**Institution:** University of Cambridge

**Unit of Assessment:** UoA17b

**Title of case study:** Novel Technique For Monitoring Volcanic Plumes: From Innovation To Operational Application

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

Measurements of sulphur dioxide emissions from volcanoes provide critical evidence for forecasting eruptions. From 2001 the research team led by **Clive Oppenheimer** (Department of Geography, University of Cambridge: Lecturer 1994-2003; Reader 2003–12; Professor 2012–) has shown that a new technique based on UV spectroscopy can revolutionise such measurements. The approach (awarded a US patent in 2006) has since 2008 come to underpin the state-of-the-art in operational surveillance of volcanic emissions worldwide, contributing significantly to hazard assessment and emergency management at over thirty volcanoes, and helping to save lives by providing early warning. The team has trained and supported volcanologists around the world in the methodology (in Costa Rica, 2008; Java, 2010; Iceland, 2012), and has helped in collecting data during volcanic crises (e.g. Merapi, 2010), contributing to planning decisions and the safety of local populations.

## 2. Underpinning research (indicative maximum 500 words)

Sulphur dioxide is a key constituent of volcanic gas emissions. Changes in the $SO_2$ flux are often an important precursor of eruptions or eruptive transitions. The ability to monitor $SO_2$ emission continuously, reliably and inexpensively is therefore a critical aspect of volcanic hazard assessment and risk management. Research outlined here concerns the development and implementation of new technology for $SO_2$ measurement that has revolutionised the worldwide surveillance of volcanoes.

Much of the underpinning research was funded by the EC. In 2001, **Oppenheimer** was co-investigator on the MULTIMO project (led by J. Neuberg, University of Leeds; see Section 3b), and responsible for gas monitoring. He became aware of the availability of small (400g), low-power (1 Watt), cheap (US$2000) UV spectrometers. Recognising their potential, with Galle (employed as a research associate), he designed and conducted the first volcanological field experiments with the new device (at Masaya Volcano, Nicaragua). The prevailing technology (the 'COSPEC') was costlier, less capable, power-hungry and ageing, and the attraction of the new system for volcanic gas surveillance was easy to communicate (see 3a(i)). In 2006, a modification of the instrument was awarded a US patent (number 7,148,488: "Apparatus for measuring radiation and method of use"). **Oppenheimer** is a co-holder of the patent and the instrument described has been distributed under the name of 'FLYSPEC'.

The first experiments demonstrated that the spectrometer was capable of accurate measurement of a wide span of $SO_2$ abundance. They were published in 2002 (see 3a(i)). With Research Associates McGonigle (2001–4) and Tsanev (2002–7) (see 3b), **Oppenheimer** set about validating the methodology through field trials and rigorous evaluations of spectra from first principles (2002–7). This included side-by-side field experiments with the 'COSPEC', in collaboration with colleagues at volcano observatories and institutes, including Italy's National Institute for Geophysics and Volcanology (INGV), responsible for operational surveillance of Mt Etna, and the U.S. Geological Survey Hawaiian Volcano Observatory, which monitors Kīlauea volcano, Hawaii. Several papers reported the inter-comparisons, corroborating the accuracy and reliability of the methodology (see 3a(ii, iii)).

The team designed and constructed the first ruggedized scanning system (see3a(ii)), which was the forerunner of automated systems now used operationally, e.g., by the Montserrat Volcano Observatory (see3a(iv)). It exploited the full spectral coverage of the UV spectrometers to measure other gas species,(including hydrogen sulphide in 2002, nitrogen dioxide in 2003, and bromine monoxide in 2004. It also applied the technique to studies of the atmospheric chemistry of volcanic plumes, and emissions associated with agricultural burning, aviation and industrial accidents. In 2004, **Oppenheimer** and Tsanev helped to develop a new method for calculating $SO_2$ fluxes that continues to be used operationally for analysing data collected daily at Etna and Vulcano (see 3a(v)). Later, Boichu (Marie Curie Fellow, 2007–8) joined the group and developed a methodology to measure volcanic $SO_2$ fluxes with very high temporal resolution, (based on correlation techniques and using two spectrometers attached to telescopes with cylindrical lenses; see 3a(vi). Owing to recognition of his work in UV spectroscopy, **Oppenheimer** was invited in 2003 to join the U.S. Antarctic Program to research Erebus volcano. He has now participated in ten field seasons in Antarctica, latterly as a co-principal investigator of the Mount Erebus Volcano Observatory (NSF-funded). Erebus volcano has provided a natural laboratory to test further developments of the UV technology.

