The current issue and full text archive of this journal is available on Emerald Insight at:
www.emeraldinsight.com/0965-3562.htm

Received 22 September 2019
Revised 29 September 2019
Accepted 8 October 2019

WOVOdat – the global volcano unrest database aimed at improving eruption forecasts

Fidel Costa
Earth Observatory of Singapore, Nanyang Technological University, Singapore and Asian School of the Environment, Nanyang Technological University, Singapore
Christina Widiwijayanti, Thin Zar Win Nang, Erickson Fajiculay and Tania Espinosa-Ortega
Earth Observatory of Singapore, Nanyang Technological University, Singapore, and
Christopher Newhall
Earth Observatory of Singapore, Nanyang Technological University, Singapore and Mirisbiris Garden and Nature Center, Albay, The Philippines

Abstract

Purpose – The purpose of this paper is to highlight the importance of a comprehensive global database on volcanic unrest (WOVOdat) as a resource to improve eruption forecasts, hazard evaluation and mitigation actions.
Design/methodology/approach – WOVOdat is a centralized database that hosts multi-parameter monitoring data sets from unrest and eruption episodes of volcanoes worldwide. Its online interface (https://wovodat.org/) allows interactive data analysis and comparison between volcanoes and eruption styles, which is needed during volcanic crises, as well as to perform basic research on pre-eruption processes, teaching and outreach.
Findings – WOVOdat aims to standardize and organize the myriad of monitoring data types at the global scale. Users can compare changes during a crisis to past unrest episodes, and estimate probabilities of outcomes using evidence-based statistics. WOVOdat will be to volcanology as an epidemiological database is to medicine.
Research limitations/implications – The success of eruption forecast relies on data completeness, and thus requires the willingness of observatories, governments and researchers to share data across the volcano community.
Practical implications – WOVOdat is a unique resource that can be studied to understand the causes of volcanic unrest and to improve eruption forecasting.
Originality/value – WOVOdat is the only compilation of standardized and multi-parameter volcano unrest data from around the world, and it is freely and easily accessible through an online interface.

Keywords Database, Eruption forecast, FAIR data, Volcano unrest

Paper type Research paper

1. Introduction

Volcanoes exhibit various pre-eruption behaviors that can be recorded using monitoring networks (geophysical, geodetical and geochemical) and can be used to anticipate what the volcano will do next. For example, an exponential increase in seismicity has been observed at some volcanoes close to eruption (e.g. Merapi eruption in 2010; Surono *et al.*, 2012). In some cases, deformation also precedes eruptions, although not all inflation episodes terminate in eruption, and not all eruptions show deformation beforehand (e.g. Chaussard *et al.*, 2013). A change in the gas flux and composition has also been reported as a useful tool to anticipate eruptions at volcanoes such as Etna (Aiuppa *et al.*, 2007).

A volcano unrest episode may include different phases or time intervals of increasing or decreasing activity, and each phase can lead to different outcomes (e.g. eruption styles). The most challenging task during volcanic crisis is to interpret the monitoring data, to better anticipate the evolution of the unrest and implement timely mitigation actions (Sobradelo and Martí, 2015). Aside from real time monitoring data, the volcanologist will rely on historical unrest and past eruptions of the same volcano. Such analysis requires the existence of a standardized

Disaster Prevention and Management
Vol. 28 No. 6, 2019
pp. 738-751

0965-3562
DOI 10.1108/DPM-09-2019-0301

and organized database of past events of the same volcano. Moreover, if the volcano has not erupted frequently or is not well studied, volcanologist may wish to consult what has happened at other volcanoes, starting first with WOVOdat and then delving into primary sources as needed. Forecasting of hazardous volcanic phenomena is becoming more quantitative and based on understanding of the physics of the causative processes (Sparks, 2003). At the same time, the field of eruption forecasting is also moving forward as a result of Bayesian Event Tree analysis to reflect multiple possible scenarios and the probability of each scenario (Aspinall *et al.*, 2003; Marzocchi *et al.*, 2007; Lindsay *et al.*, 2010; Sandri *et al.*, 2012; Sobradelo *et al.*, 2014; Newhall and Pallister, 2015). Such forecasts will benefit from comprehensive and authoritative global unrest data sets (Newhall and Pallister, 2015; Costa *et al.*, 2019).

In the recent years, there has been a large increase in the volume of monitoring data sets, with also great advances both in ground-based and remote sensing volcano monitoring (e.g. Segall, 2013; Pyle *et al.*, 2013; Carn *et al.*, 2016; Flower *et al.*, 2016; Hughes *et al.*, 2016; Reath *et al.*, 2016; National Academies of Sciences Engineering and Medicine, 2017). Moreover, data processing and analysis techniques have also been improved and automated (e.g. Beyreuther and Wassermann, 2008; Tamburello, 2015; Coppola *et al.*, 2016). Despite these advances, there are still large disparities on the data standardization between observatories even of the same country, and very few have a database that can be easily accessed and searched from outside that country.

WOVOdat is a unique comprehensive global database on volcanic unrest aimed at improving eruption forecasts. It is an international effort of the World Organization of Volcano Observatories (WOVO), but since 2009, the Earth Observatory of Singapore (EOS) has taken the lead on hosting and developing WOVOdat. It is intended to provide a comprehensive reference to understand pre-, syn- and inter-eruptive processes and to be freely accessible during volcanic crisis (Newhall *et al.*, 2017).

WOVOdat aims to standardize and organize the myriad of monitoring data from various sources and types at the global scale (Venezky and Newhall, 2007). Users will be able to compare changes of unrest in question to the unrest in the past, and estimate probabilities of outcomes using evidence-based statistics. Unrest data are used to anticipate whether an eruption is likely to occur, estimate the possible outcome and its hazards, and implement timely mitigation actions. Reference to WOVOdat is especially useful at volcanoes that have not erupted in historical or "instrumental" time and for which no previous data exist, because WOVOdat will likely contain data from analogous volcanoes. Even for volcanoes that may erupt often and for which there is an existing monitoring database, it is critical to have access to a global unrest data, since volcanoes can change their behavior from one eruption to the next.

WOVOdat has developed a stand-alone local host monitoring database system, that is currently operational and being used in PHIVOLCS (the Philippines), CVGHM (Indonesia), RVO (Papua New Guinea) and NIED (Japan). In the rest of the paper, we describe the data structure, sources and contributions and provide a couple of examples of applications. More details can be found in Newhall *et al.* (2017) and www.wovodat.org.

