Impact case study template (REF3b)

Title of case study:

The development and implementation of a scanning spectrometer system for measurement of volcanic gas fluxes

1. Summary of the impact (indicative maximum 100 words)

Research focussed on understanding volcanic degassing and developing monitoring methods to forecast volcanic activity forms the basis of this impact case; this work was carried out by a group of academic staff and early-career researchers based in Cambridge. The arrival of large fluxes of sulphur-rich gases at the surface can be used to assess magma movement and forecast volcanic activity. ***This assessment feeds into local governmental decisions regarding risk mitigation and development planning, and the viability of commercial enterprises requiring access to volcanic areas. The development of automatic spectrometer networks for monitoring sulphur dioxide emissions was pioneered by this group.*** The prototype system was developed at Soufriere Hills Volcano, Montserrat and since then, the design has been patented and adopted at 20 volcano observatories worldwide.

2. Underpinning research (indicative maximum 500 words)

For over 20 years a group of academic staff and early-career researchers based in the Cambridge Department of Earth Sciences have been involved in research focussed on understanding volcanic degassing and the role of volatiles in large volcanic eruptions. This work was initially led by Pyle and Oppenheimer and the group started to develop monitoring methods to forecast volcanic activity in the mid 2000s. Pyle moved to Oxford in 2006 and Edmonds, who had collaborated with him in this work since the mid 1990s, was appointed to a University Lectureship at Cambridge in 2007; she has played a vital part in the development of the instruments central to this work and her input to the interpretation of the data as well as the improvement and refinements of the approach have been central to the wide application of these monitoring methods. The group's research findings have been used to interpret the data acquired by these instruments in order to provide Edmond's input to the Scientific Advisory Committee commissioned by the UK Foreign Office.

The development of the scanning UV spectrometer network was underpinned by several years of field measurements and the analysis of volcanic gases and erupted tephra from Soufriere Hills Volcano, in Montserrat carried out by Dr Edmonds and Cambridge co-workers. The eruption of Soufriere Hills Volcano began in 1995 and between 1997-2001 we collected a long time series of gas emissions data, focussing on SO_2 and HCl emissions. Microanalysis of melt inclusions in erupted tephra confirmed that S-rich gases are generated at magma chamber depths (>5 km), whilst HCl gas is generated at much shallower levels in the system. The emission of SO_2 is strongly decoupled from magma eruption, whilst the emission of HCl is strongly coupled. This work led to the proposal of a degassing model, whereby deep magma generates sulphur-rich vapour, leading to a relatively constant SO_2 flux at the surface regardless of eruptive activity; whilst HCl gas emissions are generated during magma ascent, and often only first detected at the onset of eruptive activity. These insights led to the recognition that SO_2 flux is an effective proxy for deep magma supply, and HCl flux a proxy for eruption rate [see reference 1 in section 3].

During the collection of gas samples at Soufriere Hills, it became clear that, whilst gas monitoring data were essential for hazard assessment, there was a need to improve the methodology for data acquisition. At that time the SO_2 flux data at Montserrat were acquired by traversing a bulky correlation spectrometer beneath the plume by boat, which took 3-4 hours for 2-3 data points, at substantial cost. Flux measurements were collected once per week at best and there were periods of months where no data were collected at all.

The advent of small UV spectrometers, manufactured by Ocean Optics (Amsterdam; www.oceanoptics.com) and developments in the field of differential optical absorption spectroscopy, opened up new possibilities for volcano monitoring. The new spectrometers had low power requirements and were based on a CCD array of the type used in digital cameras, so the instrument could be small and portable. Edmonds and Oppenheimer recognised that, with further development, these systems had the potential to allow the acquisition of considerably more complete datasets than was previously possible. A collaboration was initiated in 2000 with Bo Galle, a colleague from Chalmers University, Sweden, to develop a scanning spectrometer system for this purpose.

