Volcanoes on borders: a scientific and (geo)political challenge

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Abstract

While the scientific community readily collaborates across international borders, the boundaries of administrative units—particularly the nation-state—can be critical in defining the availability of scientific resources, the management of crises and the use of land. Managing border eruptions can be particularly challenging when international relations between the relevant nation-states are strained or complex or when political agendas become involved. Given that over 700 volcanoes lie within 100 km of an international border, and over 1300 are within 250 km, the potential for cross-border eruption impacts is significant. This paper aims to provide an overview of the topic. It presents results from a global study of volcanoes on or near borders and uses five case studies to highlight key issues that arise in the management of risk at such volcanoes. While volcano monitoring provides critical support for hazard assessment and decision-making, its availability depends on the policies of particular governments and institutions. Furthermore, the complexity and diversity of volcanic hazards, activity and impacts can exacerbate existing cross-border inequalities in vulnerabilities, in scientific resources, in disaster management and mitigation capacity and indeed public awareness. We suggest that pre-crisis planning and communication, resource sharing and international agreements can help to mitigate the challenges of cross-border eruptions.

Keywords Transboundary crises · Volcanic risk · Science and policy · Borders

Introduction

The United Nations International Strategy for Disaster Reduction (UNISDR), which is the responsible agency for disaster risk reduction within the UN (though not the only agency involved), is currently working towards implementing the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR). The SFDRR was ratified by the UN member states in March 2015 and calls, in particular, for a stronger role for science in disaster risk reduction (Murray et al., 2015). It also identifies four spatial scales for disaster risk reduction (DRR): local, national, regional and international. While there are specific targets at each scale, critical aspects of the latter two concern resource-sharing and coordination across inter-

national borders—something identified as a challenge in disaster risk reduction (Lidskog et al. 2009). This paper considers the particular challenge of cross-border eruptions.

Volcanic eruptions have highly localised sources but national, regional (taken in this paper to mean involving multiple nation-states in spatial proximity, as in the SFDRR) and international consequences. They are complex and multiscalar, multihazard events that require consistent approaches to the management of associated risks. This paper uses a complex vision of scale: scale is not purely geographical or spatial but political and constructed (Brenner 2001; Marston 2000). Thus, while we consider border volcanoes most generally as those that are close to an international border for the purposes of our global survey, we also consider special cases in which there are vertical borders (between levels of governance in a colonial system or between a centralised institution and observatories, as in the French case). Colonial or remote governance is a particular case in which large geographical distances may be involved, but politics are proximal: decisions are made at great distance from their intensely local implications and that distance may be cultural and political as well as geographical (Bulkeley 2005; Delaney and Leitner 1997;

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Marston et al. 2005; McConnell and Dittmer 2018). We have therefore included a case study that allows us to draw some conclusions about such complex cases (referred to as “externally governed”) in which there is a degree of vertical governance (in this case, the UK governance of Montserrat, with input from the Montserratian government but in a hierarchical relationship). Finally, we have included consideration of multiscale interactions between human networks (such as trade) and volcanic activity (Boin et al. 2013; Kuipers and Boin 2015). These include the issues for shipping and for aviation (Alemanno 2011). This again is a complex view of scale (because ships and aeroplanes may be owned at large distances from volcanoes), but it also inherently involves the negotiation of international borders (Alemanno 2011; Boin and Rhinard 2008).

Politics is an inherent part of managing a transborder crisis (Alemanno 2011). “Geopolitics” refers, in the broadest sense, to geographical influences on political processes and international relationships and how these things are imagined and represented. Practical geopolitics is performed by nation-states as they interact. The study of geopolitics in geography analyses these interactions in their cultural, historical and socio-economic contexts, thinking critically about the ways in which powers position themselves (Dalby 1991; Dalby 2007). This can include the management of resources and the ways in which governments create security (Elden 2013; Kama 2016; Le Billon 2017) and can also be expressed in individual citizens’ experiences as they are derived from much wider geopolitical activities (Dixon 2016; Massaro and Williams 2013). In volcanic crises, citizens’ experiences of volcanic activity can become the defining factor of their lives for a period, and managing the impacts of eruptions is therefore important socially as well as economically. Furthermore, the material environment contributes to the making of politics in an enhanced way in volcanic crises, as governments struggle to manage a risk that is rarely on the policy agenda and as scientists seek to support them in that—often as the landscape itself is reconfigured by volcanic processes (Bobbette and Donovan 2018).

The interaction between politics and the timeframe of volcanic risk management and of eruptions themselves can be complex: often there is little planning prior to a crisis, and longer-term planning tends to be reactive, not least because the rarity of eruptions means that political actors in office for 4 years rarely consider volcanic risk as a priority (Donovan 2019; Tilling 2008). Temporally, we consider both crises and long-term management of volcanic risk in this paper (Coppola 2006). While volcanic crises provide particular critical moments in transborder contexts, the longer-term management of volcanic risk is integral too (Casadevall 1994; Kelman and Mather 2008; Mercer and Kelman 2010; Prata 2009). The management of a crisis itself depends upon longer-term scientific, societal and land use decisions and processes—

such as the establishment of monitoring networks and contingency plans and the decisions that are made about population centres and industries around the volcano (Tilling 2008).

In terms of disaster response more broadly, several institutions function at a global level. The UN Office for the Coordination of Humanitarian Affairs (UNOCHA) is responsible for ensuring that aid reaches affected areas promptly and that aid agencies do not duplicate efforts—and it can liaise with multiple governments (Coppola 2006). The World Meteorological Organisation (WMO) fulfils an intergovernmental role in providing scientific and technical support in climate-related disasters (Auld 2008). It has a strong interest in multihazard early warning systems but strongly focusses on hydrometeorological events (Zschau and Küppers 2013). For volcanological scientific advice, however, there is no obvious international agency to coordinate cross-border eruptive crises (with the exception of aviation hazard, where international cooperation is well established (Tupper et al. 2007)).

This paper offers an overview of challenges that surround volcanoes on or close to international borders. It considers volcanic crises in particular but also deals with long-term management challenges, including the establishment of effective monitoring networks and the management of volcanic areas. The management of volcanic risk in general involves diverse boundary crossings, including between disciplines, policy domains (such as air quality/health, civil defence, tourism and mining) and between institutions (such as the mandates of geological surveys and civil protection institutions). Terminology in this paper will follow the conventions of geopolitics and political geography (for an introduction to political geography, see Painter and Jeffrey (2009); see also Agnew (2004); Agnew and Muscarà (2012)). Sovereign countries will be referred to as nations or nation-states. Groups of nation-states that are spatially close to each other (such as Western Europe, Latin America) will be referred to as regions. Territories that remain controlled by another power in a colonial or remotely governed configuration will be referred to as “externally governed”.

Transboundary crises

Transboundary environmental disasters are relatively common, including, for example, nuclear accidents, disease outbreaks and major hurricanes (Boin and Egan 2012; Dhama et al. 2015; Hindmarsh 2013; Otte et al. 2004). Mitigation of risk associated with most of these events, however, falls within the remit of national hazard assessments, international bodies like the World Health Organisation (WHO) or industry-defined standards: they are widely recognised as having the potential for international impact (see Lidskog et al. (2009) for a review). In the case of most environmental hazards (such as hurricanes or tsunamis), the monitoring of the

hazard is done publicly and is visible, either through regional centres such as the Pacific Tsunami Warning Centre (Titov et al. 2005) or through national meteorological agencies using satellite meteorological products (Rappaport et al. 2009). For disease, there are international regulations and assessments that are coordinated by WHO (Fidler 2001).

Ansell et al. (2010) identify three key dimensions for transboundary crises: transgression of political boundaries (either horizontal—in the case of international borders—or vertical—in the case of escalation from local to regional to national, for example); the transgression of “functional” boundaries, which refer to policy areas (such as a crisis that affects both transport and health sectors); and the transgression of temporal boundaries (such as a crisis that has differential impacts on different time scales—for example, an eruption whose deposits are remobilised by rainfall for many years after the end of the eruption itself). An individual crisis may be characterised by one or more of these dimensions. In crises where there is significant dependence on multidisciplinary scientific information—as is the case for environmental hazard events—a fourth dimension might be transdisciplinary working (where transdisciplinary involves working not only across disciplines but between scientific, political and civil society organisations and knowledges). Most larger volcanic eruptions would classify as transboundary in their effects in crossing functional, temporal and these latter epistemic boundaries (summarised in Fig. 1). This paper considers the particular cases that also cross jurisdictional boundaries.

Wider literature on managing transboundary hazards and associated disasters considers disaster cascades and the issues around networked risk in a globalised world (Galaz et al. 2017; Olsson 2015). A disaster cascade occurs when a hazard event triggers or influences subsequent hazards or interacts with vulnerability in a way that exacerbates it and leads to another disaster; they may be linear or non-linear (Pescaroli and Alexander 2015). Thus, a hazard event in one region that

affects a critical supply chain might trigger a food shortage in another region that is heavily dependent on the supply chain. Such disasters are thus dependent on complex interactions between the human and the physical aspects of disaster and are products of a globalised world (Donovan 2016; Pescaroli and Alexander 2016; Sapat and Esnard 2013). Examples of crises that might qualify also include anthropogenic or natural-technological crises, such as the Bovine Spongiform Encephalopathy (BSE) crisis, the Chernobyl incident and Fukushima (‘t Hart 2013; Beck 1992; Hinchliffe 2001).

The European Union (EU) has experienced a number of transboundary crises (Boin et al. 2014b). It has subsequently set up a number of regulatory and organisational bodies to attempt to manage such crises, including the European Aviation Crisis Coordination Cell (EACCC) in 2010, the EU Crisis Coordination Arrangements in 2005 and various other agency-specific institutions (Boin et al. 2014a; Boin et al. 2013; Boin and Rhinard 2008; Boin et al. 2014b; Kuipers and Boin 2015). These institutions form a network model, which is an unusual form of crisis response—most nation-states take a “lead agency” approach, as in the UK (Donovan and Oppenheimer 2012). Network approaches have several advantages, particularly because they involve multiple agencies and therefore have large capacity for diverse kinds of expertise (Boin et al. 2014a). However, they may also struggle in international spaces because of clashes with sovereignty over resources at nation-state level. In general, there is no universal consensus over which kind of model works best for the coordination of transboundary crises: network approaches and lead agency approaches have advantages and disadvantages, and the best approach to managing crises may be dependent on the specific characteristics and “boundaries” of the individual crisis (Boin et al. 2013; Boin and Lodge 2016; Galaz et al. 2017).