2. Database system and online interface

2.1 Database system and data sources

More than 1,600 Holocene volcanoes worldwide have produced around 10,000 known eruptions (Smithsonian Institution, 2013), but only a small fraction of those eruptions have been monitored. We estimate that there are ~2,700 eruptions after 1950 for which at least have been monitored by one instrument. Currently there are ~900 episodes of pre-eruptive unrest with monitoring data already archived into WOVOdat, which amounts to 30 percent of the global total. Of those 900 unrest data sets, about 55 percent are from observatories, 15 percent from research projects, 10 percent from open catalogues and the rest of 20 percent are from the published literature. The four largest potential data contributors in terms of eruptive episodes by country are Indonesia, Japan, USA and Russia (Figure 1).

WOVOdat stores collective records of multi-parameters instrumental and observational data that reflect changes in seismicity, ground deformation, gas emission and any other observable that are above their normal baselines. Multi-parameter data are held and used in most volcano observatories, and global compilations have been made of individual types of monitoring data, e.g., seismic, or deformation, or gas, but only in WOVOdat are multi-parameter data brought together from around the world and made easily accessible on common timescales, in side-by-side comparisons. Maintaining consistency of data is important for comparative studies between unrest episodes, therefore data have been archived following standard formats and complemented with its metadata to capture data quality and accuracy.

The database is created following the structure and format described in the WOVOdat 1.0 report (Venezky and Newhall, 2007), updated in WOVOdat 1.1 (https://wovodat.org/doc/database/1.1/index.php). The volcano table is the center point of the data structure from which all other data can be linked. Monitoring data are generally linked from the station where the data were collected, to the network of stations, and to the volcano (Figure 2). The data are managed with MySQL, an open source relational database management system (RDBMS) for web-based application. The hierarchical database allows connection between each data entity, e.g. seismicity and deformation time series from different station can be interconnected with eruption phases and alert levels.

The main activity of the WOVOdat project (as of 2019) is data population, and the objective is to include all processed data of historical unrest from all reliable sources, including but not limited to that which led to eruption. Fields include monitoring data and metadata, the eruption chronology from the early stages of unrest, throughout the eruption and return back to normal level. In addition, the database contains volcano background information, monitoring metadata and supporting data such as reports, images, maps and videos, as well as the alert levels issued were applicable (e.g. Winson *et al.*, 2014). Nearly all data in WOVOdat are time-stamped and geo-referenced, so that they can be analyzed in both space and time. The full coverage and detail of the data set are needed so that they can be used for forecasting both eruptions and non-eruptive outcomes.

The ownership of data in WOVOdat remains with the individuals and organizations that originally collected the data. Active data that are younger than a two-year grace period are generally not available, because they might still be in use by observatories and other contributors. WOVOdat welcomes any volcano monitoring data, but it respects the

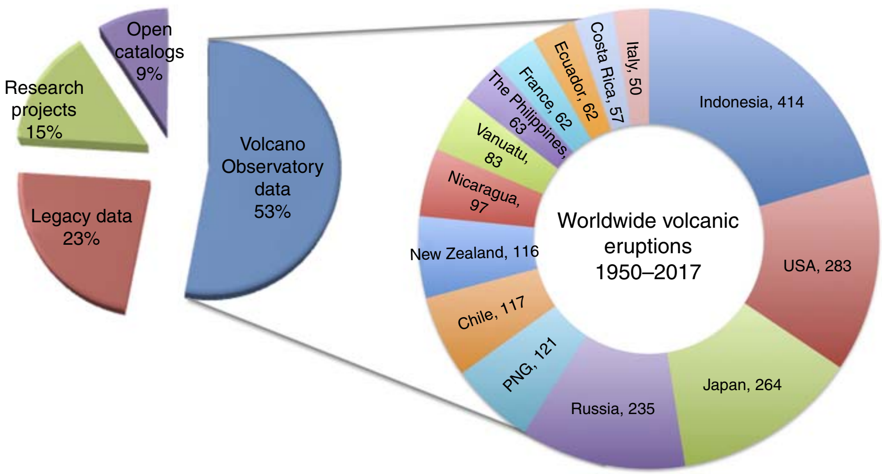
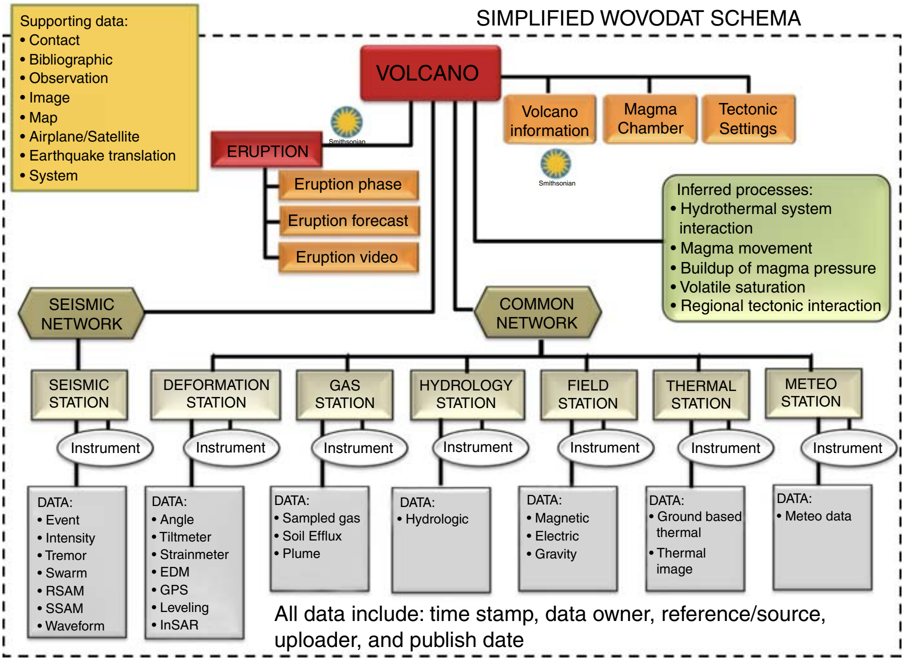


Figure 1.
Estimated number of unrest episodes for the 14 largest country contributors that could be archived in WOVOdat, based on numbers of known eruptions (Smithsonian Institution, 2013) or other episodes of unrest from 1950 to 2017



Notes: WOVOdat is organized in a MySQL hierarchical relational database management system where all available data in a specific volcano will be linked through "*volcano*" as the parent table. Data are recorded first at stations then can be linked to specific unrest/eruption through volcano. WOVOdat stores mainly processed historical unrest data where nearly all data will be time-stamped and geo-referenced, so that they can be studied in both space and time

Figure 2. Type of data stored in the WOVOdat database and the hierarchy of the data management

prerogative of those who collected the data to have first option in interpretation and publication. The data policy provides rules and guidelines on the usage of data, and all users agree to abide by the terms of the data use agreement. To give proper credit to data contributors and to be able trace back to original source of the data, all data in the database also link to data owner, data uploader, published date and bibliographic references.