A successful field trial of the spectrometers was carried out in 2001 and work commenced on designing, building and implementing a network of three spectrometers, completed in its first iteration in 2003. Between 2003 and 2012, the data collected by the network has produced the most detailed time series of volcanic SO_2 emissions from any volcano, worldwide. The dataset has been a **key input to bi-annual risk assessments by the Scientific Advisory Committee**, made up of volcanological experts, commissioned by the UK Foreign Office. The Government of Montserrat base much of their planning decisions on the risk assessment. Between 2003 and 2012, the automated scanning spectrometer design was implemented at 20 volcanoes worldwide. Edmonds has been directly involved with advising and collaborating with schemes for White Island (New Zealand), Etna and Stromboli (Italy) and Tungaragua (Ecuador).

Members of the Cambridge group working on this project and acting as co-authors on publications have included:
Dr Edmonds (Cambridge: 1994-2001, 2007-present), Dr Humphreys (Cambridge 2006-2010), Dr Martin (Cambridge 2004-present), Dr Mather (Cambridge 2001-2006), Prof Oppenheimer (Cambridge: 1993-present), Prof Pyle (Cambridge 1986-2006).

External Collaborators include:
Dr Christopher (previously at Cambridge now at University of the West Indies), Prof A. Aiuppa (of University Palermo, Italy), Dr M. Burton (of University Pisa, Italy), Dr T. Caltabiano (of University Catania, Italy), Prof Galle (of Chalmers University, Sweden), A. J. S. McGonigle (of Sheffield University), G. Giudice, C. Geyer, A. R. Hayes, R A Herd, L. A. Horrocks, R. Moretti, G. Salerno, G. Thompson.

3. References to the research (indicative maximum of six references)
Those which best indicate the quality of the underpinning research are indicated (*). Members of the Cambridge team are shown in bold.

*** Edmonds, M**., A. Aiuppa, **M. Humphreys**, R. Moretti, G. Giudice, **R. S. Martin**, R. A. Herd, and T. Christopher, 2010. Excess volatiles supplied by mingling of mafic magma at an andesite arc volcano. Geochem. Geophys. Geosyst., doi:10.1029/2009GC002781. Citations 11.

*** Edmonds, M**., **C. M. Oppenheimer**, **D. M. Pyle**, R. A. Herd and G. Thompson, 2003. SO_2 emissions from Soufrière Hills Volcano and their relationship to conduit permeability, hydrothermal interaction and degassing regime. J Volcanol Geotherm Res, 124, 1-2, 23-43. doi: 10.1016/S0377-0273(03)00041-6. Citations 68.

Edmonds, M., R A Herd, B Galle and **C. Oppenheimer**, 2003. Automated, high time-resolution measurements of SO_2 flux at Soufrière Hills Volcano, Montserrat, Bulletin Volcanology, 65, 578-586, doi: 10.1007/s00445-003-0286-x. Citations 66.

McGonigle, A. J. S., **C. Oppenheimer**, A. R. Hayes, B. Galle, **M. Edmonds**, T. Caltabiano, G. Salerno, M. Burton, **T. A. Mather**, 2003. SO_2 fluxes from Mount Etna, Vulcano, and Stromboli measured with an automated scanning ultraviolet spectrometer. J Geophys Res, 108, B9, doi:10.1029/2002JB002261. Citations 35.

Galle, B., **C. Oppenheimer**, A. Geyer, A. J. S. McGonigle, **M. Edmonds**, L. A. Horrocks, 2003. A miniaturised ultraviolet spectrometer for remote sensing of SO_2 fluxes: a new tool for volcano surveillance. J Volcanol Geotherm Res, 119, 241-254, doi:10.1016/S0377-0273(02)00356-6,. Citations 171.

*** Edmonds, M., D. M. Pyle** and **C. Oppenheimer,** 2001. A model of degassing at Soufrière Hills Volcano, Montserrat, West Indies, based on geochemical data, Earth Planet Sci Lett, 186, 159-173, 186, 159-173, doi:10.1016/S0012-821X(01)00242-4,. Citations 60.