Research on these wider cases suggests that there are several stages in crisis management that can be challenging in

Boundary types	Political boundaries	Functional boundaries	Disciplinary/epistemic boundaries	Temporal boundaries
	Boundaries between nation states Boundaries between provinces Vertical boundaries – local/provincial/national	Boundaries between policy areas: transport, geology and mines, interior, healthcare, agriculture, air quality	Scientific: seismics, geochemistry, social... Decision-making Emergency response	Syn-eruption hazards; post-eruption hazards; long-term community impacts, restructuring, recovery
Issues arising	Legitimacy; data sharing; communication; coordination; institutions	Communication; coordination; leadership; disparate capacities	Communication; expertise; legitimacy; roles/remits	Long-term management; crisis response; surge capacity; mobilisation

Fig. 1 Summary of boundary types discussed in the text, building on Ansell et al. (2010)

transboundary cases (Ansell et al. 2010); sense-making (the need for authorities to understand the situation and its needs); surge capacity (the ability to manage a surge in demand for services); coordination capacity (networked or lead agency); and boundary-spanning protocols (to ensure that decisions are taken at appropriate levels). Public communication in different contexts and at different scales is a further and considerable challenge (Olsson 2013; Olsson 2015). In volcanic crises, these issues largely affect civil protection institutions and the designated scientific bodies (De la Cruz-Reyna and Tilling 2008; Fearnley et al. 2018; Solana et al. 2008; Surono et al. 2012).

The volcanic case

The impacts of volcanic eruptions can readily cross international borders, particularly for volcanoes situated close to frontiers and in respect of ash hazard (and tsunami triggered by volcanic activity). Ash clouds and associated fallout can impact airspace, the built and rural environments more than 100 km from source (Blong 2013; Guffanti and Tupper 2014; Wilson et al. 2012). Volcanic ash from large magnitude explosive eruptions has been found at great distances from the source—for example, ash from the 946 CE eruption of Mount Paektu (China/Democratic People's Republic of Korea (DPRK)) is found in Hokkaido, Japan (Horn and Schmincke 2000) and ash from the 39,000-year BP eruption of Campi Flegrei (Italy) extends across Asia Minor (Giaccio et al. 2008). Ash clouds can pose a threat to aircraft in flight and result in global disruption of civil aviation. While the aviation sector has developed clear if evolving protocols for dealing with volcanic ash clouds (Tupper et al. 2007), international cooperation in other aspects of volcanic risk management is patchy. This has been exposed repeatedly during past eruptions, including those of Nabro (Eritrea, 2011) (Goitom et al. 2015), Chaitén (Chile, 2008) (Major and Lara 2013), Puyehue-Cordón Caulle (Chile, 2011–2012) (Elissondo et al. 2015) and Calbuco (Chile, 2015)—and in episodes of volcanic unrest (that have not yet culminated in eruption), such as experienced at Mount Paektu (2002–2005), and Cerro Negro (Nicaragua, 2015).

This paper draws on five case studies to elucidate the risk management challenges posed by transboundary volcanoes and volcanic crises for scientists and for governments. It takes a mixed-method approach, including interviews and participant observation. It seeks to document and analyse the challenge of managing transborder volcanic crises, based on evidence from a diverse range of settings, and to suggest approaches for dealing with such crises.

Methods

This study uses a range of quantitative and qualitative methods. The initial survey of border volcanoes used the Large Magnitude Eruptions (LaMEVE) database (Croswell et al. 2012), which includes larger magnitude eruptions from the Quaternary period and a Geographical Information System (GIS) to identify Quaternary volcanoes within 25, 100 and 250 km of international borders. This was then combined with the Global Volcanism Programme (GVP) database to extract additional information about volcanoes that have evidence of Holocene activity and ensure that all GVP volcanoes are also represented. Once the relevant volcanoes were identified, they were studied in more detail to identify the most challenging and potentially high risk (particularly those with Holocene activity or unrest and in the presence of large populations). Note that only volcanoes close to land borders were considered—maritime borders were ignored for the GIS assessment but are discussed below. Population data were obtained from the European Commission Joint Research Centre Global Human Settlement population grid (JRC 2015).

A multimethod approach was used to analyse five case studies of volcanoes or eruptions with geopolitical or international impact (Creswell and Clark 2007). Interviews and focus groups involving scientists, local officials and members of the public were also used in case study locations (Argentina, Chile, China, DPRK, Montserrat, Iceland and the UK). Other interviews were conducted at international conferences or via Skype (Eritrea and Ethiopia). All but two interviews were conducted by AD; the others were conducted by CO.

Interviews were semi-structured and lasted from 30 min to 2 h. The questions were tailored for particular groups. Scientists and local officials were asked about their own institutional structures and mandates, their impressions of the institutional frameworks for volcanic risk management in neighbouring countries, their experiences of past volcanic crises or challenges around the management of the volcano, their views about local populations on each side of the border and their views on the particular scientific and technical problems around volcanoes close to borders. Members of the public were asked about their experience of recent volcanic crises (the management, availability of information, evacuations), their views about volcanic risk from volcanoes in their own and neighbouring countries, their trust in authorities and the information that they receive and their impressions of the effect of the border in the management of the volcanic areas. Interviews were transcribed and coded thematically. Ethnographic research was also carried out in case study locations. Ethnography involves detailed note-taking and observations, alongside interviews and documentary analysis (Bryman 2015).

Transcripts, ethnographic field notes and documents were coded in NVivo (a computer programme designed for the coding of qualitative data, widely used in the social sciences) using a grounded theory approach (Strauss and Corbin 1997). In this approach, the thematic codes, based on the content of the data (topics), are developed sequentially in a first-pass over the data, so that the themes are generated by the data themselves. A second pass is then taken over the data in order to ensure that the codes are universally applied throughout the dataset. Finally, the quotations in each code are examined to look for patterns, contradictions, information and controversies. These are then summarised in the text in the “Results” section, and quotations are used for illustration where appropriate. Details are given about interviewees to the highest level possible to preserve anonymity, in accordance with the ethics assessment undertaken for the project. In total, over 100 interviews were undertaken. These break down by case study as shown in Table 1. In the text below, some interviews are quoted directly. In other cases, responses are paraphrased to save space.

Unless otherwise indicated, information in the case study sections is derived from interviews, via the coding methods described above. Where information is factual, it has been triangulated using other methods (Table 1). The “lessons learned” sections in the case study reports analyse interview data in the wider context of the literature and infer some conclusions from the case study, as determined from the interviews, ethnography and documentary analysis.

Results

Overview of border volcanoes

The GIS exercise found 325 LaMEVE volcanoes within 25 km of an international border, 770 within 100 km and 1297 within 250 km (Fig. 2). Of the volcanoes in

the Smithsonian database (Siebert and Simkin 1994), 109 lie within 25 km of an international border. The majority of these volcanoes are in Latin America, with a number also in Africa. There are also some in Europe, North America and Asia. Those identified as having exposed populations and possible Holocene activity are shown in Table 2. The full list is available as supplementary data.

Table 2 and Fig. 2 illustrate that numerous volcanoes lie on or close to international borders and lie close to sizeable populations. The majority are in parts of East Africa (along both branches of the Rift Valley and in the Afar Region) and Latin America that are experiencing rapid population growth. Several are also in areas of recent or ongoing conflict or tension, including along the Ethiopia-Eritrea border and the border of DPRK. Several of the border volcanoes with the highest populations are around the Democratic Republic (DR) of the Congo-Uganda-Rwanda region (the Virunga Mountains and Western Branch of the East African Rift System), where long-term conflict and poverty create particular challenges (Baxter et al. 2003).

It is clear from this analysis that countries across Africa and Latin America are likely to be impacted in the event of eruptions occurring in neighbouring countries. In some cases, these may affect populations of over a million.

Large-scale transboundary issues

This section briefly discusses two specific transboundary challenges: volcanic threats to aviation and maritime activities. These are important because they raise several key issues that cut across the later case studies—particularly around resourcing for volcano monitoring. The paper then considers specific case studies.

Table 1 Summary of the qualitative methods used in this analysis

Case study	Elite interviews	Other methods used
Puyehue-Cordon Caulle	20 scientists, 9 officials	Ethnography, resident interviews and focus groups, documentary analysis (reports about the eruption, news about international agreements)
Nabro	8 scientists	Documentary analysis (development sector reports, news from media organisations)
Paektu/Changbaishan	12 scientists	Ethnography
Iceland-UK	12 scientists, 6 officials	Ethnography, resident interviews, documentary analysis (government and EU agency reports)
Montserrat	21 scientists, 7 officials	Ethnography, resident interviews, documentary analysis (government reports)
Other international	10 scientists, 3 officials	Documentary analysis (agency reports and legal documents)

Fig. 2 Results of global survey of border volcanoes. Red volcanoes are within 25 km, orange within 100 km and yellow within 250 km of an international border. Panel **a** draws on the entire Large Magnitude Eruptions database, while panel **b** shows those with Holocene eruptions (GVP) only

Aviation

The only global system for volcanic hazard warnings applies to aviation, via the volcanic ash advisory centres (VAACs).