WOVOdat refers to and links with various open access databases and catalogues that provide a variety types of related data, e.g. the Smithsonian's Volcanoes of the World (VOTW, Siebert *et al.*, 2010; Smithsonian Institution, 2013) database as primary source of description of volcanoes and historical eruptions, Japan Meteorological Agency (JMA) provides National catalogue of active volcanoes in Japan, Alaska Volcano Observatory (AVO) provides Alaska volcano information, historical eruptions and geochemistry (Cameron *et al.*, 2014), GNS Science provides volcano monitoring data in New Zealand, UNAVCO provides geodetic data. Databases for specific types of data such as InSAR (e.g. Fournier *et al.*, 2010; COMET project; Biggs *et al.*, 2014; Ebmeier *et al.*, 2018; https://volcanodeformation.blogs.ilrt.org/), lava dome growth (DomeHaz; Ogburn *et al.*, 2015) and volcanic gas emissions (Carn *et al.*, 2016; DECADE project; Clor *et al.*, 2013).

2.2 On-line interactive interface

Along with creating a database on volcanic unrest, WOVOdat team are also developing interactive web-application tools to help users to query, visualize and analyze data, which further can be used for probabilistic eruption forecasting. Web Interface is on continuous development to support interaction between WOVOdat developers, observatories, and other partners in building the database, accessing documents, submitting data, visualize and query the data (Figure 3).

The main visualization tool in WOVOdat enables comparison of processed monitoring data, e.g., earthquake hypocenters, displacements and gas flux time series from different episodes of unrest from a single volcano, or between two different but analogous volcanoes. Using "Single volcano view" or "Side by side comparison" visualization menu (Figure 4), it is possible to plot multi-parameter monitoring data sets in one stack of graphs on the same time scale, which allow to track the progress of the past unrest toward eruption. The "Temporal evolution of unrest" menu allows plotting changes in monitoring data through time and synchronically correlates it with the manifestation of the unrest (termed as eruption phases; e.g. phreatic explosion, dome extrusion, explosion, etc.) and alert level changes (Figure 5).

A Boolean search tool allows the user to query specific volcano information, and its eruptions and retrieve available monitoring data related to a specified eruption time. These search results can then also be displayed in an interactive time-series visualization of eruption phases, alert level information and monitoring data related to the eruption.

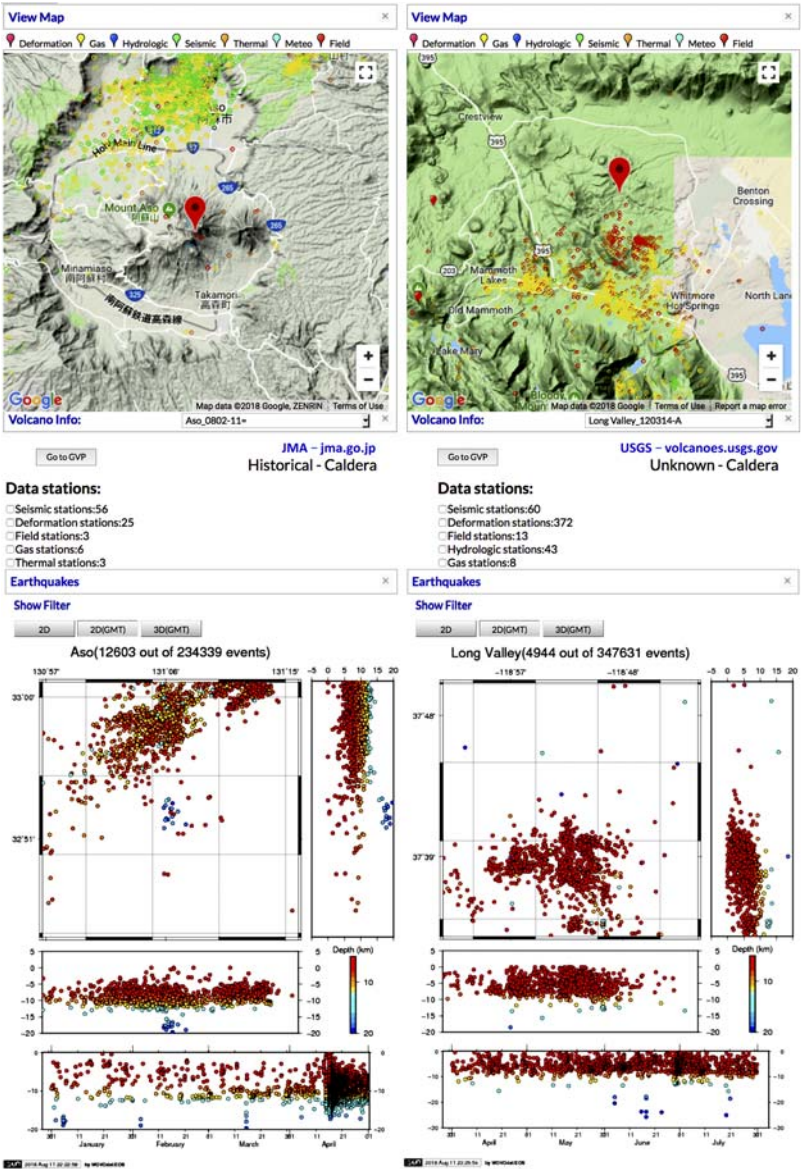
We have also created "WOVOdat analytics tools" (Fajiculay *et al.*, 2017), a user-friendly web application of various statistical and Machine Learning algorithms that allow users to perform analysis of temporal and spatial monitoring data e.g. seismic counts, gas emission rate, tiltmeter, GPS, seismic events, etc. The tools also allow users to perform post-processing procedures interactively to the data, e.g. inverse and logarithmic function, first or second derivatives, time averaged, cumulative value over time, trend analysis, etc.

