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Practising an explosive eruption in Iceland: outcomes from a European exercise

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Abstract

A 3 day exercise simulating unrest and a large explosive eruption at Katla volcano, Iceland, was conducted in January 2016. A large volume of simulated data based on a complex, but realistic eruption scenario was compiled in advance and then transmitted to exercise participants in near-real time over the course of the exercise. The scenario was designed to test the expertise and procedures of the local institutions in charge of warning and responding to volcanic hazards, namely the volcano observatory, national civil protection, and the local university-science sector, as well as their interactions with the European science community and the London Volcanic Ash Advisory Centre. This exercise was the first of this magnitude and scope in Iceland and has revealed many successful developments introduced since the 2010 Eyjafjallajökull and 2011 Grímsvötn eruptions. Following the exercise, 90% of participants said that they felt better prepared for a future eruption. As with any exercise, it also identified areas where further development is required and improvements can be made to procedures. Seven key recommendations are made to further develop capability and enhance the collaboration between the volcano observatory, volcano research institutions and civil protection authorities. These recommendations cover topics including notification of responders, authoritative messaging, data sharing and media interaction, and are more broadly applicable to volcanic institutions elsewhere. Lessons and suggestions for how to run a large-scale volcanic exercise are given and could be adopted by those planning to rehearse their own response procedures.

Keywords: Exercise, Practice, Explosive eruptions, Iceland, Volcano observatory, Hazard response, Preparedness, Risk management, International response to volcanic crises

Introduction

Practising and testing emergency procedures are fundamental for ensuring effective responses in operational environments during real crises. Conducting realistic exercises provides a means to validate contingency plans, to develop individuals' competencies and give them practice in carrying out their roles and to test established procedures in order to reduce and/or manage disaster risks (Payne 1999; Perry 2004; Peterson and Perry 1999). The practice of running exercises is common in many disciplines where crises management procedures need to be in place to react to possible emergencies, for example in civil protection, hospitals, the emergency services, and the nuclear power industry (Hart 1997; Lakey et al. 1983; Larsson et al. 2015; Kim 2013; Kim 2014; Payne 1999; Berlin and Carlström 2011, 2015). In these fields, three main types of exercises have been identified (Berlin and Carlström 2015): 1) *Drills exercises* aimed at reinforcing an individual's knowledge and skills in a single organisational field, for instance fire-fighting techniques for the fire department; 2) *General or strategic exercises* relying on a simulated event to evaluate the outcomes of different interventions and therefore aimed at testing the management of the emergency team rather than individuals' skills; 3) *Collaboration exercises*, which are a combination of the first two types and involve organisations that are not all represented at one site. The objective of collaboration exercises is to develop and practice collaboration at all levels between different organisations so that their coordinated response to an emergency will be optimal. Such cross-sector collaborations make the design of these exercises more challenging (Berlin and Carlström 2011, 2015).

Collaboration exercises can have many benefits, including testing how the overall response works, identifying problems due to overlaps in responsibilities, testing

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the interface between agencies and assisting people from different agencies to understand each other's roles and to build and strengthen relationships (Payne 1999). For example, a study by Larsson et al. (2015) revealed that decisions made in Sweden during the response to the 2010 Eyjafjallajökull eruption strongly benefited from pre-crisis joint agency training and exercises that had been conducted, even though the exercised scenarios were unrelated to volcanic crises.

Exercises can take a variety of forms from discussion-based table-top exercises, to functional exercises, through to real world full-scale exercises, depending on their objectives. Irrespective of the type, debriefing post-exercise is as essential as the exercise itself (Kim 2013, Payne 1999) to guarantee that the outcomes are the subject of future implementations or review. An exercise which identifies areas for improvement is just as successful, in fact perhaps more so, as one where everything runs exactly as planned. It is important that one of the main drivers of an exercise is to detect loop-holes, errors, oversights and other problems (Hart 1997).

Managing an emergency situation due to a volcanic event requires cooperative effort between different organisations. These institutions may include, but are not limited to, a volcano observatory, a national/state geological or geophysical institution, local police, national civil protection authorities, politicians and volcano research institutions. Such multi-agency involvement increases the complexity of the response, as plans need to be coordinated between different areas of expertise. A study of the response to the 1995 eruption of Ruapehu, New Zealand (Paton et al. 1998), recommended the development of comprehensive inter-organisational networks, accompanied by exercises. They highlighted that exercises and simulations were a key component of preparedness training, providing opportunities for practising skills and using knowledge in realistic scenarios and conditions.

Within the volcanological community, the practice of rehearsing procedures to respond to potential volcanic crises has become more common in recent years. However there are only a limited number of published examples of large-scale exercises performed for volcanic areas (Barberi and Zuccaro, 2004; Lindsay et al. 2010; Marzocchi and Woo 2007; Ricci et al. 2013). These are mostly for volcanoes that have a low eruption probability but a very high risk, due to high population density. Most of these exercises have involved both scientists, as providers of data and interpreters of the event and the hazard assessment, and decision makers, as users of such information to quantify the risk and to design appropriate mitigation actions.

Between November 2007 and March 2008 the Ministry of Civil Defence and Emergency Management of New Zealand tested its national preparedness for a volcanic eruption in the Auckland Volcanic Field which underlies New Zealand's largest city (Doyle et al. 2015; Lindsay et al. 2010; O'Rouke and Coetzee 2008). The exercise scenario involved more than 1500 people and 125 institutions (Deligne et al. 2017). Because of its unusual four-month duration, this large-scale exercise was able to include a realistic timeline for precursory activity until the onset of the eruption. In this way contingency plans, but also connections between local, regional, national and international agencies could be tested, as well as the implementation of new approaches for eruption forecasting, to support the near-real time volcano monitoring and decision-making (Lindsay et al. 2010).

In Italy, the area surrounding Mount Vesuvius and Campi Flegrei is at high risk due to potential eruptions from these two volcanic systems. In 2006 and 2014, two major exercises took place to improve preparedness for eruptions at both volcanoes. The "Mesimex" exercise in 2006 (Barberi and Zuccaro 2004; Marzocchi and Woo 2007; Ricci et al. 2013) involved contributions from civil protection in assessing evacuation plans in the surrounding towns. The "Vuelco" exercise in 2014 (Papale and De Natale 2015) reviewed the scientific response capabilities and the effectiveness of communication with civil protection authorities.

The work presented here focuses on Iceland and the current procedures in place to manage volcanic crises. Despite the low population density living close to the majority of Icelandic volcanoes, the population exposed to volcanic hazards increases significantly when tourists are considered. In addition, the potential for volcanic ash to affect local and international air transport (as clearly demonstrated during the Eyjafjallajökull 2010 eruption) is a significant factor (Budd et al. 2011; Mazzocchi et al. 2010). The Icelandic Meteorological Office (IMO) is responsible by law for monitoring all natural hazards in Iceland and issuing warnings and forecasting when possible. IMO is also designated by the International Civil Aviation Organization (ICAO) as the volcano observatory with responsibility for volcano surveillance in Iceland to mitigate risks to aviation in case of explosive eruptions. Consequently, IMO and the London Volcanic Ash Advisory Centre (VAAC), hosted by the UK Met Office, conduct regular small-scale exercises called VOLCICE (Reichardt et al. 2017). This is a series of monthly exercises between IMO, ISAVIA (the air service provider in Iceland) and the London VAAC to test the specified ICAO aviation response procedures (ICAO 2014). In each VOLCICE exercise a scenario involving a volcanic eruption in Iceland or Jan Mayen, Norway is responded to over the course of a working day. Occasionally these exercises are run on a national level in Iceland to also address the ground-based impacts of potential eruptions. In these cases, participants are expanded to include civil protection and other relevant stakeholders, such as the Icelandic electrical companies, who will have to react and implement adequate responses in the event of an eruption. Annually a larger scale pan-European "VOLCEX" exercise is held, aimed at testing communications channels and contingency plans for responding to ash in the atmosphere that might threaten aviation (ICAO 2016). These involve meteorological watch offices across Europe, together with EUROCONTROL and the London and Toulouse VAACs. Approximately every 2 years the VOLCEX focuses on an Icelandic volcano.