4. Details of the impact (indicative maximum 750 words)

The main impact of this work has been:

a) the development and implementation of networks of scanning UV spectrometers to measure volcanic SO_2 flux, continuously and automatically;

b) the application of the datasets generated to used to forecast volcanic activity and influence local government planning.

The development of the scanning UV spectrometer networks to monitor SO_2 fluxes has revolutionised the way in which volcanic gas monitoring data is acquired and utilised globally, and as a consequence the value of gas monitoring has increased significantly.

At Soufriere Hills Volcano, the SO_2 flux data is critically important during the 1-2 year-long pauses that occur every few years. Currently (July 2013), the volcano is in a prolonged pause that has lasted two years. It is important to be able to assess whether the eruption has stopped, or has merely paused, in order for the local government to plan development and to approve access to volcanic areas (both for domestic and commercial purposes). A Scientific Advisory Committee (SAC) was commissioned by the UK Foreign Office to provide a risk assessment, based on the monitoring data (between 2003 and present). There are three criteria for recognising the end of the eruption (based on seismicity, ground deformation and gas flux). The end of the eruption will be marked by SO_2 fluxes that are consistently less than 50 t/d for more than 12 months (in tandem with little or no ground deformation, and no seismicity). Given that we believe that the SO_2 flux at the surface is a direct indicator of deep magma supply (see underpinning research), and that it has been shown that the influx of magma at depth is associated with only weak seismicity and ground deformation, the SO_2 flux is the most important dataset for recognising the end of the eruption (see SAC reports, particularly Report 13; www.mvo.ms). So far, the SO_2 flux has remained high, even during long (>24 months) pauses, which indicates that gas-rich magma is being supplied at depth and that the eruption will probably resume. This assessment allows local government to make decisions about where to build new infrastructure (they have focussed their efforts in the north of the island, away from volcanic areas) and whether to attempt large projects with commercial value, which might bring in revenue but must be weighed against the possibility of a resumption in volcanic activity, which will bring them to a halt (e.g. geothermal power and aggregate mining, both in volcanic areas, and both requiring dredging of the area around the jetty).

The Director of the Disaster Management Coordination Agency, Government of Montserrat (http://dmca.gov.ms/), will "*provide independent assessment and corroboration of the societal impact of the scanning spectrometer system for the measurement of volcanic gas fluxes, developed by University of Cambridge researchers, on the island of Montserrat in the West Indies.*" He will also corroborate the value of the SO_2 monitoring network, initiated by this group of Cambridge scientists, for risk assessment, risk mitigation and planning and that "*The reports of the Scientific Advisory Committee rely heavily on these kinds of monitoring data to produce probability-based forecasts, which are then used by the civil authorities to make decisions on hazard mapping, exclusion zone management, land use planning, development and investment."*

Specific details can be found in the **Reports of the Scientific Advisory Committee**, commissioned by the Foreign Office for Government of Montserrat, Montserrat; www.mvo.ms/resources/downloads.

Report 13, based on a meeting held 7-9 September 2009, executive summary, page ii: "…Measurements of the flux of SO_2 and deformation of the ground surface on and around the volcano have, unlike the seismicity, shown signals as strong as ever. We consider these to indicate that the deeper part of the system is still receiving magma and that the volcano may resume surface activity at any time…"
http://www.mvo.ms/resources/downloads/finish/40-sac-13/931-sac13main/0

Report 10, based on a meeting held 14-16 April 2008: "It is possible that lava extrusion will never resume. For this to happen … signals for ground deformation, SO_2 emission and long-period seismicity would fall below the threshold levels we defined previously. To be assured that those conditions have become established, all these signals would need to remain below these threshold levels for about one year. When we test these criteria at the moment we find that the deformation and gas measurements do not meet them. We find that

there is at least a 98% probability that the process that powers the eruption … is still occurring."
http://www.mvo.ms/resources/downloads/finish/44-sac-10/893-sac10main/0