This networked system, the International Aviation Volcano Watch (IAVW), was developed in 1993 through the WMO, the International Civil Aviation Organisation (ICAO) and the airlines (Guffanti and Tupper 2014). The volcano

Table 2 Holocene (GVP) volcanoes within 25 km of a border and with > 10,000 people living within 10 km, with population rounded to nearest hundred

Volcano name	Country/countries	Population 10 km	Population 25 km	Population 100 km	Activity evidence	Last known eruption
Muhavura	Uganda-Rwanda (DRC)	201,200	947,000	1,184,800	Evidence Credible	Unknown
Apaneca Range	El Salvador (Guatemala)	160,900	787,400	226,000	Evidence Credible	Unknown
Nyiragongo*	DR Congo (Rwanda, Uganda)	143,300	1,767,500	5,861,200	Eruption Observed	2017 CE
Fort Portal	Uganda (DRC)	146,800	542,200	2,453,300	Eruption Dated	2120 BCE
Bufumbira	Uganda (Rwanda, DRC)	135,500	623,100	10,302,000	Evidence Uncertain	Unknown
Tajumulco	Guatemala (Mexico)	101,800	747,500	6,602,300	Evidence Credible	Unknown
Karisimbi*	DRC-Rwanda (Uganda)	90,800	866,500	2,552,000	Eruption Dated	8050 BCE
San Diego	El Salvador-Guatemala	58,000	156,900	7,423,200	Evidence Credible	Unknown
Olot Volcanic Field	Spain (France)	49,000	118,500	6,261,700	Evidence Credible	Unknown
Chingo	Guatemala-El Salvador	51,000	696,100	6,820,400	Evidence Credible	Unknown
Visoke	DRC-Rwanda (Uganda)	47,600	825,900	10,522,000	Eruption Observed	1957 CE
Suchitan	Guatemala (El Salvador)	48,900	294,300	8,216,200	Evidence Credible	Unknown
Tshibinda	DR Congo (Rwanda, Burundi)	41,400	1,059,700	7,898,200	Evidence Credible	Unknown
Dallol*	Ethiopia (Eritrea)	42,440	42,440	1,055,500	Eruption Observed	2011 CE
Quezaltepeque	Guatemala (Honduras, El Salvador)	38,100	215,200	3,542,100	Evidence Credible	Unknown
Kilimanjaro	Tanzania (Kenya)	35,600	369,000	3,286,900	Evidence Credible	Unknown
Paektu/Changbaishan*	China-DPR Korea	33,300	37,400	1,552,200	Eruption Observed	1903 CE
Tacana	Mexico-Guatemala	32,700	426,900	6,420,400	Eruption Observed	1986 CE
Ipala	Guatemala (El Salvador, Honduras)	27,000	193,500	6,811,000	Evidence Credible	Unknown
Cumbal	Colombia (Ecuador)	23,300	146,200	164,400	Eruption Observed	1926 CE
Moyuta	Guatemala (El Salvador)	25,200	223,200	4,138,000	Evidence Credible	Unknown
Liamuiga	Saint Kitts and Nevis (Dutch Antilles)	22,400	44,600	173,300	Eruption Dated	160 CE
Santa Ana	El Salvador (Guatemala)	21,000	1,043,800	6,206,300	Eruption Observed	2005 CE
Ch'uga-ryong*	DPRK-South Korea	20,000	181,100	14,256,600	Evidence Uncertain	Unknown
Ixtepeque	Guatemala (Honduras, El Salvador)	16,600	222,200	6,849,200	Evidence Credible	Unknown
Kazbek*	Georgia (Russia)	13,300	336,000	6,054,200	Eruption Dated	750 BCE
Bombalai	Malaysia (Philippines)	11,400	423,100	1,048,500	Evidence Uncertain	Unknown
Nabro*	Eritrea (Ethiopia)	10,000	18,100	56,300	Eruption Observed	2012 CE

Evidence for Holocene eruptions and last known eruption dates (taken from the Smithsonian Institution Global Volcanism Network database; Siebert and Simkin (1994)) are also indicated. Nation-states in bold outside the brackets indicate volcano location; bracketed ones are those nearby. Asterisks by the volcano name indicate that the border is either contested or in a region of conflict or tension. Population data are from the JRC database as noted in the methods

observatories contact the Meteorological Watch Office in their nation with a warning about ash (a Volcano Observatory Notice to Aviation, VONA). The Watch Office then alerts the relevant VAAC and the VAAC runs atmospheric dispersion models (Guffanti and Tupper 2014; Neal et al. 2009; Simpson et al. 2002). The Watch Office then issues a warning—a SIGMET—for aviation (Guffanti and Tupper 2014). A critical issue with this is touched on by the following interviewee:

“So if there is a Volcano Observatory and if they happen to receive any information about the eruption then they may—if the communication circuits work and they're not too busy—get that information to somebody who might understand it and transmit it. And then if the Volcanic Ash Advisory Centre receives that information, and they can see the eruption on satellite and it's not covered by cloud, then they'll get a decent product back and then maybe the country concerned will put out a warning which might be received by the aircraft involved”. (*Scientist 5, September 2013*)

These processes are thus dependent on the presence of volcano observatories and their ability to fund this work, on the constraints and operational capacity of the Meteorological Offices and on communication systems. More recently, efforts have been made to put more onus on the VAACs themselves—not least because of the regional, rather than national, aspect of the hazard. This also allows the better resourced institutions to take the lead, and ash clouds are often detected by Meteorological Offices where volcano observatories do not exist. However, there are still fundamental uncertainties within the science pertaining to eruptive source conditions, physical processes controlling the evolution of volcanic plumes, atmospheric dispersion modelling and ash observations from the ground, air or space (Bonadonna 2006; Bonadonna et al. 2015)—and different VAACs use different models.

Annex 3 to the Convention on Civil Aviation deals with the responsibilities of nations to monitor volcanoes:

“... what it originally said was something like if there's a volcano report it will be passed on ... And since then we've had all these discoveries about what the real world is like ... And long debates about the nature of power if you like and of the power of the volcanologists to change that within the States concerned. So obviously typically the poorly resourced observatories are in the poorly resourced States. So we are limited in what we can do but we did strengthen the wording in the requirement to read that States with active or potentially active volcanoes shall arrange that selected State volcano ... and surrounding countries are encouraged to help

basically, we can't make you but please look after your neighbour or if you're in the UK then please look after Montserrat and so on. (*Scientist 5, September 2013*)

These efforts are still underway and are challenged by resource imbalances between nations as well as by the nature of international-level bureaucracy: wordings have to be agreed by all of the nation-states concerned, as with UN documents like the Sendai Framework, and this can lead to very vague recommendations, particularly where powerful states dominate the discourse. Indeed, UN organisations can be challenging to deal with because they involve a great deal of diplomacy, and the funding source for these projects is not clear. In order to facilitate the funding of volcano monitoring in developing countries, ICAO has put in place a procedure for nation-states to claim costing for volcano monitoring from airlines. Landing or overflight charges can be levied, and individual claimants can then allocate these to volcano observatories at their discretion—but this does depend on them using that discretion.

An interesting aspect of this encounter between meteorological institutions and those of volcanology is the operational difference. While volcanologists deal with rare events, it is “relatively easy” for meteorologists to get the attention of government (Johnson et al. 2005)—see also the media frenzy around extreme weather events, from the October 1987 UK windstorm (Morris and Gadd 1988) to Hurricane Katrina (Fleetwood 2006). Interviewees noted that engaging governments (and thus obtaining funding) with volcanoes is challenging unless something is very obviously happening—which it usually is not. This issue is compounded by the need to maintain the funding for long periods of time—such that providing instruments for a 5-year research project will not fulfil the volcano monitoring needs in the long term. These issues continue to be challenging for the entire volcanology community. Interviewees throughout the project in all case study regions mentioned this challenge. One suggestion was for outside researchers from developed or better resourced nations to fund instruments, with in-country agencies agreeing to maintain the instruments beyond the initial project. Indeed, one scientist commented concerning the 2002 eruption of Nyiragongo (DR Congo):

“When I went there in 2002 I was amazed to learn that their scientists had not been paid salary for something like two years, I forget the exact number, but it was a long time. And I asked them ‘Well how did you survive?’ and they said ‘We grow vegetables.’ But they were there maintaining the monitoring, they were watching the instruments, it was remarkable dedication”. (*Scientist 8, January 2014*)

A final challenge in the aviation context is the funding issue between nations: “How much sympathy would you have in a developing country for rich people in planes?” (scientist 8, January 2014). Improving cost recovery and equality is possible in the aviation sector—costs can be recovered from airlines, as noted above, but political will has to exist to redistribute the money. One scientist commented,

“... in the case of Indonesia I think if Garuda Airlines and maybe the other Indonesian airlines were to force the issue and say ‘Look we’re all very concerned about this, it’s not just the Aussies, but we ourselves are concerned about it’, then it would help the Indonesian Government to act on it”. (*Scientist 5, September 2013*)

This demonstrates the complexity of these challenges at the science-policy interface: there are geopolitical concerns, development concerns and economic issues that collide when trying to negotiate an increase in volcano monitoring infrastructure and capacity, as noted by interviewees. All of this suggests the need for a holistic approach, in which scientists collaborate with industry and governments within their country, as well as build links with scientific partners overseas—particularly those who are willing to share resources. In Indonesia, for example, the responsible institution, Pusat Vulkanologi dan Mitigasi Bencana Geologi (PVMBG), now works closely with the Darwin VAAC and issues VONAs.

Shipping

Though volcanoes close to a sea border (i.e. the coast) were not considered in the GIS exercise, it is worth noting that there are many hundreds of such volcanoes globally. The Law of the Sea (United Nations Convention on the Law of the Sea (UNCLOS), 1982) defines a country’s “territorial waters” as 12 nautical miles (22.2 km) from the coastline at low tide. Vessels are allowed “right of innocent passage” through these waters, and nations are responsible to provide and publicise information about dangers within them. During the eruption of the Soufrière Hills Volcano on Montserrat, this took the form of “Maritime exclusion zones”, through which vessels were either not allowed or were allowed in daylight hours for transit only (no stopping), due to the threat of pyroclastic flows (that were capable of travelling across open water (Wadge and Aspinall 2014)).

The “exclusive economic zone” (EEZ) is defined as the area within 200 nautical miles of the coast. The EEZ was intended to protect the rights of states to resources within its waters; however, states must allow passage through the EEZ (though they may require identification of vessels, especially in protected areas). The EEZ, in general, falls under the laws of the High Seas, rather than any territorial laws. The issue of

territorial waters is rarely discussed or considered in volcanology and yet could potentially be important in the event of an eruption of a small island or a coastal volcano—or the disruption of a major port or seaway due to volcanic activity. For instance, the explosive eruption of Dubbi in 1861 resulted in substantial fallout of tephra across parts of the Red Sea and low visibility (Wiat and Oppenheimer 2000). This event occurred prior to opening of the Suez Canal but a similar event today could result in significant disruption to international maritime traffic in this important sea route. Eruptions such as Krakatau, 1883, similarly present a substantial hazard to maritime traffic (Winchester 2003).

Global issues: summary

The major issues that exist at a global scale for transportation (and therefore present risks to trade and food security) thus concern the need to monitor volcanoes in poorly resourced countries and to ensure adequate communication between countries concerning volcanic activity. The importance of volcano monitoring—and pre-eruption hazard assessment—cannot be understated (Tilling 2008) but is very challenging to communicate to governments. International collaborations can aid this, as noted above, but again agreements take time to ratify. The formality involved in international-scale agreements means that they are frequently very slow—as has occurred with the ICAO and WMO, discussed by interviewees. It is also the case for many of the collaborations discussed later in this paper—in many contexts, diplomatic letters have to be exchanged between agencies, governments and sometimes National Academies, in order for field visits to take place. Here, much can also be learned from the Volcano Disaster Assistance Programme (VDAP) in the USA (Pallister and Ewert 2015). An “unbreakable tenet” of the VDAP is to only work in country when invited:

“Crises are a very tricky time for the local scientists and the last thing they want are some scientists coming around that they don’t trust. So a lot of the VDAP work really consisted of trying to just help local scientists to develop their own networks and then in a time of crisis the local scientists themselves would be ready to deal with it”. (*Scientist 8, January 2014*)

The building of trust between countries can be more challenging, however. While development funding may be available—such as that from the United States Agency for International Development (USAID) to VDAP—this varies considerably and for complex reasons—interviewees discussed political challenges in obtaining funding without

particular stipulations on their activities or simply because volcanic risk is not prioritised. Additionally, there may be concerns that development funding can be deployed to increase political influence—also noted by experienced scientist interviewees.