Despite the frequency of these exercises, the full chain of interaction that would occur during a real volcanic eruption in Iceland is rarely tested. In particular, these exercises do not fully integrate the necessary scientific interactions that would occur, as well as the broader context in which an event would be placed (international and local civil protection, media interest, etc). Although general guidelines for scientists have been developed on how to respond to volcanic crises (Giordano et al. 2016; Newhall et al. 1999), opportunities to practice and develop these skills for a volcanic event are limited.

To address these broader aspects, two collaboration exercises were held in 2014 and 2016 to simulate volcanic eruptions in Iceland. They were conducted within the FUTUREVOLC project, a European consortium of 26 partners, including many relevant organisations in the volcanological community. This paper focuses mainly on the second exercise that ran for 3 days and involved the entire FUTUREVOLC community, as well as external contributors, responding to a realistic eruption scenario at Katla volcano. The objectives of this exercise were not only to test the operational procedures (a standard exercise goal), but also to test the use of international scientific expertise during a crisis, which was a unique and ambitious target. The many data streams created and used by this large community pose challenges for technical operations and scientific interpretation by the Icelandic institutions, hence the exercises had a significant focus on data use and sharing.

Exercises which cover the whole response chain from monitoring at the volcano observatory, through interpretation, to alerting civil protection, and ultimately issuing warnings to the general public and practising responses such as evacuations are highly complex to design and run. The least exercised parts of the response chain are the interpretation of data and the formulation and issuing of warnings, and exercises aimed at practicing these are probably the most difficult to design and execute. The example described here suggests how to design and run such an exercise.

We believe that the practice of running exercises within the volcanological community (on both small and large scales) is extremely beneficial and should be encouraged and supported. Similarly, the sharing and reporting of exercise experiences is necessary to build awareness of their importance and establish best practices. The aims of this paper are to document what has been learnt from conducting these large-scale exercises, to present what we have found to be good practice for running such an exercise, and to demonstrate the value of doing them well.

An overview of the planning and execution of the exercises is given in the next section, while more details on the exercise preparation and scenario can be found in the Additional file 1. Outcomes and issues identified during the Katla exercise are summarised in the results. In the discussion we focus on the main results that had an impact on the emergency procedures in place in Iceland as well as those that involve collaborators in Europe. We also highlight the key lessons learnt about running a large volcano exercise. The approach and the methodologies presented here can be adopted by other institutions interested in running similar tests and, in this way, we hope this paper contributes to designing common guidelines for effective volcanic exercise execution.

FUTUREVOLC project overview

The FUTUREVOLC project grew from the need for a more holistic approach to volcanic hazard monitoring, assessment and eruption response for volcanoes in Iceland following the eruptions of Eyjafjallajökull in 2010 and Grímsvötn in 2011. The project was funded by the FP7 Environment Programme of the European Commission and ran from October 2012 to March 2016, with 26 project partners from academia, civil protection and industry groups. The project was led by the University of Iceland together with IMO and it combined European expertise across the full spectrum of volcanic processes, monitoring, modelling and civil protection response.

The main objectives of FUTUREVOLC were to (i) establish an integrated volcanological monitoring system for Icelandic volcanoes through European collaboration; (ii) develop new methods to evaluate volcanic crises; (iii) increase scientific understanding of magmatic processes, and (iv) improve delivery of relevant information to civil protection and other authorities.

The focus here is on the fourth objective. In Iceland, the national response framework for volcanic events is currently based upon interaction and coordination between IMO (the volcano observatory), the National Commissioner of the Icelandic Police (NCIP, the national authority for Civil Protection), the Institute of Earth Sciences of the University of Iceland (UI, the academic sector), and ISAVIA (the national air navigation service provider of Iceland, for flight safety issues). Good communication and interaction between all these organisations are essential and well-established procedures are in place (Fig. 1). These procedures are constantly reviewed whenever new events or scenarios may suggest the need for improvement (Thorkelsson et al. 2012).

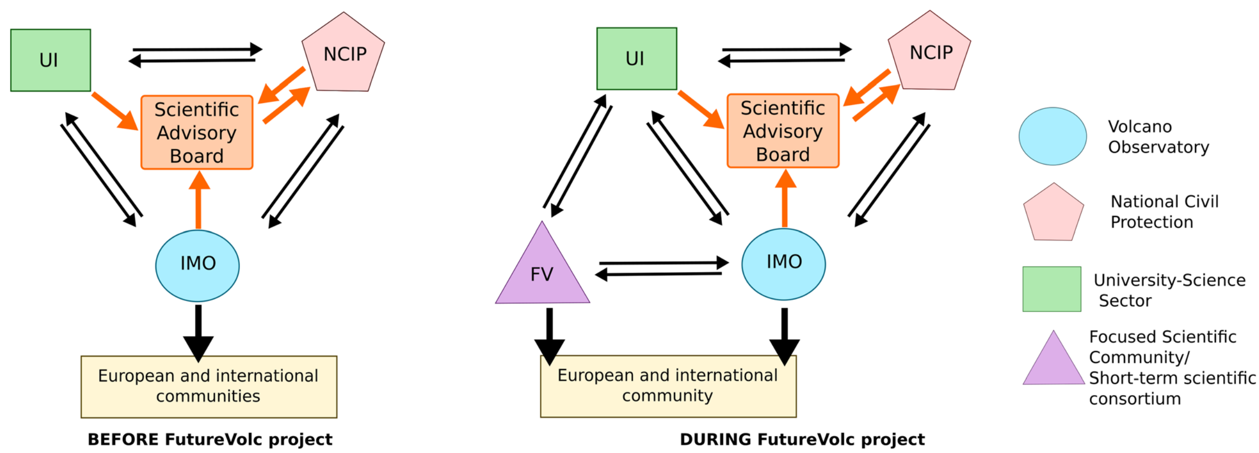

Fig. 1 Diagram showing the crisis communication channels between the volcano observatory (circle), the national civil protection (pentagon) the university-science sector (square), and other scientific community members (triangle). To the left are the arrangements prior to the FUTUREVOLC project and to the right are the exercised arrangements. The arrows indicate the flow of communication between the organisations (black) and in relation to the scientific advisory board (orange)

An additional contributing group to FUTUREVOLC was the 16 academic institutions involved in the project. Multi-disciplinary interpretations of observations and data are becoming increasingly important to decipher the nature of the processes that could lead to an eruption. However, international academia has no defined role within the Icelandic response framework and for this reason the processes for involving these organisations are ad-hoc and less well coordinated. Ensuring that volcano observatories can make the best use of all available data, including monitoring equipment and data acquired by academic partners is vital. One aim of FUTUREVOLC was to establish this link more firmly for Iceland and foster interaction and knowledge exchange between different scientific disciplines during unrest and eruption. To this end, an explicit component of the project was to conduct two exercises to test and demonstrate existing and new response procedures, data flow and communication channels across all partners.

The exercise methodology

Two types of collaboration exercises were conducted within FUTUREVOLC: (1) a communication exercise in 2014 and (2) an end-to-end exercise in 2016. The specific objectives for both exercises are described below. In both cases all project participants (either science/data providers or users) were included and they were required to act and respond as if the volcanic event was real. The second exercise also included key stakeholders such as the London VAAC, the media and international civil protection interests. The planning and execution of these exercises drew heavily on the institutional experience of IMO, NCIP and the UK Met Office gained from the VOLCICE and other thematic exercises.

Communication exercise in 2014

The first exercise was conducted in June 2014. This was designed to test the notification and communication processes between FUTUREVOLC partners. The objectives of this first exercise were to (1) test a new notification system for responders and scientists (Fig. 2); (2) test communication tools and procedures; (3) test the response of FUTUREVOLC members and assess the chains of communication, with a specific focus on whether the key contact persons at each institution received the information they required in a timely manner.