With data analytics, we should be able to find the most diagnostic unrest indicators, and identify precursory patterns for different eruptive styles. When a volcano is entering a new unrest episode, one can compare it with previously known diagnostic patterns (e.g. Potter *et al.*, 2015), to estimate probabilities of how the unrest will evolve, whether an eruption is likely to occur, and its outcome. The more complete the data, the better evidence-based statistical results will be, and thus improving forecasting accuracy.

2.3 Stand-alone package

In addition to the web-based version of WOVOdat, we have also developed a standalone package, an open source system, that is freely available for observatories that wish to adopt it

Figure 3.
Screenshot of WOVOdat (https://wovodat.org/) main webpage with main menus and tools



Notes: Data compiled from JMA seismological bulletin (www.data.jma.go.jp/svd/eqev/data/bulletin/index_e.html) and NCEDC earthquake catalog (http://www.ncedc.org/ncedc/catalog-search.html)

Figure 4. Example of side by side comparisons of geographic settings and seismicity for two different episodes of caldera unrest: Aso-Japan (1 January – 1 May 2016) and Long Valley-USA (1 March – 1 July 1992)

and develop their own database. WOVOdat provides a ready installable MySQL database template as well as open source interactive tools for users to submit, query, visualize and mining data with objectives to have efficient and systematic data archiving system. This allows interactive retrieval and display of historical and current data, including synchronized time plots of changes in various parameters, as well as comparisons of unrest within or

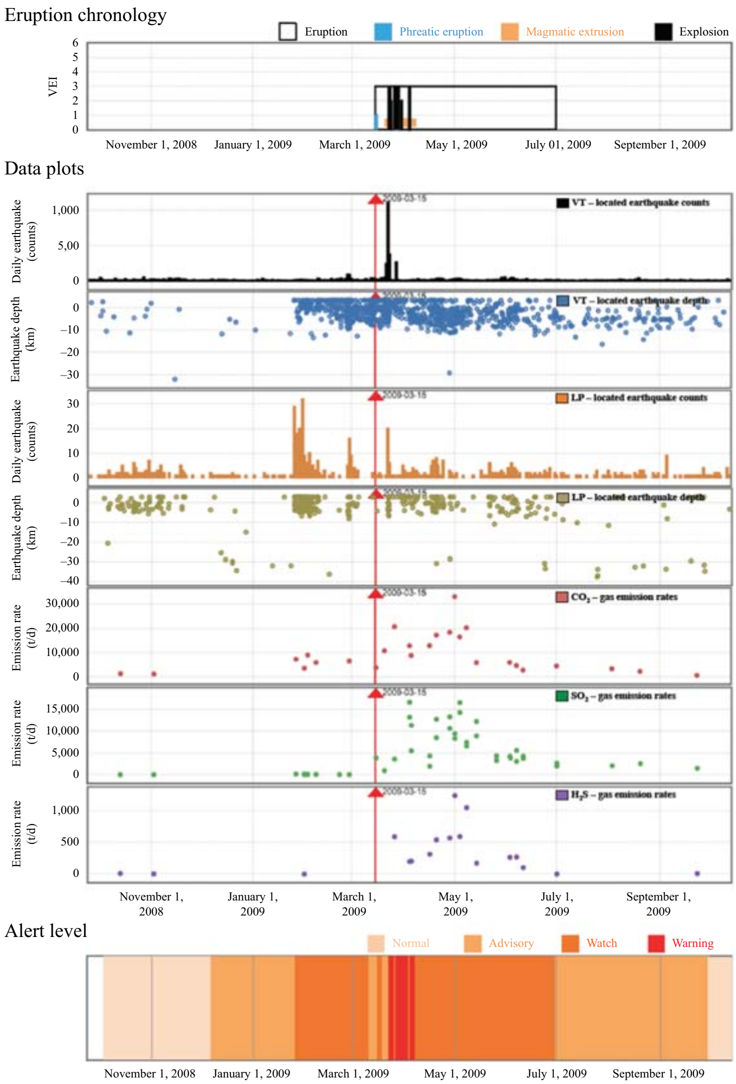


Figure 5.
An example of a complete unrest episode, covering pre-, syn-, and post-eruption of Redoubt in 2008-2009, started from normal and returned back to normal alert level

Notes: The evolving unrest of Redoubt 2009 covering eruption chronology represented by different eruption phases, alert level changes, with the corresponding spatio-temporal seismicity (swarm) and gas emission rates. Unrest spanning small ash-and steam explosion (March 15, 2009); lava effusion (March 22 –23) accompanied by intermittent explosions (March 23rd –April 4th). Extrusion ceased on April 6th. Data compiled from Dixon *et al.,* 2010; Dixon *et al.,* 2011; Lopez *et al.,* 2013; Werner *et al.,* 2012; Werner *et al.,* 2013

between analogous volcanoes. This is in part to better communicate to the community how the database can be effectively used and thus increase the openness of observatories to data submissions. The WOVOdat standalone version has been already adopted by PHIVOLCS (the Philippines), CVGHM (Indonesia), RVO (Papua New Guinea) and NIED (Japan).

3. The use/application of WOVOdat

WOVOdat is primarily for organizing, archiving and serving the data of volcanic unrest and gleaning insights useful for eruption forecasting. In addition, it can be used for primary and secondary school learning about what volcano monitoring is and how it can be used to anticipate eruptions, research projects in academia, research and forecasting in observatories and research on data analytics. Some examples of applications are given below.

3.1 WOVOdat platform as monitoring data management system

The WOVOdat project aims at collating worldwide unrest data, so it was designed as an efficient RDBMS. It enables the creation and administration of vast amounts of multi-parameter monitoring data that is stored in tabular format with rows and columns. It also provides easy access through web application. Such a capacity and versatility make it ideal for any new institution who wishes to develop a monitoring database to adopt it at the local host level. In addition to storing and administering multiparametric monitoring data, WOVOdat structure allows integrating across diverse data formats and into common standards to drive greater data availability, provide easy access and visual interactive capabilities. Streamline data access facilitates efficient queries, allows creating correlation between data through time and space. The recent advancement of data science, leveraging the power of Machine Learning and Open Source tools will allow faster data analysis, finding trends and patterns, improve the quality of information. This should allow a data-driven volcano community to better understand volcanic processes and improve eruption forecasts for decision optimization.

3.2 Comparative studies

During crisis response at a volcano with no or insufficient historical data about prior unrest, it is helpful to access and interrogate historical unrest at other similar (analogous) volcanoes or unrest with similar characteristics (analogous unrest). This should be able to better evaluate the likely outcome of an impending eruption (e.g. Sparks, 2003; Newhall *et al.*, 2017).