International institutions for volcano monitoring oversight have been suggested on occasion (Donovan and Oppenheimer 2012; GVM 2014b; Loughlin et al. 2015) but never truly realised—perhaps due to a lack of funding. The aviation sector, with some important contributions from individuals, has been used to further the cause of volcano monitoring, but ultimately the political and economic circumstances of individual nations can be very limiting. The World Organisation of Volcano Observatories could potentially fill this role but would need considerably more resources than it currently has to work at the same level as an institution like the WMO. It would also require formal constitution and internationally recognised mandate—quite a formidable challenge.

Case studies

The next sections present five case studies, using qualitative data from interviews, ethnography and documentary analysis, as described in the “Methods” section. These are presented in a consistent format for ease of reading and are summarised in Table 3 at the end of the paper. Initially, the eruption or crisis is described chronologically. There is then a discussion of lessons learned for each case study. As noted above, information here is from qualitative data unless referenced otherwise.

Puyehue-Cordón Caulle: imbalanced resources between nations

Pre-eruption The 2011 eruption of Puyehue-Cordón Caulle in Chile demonstrated the importance of pre-eruption planning and investment in scientific monitoring. Chile was in the process of implementing a 5-year programme of intensive monitoring following the 2008 eruption of Chaitén volcano, while Argentina lacked infrastructure for volcano monitoring, and was dependent on information from Chile, from satellite data and from ash cloud dispersion models produced by the Buenos Aires VAAC. The two countries have different institutional structures for disaster management and scientific advice and different scientific strengths. Chile had at the time of the eruption a centralised approach for civil protection, in which operations are run from Santiago, while Argentina has a federal system of governance. This meant that while decisions were taken centrally in Chile, they were taken at municipal level in Argentina. This made it challenging for scientists and officials in Chile to know who to contact in Argentina: contact with Buenos Aires was of limited use. One scientist

from Chile commented that it was difficult to understand the multiplicity of institutions in Argentina, for example.

During the eruption In June 2011, Puyehue-Cordón Caulle erupted explosively, with an estimated VEI of 5 (Bonadonna et al. 2015). It produced a large volume of silicic tephra, much of which was rapidly transported by the wind towards Argentina (Bonadonna et al. 2015). Locally, this caused problems with structures (houses collapsing as a consequence of the ash loading), public health (volcanic ash can trigger or exacerbate respiratory conditions), agriculture (many animals were killed by heavy ashfall that caused breathing difficulties) and aviation (Bariloche airport was closed for months, and flights were grounded in Buenos Aires for several weeks). Full details of these and other impacts may be found in Elissondo et al. (2015). This was not the first Chilean eruption to impact Argentina, and recent analysis of lacustrine deposits has demonstrated the relative regularity of ash impacts in the region most badly affected by the 2011 eruption (Bertrand et al. 2008).

The eruption also produced different volcanic hazards in the two countries. Close to the vent (in Chile), ballistically ejected tephra, an obsidian lava flow threatened tourists and implications for local communities were not immediately clear in the early stages, though turned out to be minimal. Thick ashfall affected both countries acutely, but the worst effects were felt in Villa La Angostura, Argentina, due to the prevailing wind patterns, with up to 17 cm of coarse ash accumulating there in the first hours of the eruption (Wilson et al. 2013) and eventually more than 1 m of ash mantling the ground (Elissondo et al. 2015; Pistolesi et al. 2015). Communication challenges in Argentina reflected the difficulty of transferring information from the local to regional and national levels and the very limited awareness of volcanic risk prior to the eruption. There was no clear system in place for providing warnings or making decisions about volcanic eruptions in Argentina, either from scientists or from civil defence—Argentinian civil defence is optimised for other hazards such as wildfires rather than eruptions. Decisions are generally made locally by mayors, who were felt by interviewees to have been influenced by local economic concerns from the ski industry to downplay the eruption impacts.

Cross-border communication was informal, with scientists in Argentina dependent on reports from OVDAS to get information about ground-based monitoring. The Buenos Aires VAAC was engaged with ash monitoring for aviation, but there was little support on the ground. Interviewees raised the issue of alert levels in particular: while SERNAGEOMIN has volcano alert levels (red, orange, yellow and green), the Chilean civil protection alert levels (which are multihazard) only have three levels (red, yellow and green). There are no alert levels on the Argentinian side and the complexity of the levels on the Chilean side opened up the

Table 3 Summary of the case studies analysed in this paper

Case study	Puyehue-Cordón Caulle	Nabro	Paektu	Eyjafjallajökull	Soufrière hills
Reason for selection	Diverse resources between countries	Region of conflict and low development	Sensitive border	Significant impacts at regional scale	Cultural differences and colonial governance
Key agencies	SEGEMAR and NCP (Argentina); SERNAGEOMIN and ONEMI (Chile)	Eritrean Institute of Technology and Eritrean Army; Ethiopia—Afar Regional Government	CEA (China), KEB (DPRK)	IMO, UI (Iceland); Met Office, BGS (UK)	UWI (West Indies), BGS (UK), IGP (France)
Monitoring	No	No	Yes—both sides but no data sharing	Yes	Yes
Did a hazard map and/or hazard assessment exist?	The preliminary hazard map was published in 2012	No—eruptive history not known	Some attempts have been made, but without good data for the Korean side of the border, this is challenging	Yes, for local hazards in Iceland. Planning for aviation hazard done by IMO and UK Met Office (VAAC)	Wadge and Isaacs (1986)
Did alert levels exist?	Yes, in Chile, but civil defence alert levels in Chile differ from those used by OVDAS	No	No	Not at ground level - aviation system used	Many iterations during the eruptions
How were alert levels managed?	Set by OVDAS (scientific) and ONEMI (CP) in Chile	N/A	N/A	Aviation level set by IMO	Set by MVO
Contingency plans	No	No	No	Only in Iceland	No
Evacuation decisions	ONEMI; local mayors in Argentina	Eritrean army	Chinese/Korean governments	Icelandic CP	NDPRAC
Transborder notification	Informal, via scientific networks	None	None	Between IMO and UK Met Office (VAAC)	Yes—colonial relationship
Resource issues (funding)	•Not well resourced but improving	•Very poorly resourced	•China well resourced; DPRK poorly resourced	•Well resourced	•Well resourced in theory but UK government reluctant to fund
Institutions	•Diverse institutional structures and little understanding of the other side	•Institutions not used to or optimised for dealing with volcanic crises	•Complex and opaque government structures	•Government structures that are complex can create confusion, particularly over functional boundaries (see Fig. 1)	•Required new institutional structures
Data sharing	•Data sharing not straightforward because of legal issues	•No communication between countries at government level	•Legal restrictions on data sharing (Chinese government policy)	•IMO transparent about data	•Some issues early in crisis to work with wider Caribbean networks but generally all managed on-island
Communication and collaboration	•Communication via informal networks (OVDAS reports)	•Diplomatic challenges due to sanctions on Eritrea and war between it and Ethiopia •Third parties can be important in aiding collaboration	•No collaboration—third parties can be useful here	•Strong communication between scientific institutions; less effective at government level	•Cultural differences in risk tolerance, particularly between political cultures
Scientific issues	•Imbalance of expertise •Different impacts from the eruption	•No pre-crisis monitoring •Limited expertise that is not necessarily specialised in volcanic risk	•Monitoring network configuration when border crosses the edifice •Isolation of DPRK limits opportunities for expert training •Lack of good data means that some hazard maps stop at the border	•In-country management requires different approaches to transboundary management	•Need to form new institution and carry out hazard assessments, etc.

Table 3 (continued)

Case study	Puyehue-Cordón Caulle	Nabro	Paektu	Eyjafjallajökull	Soufrière hills
(Geo) political issues	•Some geopolitical sensitivities related to past disputes	•War zone inhabited by tribal communities and militia with poor links to national government	•UN sanctions on DPRK create problems in advancing the science and in obtaining instruments	•Lack of preparation in UK and mainland Europe for this kind of incident	•Colonial dynamics affected trust in governments •Eruptions can shift power dynamics between nations if one is badly affected
Civil defence issues	•Imbalance of experience and expertise—Chile used to earthquakes and eruptions; Argentina not	•Dependence on military in both countries, but Ethiopia is more complex due to Afar regional politics	•Both countries have army bases close to the volcano	•No plans in UK for eruptions at this time •Iceland CP had plans in place and acted on them	•Disaster management was previously optimised for hurricanes rather than volcanoes

possibility of misunderstandings, as is clear from the interviews.

Post-eruption Since the 2011 eruption, some progress has been made in creating stronger links between the Observatorio Volcanico de los Andes del Sur (OVDAS, a Chilean organisation) and scientific and civil protection institutions in Argentina, but resources for volcano monitoring in Argentina remain scarce. Argentina has recently set up a volcano observatory via its geological survey, SEGEMAR.

Lessons learned Cross-border interagency communication prior to the crisis would have made considerable difference—Chilean authorities did not know who to contact in Argentina because of very diverse systems (centralised versus federal). Citizens in Argentina were not aware of the risk from volcanic eruptions, and the political issues at local level exacerbated the situation. Argentina also has different scientific strengths to Chile, and relatively few volcanologists, so the eruption demonstrated considerable differences in scientific resources. The civil defence in Argentina also had little experience with eruptions and had to adapt its procedures accordingly. Sense-making in Argentina was challenging, as was meeting the demand for support (surge capacity). There were also problems with boundary-spanning and coordination within the country. These issues will be dealt with in detail in a subsequent paper; a summary is given here.

Nabro: eruption in a region of political unrest

Nabro is a large stratovolcano with a summit caldera located in Eritrea but very close to the border with Ethiopia (Fig. 2). It is just a few kilometres away from Mallahle volcano on the other side of the border, which is also truncated by a wide summit crater. Both volcanoes are populated, with over 10,000 people within 10 km range (Table 1).