The scope of this first exercise was deliberately limited, as without effective communications it was acknowledged that anything more complicated was likely to fail. Checking and proving communications across the whole range of stakeholders and contributors was an essential first step for the success of a more ambitious exercise.

The exercise was led and coordinated by IMO and was run over 1 day, timed to coincide with a planned VOLCICE exercise. This brought more realism to the situation and allowed the end-to-end processes at IMO to be tested. The exercise scenario involved a large (20 km column height) but short-lived (4.5 h) eruption at Hekla volcano in south Iceland.

A post-exercise questionnaire was sent out to all participants to enable the exercise to be evaluated. The questions included if and how partners had received the notifications, what additional information they would have liked (if any), how they responded, who they communicated with and how, how they reacted in real-time to notifications from IMO when activity was changing and any lessons that had been learnt. Based on the findings, five key areas for improvement were identified -notification, response, communication, data sharing and

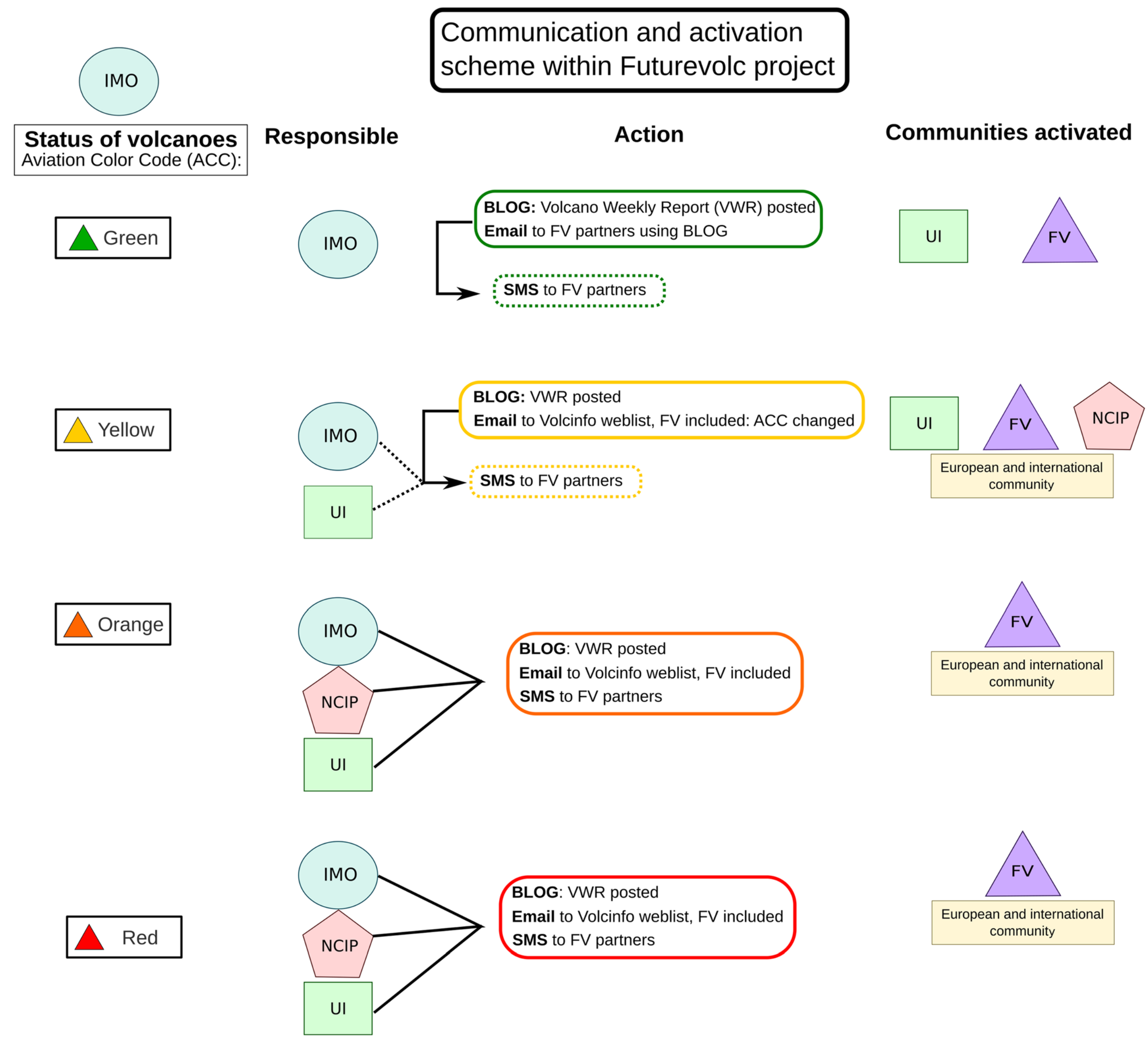

Fig. 2 The FUTUREVOLC (FV) notification process and management implemented during the first exercise. The institutions responsible for making decisions are indicated in the second column. Three main communication channels are considered here: email, posts to the FUTUREVOLC blog, and SMS text messages. The Volcinfo weblist is an email dissemination list owned by IMO and used to send out information on volcanic activity in Iceland. It includes all FUTUREVOLC members in addition to a wide international recipient list. In an event, experts from IMO, UI and NCIP discuss the activity and depending on how unusual the event is, e.g. if it is of pure scientific interest and/or requires monitoring, they will decide whether to update different stakeholders including the FUTUREVOLC consortium. The dotted polygons indicate actions that are at the discretion of the responsible organisation(s)

data discussion - and an action plan was formulated to address these.

A key issue identified was the need to improve communication across the whole scientific consortium for discussing data (either direct observations or processed results) amongst the different disciplines. The most common tools for communication were email and telephone, formats which do not lend themselves well to multi-disciplinary discussion, but which are readily available to most parties during a volcanic crisis. Whilst there were excellent examples of data sharing within subject-area groups and between individual partners, the exercise revealed a clear need to improve data integration across the different observations and disciplines. The use of a newly developed blog site aimed at promoting cross-disciplinary discussions was trialled, but this revealed problems that needed to be addressed before it could be considered to provide support for discussions during a crisis (Witham et al. 2015).

The actions from this exercise were a necessary first step in the design and planning of the second exercise. The main change implemented after the first exercise was the earlier activation of the UI group by IMO as part of its response procedure.

End-to-end exercise in 2016

The "end-to-end" exercise took place on the 25–27 January 2016, with some initial event information released during the preceding day. The aim of this second exercise was to provide an end-to-end test of the Iceland volcanological supersite established through FUTUREVOLC (Dumont et al. 2018). The exercise was designed to test the human networks, data sharing tools, decision-making procedures, and communication channels to end-users.

Icelandic volcanoes exhibit a wide range of eruptive styles, which pose different hazards and may require different responses, meaning it is not feasible to design a single exercise to test all eruptions. Following the gas-rich eruption at Bárðarbunga in 2014–2015 (Gislason et al. 2015; Gudmundsson et al. 2016; Pfeffer et al. 2018; Sigmundsson et al. 2015), which required a real response from the project and operational partners (Barsotti et al. 2019), it was decided that this exercise needed to test the project's response to a large ash-rich eruption for which specific tools were developed during the project (e.g. Dürig et al. 2018; Woodhouse et al. 2016).

Specific objectives identified for the 2016 exercise were to test: (1) the notification system and internal communication (including the response level/preparedness of each partner); (2) data sharing through the new FUTUREVOLC data portal and associated scientific exchanges between the volcano observatory and academia; (3) the field activity coordination within Iceland for the scientific community; (4) the dissemination of timely information to end-users including civil protection and the VAAC. A minimum exercise duration of 3 days was deemed to be necessary to ensure that the whole response procedure could be tested - from precursory activity through to the onset and end of an eruption – and allow the involvement of most participants whatever their specialty.