In a wider context, our development on Montserrat led directly to a US patent (filed by B. Galle, in 2010, details below), describing the innovative use of a scanning apparatus (made up of a telescope, and prism, rotated using a stepper motor), which, when attached to the UV spectrometer via a fibre optic cable, allows complete automated scanning through the plume and calculation of SO_2 fluxes, given a knowledge of the plume speed through the scanned section. Scientists from other volcano observatories came to Montserrat to learn about the methods that we developed for automated gas monitoring, and they later set up their own networks, such as Dr Mike Burton (INGV), who later installed a spectrometer network on Etna and Stromboli, Dr Nick Varley (Colima Volcano) and Dr Santiago Arrellano (Ecuador). The scanning UV spectrometer network, based on differential optical absorption spectroscopy (DOAS) for retrievals, has been adopted at 20 other volcanoes worldwide, and all of the peer-reviewed papers resulting from the networks cite our work as the first example. Over the last few years, improvements have been made to the DOAS scanning spectrometers, including adopting new geometries for scanning and more sophisticated hardware, but the design and idea behind the systems remains the same.
The Director of the Disaster Management Coordination Agency, Government of Montserrat, will also testify that *"the lessons on Montserrat are actively being sought by regional partners with volcanic risks."*

Other evidence of take-up of system at other volcano observatories for volcano monitoring, based on example research papers citing our work:
Arellano SR, Hall M, Samaniego P, Le Pennec J-L, Ruiz A, Molina I, Yepes H, Degassing patterns of Tungurahua volcano during the 1999-2006 eruptive period, inferred from remote spectroscopic measurements of SO_2 emissions (2008) J Volcanol Geotherm Res 176,151-162, doi:10.1016/j.jvolgeores.2008.07.007.
Burton M.R., Caltabiano T, Mure F., Salerno G., Randazzo D., SO_2 flux from Stromboli during the 2007 eruption: Results from the FLAME network and traverse measurements (2009) J Volcanol Geotherm Res 182, 214-220, doi:10.1016/j.jvolgeores.2008.11.025.
Galle B, M Johansson, C Rivera,Y Zhang, M Kihlman, C Kern, T Lehmann, U Platt, S Arellano, and S Hidalgo, Network for Observation of Volcanic and Atmospheric Change—A global network for volcanic gas monitoring (2010) J Geophys Res 115, doi:10.1029/2009JD011823.

5. Sources to corroborate the impact (indicative maximum of 10 references)

i) **The Director of the Disaster Management Coordination Agency**, Government of Montserrat (http://dmca.gov.ms/).
ii) **United States of America Patent**: Method and device for measuring emissions of gaseous substances to the atmosphere using scattered sunlight spectroscopy.
Inventor: Bo Galle; Publication Number: 20100231906; Publication Date: 2010-09-16.
Excerpt: "...Technological development during the recent decades has resulted in sensitive and fast multi-channel array detectors, powerful computers, and algorithms for modelling of radiative transfer and accurate analysis of differential absorption spectra. This has led to an alternative to the COSPEC-instrument: a miniature fiber optic ultraviolet differential optical absorption spectrometer: the mini-DOAS, which is described in Galle B., **Oppenheimer C**., Geyer A., McGonigle A., **Edmonds M**. and Horrocks L., "A miniaturised ultraviolet spectrometer for remote sensing of SO_2 fluxes: a new tool for volcano surveillance". J. Volcan. Geo. Res, v 119, 2003, 241-254, doi:10.1016/S0377-0273(02)00356-6. The mini-DOAS has been further developed in that the instrument was coupled to a scanning device consisting of a quartz-prism attached to a computer-controlled stepper-motor, providing a means to scan the field-of view of the instrument over 180°, see **Edmonds M**., R. A. Herd, B. Galle and **C. Oppenheimer**, "Automated, high time-resolution measurements of SO_2 flux at Soufriere Hills Volcano, Montserrat", Bulletin of Volcanology, 65, 578-586, 2003...."