The difficulty of interpreting volcanic unrest is especially notable in calderas, where many episodes of unrest rarely lead to eruption. Calderas are considered among the most complex and dangerous volcanoes, yet very few episodes of past unrest were monitored instrumentally and even fewer led to eruption, so our ability to systematically archive data related to worldwide caldera unrest is very important. There are more than 440 calderas worldwide, 97 of them have been active during the Holocene (Newhall and Dzurisin, 1988; Geyer and Martí, 2008; Sobradelo *et al.*, 2010; Siebert *et al.*, 2010). From a review of the known unrest at calderas from 1988 to 2014 (Acocella *et al.*, 2015), it appears most of their unrest episodes are increases in seismicity (swarm), surface deformation, gravity changes and degassing. Although most caldera unrest does not lead to an eruption, nearly every eruption is preceded by unrest. To explore this case we can use WOVOdat's "side by side comparisons" visualization tool that allows plotting of the geographical distribution and depth of seismicity (Figure 4). We can compare the effect of a tectonic earthquake on two different caldera systems. In one example, the 2016 Kumamoto earthquake sequence involved three large events (Mw⩾6.2 on April 14–16, 2016) and produced dynamic triggering of seismicity in Aso caldera (JMA seismological bulletin, www.data.jma.go.jp/svd/eqev/data/bulletin/index_e.html) with a spatial gap around Aso (Uchide *et al.*, 2016). Aso volcano was already having small eruptions during this period, and in April 16–30 there were additional ash explosions following the regional earthquakes, perhaps pointing to a causal relation between the two phenomena. In a contrasting second example, immediately after the June 28, 1992 Mw 7.3 Landers earthquake, Long Valley (USA) 400 km to the north increased seismicity (Northern California Earthquake Data Center' earthquake catalog, https://ncedc.org/) and showed volumetric strain suggesting increased pressure from rising bubbles as a mechanism for remotely triggered seismicity (Linde *et al.*, 1994). The Landers earthquake also triggered caldera uplift up to ~5 mm in the six days following the earthquake (Hill, 2006), but in this case no eruptions or explosions occurred. The database schema of WOVOdat also includes an Inferred Processes table to store historical (in most cases from the peer reviewed literature) inferences about processes causing volcanic unrest that include hydrothermal system interaction, magma movement, buildup magma pressure, volatile saturation and regional tectonic interaction. When used with due caution, these inferences can be useful keywords or pointers to comparable processes at various volcanic systems, such as discussed in the two examples above (Figure 4).

3.3 Understanding evolving unrest

WOVOdat can interactively display the locations of monitoring stations, hypocenter maps and profiles and time-series plots of user-selected parameters (Figure 5). The temporal changes in monitoring data can be annotated with the onset of eruption, individual phases of eruptions and alert level.

As an example of how WOVOdat can be used to visualize the chronology of events related to an eruption, we report the sequence at Redoubt volcano in 2009 (Figure 5), including eruption phases (Bull *et al.*, 2012), alert level changes (Bull *et al.*, 2012), spatiotemporal seismic swarms (AVO catalog, Dixon and Stihler, 2009; Dixon *et al.*, 2010, 2011) and gas emission rates (Werner *et al.*, 2012, 2013; Lopez *et al.*, 2013).

Redoubt has been used as an example of a volcano that could reawaken quickly (Power *et al.*, 2013). The 2009 eruption of Redoubt Volcano shares many similarities with eruptions documented most recently at Redoubt in 1966–1968 and 1989–1990 (Bull *et al.*, 2012). The earliest precursors to both 1989–1990 and 2009 eruptions were subtle and included increased gas emission, heat flux, and snow melt in the summit crater and ground deformation in 2008 (Miller, 1994; Gardner *et al.*, 1994; Power *et al.*, 1994; Bull and Buurman, 2013; Grapenthin *et al.*, 2013). The 2009 eruption was preceded by a marked increase in deep long-period (DLP) events at 28–35 km depth that began roughly 2.5 months before the onset of magmatic explosions (Power *et al.*, 2013). This corresponds with the initial appearance of CO_2 gas emissions (Werner *et al.*, 2013), before SO_2 emission that appeared following the phreatic explosion on March 15, 2009. The onset of magmatic explosions on March 22 was preceded by a strong, shallow swarm of repetitive earthquakes that began less than three days before an explosion. Lava effusion (March 22–23) accompanied by intermittent explosions (March 23 to April 4) until the extrusion finally ceased on April 6. The occurrence of precursory DLP events suggests that the 2009 eruption may have involved the rise of magma from lower crustal depths, a diffuse magma source region at 25–38 km depth. Future monitoring programs should be designed to capture seismicity in this depth range (Power *et al.*, 2013). Close tracking of seismic activity allowed the AVO to successfully issue warnings prior to many of the hazardous explosive events that occurred in 2009 (Bull *et al.*, 2012; Power *et al.*, 2013).

The spatio-temporal visualization allows user to look for systematic relations between unrest and eruptive style and address questions such as:

- On average, how many cases of phreatic eruption will be followed by magmatic eruption within a month? How many of those will become plinian eruptions?
- What multi-parameter data will serve as indicators for changes in the style of eruption, or when an eruption has ended?
- What parameters will be the best indicators in changing alert levels (up if unrest is heading toward more significant eruption or down if it is waning or ending).

3.4 Pattern recognition applications

As the database grows more complete, users will be able to analyze patterns of unrest in the same way that epidemiologists study the spatial and temporal patterns and associations among diseases. The multi-parameter monitoring data sets considered here documented the variations in the geophysical, geochemical and geodetic signals from a volcano normal state (baseline level) and throughout the unrest. We termed as "unrest indicators" those which defined quantifiable changes, as threshold value and/or rate variation for interpreting unrest. Compiling indicators from past episodes of unrest at a single volcano or at similar volcanoes can be used as statistical evidence to estimate the outcome probability of any new unrest.

Potentially, more than a century's worth of volcano monitoring data could be studied in the same way that epidemiologists study the occurrence, symptoms and origins of disease. A whole new field of volcano epidemiology awaits, and we anticipate that it will significantly improve eruption forecasts as well as address a variety of research questions. For example, a volcanologist responding to a crisis will usually ask, "Where has unrest like (the present) been seen before, and what happened?" Statistics of previous outcomes might be used in probabilistic event trees.