Pre-eruption There was no known historical activity from Nabro, and the volcano was not monitored. An informal international response, using satellite data and social media, confirmed that the eruption was of Nabro and not Dubbi, as originally thought (Goitom et al. 2015). Such informal responses can be useful but also raise ethical issues (see Giordano et al. (2016)).

During the eruption In June 2011, Nabro erupted for the first time in recorded history, yielding the largest SO₂ emission since the eruption of Mount Pinatubo in 1991 (Bourassa et al. 2012). Tephra fallout extended across Mallahle and further into Ethiopian territory, and two lava flows were produced, one of which extended for ~15 km criss-crossing the border (Goitom et al. 2015). Although there was no volcano monitoring on the ground whatsoever, Eritrean authorities

were able to evacuate local populations in Sireru, Afambo and Nebro villages, who were alerted by strong seismic shaking prior to the eruption. There had been a felt earthquake on 31 March 2011, and another occurred on 12 June, the day of eruption onset (Goitom et al. 2015). An estimated 11,780 people were evacuated in Eritrea, and seven lives were lost during the eruption (Goitom et al. 2015). Entire villages were buried by tephra within Nabro's caldera, and there were significant losses of livestock and agricultural land. Several thousand people were internally displaced and ultimately resettled far from the volcano, and a number of residents from nearby areas of Ethiopia crossed the border into Eritrea. One estimate places the cost at US\$ 3million (Goitom et al. 2015). Details of the emergency management can be found in Goitom et al. (2015).

There are no diplomatic relations between Ethiopia and Eritrea, but many people crossed the border locally due to the eruption—suggesting that cross-border volcanic eruptions in other regions could also involve refugee crises. Indeed, the Global Forum on Migration and Development (GFMD) report that those who crossed into Eritrea received aid there (GFMD 2016).

To our knowledge, no official evacuation was ordered in Ethiopia, and information was not exchanged between the countries during the crisis. However, collaboration by both sides with international scientists was possible (Hammond 2016), demonstrating the potential for third parties to foster scientific exchange in difficult circumstances. This collaboration had started prior to the eruption in 2011 and continued beyond it (Hammond 2016). There were reports that the Ethiopian government struggled to agree with the Afar Regional Government (ARG; in Ethiopia) concerning the required level of aid—the ARG argued that almost 48,000 people were immediately affected by the eruption and that there were significant issues with water contamination (Yirgu et al. 2014), livestock loss, water shortage and health with 167,000 people in danger. They reported 31 deaths (IRIN 2011).

Post-eruption In 2017, the Eritrean Afar State in Exile (EASE), a political organisation that represents the Afar people in Eritrea, accused the Eritrean government of neglect: an EASE press release suggests that those who were displaced in the region were not cared for adequately due to state oppression of the Afar indigenous people. They suggested that Eritrea had used the eruption to further its oppression of these groups (EASE 2017). It is also claimed that during the eruption, an exiled Eritrean opposition group based in Addis Ababa had asked the international community to put pressure on Eritrea to allow international aid into the country (Sudan 2011).

Both of these narratives between different groups within Ethiopia and Eritrea demonstrate some of the complexities of managing an eruption on a border. The legacy of conflict

in the region is critical, but there are also tensions between the semi-nomadic Afar communities that inhabit the Danakil region on both sides of the border and their lack of communication and representation with national governments: both ARG and EASE accuse the national governments in Ethiopia and Eritrea respectively of failing to deal with the crisis that was affecting Afar peoples. As well as the jurisdictional border, then, the formal and informal vertical borders within nation-states were an issue here.

Access to the eruption site was very limited due to the ongoing hostility between Ethiopia and Eritrea and limitations to travel beyond Asmara for foreign nationals in Eritrea, particularly affecting international scientists. The geopolitical tensions between and within nations made it very challenging for any aid to get through rapidly, and internal conflict between the various local and national authorities exacerbated the situation. Communication links between the site of the eruption and the larger populated areas of both countries are relatively poor and dependent on radios. While Eritrean authorities had some warning of the eruption via the USGS earthquake alert service (Wald et al. 2008) to an international colleague who happened to be in Asmara, the absence of volcano monitoring was a major hindrance to management, and in any case, no warning was released to Ethiopia by the Eritrean authorities according to interviewees. The centralised governance with limited communication over peripheral areas was also a challenge during this eruption: structures of government can be important in ensuring a swift response and appeals to international aid. This was a problem on both sides of the border in 2011, according to interviewees.

However, it is worth noting that while political diplomacy does not exist between the countries, relationships do exist at lower levels. From interviews, it is clear that Eritrean scientists have worked with Ethiopian scientists in the past. It is also possible for third parties to collaborate with each side—and science is viewed as not being a political threat. The importance of this can be emphasised during crises, as highlighted by one interviewee involved in the crisis:

“Then of course Nabro erupted which kind of brought home to the politicians how important it is to understand this [volcano monitoring] so that helped. Just realising science is actually somewhere we can actually do this because it's not political and no one really cares about that”. (*Scientist 13, October 2016*)

Interviewees also mentioned that there are different issues with civil institutions and scientific disciplines in Eritrea and Ethiopia. Eritrea has a strong focus on mining geology rather than hazards geology: there is no real infrastructure to manage

hazards other than the army according to interviewees. In Ethiopia, the challenge is to integrate a range of university and official geological survey groups in a programme of volcano monitoring across the country (Vye-Brown et al. 2016), and again, based on interviews and documentary evidence, the civil defence capacity in the Afar region is limited. Communicating risk between the countries is unlikely at the governmental level; however, there are links at a scientific level between the two countries via the Eastern and Southern African Seismic Working Group.

Lessons learned The governance lessons from the Nabro eruption are similar to those from other eruptions in terms of preparedness versus reactive mitigation. However, the crisis was complicated by its border context and particularly by the lack of diplomatic contact between the nations and the wider diplomatic isolation of Eritrea. It also highlights the significant inequalities in resources and expertise between nations that result from such isolation. Working in countries that are isolated is extremely challenging and so rarely attempted. While there is much volcanological research underway in Ethiopia, there is much less international collaboration with Eritrea. The lack of infrastructure makes it difficult to apply Ansell et al.'s (2010) model here, though we note that a key issue was the general capacity of the communities and governments to cope with the needs that emerged as a result of the eruption. Sense-making was significantly coloured by geopolitical complexity: the central governments were interpreting reports from the region through a geopolitical lens as a result of disagreements with provincial governments and indeed organisations (such as the ARG and EASE), as well as the broader conflict between the nation-states themselves. The suffering of individuals on the ground as a result of these complexities has been noted by international actors (IRIN 2011).

Laki, Holuhraun and Eyjafjallajökull: a historical context and recent events

In 1783–1784, a series of fissure eruptions at Lakagígar in South Iceland provoked famine in Iceland and may have had wider impacts in Europe (Oppenheimer 2011; Schmidt et al. 2011; Witham and Oppenheimer 2004). The eruption of Eyjafjallajökull in 2010 showed that Icelandic volcanoes could affect global aviation (Budd et al. 2011). A future Laki-style eruption would likely also disrupt aviation (the 1783–1784 episode manifested in a series of eruptions over an 8-month period) and could also affect air quality, causing respiratory problems in humans and livestock, as well as crop damage (Thordarson and Self 1993). Following the 2010 eruption, international investment has improved the already-strong volcano monitoring networks in Iceland (Sigmundsson et al. 2013). Collaboration between institutions in the UK and Iceland

(particularly the Icelandic Meteorological Office and the UK Meteorological Office and also involving the British Geological Survey) has been strong, enabling data sharing and facilitating planning for a future event (Donovan and Oppenheimer 2012).

Pre-eruption, 2010 The Icelandic Meteorological Office (IMO) was responsible for monitoring Icelandic volcanoes and collaborated closely with the University of Iceland. IMO also ran daily simulations with the London Volcanic Ash Advisory Centre (VAAC) for a hypothetical eruption of Katla volcano with the particular weather patterns for the day: there were channels for communication on the specific issue of aviation, described by interviewees. However, other forms of risk from volcanoes in Iceland were not considered by the UK government as an issue (Oppenheimer 2010).

During the eruption From a political perspective, the 2010 eruption of Eyjafjallajökull was critical in alerting the governments of Northern Europe to the possibility of volcanic ash from Iceland affecting a much larger area. This demonstrates the generally reactive political attitude to volcanic eruptions, as is the case for all of the case studies in this paper. In the UK, the Eyjafjallajökull eruption had been a shock for government (sense-making):

“Certainly the volcanic ash came rather out of the normal run of the mill, and we didn’t have a specific policy team, so the emergencies team stepped into action”.
(UK Official 1, October 2013)

During the crisis, the approach within government departments in the UK was to try to get people together whose expertise might be important. Within The Department for Environment, Food and Rural Affairs (DEFRA) for example:

“We recognised there might be an impact on the environment and on farming, so we thought about people like air quality people, water quality, water availability, grasslands, so livestock, and pulled together the relevant policy teams from around the department who lead on all these things. They in turn had their own science contacts in the world and we, within a few days, had picked up quite a network of people”. (UK Official 1, October 2013).

The potential issues with air quality, ash deposition and water contamination were dismissed after a few days in communication with Scottish environmental monitoring agencies because the level of ash detected was not significant.

Engagement across government (between departments) was mainly via the Scientific Advisory Group in

Emergencies (SAGE), which was rapidly constituted to include a number of relevant experts. The initial response was precautionary:

“I think again the policy problem was in the absence of really good information about how things are partitioning with respect to height ... but actually the cloud has gaps in it but we couldn’t identify where the gaps are ... some layers were less than we thought ... some layers were free of particles ... It would have really helped to have a bit more knowledge in that sense ... I think in terms of politics you’re almost forced into a precautionary position because, okay, it might be perfectly safe to fly aeroplanes through this stuff but I wouldn’t want to be the person who’d take the decision and there have been a crash and a lot of people dead”. (*UK Official 2, October 2013*)

One of the interesting aspects of the eruption from the UK side was the need to monitor the environment for signs of impact. While information about the impacts of ashfall could come from Iceland, there was little evidence to establish whether or not ash was actually reaching the UK. The overwhelming comment from government interviewees was that “very little information was available” in this regard—they had identified key experts within the UK on the issues of ash, health hazard and fluorine deposition, but the question of how best to detect any deposition took a bit of time to solve.

“You could have potentially a very big event which might bring in quite a lot of ash but it might be over a very short period of time and so you might be left with quite a bit of ash on vegetation which animals would then eat, but not have any big air pollution signal, if a lot of the pollution was actually ash itself rather than various gases that would be picked up by the air pollution monitoring”. (*UK Official 4, October 2013*)

One official suggested that the most obvious analogue for the 2010 crisis was the 1986 Chernobyl incident, because of the small size of the signal being looked for and the distance from the source.

