipwrecked sailors with carpentry skills led to building of longboats; WW2 onwards – construction of modern amenities, including sanitation, school, wireless station, store, hospital (1942–46); technical & agricultural improvements; canning factory built (1949)	*N/A*	Improved roads and buildings; new fishing factory built (2009); underground cabling installed (2013)
	V	Gradual reduction in traditional methods		Frequent repair of only harbour (ongoing); most buildings vulnerable to seismic activity; one route out of Settlement; reliance on modern equipment; sub-optimal hospital facilities
Communications	R	Increasing links with outside world	Rapid introduction to modernism	Good links with outside world; cheap telephony (2006); television (2001); wireless internet (2009); uptake of social media (2011)
	V	Effectively cut-off from the outside world from 1817 to WW2		Reduction in community interaction
Migration	R	Arrival of "shipwrecked" sailors who brought new knowledge, techniques and expertise (e.g. longboat building)	11 of 264 islanders stayed in the UK following the evacuation	Earnings comparatively low (to Europe and S.Africa) therefore limited options for emigration; not possible to gain formal qualifications on-island; scheme in place for further education off-island (all seen as both a vulnerability [entitlements] but also resilience [retaining & honing capacity]
	V	Mass out-migration from 1890 – population of just 50 in 1892 – community almost deemed unsustainable.		

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Table 3. Description and evaluation of communication strategies employed on Tristan da Cunha.

	Exercise	Involvement and Uptake	Response and Feedback	Adaptation
A	Overview of eruptive history and transparent discussion of uncertainty	Twelve island council members; Island Administrator; Disaster Management (DM) Co-ordinator	(i) Group reflection of difficulties involved in eruption forecasting under uncertain conditions (ii) Concerns raised about having to wait for signs of volcanic unrest (if at all) before refining of scientific opinion (iii) Realisation of the importance of on-island preparedness (iv) Initiation and design of evacuation exercise (v) Commitment to scenario planning exercise	(i) Update of DM plan
B	Town Hall (summarised and tailored version of (A); Discussion of evacuation exercise	Community members (~55% attendance)	(i) No questions raised about volcanic hazards and risk (ii) Instead, meeting provided a platform for community to raise questions about evacuation drill (iii) Sense of misunderstanding and resistance about the rationale for building a DM centre	(i) Preparation of personal emergency supply kits
C	Evacuation exercise	Community members (95% attendance)	(i) Feedback largely positive (ii) Minority voiced dissatisfaction and failed to understand its purpose (not aided by incompletion of DM centre build) (iii) Drill highlighted a number of defects in the evacuation plan	(i) Significant improvements to evacuation drill (ii) Alteration and clarification of roles (iii) Desire to repeat drill annually
D	School outreach initiatives (2x earth science lessons (including BGS School Seismometer project); 2x island field trips; documentary film project)	Twelve pupils from St Mary's School; Education Adviser	(i) High level of engagement; although challenging to extract feedback (ii) Regular inspection of helicorder data (iii) Other interested islanders present for visit to 1961 dome (field trip 1 of 2) (iv) Students involved in data collection (fumarole observations and temperature measurements) (v) Filmed interviews arranged (by students) with four elderly islanders	(i) Alterations to school curriculum to include geophysical hazards and disaster risk reduction themes, and new data about the eruptive history for the "Tristan Studies" module
E	Scenario planning exercise	Eight island council members; Island Administrator; Disaster Management Co-ordinator	(i) Brief initial hesitation of voicing opinions (Island Administrator obliged to dominate conversation) (ii) Desire to reduce scientific uncertainty (iii) Recommendation to provide and support effective early warnings by real-time monitoring (deployment of further equipment required e.g. seismometer array and strain-meters) (iv) Realisation of importance of increasing on-island capability (v) Recommendations for protocol amendments, infrastructure and resource improvements	(i) Design changes to DM centre (ii) Alterations to DM plan (particularly clarification of roles) (iii) Addition of scenario planning exercise to decision making processes (iv) Active exploration of Nightingale Island as possible evacuation site (desalinisation solutions) (v) Plan to repeat evacuation exercise (altering scenario)
F	One-to-one conversations with islanders	~60% of community members	(i) Gratitude for contact (ii) Appreciation for individual-level communication – felt able to ask questions and voice opinions freely	(i) Preparation of personal emergency supply kits
G	Bi-annual meetings with officials at the Foreign & Commonwealth Office	Tristan da Cunha & Pitcairn Desk Officer(s); FCO Adviser; PhD supervisory team (including Head of Volcanology at the British Geological Survey)	(i) Discussion of plans for DM improvements; building DM centre (ii) Request for report summarising research findings, plus recommendations (iii) Support of new collaborative project between volcanic risk and economics researchers, FCO and Tristan government (recently funded)	(i) Temporary lengthening of DM Co-ordinator contract to 2012 (ii) Volcanic risk put into long term planning for island

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Table 4. Eight scenarios presented for deliberation at the planning workshop. Each scenario has a relative risk level which 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. Volcanological terminology (e.g. scoria cone) were introduced at the first council meeting. Use of the term "the volcano" was used to reflect locally accepted terminology for the 1961–62 eruption, and just "volcano" for an eruption. Chosen scenarios to "play out" are in italics.