4. Current priorities in WOVOdat

(1) Promote active participation of volcano observatories on developing their local host unrest database using WOVOdat standard and schema, which will link to their operational (real time) monitoring system. This will allow observatory staff to explore unrest pattern at their volcano, and use the knowledge of past unrest to evaluate the unrest in question and to forecast its further course. This experience also helps to systematically archive and preserve the unrest data, and to optimize or improve the use of WOVOdat analytics tools.

(2) Populate, populate and populate. The success of eruption forecasts depends significantly on data completeness. The more data in WOVOdat, the more useful it will be. We actively solicit data contributions from volcano observatories, government institutions and individual researchers and projects to agree on data sharing and enable Findable, Accessible, Interoperable and Reusable (FAIR) data across the volcano community. WOVOdat also welcomes automatic data upload, data analytics tools and scripts that will optimize the Boolean search engine and data display.

(3) Develop examples of uses of the database for anticipation of volcanic eruptions using probability theory and event trees (e.g. Newhall and Pallister, 2015), and machine learning methods to find analog volcanoes and eruptions (e.g. Fajiculay *et al.*, 2017).

Acknowledgments

We thank the USGS/USAID Volcano Disaster Assistance Program (C. Dan Miller, J. Pallister) for seed funding to get WOVOdat going, and to the Earth Observatory of Singapore (K. Sieh, Director) for major funding to turn the concept into reality. Other colleagues that are contributing or have contributed to WOVOdta on various ways include Jacopo Selva, Warner Marzocchi, Paolo Papale, Giuseppe Puglisi and Danilo Reitano (INGV); Florian Schwandner (ETH, NTU and currently at JPL), Eisuke Fujita and Hideki Ueda (NIED); Renato Solidum, Mariton Bornas, Maricel Capa, Jane Catapang (PHIVOLCS); Kasbani, Mochammad Hendrasto, Hendra Gunawan, Agus Budisantoso, IGMA Nandaka, Hanik Humaida (CVGHM); Noritake Nishide, Satoshi Harada, Hitoshi Yamasato, Takeshi Koizumi, Yohko Igarashi, Koji Kato, Yoshiaki Fujiwara (JMA); Sarah Ogburn, Stephanie Prejean, Jeremy Pesicek (VDAP), Nico Fournier, Gill Jolly (GNS); Shinji Takarada and Joel Bandibas (GSJ); Freysteinn Sigmundsson (University of Iceland) and Kristin Vogfjord (IMO), Simon Carn and Verity Flower (MTU), Matt Pritchard (Cornell), Juliet Biggs, Steve Sparks and Jo Gottsmann (Univ of Bristol), Steve Malone (Univ of Washington), Steve McNutt (University of South Florida); Tom Simkin, Jim Luhr, Lee Siebert, Paul Kimberly, Ed Venzke, Liz Cottrell, and Ben Andrews (Smithsonian); and Chuck Merteens (UNAVCO). We also thank Sue Loughlin (BGS) for highlighting the opportunity to contribute to this report.

References

Acocella, V., Di Lorenzo, R., Newhall, C. and Scandone, R. (2015), “An overview of recent (1988 to 2014) caldera unrest: knowledge and perspectives”, *Reviews of Geophysics*, Vol. 53 No. 3, pp. 896-955.

Aiuppa, A., Moretti, R., Federico, C., Giudice, G., Gurrieri, S., Liuzzo, M., Papale, P., Shinohara, H. and Valenza, M. (2007), “Forecasting Etna eruptions by real-time observation of volcanic gas composition”, *Geology*, Vol. 35 No. 12, pp. 1115-1118.

Aspinall, W.P., Woo, G., Voight, B. and Baxter, P.J. (2003), “Evidence-based volcanology: application to eruption crises”, *Journal of Volcanology and Geothermal Research*, Vol. 128 Nos 1-3, pp. 273-285.

Beyreuther, M. and Wassermann, J. (2008), “Continuous earthquake detection and classification using discrete Hidden Markov Models”, *Geophysical Journal International*, Vol. 175 No. 3, pp. 1055-1066.

Biggs, J., Ebmeier, S.K., Aspinall, W.P., Lu, Z., Pritchard, M.E., Sparks, R.S.J. and Mather, T.A. (2014), “Global link between deformation and volcanic eruption quantified by satellite imagery”, *Nature Communications*, Vol. 5 No. 1, doi:10.1038/ncomms4471.

Bull, K.F. and Buurman, H. (2013), “An overview of the 2009 eruption of Redoubt Volcano, Alaska”, *Journal of Volcanology and Geothermal Research*, Vol. 259, pp. 2-15.

Bull, K.F., Cameron, C., Coombs, M.L., Diefenbach, A., Lopez, T., McNutt, S., Neal, C., Payne, A., Power, J.A., Schneider, D.J., Scott, W.E., Snedigar, S., Thompson, G., Wallace, K., Waythomas, C.F., Webley, P. and Werner, C.A. (2012), “The 2009 Eruption of Redoubt Volcano, Alaska”, in Schaefer, J.R. (Ed.), *Report of Investigations of the Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys 2011-5*, Department of Natural Resources, State of Alaska, 45pp., available at: http://pubs.er.usgs.gov/publication/70007150

Cameron, C.E., Snedigar, S.F. and Nye, C.J. (2014), “Alaska volcano observatory geochemical database, Alaska division of geological & geophysical surveys digital data series 8”, available at: https://doi.org/10.14509/29120 (accessed October 19, 2016).

Carn, S.A., Clarisse, L. and Prata, A.J. (2016), “Multi-decadal satellite measurements of global volcanic degassing”, *Journal of Volcanology and Geothermal Research*, Vol. 311, pp. 99-134.

Chaussard, E., Amelung, F. and Aoki, Y. (2013), “Characterization of open and closed volcanic systems in Indonesia and Mexico using InSAR time series”, *Journal of Geophysical Research: Solid Earth*, Vol. 118 No. 8, pp. 3957-3969.

Clor, L.E., Fischer, T.P., Lehnert, K.A., McCormick, B. and Hauri, E.H. (2013), “A new comprehensive database of global volcanic gas analyses”, *American Geophysical Union, Fall Meeting, V13A-2587, AGU*, San Francisco, December, available at: https://ui.adsabs.harvard.edu/abs/2013AGUFM.V13A2587C

Coppola, D., Laiolo, M., Cigolini, C., Donne, D.D. and Ripepe, M. (2016), “Enhanced volcanic hot-spot detection using MODIS IR data: results from the MIROVA system”, *Geological Society*, Vol. 426 No. 1, pp. 181-205.