**3. References to the research** (indicative maximum of six references)

(i) Galle, B, Oppenheimer, C, Geyer, A, McGonigle, A, Edmonds, M & Horrocks, LA (2002) A miniaturised ultraviolet spectrometer for remote sensing of SO2 fluxes: a new tool for volcano surveillance, *Journal of Volcanology and Geothermal Research*, 119, 241–254. (This is the third most highly-cited paper in the serial since 2000 – out of nearly 2800 papers, Web of Science)

(ii) McGonigle, AJS, Oppenheimer, C, Hayes, AR, Galle, B, Edmonds, M, Caltabiano, T, Salerno, G, Burton, M, & Mather, TA (2003) Sulphur dioxide fluxes from Mount Etna, Vulcano, and Stromboli measured with an automated scanning ultraviolet spectrometer, *Journal of Geophysical Research-Solid Earth*, 108 (B9), 2455, doi:10.1029/2002JB002261

(iii) Elias, T, Sutton, AJ, Oppenheimer, C, Horton, KA, Garbeil, H, Tsanev, V, McGonigle, AJS, & Williams-Jones, G (2006) Intercomparison of COSPEC and two miniature ultraviolet spectrometer systems for SO2 measurements using scattered sunlight, *Bulletin of Volcanology*, 68, 313–322.

(iv) Edmonds, M, Herd, RA, Galle, B & Oppenheimer, C (2003) Automated, high time-resolution measurements of SO2 flux at Soufrière Hills Volcano, Montserrat, 2003, *Bulletin of Volcanology*, 65, 578–586.

(v) Salerno, GG, Burton, MR, Oppenheimer, C, Caltabiano, T, Tsanev, VI, Bruno, N & Randazzo, D (2009) Novel retrieval of volcanic SO2 abundance from ultraviolet spectra, *Journal of Volcanology and Geothermal Research*, 181, 141–153.

(vi) Boichu, M, Oppenheimer, C, Tsanev, VI & Kyle, PR (2010) High temporal resolution SO2 flux measurements at Erebus volcano, Antarctica. *Journal of Volcanology and Geothermal Research*, 190, 325–336.

**(b) R&D support for the team's research in UV spectroscopy (Oppenheimer as UK co-I in all cases; and mentor for Marie Curie award)**

2001–2004 FP5: Multi-disciplinary monitoring, modelling and forecasting of volcanic hazard (MULTIMO), c. £100,000 (with Research Associates Galle and McGonigle, 2001–2002)

2002–2005 FP5: Development of Optical Remote Sensing Instruments for Volcanological Applications (DORSIVA), £112,678 (with Research Associate Tsanev, 2003–2005)

2005–2010 FP6: Network for Observation of Volcanic and Atmospheric Change (NOVAC), £112,280 (with Research Associate Tsanev 2005–2007)

2007–2008 FP6 Marie Curie action: Volcanic gas and aerosol emissions: ground based remote sensing, atmospheric impact and modelling of magma degassing processes (with PDRF Boichu, 2007–2008)

2008–2012 FP7: Mitigate and assess risk from volcanic impact on terrain and human activities (MIAVITA), €127,000 (with PDRA Boichu, 2009–2011)

2008–2013 NERC, Dynamic Earth and Geohazards, National Centre for Earth Observation, £251,000 (with Research Associate Tsanev, 2009–2012)

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

The key beneficiaries of the research are the worldwide volcano observatory community, and thus the populations protected through their monitoring efforts. In addition, the team led by **Oppenheimer** has played an active role in public engagement and science education. The impact falls into three categories, as follows:

**(i) *Provision of training and tools for operational volcano monitoring*:** From 2008 (see 3b, NERC) Tsanev has developed hardware and software for automated measurements of $SO_2$ emissions using UV scanners. This involved design of improved scanning systems, environmental sealing, and firmware control of the opto-mechanics. During the REF period, six scanners were delivered to the Montserrat Volcano Observatory (2011; Plate 1), two to INGV-Catania (2011, funded by the Italian Department of Civil Protection), one to the Icelandic Meteorological Office (2012) and one to the Center of Volcanology and Geological Hazard Mitigation (CVGHM), Indonesia (2013). The team also provided equipment to the National Seismological Network, University of Costa Rica in 2008 and the Merapi Volcano Observatory (Indonesia) in 2010. The research team has also provided advanced training in the application of UV spectroscopy to measurement of volcanic $SO_2$ emissions, and has supported the wider community via distribution of open software.

This equipment is used in installations for operational $SO_2$ flux observations, or for rapid response during emerging episodes of volcanic unrest. The Co-Leader of Gas Geochemistry Research and Monitoring at INGV-Catania wrote that UV scanners designed and built by the Cambridge team are "*fully integrated in the scanner networks of Mt. Etna and Vulcano, successfully providing automatic real-time $SO_2$ flux data. At Mt. Etna, notable is the contribution that this equipment has provided during the repeated episodes of volcanic unrest occurred since 2011… 38 short-lived but powerful explosive events have occurred, and the network has regularly highlighted its ability in the automatic tracking of $SO_2$ flux. This has provided fundamental insight into volcanological processes and for operational volcano monitoring and surveillance*". (see 5(i).)