Dome growth and lava flows just to the west of the volcano. Preceded by 2 month of earthquakes (repeat of 1961)	MEDIUM
Six hours of earthquakes followed by a submarine eruption. Pumice seen to west of the Settlement (repeat of 2004)	LOW
Scoria cone growth on the Base above the Settlement, subsequent breaching by lava flow. No earthquake warning.	MEDIUM
Maar formation (large explosions that form deep craters like the Ponds) on the Base near Big Gulch. No warning.	MEDIUM
Dome growth and lava flows near the Caves. Earthquakes only felt by those in the South.	LOW
Large, explosive eruptions from the summit; volcanic bombs reaching the edge of the Base. Ash clouds erupted and some ground collapse. Two weeks of earthquakes leading up to event.	*HIGH*
Scoria cone growth near Hillpiece, erupted without warning	*MEDIUM*
Four months of earthquakes felt at the Settlement, but volcano never breaks the surface	*LOW*

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Table 5. Scenarios chosen for discussion. Stages of each scenario are outlined (separations indicate pauses for discussion). Questions and a list of considerations, discussed at each stage, are summarised.

Scenario summary	Stage	Question prompts (each scenario; each stage)
Four months of earthquakes felt at the Settlement, but a volcano never breaks the surface (Low risk).	It is a normal working day, earthquake is felt in the village and objects move on desks and shelves	What is the general response? What is the Administrator's response?
	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.	Considerations: – Mobilising outside help – Bad weather/seas – Building damage (Factory; residential and non-residential)
	The earthquakes suddenly come to a complete stop, none are felt again and no volcano breaks the surface	– Hospital patients? How to care for/move? – Health and injuries (particularly agitated asthma and arthritis)
Scoria cone growth near Hillpiece, erupted without warning (Medium risk).	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.	– Harbour damage – Damaged water supply – Road washout – Dealing with media – Contact with family and friends outside of Tristan
	The eruption continues for the next week and a volcanic mound is built almost 40 m in height. Ash and rock is blown towards the Settlement.	– Insufficient time to bring out scientist(s) – No ship due for at least one month – Insurance – Effects of volcanic activity
Explosive eruption from summit, with volcanic bombs (rocks) reaching the edge of the Base. Ash clouds erupted and ground collapse occurs. Two weeks of earthquakes (High risk).	Earthquakes increase in intensity and frequency for the next two weeks and can be felt all over the island. Rockfalls cause damage to homes and the roads begin to crack and buckle.	on flora and fauna – Vehicles required to aid evacuation – Machinery availability – Boat mobilisation – Ship arrivals – Animal care – People in different places around the island (e.g. patches)

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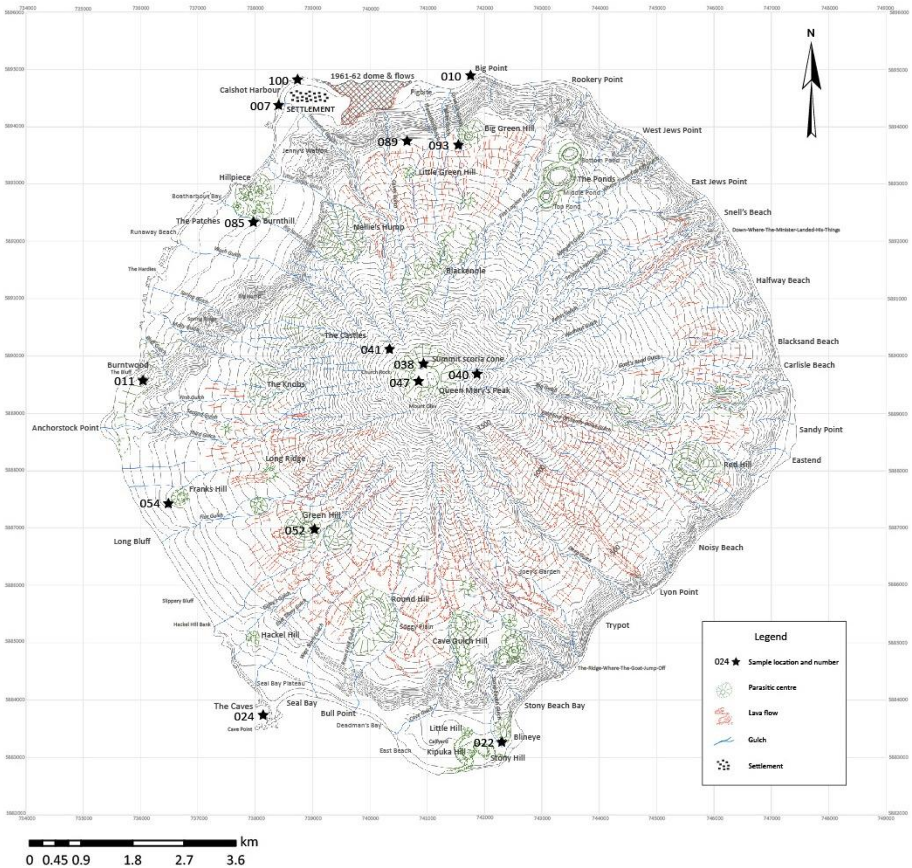

Fig. 1. Map of Tristan da Cunha including sampling sites for $^{40}Ar/^{39}Ar$ dating. The Settlement is located in the North of the island. (Modified from Dunkley, 2002.)