Costa, F., Widiwijayanti, C. and Humaida, H. (2019), “Data from past eruptions could reduce future Volcano Hazards”, *Eos*, Vol. 100, available at: https://doi.org/10.1029/2019EO118941

Dixon, J.P. and Stihler, S.D. (2009), "Catalog of earthquake hypocenters at Alaskan volcanoes: January 1 through December 31, 2008, U.S. geological survey data series 467", available at: https://doi.org/10.3133/ds467 (accessed June 22, 2016).

Dixon, J.P., Stihler, S.D., Power, J.A. and Searcy, C.K. (2010), "Catalog of earthquake hypocenters at Alaskan volcanoes: January 1 through December 31, 2009, U.S. geological survey data series 531", available at: https://doi.org/10.3133/ds531 (accessed June 22, 2016).

Dixon, J.P., Stihler, S.D., Power, J.A. and Searcy, C.K. (2011), "Catalog of earthquake hypocenters at Alaskan volcanoes: January 1 through December 31, 2010, U.S. geological survey data series 645", available at: https://doi.org/10.3133/ds645 (accessed June 22, 2016).

Ebmeier, S.K., Andrews, B.J., Araya, M.C., Arnold, D.W.D., Biggs, J., Cooper, C., Cottrell, E., Furtney, M., Hickey, J., Jay, J., Lloyd, R., Parker, A.L., Pritchard, M.E., Robertson, E., Venzke, E. and Williamson, J.L. (2018), "Synthesis of global satellite observations of magmatic and volcanic deformation: implications for volcano monitoring & the lateral extent of magmatic domains", *Journal of Applied Volcanology*, Vol. 7 No. 1, p. 2.

Fajiculay, E., Win, N.T.Z., Widiwijayanti, C., Costa, F., Newhall, C.G. and Ratdomopurbo, A. (2017), "Improving WOVOdat online tools for eruption forecasts", IAVCEI General Assembly, Portland, OR.

Flower, V.J.B., Oommen, T. and Carn, S.A. (2016), "Improving global detection of volcanic eruptions using the Ozone Monitoring Instrument (OMI)", *Atmospheric Measurement Techniques*, Vol. 9 No. 11, pp. 5487-5498.

Fournier, T.J., Pritchard, M.E. and Riddick, S.N. (2010), "Duration, magnitude, and frequency of subaerial volcano deformation events: new results from Latin America using InSAR and a global synthesis", *Geochemistry, Geophysics, Geosystems*, Vol. 11 No. Q01003, available at: https://doi.org/10.1029/2009GC002558

Gardner, C.A., Neal, C.A., Waitt, R.B. and Janda, R.J. (1994), "Proximal pyroclastic deposits from the 1989–1990 eruption of Redoubt Volcano, Alaska – stratigraphy, distribution, and physical characteristics", *Journal of Volcanology and Geothermal Research*, Vol. 62 No. 1, pp. 213-250.

Geyer, A. and Martí, J. (2008), "The new worldwide collapse caldera database (CCDB): a tool for studying and understanding caldera processes", *Journal of Volcanology and Geothermal Research*, Vol. 175 No. 3, pp. 334-354.

Grapenthin, R., Freymueller, J.T. and Kaufman, A.M. (2013), "Geodetic observations during the 2009 eruption of Redoubt Volcano, Alaska", *Journal of Volcanology and Geothermal Research*, Vol. 259, pp. 115-132.

Hill, D.P. (2006), "Unrest in Long Valley Caldera, California, 1978–2004", *Geological Society*, Vol. 269 No. 1, pp. 12-24.

Hughes, E.J., Yorks, J., Krotkov, N.A., da Silva, A.M. and McGill, M. (2016), "Using CATS near-real-time lidar observations to monitor and constrain volcanic sulfur dioxide (SO 2) forecasts", *Geophysical Research Letters*, Vol. 43 No. 20, pp. 11089-11097.

Linde, A.T., Sacks, I.S., Johnston, M.J.S., Hillt, D.P. and Bilham, R.G. (1994), "Increased pressure from rising bubbles as a mechanism for remotely triggered seismicity", *Nature*, Vol. 371 No. 6496, pp. 408-410.

Lindsay, J., Marzocchi, W., Jolly, G., Constantinescu, R., Selva, J. and Sandri, L. (2010), "Towards real-time eruption forecasting in the Auckland volcanic field: application of BET_EF during the New Zealand national disaster exercise 'Ruaumoko' ", *Bulletin of Volcanology*, Vol. 72 No. 2, pp. 185-204.

Lopez, T., Carn, S., Werner, C., Fee, D., Kelly, P., Doukas, M., Pfeffer, M., Webley, P., Cahill, C. and Schneider, D. (2013), "Evaluation of Redoubt Volcano's sulfur dioxide emissions by the ozone monitoring instrument", *Journal of Volcanology and Geothermal Research*, Vol. 259, pp. 290-307.

Marzocchi, W., Sandri, L. and Selva, J. (2007), "BET_EF: a probabilistic tool for long- and short-term eruption forecasting", *Bulletin of Volcanology*, Vol. 70 No. 5, pp. 623-632.

Miller, T.P. (1994), "Dome growth and destruction during the 1989–1990 eruption of redoubt volcano", *Journal of Volcanology and Geothermal Research*, Vol. 62 No. 1, pp. 197-212.

National Academies of Sciences Engineering and Medicine (2017), *Volcanic Eruptions and their Repose, Unrest, Precursors, and Timing, Volcanic Eruptions and their Repose, Unrest, Precursors, and Timing*, National Academies Press, Washington, DC, available at: https://doi.org/10.17226/24650

Newhall, C.G. and Dzurisin, D. (1988), "Historical unrest at large calderas of the world, US geological survey bulletin No. 1855", available at: https://doi.org/10.3133/b1855

Newhall, C.G. and Pallister, J.S. (2015), "Using multiple data sets to populate probabilistic volcanic event trees", in Shroder, J.F. and Papale, P. (Eds), *Volcanic Hazards, Risks and Disasters*, Elsevier, Boston, pp. 203-232.

Newhall, C.G., Costa, F., Ratdomopurbo, A., Venezky, D.Y., Widiwijayanti, C., Win, N.T.Z., Tan, K. and Fajiculay, E. (2017), "WOVOdat – an online, growing library of worldwide volcanic unrest", *Journal of Volcanology and Geothermal Research*, Vol. 345, pp. 184-199.