Post-eruption UK government planning after this crisis was relatively slow, because of appointments and changes within various departments. Other departments worked on their own evidence-gathering (e.g. Public Health England, 2012). The Department for Transport established plans for an evacuation of UK tourists from across Europe. DEFRA led on air quality hazard. Following the 2010 eruptions, the UK government had made plans concerning two Icelandic eruption scenarios—the “Laki scenario” and the “explosive

eruption” scenario. “Lessons Learned” exercises also took place across government.

“Lessons learned exercises are a start if you like, what’s terribly difficult to do is make sure that there was follow up ... to these things at a reasonable time”. (*UK Official 2, October 2013*)

The major issue here is the same that occurs following many volcanic crises: volcanoes erupt rarely, and their significance on political timescales is so transient that they are rapidly drowned out by other concerns. An interviewee explained:

“Preparedness is not just the having the plan but the exercising and the rethinking of the plan all the time, which is much easier said than done”. (*UK Official 2, October 2013*)

This is challenging given the vast array of other environmental issues that are more challenging and ongoing (ranging from animal diseases to air pollution).

Further afield, the European Commission also made plans for crisis management, following the appointment of a Chief Scientific Advisor in 2012:

“The Icelandic story was a particularly interesting one because it was also a challenge for science because so many different disciplines needed to talk to each other, not just geologists and atmospheric modellers but also the aircraft engineers and economists and many other people”. (*EU Official 1, October 2013*)

At a regional scale, managing these disciplinary boundaries alongside the international ones was a challenge. The European Commission is not directly involved in the closure of airspace but rather has a “coordinating role” as a “solution broker in a crisis” (*EU Official 2, Oct 2013*). The 2010 events did also highlight the opportunity for a combined European airspace and led to the establishment of the European Aviation Crisis Coordination Cell (Christensen et al. 2013; Parker 2015). The European Commission also had a role in ensuring the rights of passengers and helping those whose visas expired while they were stranded. Following the 2010 events, a learning process was initiated at the Commission. This demonstrated the need for greater coordination across the airspace—both in terms of governance and in terms of scientific testing and research. Close links with national academies facilitate the input of science into policy, as does the work of the Joint Research Centre, which runs a Global Disaster Alert System. An official stated that:

“Of course also during the crisis it's necessary that you interact directly with all the countries involved and in fact this also happened during the Iceland crisis, there were almost permanent meetings with representatives from the national civil protection authorities, including by the way also the Iceland authority which does not belong to the EU”. (*EU Official 1, October 2013*)

The additional level of administration at regional level in Europe, via the EU, is informative in several respects. It provides an opportunity for coordination (so that airspace closures, for example, are logical). It also provides an opportunity for the enhancement of preparedness and education across the Member States. For flood hazard, for example, the EU runs the European Flood Awareness System (EFAS) (Demeritt et al. 2013). There are also regional policies, such as the Water Framework Directive, that link together networks of national institutions with responsibility. Some of these approaches are being exported to other regions and to other types of hazard.

However, in spite of these events, at the time of interviews, there were no official working groups internationally:

“I mean the logic would suggest you should do something like set up an international working group actually then chaired by the Icelanders and think through the planning from there. That didn't happen as far as I'm aware and it would be interesting to think what auspices somewhere under the EU or the obvious place, possibly under OECD but it would be really useful to have something like that”. (*UK Official 2, October 2013*)

Considerable progress was made from the UK government's point of view, according to interviewees, however, in establishing collaboration between UK and Icelandic scientists, in the installation of ground-based radar technology for ash cloud detection and monitoring in Iceland and on relaxing the regulatory regime beyond the precautionary principle (largely due to economic concerns) (Christensen et al. 2013; Kuipers and Boin 2015; Parker 2015).

In 2014, when a large fissure opened at Holuhraun to the north of Vatnajökull, following a dyke intrusion from Bárðarbunga volcano, a small scale version of the Laki scenario unfolded (Gudmundsson et al. 2016; Sigmundsson et al. 2015). Indeed, subsequent work has demonstrated that air quality in Northern Europe was affected by this eruption (Ilyinskaya et al. 2017; Schmidt et al. 2015). During the Holuhraun eruption, the concerns about aviation were limited due to very little ash being produced—but the Icelandic tourist industry was badly affected by the eruption because they were unable to take tourists into the area due to the high levels of gas (Donovan 2018b). This caused some consternation in the industry.

Lessons learned This case study demonstrates three key points. There is no neat solution to institutional structure (networked versus lead agency) in international spaces, because different places within a region face very different problems in terms of coordination (Boin et al. 2014a). Secondly, “sense-making” in a crisis is a particular challenge when that crisis is as multiscalar as the ash problem in Europe: actors dealing with a complex and unanticipated problem that has several potential outcomes can struggle to prioritise resources and make sense of the information that is coming in. This is particularly the case when policy domain boundaries and epistemic boundaries are crossed. Finally, as demonstrated in previous case studies, reactive governance in transboundary crises is not very effective—particularly where substantial populations are concerned—boundary-spanning protocols are needed.

Paektu/Changbaishan volcano: a sensitive border region

This case study is slightly different to the previous three: no eruption has taken place at Paektu since the current border was established in the 1960s (Donovan 2018a), but the volcano has experienced unrest and remains of concern to both countries in part because of the geopolitical context and also because of considerable investment in volcano tourism in recent years, described by interviewees.

Paektu volcano (Fig. 3) is on the border between the DPRK and China (in China it is called Changbaishan or Tianchi, whereas in DPRK, it is known as Mount Paektu or Paektusan; it is also referred to sometimes as Baitoushan; all these names are transliterations of “white-headed mountain” or “always-white mountain”). It is a large stratovolcano with a summit caldera that is now occupied by a lake, several kilometres in diameter and several hundred metres deep (Xu

Fig. 3 Changbaishan/Paektu Volcano (Tianchi Lake), China/DPRK, July 2013

et al. 2012). In c. 946 CE, the “Millennium eruption” of Paektu resulted in significant ash fall as far away as Hokkaido (Chen et al. 2016). In this context, elevated gas emissions and increased seismicity recorded between 2002 and 2006 caused concern across East Asia (Xu et al. 2012). In response to this episode, the Chinese government substantially increased the resourcing of monitoring Changbaishan but with instrumentation strictly on their side of the international frontier (Xu et al. 2012). However, monitoring networks are most effective when they have full coverage of the edifice (McNutt 2005), and there is no collaboration between China and the DPRK to facilitate this. While there are several monitoring stations in the DPRK, their equipment and its maintenance are limited, and power blackouts occur, as experienced during fieldwork and described by interviewees. In the event of a future explosive eruption sourced from within the caldera, it is likely that both countries would be affected, but, owing to the disposition of the crater topography, the summit lake water would likely be expelled towards the Chinese side. Indeed, there are lahar deposits from the volcano in Jilin city, 360 km away (Wei et al. 2013; Xiang et al. 2000).

There are concerns that a major eruption in the future could provoke a humanitarian crisis if large numbers of Koreans cross the border into China:

“Actually another issue is if there is eruption in the Baitoushan lots of people from North Korea will move to China because they lost their farms, their house, you know they have no food. Probably lots of people, refugees, would move to China and China would have lots of problem, you know, so that would be a big problem in East Asia, it's not a one country problem, it's a big problem”. (*Scientist 31, August 2013*)

Furthermore, UN sanctions, primarily driven by the USA, significantly inhibit the ability of DPRK scientists to purchase instruments and collaborate externally. The difficulty of obtaining foreign visas makes conference attendance a challenge, and limited access to the Internet also restricts the ability of scientists to keep up to date, both with literature and with software. Very limited contact with scientists outside of DPRK means that DPRK scientists are effectively doing volcanology in isolation from the cutting edge of the discipline. They do not visit active volcanoes in other countries, for example, and only have limited access to journal articles (Donovan 2018a).

The Korean Earthquake Bureau (KEB) is responsible for monitoring the volcano from the Korean side, while the China Earthquake Administration (CEA) is responsible for operational surveillance on the Chinese side. There are significant Chinese government controls on geophysical data sharing (due in part to the sensitivity of the border region), and so collaboration between the two nations is extremely

challenging. Interviewees explained that the CEA has recently augmented its monitoring network around the volcano (and around other volcanoes in China including the Longgang volcanic field, to the West of Paektu/Changbaishan). (The other volcano with significant monitoring is Tengchong volcano on the border with Myanmar—mentioned by Chinese interviewees who are also concerned about the border issues there.) There is however relatively little awareness of volcanic risk in the local Chinese population (perceived by interviewees): the primary associations of Changbaishan in China are with the Geopark on its slopes.

“... the people around the Chinese side of Mountain Paektu had some sort of complaining that whenever talking about the threat, I mean potential possibility of eruption of Mountain Paektu: it can hurt their tourism, their economy. So they don't want that mountain to be famous in that sense, they want their mountain to be famous for a nice spot for a photo and picturesque landscape and everything, not volcano”. (*Scientist 12, September 2015*)

The border itself is also problematic in understanding the volcano:

“Chinese scientists ... were not allowed to just go over to North Korea. Their own government, the Chinese government forbid them to do that, so they would actually like to have a little better relationship, but they don't have much as it is”. (*Scientist 8, January 2014*)

Again, the importance of establishing collaborations and procedures for eruption management is emphasised by interviewees. There are also major scientific challenges. As far as the international literature is concerned, the stratigraphy of the volcano has mainly been studied on the Chinese side (Pan et al. 2017; Wei et al. 2007)—and the interpretation presented differs from that of DPRK scientists (Donovan 2018a). Establishing the history of the volcano—including its large and small, flank eruptions—is a prerequisite for comprehensive hazard assessment. However, this is challenging because each group of scientists only has access to part of the volcanic edifice:

“The larger part of the volcano belongs to China and the smaller part belongs to DPRK so it is very difficult to research about the volcano”. (*Scientist 2, August 2014*)

Some limited hazard assessment for the volcano has been done—partial hazard maps have been constructed by Chinese and South Korean scientists, for example—but these efforts are hampered by limitations in data availability (Donovan 2018a).

In geopolitically sensitive contexts, there may be a role for third-party researchers—as in Eritrea/Ethiopia. Successful research collaborations have been achieved with DPRK (Hammond 2016; Horn and Schmincke 2000). Furthermore, DPRK scientists are collaborative:

“We are very much eager to contact with the international organisations. We are in contact with China annually. If there is an international seminar and we are invited we will go there”. (*Scientist 3, August 2014*)

This was also the case in the 1990s (Horn and Schmincke 2000).