Katla volcano was chosen as the subject of the exercise due to its potential to generate several hazards both prior to and during an eruption (Eliasson 2014; Gudmundsson et al. 2008). Katla is located in south Iceland under the Myrdalsjökull glacier with a 400–600 m thick ice cap covering the central volcano (Fig. 3). Past eruptions at Katla have comprised both large-scale explosive activity in the central volcano as well as explosive and effusive activity along its north-east trending fissure swarm. This fissure swarm is where one of Katla's biggest eruptions, the Eldgjá eruption, took place in 934 AD (Larsen 2000; Óladóttir et al. 2008; Thordarson and Larsen 2007). Katla is one of the highest risk volcanoes in Iceland due to the relatively high number of people (locals and tourists) potentially exposed to volcanic hazards in the area and the fact that access to the region is limited to the Iceland ring road (Gudmundsson et al. 2008).

A team of Icelandic and international scientists was tasked with defining a realistic scenario and providing a consistent multi-disciplinary dataset that would be streamed in (near) real-time during the exercise. The timeline of the main geophysical events specified by this team to characterize the volcanic unrest at Katla is summarised in Fig. 4. Full details on how the exercise was designed and how the volcanological scenario evolved through the 3 days are provided in the additional file 1.

The timing of the exercise was chosen to occur during a VOLCICE exercise. This provided an existing operational framework into which the exercise could be integrated. All the FUTUREVOLC partners involved in the exercise were required to act and respond as if the volcanic event was real. Most collaborators participated during office hours only (08:00–17:00 UTC), except the operational partners, IMO and London VAAC, who continued to play overnight whilst the eruption was ongoing.

Figure 5 provides a detailed overview of the exercise timeline, associated phenomena in the scenario, events and consequent actions. This figure summarises the actions taken by the different players and how these were linked and triggered by the "status" of the volcano (simplified by the aviation color code) or by the latest observation or information available on the event's progress.

During the 3 days the aviation sector was kept informed through the standard notification and alerting procedures, which included phone calls from IMO regarding changes in the aviation color code. This information meant that the London VAAC was able to produce timely Volcanic Ash Advisories (VAA) for the appropriate parts of exercise. Two scientific advisory board (SAB) meetings (including representatives from IMO, NCIP and UI) were held at IMO on the first 2 days to discuss the observational data and assess the on-going event.

To ensure that there was no confusion with a real eruption, caution was taken during the whole exercise and all documents and data released were tagged with a message stating that they were related to a FUTUREVOLC exercise. Examples of the types of data produced during the exercise by the players as a result of analysis and processing are given in Fig. 6.

In order to evaluate the success and the efficacy of the exercise a structured debriefing was performed. This involved a cross-organisational debriefing, an evaluation of the exercise by the exercise coordination team, a debriefing at each local institution and the dissemination of a

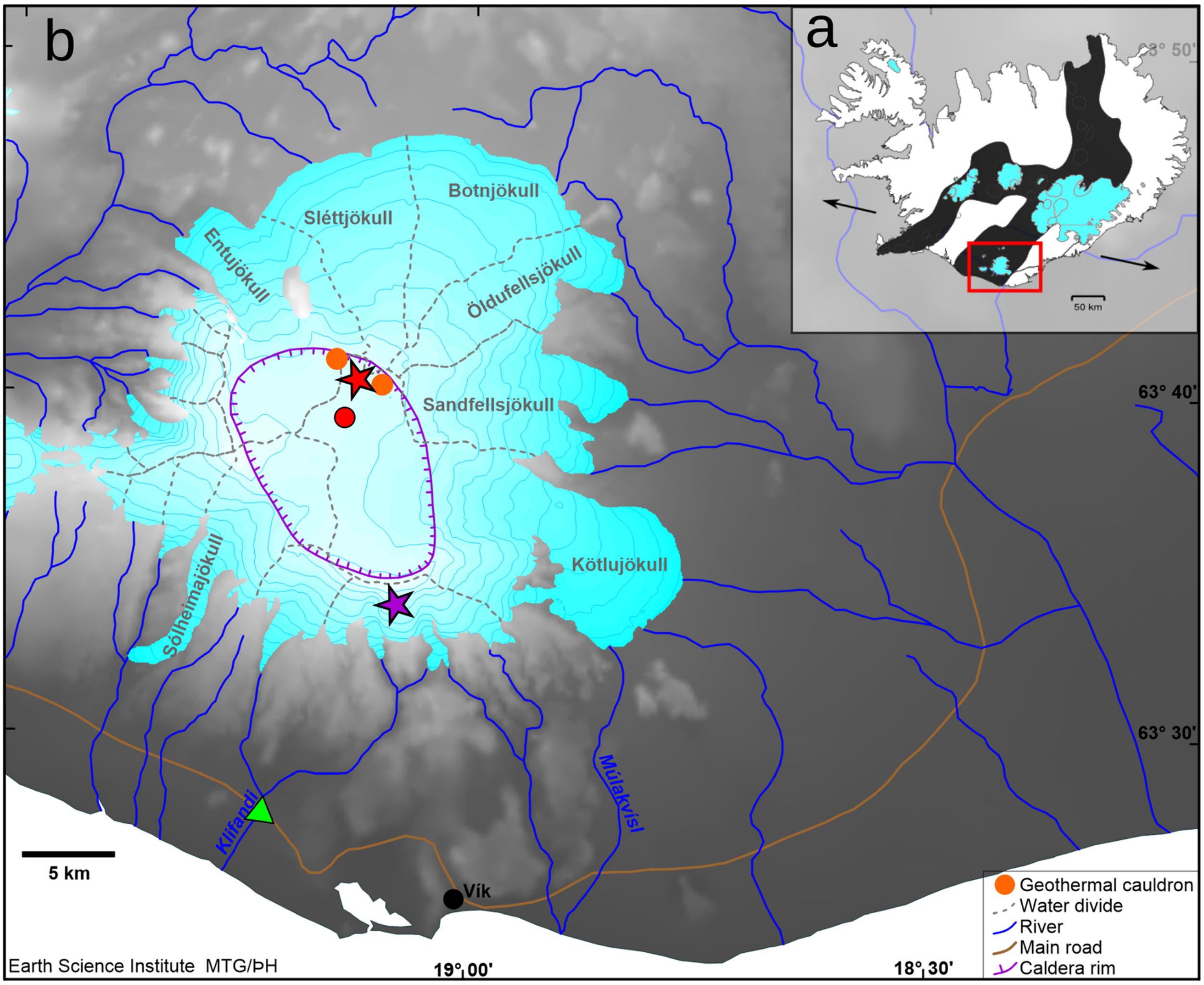

Fig. 3 a Location of Katla in south Iceland (red box) and the volcanic zones distributed along the divergent plate boundaries (dark grey zone). The glaciers are coloured in cyan and the closed lines depict the volcanic centres. **b** The Mýrdalsjökull glacier (cyan) and the subglacial Katla volcano. The glacier contours are spaced every 100 m. The borders of the caldera are indicated by a purple hatched line. The watersheds beneath the icecap are indicated by the grey dashed lines and the rivers are in dark blue. The purple star shows the exercised centre of the seismic activity at Gvendarfell. The red circle within the caldera indicates the Mogi source of deformation associated with the exercise's main eruption and the red star corresponds to the eruption site. The geothermal cauldrons of relevance to the exercise are shown by orange circles. The ring road is plotted in light brown and the green triangle indicates a road bridge that was swept away on day 1 of the exercise

structured questionnaire to all the participants to evaluate their perception of its success and gain feedback. Internal reviews were performed rapidly after the exercise at each operational institution, as well as a joint one in Iceland, allowing discussion and decisions on the follow-up actions.

Results

The scope and scale of a three-day exercise provided an unprecedented test of response procedures allowing the identification of gaps and areas of possible improvement for a contingency plan for Iceland that includes foreign institutions. This exercise was the first of its type in Iceland and was positively engaged in by FUTUREVOLC project partners and local institutions such that the response in terms of meeting organisation, data flow, etc., was very realistic.