The Staff Geochemist at the Hawaiian Volcano Observatory writes: "*We found the importance of the new spectrometer system demonstrated convincingly at Kilauea in early 2008 as the volcanic system was building to a summit eruption. Through the first two months of 2008 the FLYSPEC told us that emissions from Kilauea were higher than we'd seen them in over 20 years. The high $SO_2$ emissions quantified by the FLYSPEC led the National Park to close the south portion of Crater Rim Drive in February to protect visitor safety. Our ability to rapidly measure $SO_2$ and rapidly report the values had a clear and positive effect on our knowledge of the gas hazards*…" (see 5(ii))

**Plate 1. Testing UV scanners on Montserrat**

**Plate 2. Portable scanner in use during Merapi eruption**

**(ii) *Support during volcanic emergencies*:** The research team has collaborated with national agencies to assist with $SO_2$ measurements during volcanic crises, notably at Merapi volcano (Java) in 2010 (Plate 2). This provides an example of how training, provision of equipment and on-the-ground support combined to reinforce efforts to assess hazards of one of the largest eruptions of the past decade, and the deadliest since 1985.

The Indonesian institutions responsible for monitoring Merapi volcano are the CVGHM and the BPPTK (Volcanological Research and Technology Development Centre). The research team's collaboration with these institutions began in April 2010 with training for six members of Merapi Volcano Observatory's staff. This covered theory and practice in data acquisition and processing. Hardware and software to perform gas monitoring was donated to the Observatory. In October 2010, Merapi volcano showed increasing signs of unrest. Following a request from CVGHM, Boichu (PDRA on MIAVITA; see 3(b)) travelled promptly to Indonesia to assist with gas surveillance and data evaluation and interpretation. The ground observations provided critical information, especially before Merapi's opening explosion on 26 October, by demonstrating that the volcano's gas output was significantly higher than seen in the lead up to previous eruptions. This suggested that a large body of magma was intruding into the volcano, and that should it reach the surface, the ensuing eruption would likely exceed the size of preceding events. The 2010 eruption proved to be Merapi's largest in over a century.

Decision making, especially concerning the establishment of exclusion zones on the volcano, was based firmly on evidence from $SO_2$ observations and geophysical and satellite radar data. The Head of Division for Research and Technology Development on Geological Hazard in Indonesia wrote that: "*Connecting to [**Oppenheimer's**] work with UV DOAS for $SO_2$ monitoring in Merapi, I would like to say ..: 1. Monitoring $SO_2$ by using UV DOAS in the year of 2010 was very important, instead of COSPEC instrument which have not worked since the eruption 2006. 2. ...When Merapi began unrest, all monitoring data increased clearly. We need[ed] something [like] a decisive parameter to 'justify' my interpretation that Merapi will erupt explosively. And I found [this in] … UV DOAS monitoring*" (see 5(iii)). The crisis escalated rapidly and there were 367 fatalities. Nevertheless, over 400,000 people evacuated, and it has been estimated that "*because of the effective warnings by CVGHM and the response by BNPB* (the Indonesian national emergency response agency) *and their provincial and local counterparts, 10,000 to 20,000 lives were saved by evacuations*" (based on BNPB reports, see 5(iv)).

**(iii) *Public engagement*: Oppenheimer's** research efforts have been publicised in several documentaries. He was closely involved a 2009 film for Teachers TV (a government-funded broadcasting service). The film, *Journey to Etna*, formed part of the series *How Science Works* (see 5(v)), and featured demonstrations of real-time measurement of $SO_2$ flux. Over 700 schools used the videos and associated materials in the classroom.

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

(i) Letter received by email in 2013 from person 1 (Co-Leader of Gas Geochemistry Research and Monitoring, INGV)

(ii) Letter received by email in 2013 from person 2 (Staff Geochemist, Hawaiian Volcano Observatory, U.S. Geological Survey)

(iii) Email received from person 3 (Head of Division for Research and Technology Development on Geological Hazard, Geological Agency, Ministry of Energy and Mineral Resources, Indonesia)

(iv) Jousset P, Pallister J, Surono, 2013, The 2010 eruption of Merapi volcano, *Journal of Volcanology and Geothermal Research*, 261, 1–6 (editorial introduction to a special issue, summarising the event; and confirming the involvement of the MIAVITA team.)

(v) *Journey to Etna* (2009) can be viewed at: http://www.tes.co.uk/teaching-resource/How-Science-Works-Journey-to-Etna-6047848/