Investigations of Paektu have also been undertaken in South Korea:

“So we know if that erupts that the critical hazard will affect China and North Korea, not South Korea, but the volcanic ash will eventually, directly or indirectly, affect Korea, South Korea. So we are doing some research on the monitoring, we want to sensing monitoring because we are not allowed to approach the Mountain Baektu in terms of monitoring”. (*Scientist 12, September 2015*)

In 2011, however, the two Koreas did hold a meeting of scientists concerning the volcano. An interviewee suggested that there had been plans to hold further meetings, but these did not materialise. The geopolitics is largely the cause of sadness on both sides, summed up here:

“Strong countries, powers, they are determined to divide the Korean peninsula. It's not by our own we are ... we are just forced to be divided”. (*Scientist 31, August 2014*)

Geopolitics is therefore a constant challenge in managing science around Paektu—both emotively, because of the relevance of Paektu to Korean people across the entire peninsula (Donovan 2018a), and scientifically, because data sharing, close collaboration and effective monitoring are extremely challenging under rapidly evolving circumstances.

Soufrière Hills, Montserrat: an example of complex colonial governance across cultures

Montserrat is a UK Overseas Territory in the Eastern Caribbean. It has a Governor, who is appointed by the UK Foreign and Commonwealth Office, and a locally elected legislature (Donovan et al. 2013; Donovan and Oppenheimer 2014). While the transboundary impacts of the eruption of the Soufrière Hills Volcano were relatively minor in terms of ashfall in neighbouring islands, it is a transboundary eruption because of the colonial

context: it crossed cultures in the process of governance and crossed functional boundaries within government. The government of the UK, with ultimate responsibility for the safety of the islanders, has a very different approach and culture to both the local government of Montserrat and to the residents of the island.

Pre-eruptions The UK government had made no plans to manage an eruption, although the volcano was monitored. At the start of the eruption, there was no volcano observatory on the island. Monitoring data were collected regularly by the Seismic Research Unit (SRU) in Trinidad. In 1995, the Montserrat Volcano Observatory (MVO) was established and ratified by government Act in 1999 (Aspinall et al. 2002). From 1996 to 2008, it was managed by the British Geological Survey (International) and subsequently by the Seismic Research Centre (SRC, formerly SRU) in collaboration with the Institut du Physique du Globe du Paris (IPGP) until 2013 and then by SRC alone. During this time, the political structures for volcanic risk management changed as the island, and governments in Montserrat and the UK, adapted to the eruption (Donovan et al. 2013; Wilkinson 2015).

During the eruptions The eruptions began in 1995. There were a number of complexities that hindered effective management of this eruption from a political perspective, described by interviewees from the policy side. First, there was a lack of clarity concerning responsibility for emergency response. This had been part of the Chief Minister's (CM) Office in 1995 but was transferred to the Governor's Office shortly after the onset of eruptive activity (Donovan et al. 2013; Donovan and Oppenheimer 2014). While the CM had responsibility for most internal affairs, the Governor was personally responsible, to the UK government, for the safety of people on the island. The capital city, Plymouth, was located on the slopes of the volcano within a few kilometres of the active crater and was ultimately destroyed as a consequence of the eruption (Kokelaar 2002).

The political challenges of the eruption were clearly linked to the island's colonial history as well as its present by Montserratian interviewees, as noted by other authors (Haynes et al. 2008; Hicks and Few 2015). Montserrat had almost reached economic independence in 1995 (though had repeatedly voted against political independence). That the UK had effectively used the eruption to gain greater control over the legislative agenda on Montserrat was noted by several interviewees, who provided details of opportunities that the UK government had taken to strengthen its control over law-making in return for the aid that Montserrat needed. The balance of power between Montserrat and the UK was dramatically changed by the eruption, according to interviewees, who described the UK's increasing interference in Montserratian affairs.

Interviewees on Montserrat also mentioned the Caribbean Disaster Emergency Management Agency (CDEMA), which is important in transferring resources around the region and coordinating a regional-scale response. The demographic of the island also changed significantly, as over two thirds of Montserratians relocated (Clay et al. 1999; Pattullo 2000). The effects on neighbouring islands thus went beyond purely physical impacts: many of the Montserratians who left Montserrat moved to other islands—and those who went to the UK or USA had to travel via Antigua, causing considerable pressures on a neighbouring island during the height of the crisis.

Lessons learned The eruption on Montserrat demonstrates the challenges of integrating different government practices and policies that have different cultural biases: while the UK government was strongly risk-averse, for example, and took a risk-centred approach to management, the government on the island was less prepared to act because of concern about economic impacts and a higher risk tolerance (Clay et al. 1999; Donovan and Oppenheimer 2014). It also shows the importance of anticipation and planning and the need for scientific structures with clear responsibilities and reporting structures to be in place prior to the eruption. The source of funding for scientific efforts should also be clear: in 2004, for example, the Royal Society critiqued the UK Department for International Development for its reluctance to fund research (Donovan et al. 2013). This had been a problem on Montserrat, where attempts were made to distinguish research from volcano monitoring for funding purposes, even though the two pursuits are closely linked (Donovan and Oppenheimer 2015).

Sense-making was an issue early in the crisis: both governments (and scientists) had to adapt to a vastly different context very quickly, and both had to work within their bounds and responsibilities, as well as their past experiences of hazards. However, this case study also demonstrates the complexity of colonial governance—not strictly about “volcanoes on borders”, but about *externally governed* volcanoes, of which there are a number (including on Guadeloupe, Martinique, Tristan da Cunha, Réunion and Ascension Island). Some of the lessons from this context concerning diverse political and cultural approaches to risk, and the challenges of funding volcano monitoring, may be applicable to border volcanoes, particularly where there is a strong inequality of resources between the neighbouring countries and where there is the potential for the eruption to change the power dynamics between nations—as was the case for Montserrat.

Surge capacity and coordination were also significant problems here, not least because of the location of the capital city on the side of the volcano: this meant that much of the island’s population had to be evacuated from their homes, and led to overcrowding, in inappropriate conditions (often in churches),

in the north of the island (Pattullo 2000). Resourcing was a significant issue (Clay et al. 1999), as was coordination between the governments (Wilkinson 2015). Each of these has geopolitical implications concerning balance of power between nations, since the impact of the crisis on the UK was minor, but on Montserrat was catastrophic (Pattullo 2000; Donovan and Oppenheimer 2014; Hicks and Few 2015). Similar issues have been encountered in other hazard events in externally governed territories—such as Hurricane Maria in Puerto Rico in 2017 (Rodríguez-Díaz 2018; Caban 2019). The role of geological events in shaking geopolitical relationships between nation-states has also been observed elsewhere—for example, by Paudel and Le Billon (2018).

Discussion

The case studies presented here demonstrate that there are many factors involved in the management of cross-border eruptions. While each of these has spatially situated particularities, there are broad patterns between the cases. There is a complex and dynamic interaction between existing intergovernmental relationships at multiple scales, urgent issues in a crisis and the relative availability of both expertise and resources. There are also significant social, cultural and political issues. These things are difficult to separate from the science in practice: as has been noted in the science studies literature, science cannot operate in a vacuum; it is dependent on funding and political support, particularly where risk assessment and management are concerned (Donovan and Oppenheimer 2014; Jasanoff 1999). In the case of eruptions on borders, science is fundamentally grounded in certain respects—such as the need for ground-based monitoring systems—while it transcends boundaries in other ways (e.g. through scientific collaborations—which can themselves take place even where political interaction is challenging, as we have shown above).

Geographical issues and the politics of scale

Inequalities of expertise and monitoring resources

Our global survey shows that there are many volcanoes that could affect multiple nation-states on the ground, in the seas and in the air, and that the nations concerned range from those with significant investment in volcano monitoring to those struggling with development issues and internal or external conflict. This is one of the important challenges facing the volcanological community: the need to share resources and to work across jurisdictional borders sensitively. The IAVCEI guidelines for volcanologists during crises provide some useful principles (Newhall et al. 1999; Giordano et al. 2016). However, a global database of expertise and resources

would also be useful, particularly where there is very little infrastructure in place for managing these events—or even some form of international taskforce. Given the rarity of eruptions at most individual volcanoes, convincing governments in poorer countries that struggle to provide healthcare, education and even food for their populations that they should invest in volcano monitoring is clearly going to meet with rational objections given the need to prioritise spending. Volcano monitoring from space has obvious advantages in these contexts and has been supported by agencies such as NASA, NOAA and ESA (Cam et al. 2017; Cam and Prata 2007; Dzurisin et al. 2018). However, a global, systematic and documented (e.g. by IAVCEI or WOVO) collaboration to provide and sustain monitoring instruments, for example, might be a useful approach. Some countries with potentially active volcanoes do not have volcanologists or geophysicists with the necessary training, background and resources and lack clearly mandated responsible agencies for volcanic hazards.

Imbalances of resourcing or expertise between nations can thus be challenging not only because of differences in practice but also because of the inherent power dynamics. As noted in wider geographical studies of North–South partnerships and collaborations, the better resourced (donor) partner can (even inadvertently) assume ownership of the research and monitoring agenda without recognising the valuable knowledge from the other partner (Jamil and Haque 2017; Schmidt and Pröpper 2017). Such imbalances can create tacit assumptions that ultimately inhibit effective projects (Schmidt and Pröpper 2017). A key challenge, then, involves reflexivity (self-conscious awareness) concerning latent power dynamics in any partnership.

Problems of scale

The Icelandic eruption scenarios considered here—and the concern of proximal (Icelandic) and regional (EU) governments about the potential for ash and gas emission to affect them—demonstrate the multiscale nature of volcanic eruptions and the border problem. The various approaches by both national and regional bodies described above show that there are several layers to the governance of these crises—such as the involvement of multiple government departments working across each other, more local government departments (such as the devolved administrations in the UK) and diverse structures within different nations, and then further complexity within regional, EU-scale institutions. Such regional bodies can have important coordinating roles, as long as these are understood before the crisis. This can be linked to the vision in the Sendai Framework for DRR (UNISDR 2015), which highlights the potential role of regional and international structures for coordination.

While this example is from the political level, regional-level (e.g. Asia-Pacific, Latin American) scientific networks

are also useful—and can overcome some of the geopolitical issues that occur at higher levels. For example, we have noted from our study that there are informal networks of geologists in East Africa that have been useful in linking Eritrean and Ethiopian geoscientists and providing them with a forum in which to interact.