Nineteen of the twenty-six FUTUREVOLC partners responded to the evaluation questionnaire and some organisations provided responses from different specialist groups. Of the responders, 90% said that they felt better prepared for the next Icelandic eruption as a result of the exercise and 74% responded that their institution will do something differently as a consequence of the exercise, demonstrating a constructive outcome in terms of modifying behaviours and procedures. All participants were positive that the exercise had been a useful undertaking. Here we analyse the outcomes of the exercise in light of the four goals identified prior the exercise.

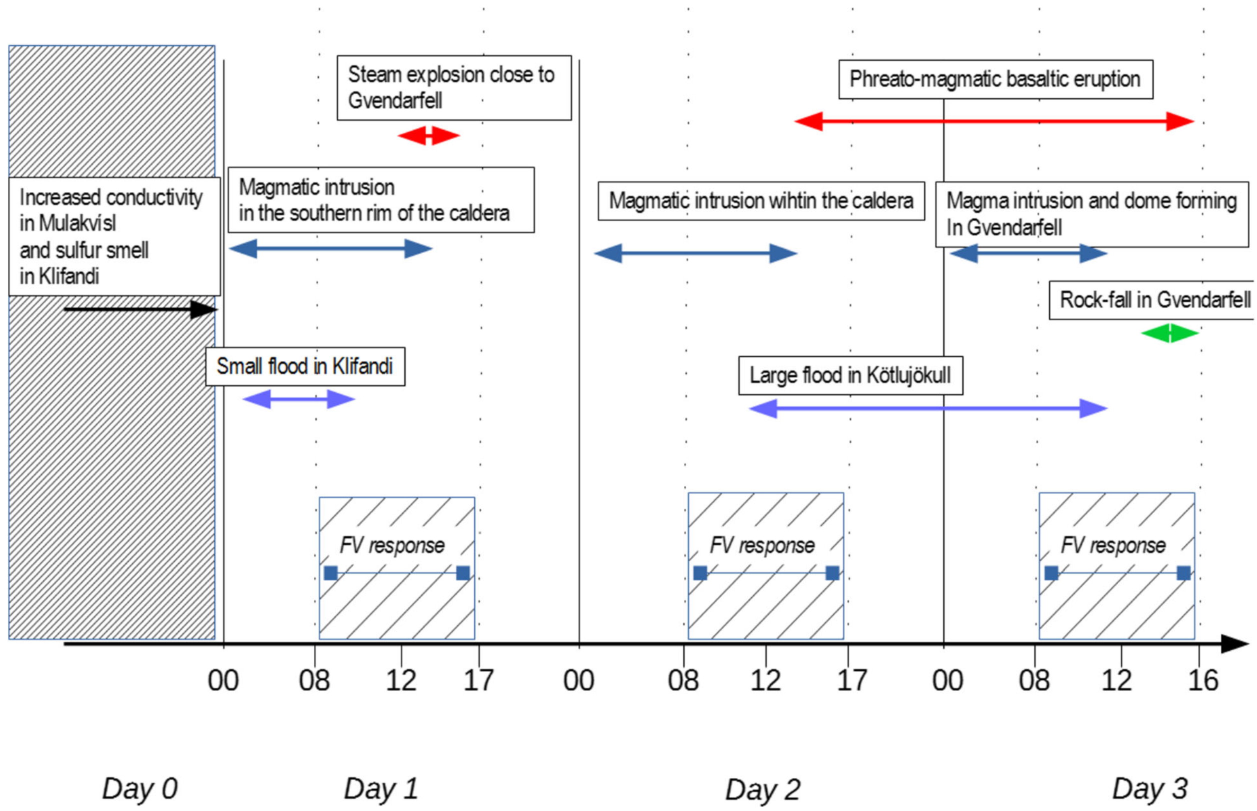

Fig. 4 Overview of the event evolution during the exercise. Most FUTUREVOLC partners participated during normal business hours only (08:00–17:00 UTC). The dashed area corresponds to the working hours during which the FUTUREVOLC community was asked to respond to the exercise. The coloured arrows provide information on the nature of the hazardous events: dark blue is used for magmatic processes, light blue is for hazardous phenomena involving water, red is for hazardous phenomena impacting the atmosphere, e.g. explosions, and green indicates surface processes such as rock-fall

Notification system and internal communication

In its first year, the FUTUREVOLC project introduced a new notification system for volcanic unrest in Iceland (Fig. 2) that formally included academic project members in the early alerting process. This was successfully tested in the 2014 exercise. In the 2016 exercise, however, the FUTUREVOLC activation process was superseded by partners using their own communication channels. Technical complications also prevented the SMS notification system from triggering the first warnings to all individuals.

From this experience, it appears clear that the notification and activation process used for the wider academic community needs to be simplified and fully established within the official procedures. Any agency working with the volcano observatory should design an internal activation system so that a notification does not depend on a specific individual.

During the exercise there was a considerable volume of communication between partners, both using online tools and via email and telephone. This was very positive and demonstrated that the project had successfully forged new relationships between organisations and individuals leading to cross-disciplinary interactions that had not occurred before. Over 90% of questionnaire responders said that they felt properly informed about the status of activity at the volcano during the whole of the exercise.

Data sharing

During the exercise, discussions on instrumentation and data took place successfully between individuals and their existing contacts in Iceland or abroad through various communication channels such as personal emails, videoconference meetings, phone calls and blog posts. Three main web-based systems were used during the exercise: the project management software, a blog and the FUTUREVOLC data portal. FUTUREVOLC's web-based project management software Basecamp (https://basecamp.com/) was designed to facilitate daily routine management of the project, work package discussions, general announcements, and also allow document and report sharing. It allows the user to send communications to the entire project community or to subgroups related to specific work packages, with emails sent each time a new message is posted. Used regularly on