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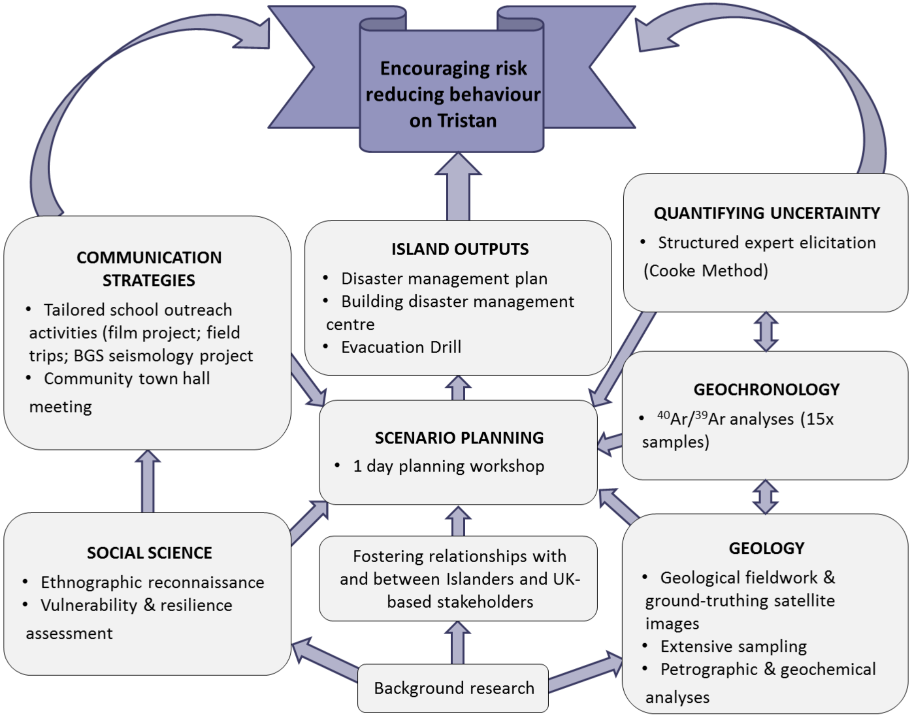

Fig. 2. Schematic of interdisciplinary research components. The data gathering phase involved collecting geological, geochronological, probabilistic and social information. This data then informed the action research phase, manifest as a scenario planning workshop.

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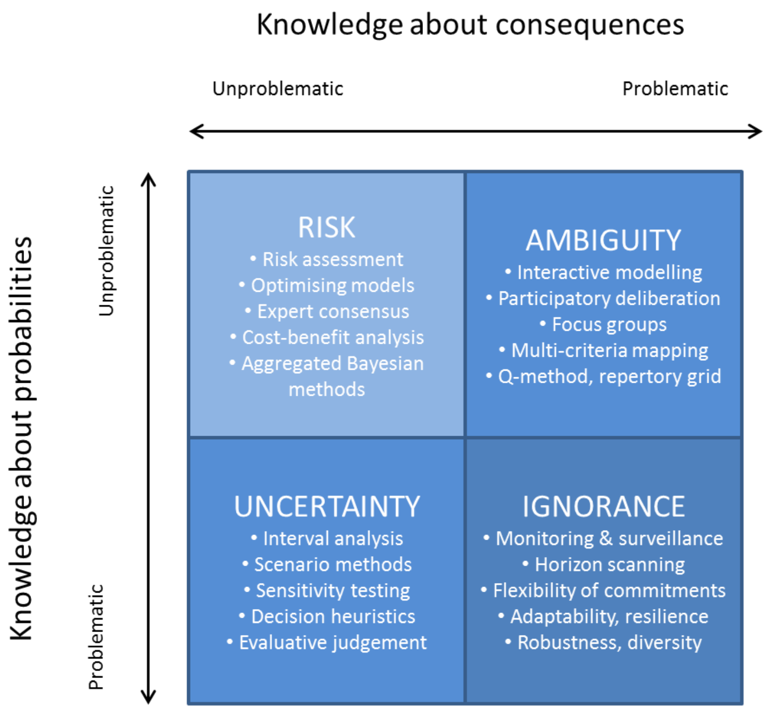

Fig. 3. Methodological options for different epistemic conditions. Axes distinguish ways in which knowledge about risk may be incomplete and refer to the challenge posed by each category of incertitude for classical scientific approaches. For example, while quantification of uncertainty may be a useful tool when consequences are understood and there is good basis for assigning probabilities, it may have little relevance in situations that are characterized by ambiguity and ignorance. Adapted from Stirling (2010).

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