Geographers have also pointed out the dangers of the concept of scale itself (Marston et al. 2005): scale can be misused to override the rights of local people (Grove 2013; Grove 2014; Swyngedouw 2004). This has led to a focus in geography on “situated” contexts rather than scales (Haraway 1988). This paper does not seek to discuss this ontological issue in detail but points out that in constructing regional or international networks, it is important to be conscious of the potential for misuse of power, resources or expertise (Blackburn 2014; Cretney 2017; Donovan 2016), either wittingly or otherwise, to oppress the vulnerable at local levels (Giordano et al. 2016; Newhall et al. 1999). This is particularly critical in cross-border work, because scientists and officials may encounter cultural differences that inhibit their awareness of social issues.

Geopolitical risk

The material and social impacts of volcanic crises can generate geopolitical forms of risk. As Montserrat experienced, other nation-states (or in Montserrat’s case, the colonial power) can take advantage of a crisis to impose their own will. In Montserrat, this took the form of increased legislative influence. In other cases, however, it might include the exercise of “soft power” through international aid or taking advantage of a gap in trade to move in (Chen et al. 2009; Mawdsley 2012; Zhang 2006). In less extreme cases, eruptions may influence relationships between nation-states in other ways—as in the meeting between North and South Korean scientists described above, which, according to interviewees, came about as a result of a seismic crisis at Paektu. Similarly, risk may be generated when non-state groups use or are accused of using a geological event to shift power dynamics, as occurred in the aftermath of the Nabro eruption.

Perceived geopolitical risks—such as Chinese fears about refugees from DPRK—can also complicate volcano monitoring and collaboration between nation-states. Such imagined geopolitical futures can act against cooperation and require considerable negotiation in the management of scientific projects (Hammond 2016).

Scientific factors

Ideally, all hazardous volcanoes would have procedures in place prior to a crisis, by which hazard assessments are routinely updated (Loughlin et al. 2015). This includes studies to

identify eruption histories and generate hazard maps and scenario plans. Baseline monitoring (geophysical, geodetic, geochemical) should be carried out by mandated agencies staffed with volcanologists with the expertise to interpret unrest (Tilling 2008). Furthermore, scientific institutions would have clear remits and responsibilities with effective contingency plans, including alert levels and other devices to aid communication. In practice, however, relatively few volcanoes are effectively monitored (GVM 2014a, b). The case studies selected here span a range of situations in this regard and enable us to identify some patterns.

Our survey identifies two particular needs around border volcanoes. A first need that proves complicated to fulfil is that of volcano monitoring networks and access to data for the neighbouring countries: where observatories are state-run, the sharing of raw data with other nations may be very challenging due to restrictions on dissemination of government data. There are various ways round this, such as sharing reports on data that include some figures, but this depends on the details of the legal systems in each place. Variations between funding availability and structure can also be a scientific challenge. In some countries, it may be very challenging to obtain funding for volcano monitoring where there are more pressing priorities or geographical challenges, and thus establishing an understanding prior to a crisis becomes important. Second, communication issues associated with scientific monitoring and assessment can also be challenging—as they are within languages and cultures, let alone between them (Donovan et al. 2019; Fearnley et al. 2018; Newhall 2017). This is particularly an issue where one country monitors the volcano but another suffers the impacts. Networks, email lists and call-down protocols can be useful in this case—but need to be developed pre-eruption (and in a common language) so that each side knows whom to call in the neighbouring country (Harris et al. 2017); see also the recently updated IAVCEI guidelines (Giordano et al. 2016).

We suggest that transboundary work in volcanology is critical to future risk management. Our results imply that, in order for such transboundary activity to succeed, additional research is needed to establish the appropriate protocols and work-arounds for transboundary volcano monitoring and risk management. This includes the use of satellite remote sensing techniques, which can in some cases overcome the need to share government-owned and protected data. However, even with much freely available data (Carn et al. 2017; Wright 2016; Wright et al. 2008), some of the highest resolution data remains commercial and requires an activation of the Disasters Charter for access. In addition, the importance of engaging with responsible agencies in-country before issuing any kind of alert or commentary cannot be overstated (Giordano et al. 2016; Newhall et al. 1999).

Politics, governance and institutions

Our study shows that there are significant challenges at political and institutional levels, particularly where many functional boundaries are crossed. We find that this is also strongly place-specific, but in general, key challenges are sense-making, communication and coordination at the political level so that decisions are consistent in both countries, particularly where this involves population movement, in the event of impending or actual eruption (Ansell et al. 2010). Another important issue is ensuring that there are institutional structures with clear roles and responsibilities, with which all decision-makers are familiar: it is important for both scientists and decision-makers to be aware of the institutional structures in the neighbouring countries, so that they can liaise effectively during a crisis. Geopolitical sensitivities, legal issues including treaties and customs and cultural differences are also important. Again, this requires inter-national, inter-cultural and inter-linguistic familiarity and liaison before the crisis.

Communication with the public and also between scientists and between decision-makers is a complex, non-linear process (Donovan and Oppenheimer 2014; Fearnley and Beaven 2018; Marzocchi et al. 2012; Paton 2008). In general, many of the issues that are faced routinely in volcanic crises, such as the need for outreach when the volcano is quiet, and the importance of transparency, also apply in cross-border situations. However, many institutions may not have considered the need for outreach where the threat is from a volcano in another country.

Other issues with institutional communication include establishing operating protocols prior to the eruption, especially where multiple institutions are involved across multiple countries. This requires sustained engagement over long periods of time, even around volcanoes that have not shown signs of activity recently. It may also involve long-term work with the media, to avoid some of the issues encountered in the 2010 ash crisis, for example (Harris 2015; Harris and Villeneuve 2018).

The presence of these factors necessitates international planning for volcanic events across borders. This cannot be achieved purely at the scientific level but requires the participation of political and civil defence institutions in international agreements.

Warning systems

Volcano alert level systems and warning systems are complex and varied (Fearnley and Beaven 2018; Fearnley et al. 2012; Potter et al. 2014; Winson et al. 2014). They also typically apply at national or sub-national level (with the exception of the aviation code). Again, there is an opportunity here for international collaboration between neighbouring nation-states to avoid contradictory or controversial cases in which

different decisions are made across a border (as occurred at Nabro, for example). This also requires social scientific input, because alert protocols are fundamentally social systems, both in how they are designed and implemented and in their impacts (Donovan et al. 2018; Donovan et al. 2017; Eiser et al. 2015; Fearnley and Beaven 2018). Different systems across a border might be justified, for example, if there is significant cultural divergence but would need to be communicated and translated to the appropriate neighbours.

Wider context: transboundary eruptions

As noted in the “[Introduction](#)”, there is a considerable literature on other varieties of transboundary crisis. Figure 1 shows that other studies have particularly identified issues of legitimacy, data sharing, communication, coordination and institutions as challenges in responding to crises across borders. The results in this study back up that assessment but also add to it (Table 3). The case studies we have presented here reveal distinctions of resourcing between nations as a key challenge—both in terms of economics (such as funding for volcano monitoring) and scientific expertise and infrastructure. These imbalances also extend to civil defence and planning. In part, these additional areas of concern occur because volcanic eruptions are low probability but high impact: unlike other transboundary disasters (such as epidemics, nuclear accidents or climate-related hazards), governments are less likely to plan for or invest heavily in volcano monitoring and risk management—particularly in the developing world (GVM, 2014). All of these issues point towards international collaboration as key in the management of transboundary eruptions - but such work must be culturally sensitive. Cultural expectations and relationships are critical and rely upon long-term investment and dialogue (including between scientific cultures and local ones). Transboundary eruptions are complex assemblages of dynamic components: institutions, practices, cultures and geologies (Donovan 2016).

Conclusions

Our study shows that the governance of volcanoes on borders is complicated by:

1. Geopolitical factors affecting the ability of scientific and civil protection institutions to monitor volcanoes and manage risks effectively when impacts span multiple nation-states
2. Lack of links between scientific institutions in neighbouring nation-states, which then impedes the exchange of information and produces disparities of funding for science between countries

3. Lack of clear communication channels between civil protection institutions in the adjoining countries
4. Lack of clear and consistent information for the populations in the affected countries

The case studies discussed here demonstrate that borders on volcanoes complicate scientific and political management of volcanic crises and also complicate consistent practice in monitoring and management between crises. Border regions are particularly sensitive—as in the case of Paektu—and this can complicate commercial considerations (such as tourism, as it does in China). Borders also engender a lack of knowledge: the population, and indeed authorities, on one side of a border may have very little knowledge of the cultural, linguistic and institutional expectations of those on the other side of the border—and may be unaware of threatening volcanoes that are relatively close to them. There may also be diverse priorities between nation-states—for example, where one of them is making substantial investments in volcano tourism, while the other is seeking to reduce risk. These social and political complexities permeate the roles of scientists because they affect how scientific advice is used and interpreted—and will also affect the availability of resources for scientific monitoring and assessment.

Recommendations

1. Pre-eruption planning for volcanoes close to international borders should include links between civil protection agencies and government planning organisations in different countries.
2. Volcano monitoring networks should be harmonised and compatible across the border where the volcano lies on an international border, and data and knowledge sharing should be enabled where volcanoes are within 100 km of a border. The production of hazard assessments should be done collaboratively, so that both sides of the border are modelled and vulnerable populations can be identified.
3. A database or registration site for resource sharing and the establishment of links between experts could facilitate collaborations, particularly in the developing world where resources are very limited. This might be facilitated by existing entities such as WOVO, and WOVOdat could also be an important resource in identifying analogue volcanoes with rich datasets.
4. International collaborations can be powerful and significant in mitigating transboundary risk if carefully managed—see Giordano et al. (2016) for recommendations for such collaborative working.
5. Communication protocols and ideally engagement with at-risk populations should be made collaboratively across

the border, with agreed approaches that address cultural, linguistic and institutional differences.

Each of these recommendations depends on the identification of the volcanoes that pose the most serious risks to multiple nations. Many of the cross-border volcanoes identified here are located in South and Central America, and East Africa, and many of them have little or no eruptive record data—and are located in areas with diverse cultures, languages and expectations. This makes risk assessment and cross-border communication very challenging. Ultimately, the challenges of border volcanoes have to be seen in the light of the issues around managing volcanic risk at non-border volcanoes. The presence of a border adds considerable institutional, cultural, linguistic, governmental and political complexity and thus clearly requires additional considerations to cases of eruptions within borders. Finally, we note that these recommendations also require substantial traversing of disciplinary boundaries between natural and social sciences at a minimum—ideally incorporating approaches from the humanities in understanding and negotiating culture and communication.

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