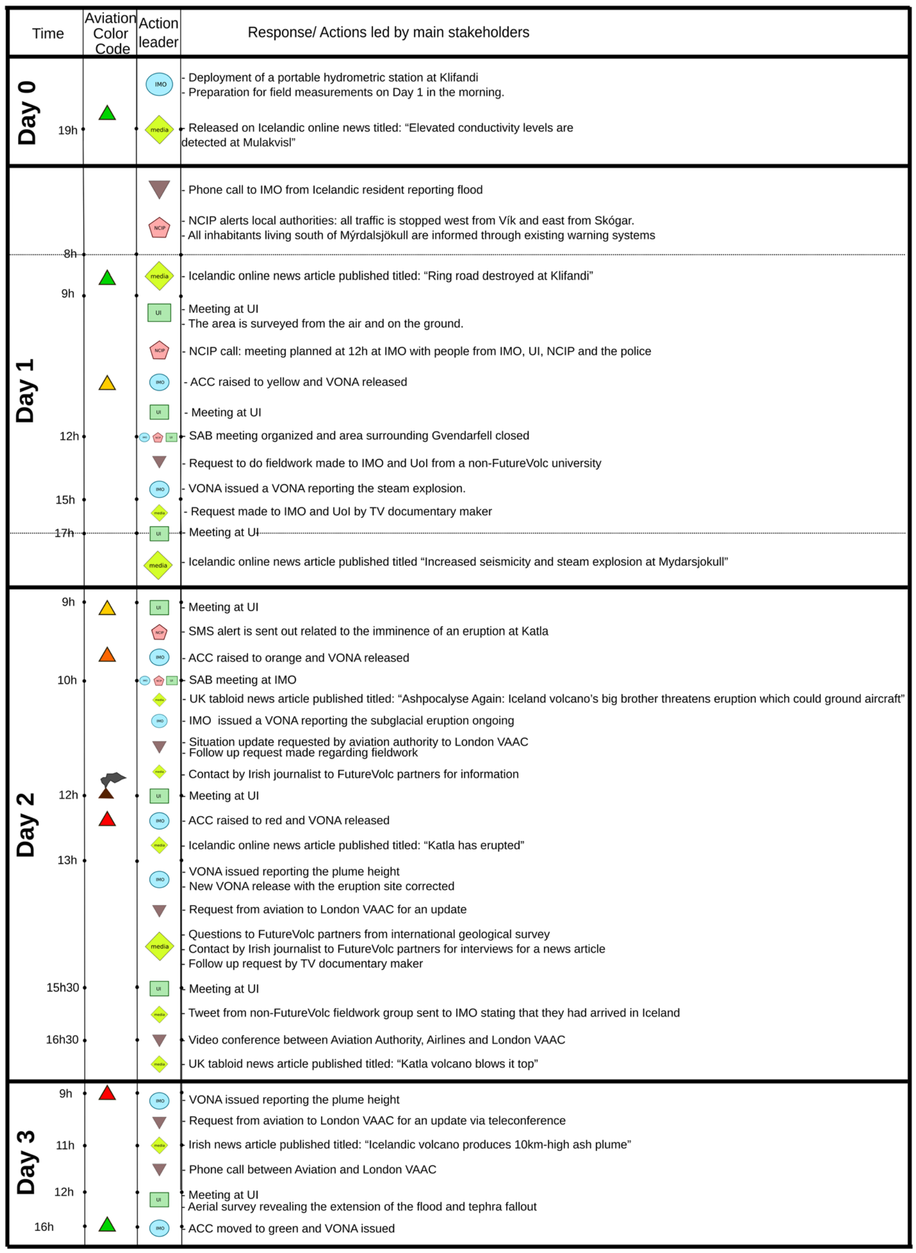

Fig. 5 Outline of the key actions by the main stakeholders (IMO, UI, NCIP, media and others (locals, aviation sector)) during the execution of the exercise. The Aviation Color Code (ACC) is indicated and the different coloured symbols are similar to those used in Figs. 1 and 2. The volcano symbol in the second column on day 2 indicates the timing of the onset of the explosive eruption

a weekly to monthly basis by the project members, people were familiar enough to launch discussions and make sure the information/data were spread to the whole or any subgroups of the project consortium. The heavy usage of such a web tool was however unexpected and created an unnecessary load of emails. Conversely, the official blog website which was created during the project to promote data sharing and scientific discussions within the consortium was underutilised, mostly due to difficulties with tracking new and specific posts. The FUTUREVOLC data hub (http://icelandicvolcanoes.is/), a data sharing platform that was one of the main objectives of the project, was tested for the first time during the exercise. This hub was intended to be the place where all the IMO monitoring data would have been hosted in order to be shared with the wider community. Project members were also authorized to upload data. Different kinds of data (from raw to processed data) could be downloaded by any users registered beforehand. This data hub was least used reflecting that this channel did not fulfil the needs and expectations of users for sharing their

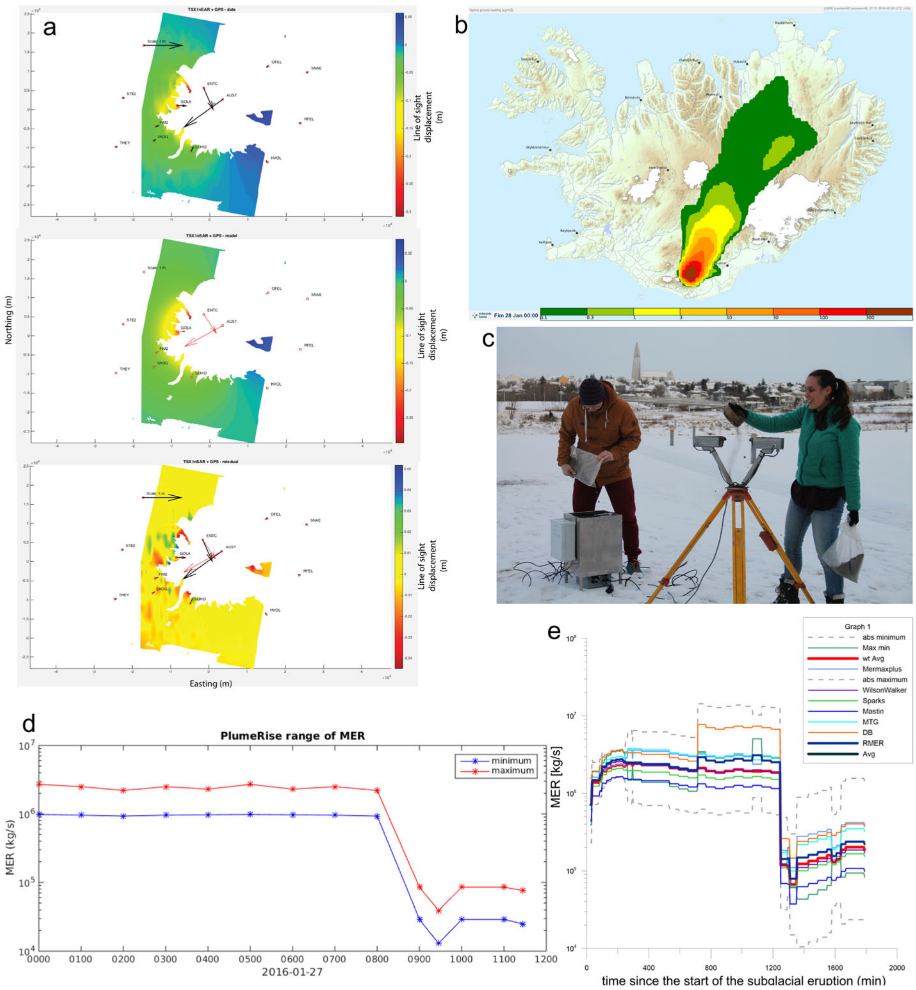

Fig. 6 Sample exercise data products processed and produced in 'real-time' by exercise participants. **a** The top panel shows surface displacement from day 1 to day 3 from GPS (black arrows) and InSAR (acquired on day 2). The middle panel shows the modelled displacement (Bagnardi and Hooper 2018) and the bottom panel shows the residual for the InSAR data, as well as a comparison of GPS data-model using black and red arrows respectively. The data reveals a deflation signal caused by a shallow source that is located at ~ 2500 +/− 200 m depth, centred beneath Katla, according to the best model solution. **b** Cumulative tephra deposit as computed by the VOL-CALPUFF model (Barsotti et al. 2008). The contours show the tephra loading in kg/m^2 at the end of the eruption. **c** Students at the University of Iceland testing new ASH-SIZER instruments (Marchetti et al. 2014) in Reykjavik during the exercise. The instruments were streamed in real-time to both UI and IMO. **d** Estimate of the mass eruption rate (MER) made using the PlumeRise model (Woodhouse et al. 2016). **e** Range of MER estimates from the REFIR integrated system (Dürig et al. 2018)

data through the community in times of crises and that there were some technical problems.

With these three data sharing systems, in addition to IMO's official email dissemination list, the information flow rapidly became confusing and overwhelming with information distributed in a poorly organised manner. The data sharing in almost real-time by a variety of partners is a very positive result, but this experience reinforced the importance of metadata covering time/date/validity to facilitate urgent searches.

Field activity coordination within Iceland

Deploying instruments in the field during a volcanic crisis exposes people to volcanic hazards (Brown et al. 2017), particularly during explosive eruption phases, meaning personnel safety is a key consideration (e.g. Carlsen et al. 2019; Deligne et al. 2018). For the majority of partners with deployable monitoring equipment there were clear pre-established channels of contact with the local Icelandic monitoring staff and good communications during the exercise. Safety forms formalised by the Icelandic institutions during the Bárðarbunga eruption, which allow them to keep track of scientists in the field and to keep individuals updated regarding the evolution of the eruption, were updated with specific information related to the exercise eruption. However, there was a lack of field safety advice available for workers outside of the Icelandic organisations. The relative ease and speed in which Iceland can be reached by air from Europe makes it a particularly attractive destination for researchers during eruptions, adding to the number of people who may wish to go into the field. Existing procedures for managing these individuals mean that as soon as the volcanic area is closed, each foreign scientist/institution that wants to take part in data collection or volcano monitoring should follow a process involving filing an application with NCIP and passing through check-points on route to the field. This process should be followed by everyone, regardless of whether they are already in close collaboration with an Icelandic institution, but this was not clear during the exercise.