Ogburn, S.E., Loughlin, S.C. and Calder, E.S. (2015), "The association of lava dome growth with major explosive activity (VEI $\geqslant$ 4): DomeHaz, a global dataset", *Bulletin of Volcanology*, Vol. 77 No. 5, available at: https://doi.org/10.1007/s00445-015-0919-x

Potter, S.H., Scott, B.J., Jolly, G.E., Neall, V.E. and Johnston, D.M. (2015), "Introducing the Volcanic Unrest Index (VUI): a tool to quantify and communicate the intensity of volcanic unrest", *Bulletin of Volcanology*, Vol. 77 No. 9, available at: https://doi.org/10.1007/s00445-015-0957-4

Power, J.A., Stihler, S.D., Chouet, B.A., Haney, M.M. and Ketner, D.M. (2013), "Seismic observations of Redoubt Volcano, Alaska – 1989-2010 and a conceptual model of the Redoubt magmatic system", *Journal of Volcanology and Geothermal Research*, Vol. 259, pp. 31-44, available at: https://doi.org/10.1016/j.jvolgeores.2012.09.014

Power, J.A., Lahr, J.C., Page, R.A., Chouet, B.A., Stephens, C.D., Harlow, D.H., Murray, T.L. and Davies, J.N. (1994), "Seismic evolution of the 1989–1990 eruption sequence of Redoubt Volcano, Alaska", *Journal of Volcanology and Geothermal Research*, Vol. 62 Nos 1-4, pp. 69-94.

Pyle, D.M., Mather, T.A. and Biggs, J. (2013), "Remote sensing of volcanoes and volcanic processes: integrating observation and modelling – introduction", *Geological Society*, Vol. 380 No. 1, pp. 1-13.

Reath, K.A., Ramsey, M.S., Dehn, J. and Webley, P.W. (2016), "Predicting eruptions from precursory activity using remote sensing data hybridization", *Journal of Volcanology and Geothermal Research*, Vol. 321, pp. 18-30.

Sandri, L., Jolly, G., Lindsay, J., Howe, T. and Marzocchi, W. (2012), "Combining long- and short-term probabilistic volcanic hazard assessment with cost-benefit analysis to support decision making in a volcanic crisis from the Auckland Volcanic Field, New Zealand", *Bulletin of Volcanology*, Vol. 74 No. 3, pp. 705-723.

Segall, P. (2013), "Volcano deformation and eruption forecasting", *Geological Society*, Vol. 380 No. 1, pp. 85-106.

Siebert, L., Simkin, T. and Kimberly, P. (2010), *Volcanoes of the World*, 3rd ed., University of California Press, Berkeley, CA, available at: www.jstor.org/stable/10.1525/j.ctt1pnqdx

Smithsonian Institution (2013), "Global volcanism program | regional volcanoes", in Venzke, E. (Ed.), *Volcanoes of the World, v. 4.6.7*, Smithsonian institution, Washington, DC, available at: https://doi.org/https://dx.doi.org/10.5479/si.GVP.VOTW4-2013 (accessed April 10, 2018).

Sobradelo, R. and Martí, J. (2015), "Short-term volcanic hazard assessment through Bayesian inference: retrospective application to the Pinatubo 1991 volcanic crisis", *Journal of Volcanology and Geothermal Research*, Vol. 290, pp. 1-11.

Sobradelo, R., Bartolini, S. and Martí, J. (2014), "HASSET: a probability event tree tool to evaluate future volcanic scenarios using Bayesian inference", *Bulletin of Volcanology*, Vol. 76 No. 1, pp. 1-15, available at: https://doi.org/10.1007/s00445-013-0770-x

Sobradelo, R., Geyer, A. and Martí, J. (2010), "Statistical data analysis of the CCDB (Collapse Caldera Database): insights on the formation of caldera systems", *Journal of Volcanology and Geothermal Research*, Vol. 198 Nos 1-2, pp. 241-252.

Sparks, R.S.J. (2003), "Forecasting volcanic eruptions", *Earth and Planetary Science Letters*, Vol. 210 Nos 1-2, pp. 1-15.

Surono, Jousset, P., Pallister, J., Boichu, M., Buongiorno, M.F., Budisantoso, A., Costa, F., Andreastuti, S., Prata, F., Schneider, D., Clarisse, L., Humaida, H., Sumarti, S., Bignami, C., Griswold, J., Carn, S., Oppenheimer, C. and Lavigne, F. (2012), "The 2010 explosive eruption of Java's Merapi volcano – a '100-year' event", *Journal of Volcanology and Geothermal Research*, Vols 241-242, pp. 121-135.

Tamburello, G. (2015), "Ratiocalc: software for processing data from multicomponent volcanic gas analyzers", *Computers & Geosciences*, Vol. 82, pp. 63-67.

Uchide, T., Horikawa, H., Nakai, M., Matsushita, R., Shigematsu, N., Ando, R. and Imanishi, K. (2016), "The 2016 Kumamoto–Oita earthquake sequence: aftershock seismicity gap and dynamic triggering in volcanic areas", *Earth, Planets and Space*, Vol. 68 No. 180, available at: doi:10.1186/s40623-016-0556-4

Venezky, D.Y. and Newhall, C.G. (2007), "WOVOdat design document: the schema, table descriptions, and create table statements for the database of worldwide volcanic unrest (WOVOdat Version 1.0), open-file report", Version 1, available at: https://doi.org/10.3133/ofr20071117

Werner, C., Evans, W.C., Kelly, P.J., McGimsey, R., Pfeffer, M., Doukas, M. and Neal, C. (2012), "Deep magmatic degassing versus scrubbing: elevated CO2 emissions and C/S in the lead-up to the 2009 eruption of Redoubt Volcano, Alaska", *Geochemistry, Geophysics, Geosystems*, Vol. 13 No. 3, available at: https://doi.org/10.1029/2011GC003794

Werner, C., Kelly, P.J., Doukas, M., Lopez, T., Pfeffer, M., McGimsey, R. and Neal, C. (2013), "Degassing of CO2, SO2, and H2S associated with the 2009 eruption of Redoubt Volcano, Alaska", *Journal of Volcanology and Geothermal Research*, Vol. 259, pp. 270-284.

Winson, A.E.G., Costa, F., Newhall, C.G. and Woo, G. (2014), "An analysis of the issuance of volcanic alert levels during volcanic crises", *Journal of Applied Volcanology*, Vol. 3 No. 1, available at: https://doi.org/10.1186/s13617-014-0014-6

Corresponding author
Fidel Costa can be contacted at: fcosta@ntu.edu.sg