For some disciplines, the deployment of instruments requires a preliminary set of analysed or modelled data to inform where the equipment should be located. For example, to collect falling tephra during an eruption meteorological data for the following hours and days, together with forecasts of the ash plume dispersion and deposition, will allow better planning of the sampling strategy in the area surrounding the eruption site. This requires additional data flow and specific communication channels to be identified in advance to make sure they will be implemented optimally during a crisis. The testing of new equipment in this exercise, including a tephra-sampler, has helped identify where such requirements exist and further response plans are needed.

Dissemination of information to end-users

Any volcanic unrest in Iceland is likely to trigger international interest. To ensure that authoritative information is being shared, IMO openly provides as much information and data as possible via its website and existing dissemination routes. The three-day exercise was the first real test of the newly implemented Volcano Observatory Notice for Aviation (VONA) reporting system at IMO. The VONA report follows a standard template provided by the International Civil Aviation Organization (ICAO 2014; Lechner et al. 2009) and is designed to be issued whenever there is an update of the aviation color code for the target volcano. During the exercise the VONA was distributed by email and contained information about the eruption status and changes in activity. However, because this system was not introduced to the project members and official stakeholders prior to the exercise, its introduction led to some initial confusion. This illustrates the need for continuous dialogue with all stakeholders when new modes of communication are introduced.

As soon as the unrest phase was identified, scientific advisory board (SAB) meetings were organised at IMO to discuss the volcano status and volcanic hazards. These involve the three main Icelandic agencies and worked well for internal communication between these bodies and reinforced practices established during previous eruptions. However no systematic reports were issued by the SAB during the exercise despite this being the standard procedure put in place during the Bárdarbunga eruption (2014–2015) (Barsotti et al 2019). The SAB report is designed to be different to the VONA as it aims to transmit a joint multi-disciplinary interpretation of the observation datasets and provide possible eruption scenarios as agreed by the three national institutions. This report is then shared externally. The lack of this report created confusion between partners who expected it to be released. This demonstrates how important it is that all established procedures are carefully checked and followed during any type of training or exercise.

The FUTUREVOLC exercise gave the London VAAC an opportunity to test its procedures in the most realistic situation possible outside of a real event, with the changing nature of the scenario providing a realistic context. Communication between IMO and the London VAAC was very good with regular telephone contact and the VAAC was first to know of any changes in activity or colour code.

One of the significant challenges for replicating reality was the use of non-standard email lists by IMO for disseminating information during the exercise. This was done in an effort to not cause confusion in the outside world, but meant that some users did not receive information. In addition, the lack of information on the IMO website (which also had been a deliberate choice in the preparation of the exercise) was identified as hindering the stakeholders in their work, which is something that would need to be addressed in any future exercise of this scale.

During the exercise participants were asked not to post to social media to prevent any external misunderstanding about the exercise status. In a real event, however, social media will quickly become full of posts related to the activity, which could be both real and false. This could impact significantly on communications and exchanges of information. During the Bárdarbunga eruption, regular posts by IMO, UI and NCIP on their own websites and social media pages significantly contributed to a reduction in the distribution of incorrect information, as these institutions are recognised as a primary source of authoritative information. This activity can be time consuming so ensuring in advance that there are clear guidelines for social media use and responsible individuals in charge of keeping accounts up to date is highly recommended.

Even with proactive dissemination of information, the news media will always want to speak to individuals directly. Feedback from participants who were contacted during the exercise made it clear that they struggled to find time to respond, even though the volume of enquiries during the exercise was considerably smaller than would occur in a real event. This is a concern as it is only likely to be worse in a real event.

Discussion

Simulating the occurrence of a natural hazard through an exercise can be a powerful and effective tool for improving the response to such events (Bignami et al. 2012; Brown et al. 2016; Pallister et al. 2019). The key drivers for the FUTUREVOLC exercises were the testing of the readiness of response plans and the identification of areas where further development was needed, which are similar to other volcanic exercises that have been reported in the literature.

The first objective of the 2016 exercise was to test the notification system set up during the project. Although several communication tools were developed during the project lifetime, this exercise has shown that to be effective the notification system in Iceland should be primarily activated using direct phone calls from IMO to the main stakeholders (including civil protection and experienced researchers at the University of Iceland). The activation of collaborators and other scientists to support the interpretation of the on-going event can then be triggered with notifications via emails and SMS. A protocol based on SMS messages was tested during the project lifetime and revealed to be a useful tool for communicating changing volcano activity to a large number of people such as the FUTUREVOLC consortium. Although the system did not work properly during the lifetime of the project, the idea of an SMS-system for the quick triggering of other institutions to respond to an eruption has been formally implemented at IMO in 2018 and its use is currently part of their contingency plans.

More generally, the use of different communication tools during the project has been an important step to evaluate communication channels and more specifically to see whether or not any of them are appropriate for a large consortium like FUTUREVOLC to use during an eruption. It is clear from our experience that platforms for communicating and sharing data should be decided on and practised prior to an emergency to avoid any confusion in partner exchanges. This allows partners to be familiar with the communication platform, making the response more efficient and rapid. Creating efficient communication channels is essential for allowing external institutions to be included in supporting daily monitoring procedures without overloading them. Debriefing discussions led to the conclusion that data sharing through a single open-access platform is not workable during a crisis. A large amount of all kinds of data, including preliminary analyses as well as volcano hazard assessments, was shared in near-real time on the same platform. This caused confusion as the most relevant products and pieces of information became buried. It was also concluded that data exchange and scientific discussions should not take place in the same platform.

Based on the exercise evaluation and partners' feedback, a number of areas stood out as needing further work and development. To address them, seven recommendations were formulated by the project team leaders. All of these relate to the more general response capability of the Icelandic Institutions and as such they have been already considered for improvement to and implementation in the operational response plans at IMO, UI and NCIP. The recommendations are also directly relevant to other institutions worldwide that are responsible for responding to volcanic emergencies.

They are:

1. Implement platforms for real-time data sharing and discussion between organisations. It is recommended that the local institutions (civil protection, volcano observatory, university and/or related institutions) make the decision together about the tools that they wish to use to communicate during a volcanic crisis with their closest partners. Such communication tools need to be practised to become familiar to individuals and therefore contribute to efficient exchanges during a crisis. Mailing lists used between the local institutions and the external partners should be kept up to date.
2. Ensure that the volcano observatory is the main source of scientific information to prevent dissemination of the wrong messages through social networks and the media. This is in line with IAVCEI protocols and recommendations from the Volcano Observatory Best Practice meetings (Pallister et al. 2019). The production and dissemination of a regular (daily) update from the volcano observatory or a multi-agency "scientific advisory board" should be a standard procedure during exercises, unrest and activity to ensure an official source of information.
3. Streamline notification activation procedures across all institutions responsible for responding to a volcanic crisis, for example by adopting a basic SMS system for a quick alert, and identify who is responsible for the activation of external collaborators. In Iceland, the scientific advisory board should include in its procedures the criteria for when and how to call out for international scientific support. This group should also have oversight of the membership of notification lists (e.g. SMS or email). By gathering people from the volcano observatory, national civil protection and university, the scientific advisory board should also be able to review and update the notification

procedures and to check coordination between the different organisations.

4. Appoint a cross-organisation fieldwork coordinator to ensure consistent safety procedures. Fieldwork coordination should be a priority. A fieldwork coordinator or a coordination team should be established at the start of any unrest/eruption to whom requests for fieldwork are directed. This person (or team) has responsibility for providing field safety information to all groups and for coordinating access/deployment to the field for non-operational teams. This may need to be a joint role between the volcano observatory, national civil protection and university/academic-sector to ensure that the latest situation is always taken into consideration. The contact details for this coordinator must be clearly available.
5. Appoint an experienced point of contact for all media interactions at each institution. A dedicated press officer to coordinate response to the media is beneficial for all parties, with some process of deferring enquiries away from individuals. This person should be in contact with the scientific advisory/management team previously described and should be updated daily. They should be proactive in organising and providing press briefings thus reducing direct email traffic to individuals. To achieve this goal, the contact details for the press officer must be clearly available to the outside world.
6. Commit to practising the response plans by testing the entire chain. The recommendation in Iceland is to implement a multi-day exercise on a 1–2 year basis to keep practising and improving the response and cooperation/collaboration at a national and international level between institutions.
7. Pre-plan the human resource distribution required during an eruption as part of preparedness activities. Each institution needs to develop a plan for how to fulfil all their required actions with the human resources that are available to them, given that there are often not enough people to cover the load in times of crises.

Legacy of the exercises on operational emergency response

The two exercises, in particular the second one, have contributed to reinforcing the collaboration between the local institutions in Iceland (civil protection/observatory/university) and to establishing new procedures in both the notification system as well as data sharing protocols. For example, since the second exercise, the University of Iceland is always activated during the monthly VOLCICE exercises organised by IMO and the London VAAC. Similarly, the contact list at IMO including people from UI has been reviewed and updated within the IMO contingency plans (in terms of both priority and people contacted).

The exercises have triggered further changes in Iceland including the implementation of a password-protected blog to share updates, data and opinions about ongoing events. The blog is currently a basic channel for quick communication between relevant parties and it was widely used during the unrest period at Öræfajökull volcano that was declared in November 2018 (Barsotti et al. 2018). A web-interface to send SMS to a variety of phone numbers has also been developed and implemented. The SMS is sent to people at IMO, UI and NCIP. Sending a SMS containing key information in a time of crisis is now part of the response process for the person on duty at IMO. Regular tests are done to verify the functionality of the system and to update the SMS-contact list. Recently IMO has invested in hiring a public relations person dedicated to dealing with the inbound and outbound flux of information and requests during a crisis due to natural hazards in Iceland. Part of their role is to liaise with the Iceland Government's National Crisis Coordination Centre press team, which was established during the 2010 Eyjafjallajökull eruption to provide a single voice of information (Bird et al. 2017).

The exercise also revealed improvements that could be made to the operational London VAAC procedures and products. For example, more formal procedures for interaction between the London VAAC forecasters and science support staff during an eruption have been implemented, with pre-scheduled meeting times now arranged that fit within the VAAC's 6-h response cycle. In addition, the exercise exposed issues with the length of commentary text that can be contained in official VAAC advisories, with some becoming truncated during the exercise. Procedures have been updated to ensure that text contents are restricted to the maximum limits.

Lessons learnt in running an exercise

We have gained considerable experience in preparing and running exercises, of which some reflects lessons learnt from exercises in other disciplines, but some is more unique to the volcanological community.

Lesson 1: It is important not to try to accomplish too much in each exercise. It is better to identify a few clear objectives to make sure these aspects are properly tested during the exercise, rather than trying to test many aspects. An emergency response plan can be seen as modular and exercises can be designed to practice only part of it. This was the approach used in the first FUTUREVOLC exercise. It provided a useful building block to not only test a few key procedures, but also gain experience in running a multi-participant exercise. This approach also allowed us to introduce the concept of exercises to those, particularly in the academic community, who were not used to this process. These participants in particular may require more information in advance of the exercise to help them understand their role and what is expected of them.

Lesson 2: Do not under-estimate the time required to build a realistic and consistent scenario for multi-disciplinary datasets, especially when experts from different institutions around the world are involved. Ensuring consistency between the various datasets plays a key role in how the exercise players will respond. Planning for the Katla exercise took ~ 2 months and approximately 1 day was needed to prepare each dataset.

Lesson 3: In addition to preparing data, decisions will be needed in advance regarding the content of any announcements or notifications that are released during the exercise. The relay of these messages during the exercise should be made by the relevant people at the local institutions involved in the exercise, but these contacts should also monitor the progress of the response and intervene, if necessary, to guide or compensate for any misunderstanding or misinformation.

Lesson 4: The start and end times of the exercise are an important consideration. It is important to consider possible different time zones and guarantee a sufficient duration for satisfactory participation. In the Katla exercise, the longer 3-day duration meant that many people, particularly in Iceland, were able to give it their full focus and properly engage during working hours. This long exercise was much more realistic than any other short exercises run in the past, allowing a larger range of multi-agency emergency response to be tested.

Lesson 5: In running an exercise there is a careful balance to be struck between restricting the dissemination of information to only the participants, so as not to cause confusion with the outside world (i.e. non-playing stakeholders and the public), versus testing the full distribution routes and email lists. In the Katla exercise real email distribution lists were not used, which was a disadvantage and led to some artificiality in communication routes. On review by the exercise coordination team, it was identified that this had reduced the exercise realism. Any exercise should be well advertised beforehand via all normal channels of communication, with information on when it will take place, what modes of communications will be used and what the purpose of the exercise is. To prevent any confusion all messages sent out should be labelled "EXERCISE - EXERCISE - EXERCISE", both at the beginning and the end of the message.

Lesson 6: Achieving success from such an exercise requires short and long-term considerations. In the short-term, conducting a review of the exercise is essential. This should be done across the whole participant group, but also within individual institutions as an opportunity to review their own response and procedures during a volcanic crisis. Translating the feedback and exercise outcomes into actions is perhaps the most important step so that lessons are truly learnt. In the longer term, it is important to document and share what has been implemented post-exercise, i.e. demonstrating what has become real. This gives value to the exercise and promotes positive engagement at both the individual and institutional level for future exercises.

Conclusion

The rationale for carrying out exercises such as those presented here is to test both established and new procedures, but also to identify areas where things do not work as expected and can be improved. The FUTUREVOLC project provided the opportunity to practice the response to an eruption in Iceland in much greater depth than the regular monthly exercises and to investigate the important role international scientific collaboration can have in managing a volcanic crisis. The review of the outcomes led to the identification of seven key recommendations for improving response procedures that can be generalised to other volcano observatories and operational contexts within the volcanological community. Based on our experience, we also provide suggestions and guidance for observatories and similar agencies seeking to develop and run exercises.

The paper reveals the importance of participating in inclusive projects that allow a wide view on the topic of responding to an eruption and shows how national and international collaborators can support local institutions that might not have a complete monitoring system. By practising the response to an eruption through multi-agency exercises, the project has helped form long-term collaborative frameworks for better practices and preparedness between organisations. The improvements identified by the FUTUREVOLC exercises have lasted longer than the project lifetime and have become part of the operational response plan at the national scale. This confirms the legacy of such a challenging project and also demonstrates the importance of running exercises, on both small and large scales, within the volcanological community and the benefits of sharing experiences about these.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s13617-019-0091-7.

Additional file 1. Description of the Katla exercise.

Abbreviations

FV: FUTUREVOLC; GPS: Global Positioning System; ICAO: International Civil Aviation Organization; IMO: Icelandic Meteorological Office; InSAR: Interferometric Synthetic Aperture Radar; NCIP: National Commissioner of the Icelandic Police; SAB: Scientific advisory board; UI: University of Iceland, Institute of Earth Sciences; VAAC: Volcanic Ash Advisory Centre;

VOLCICE: Volcanic exercise in Iceland; VONA: Volcano Observatory Notice for Aviation

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Authors' contributions
CW, SB and SD collaboratively wrote the text and led the organisation of the exercises. BO and FS contributed to the implementation of the exercises as part of the FUTUREVOLC project and provided input on the text. All authors read and approved the final manuscript.

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