Institution: University of Cambridge		
Unit of Assessment: UoA 7		
Title of case study: University of Cambridge volcanic gas monitoring systems protect life, property and livelihoods		
Period when the underpinning research was undertaken: 2002-present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Marie Edmonds	Professor of Volcanology and Petrology	Oct 2006 – present
Clive Oppenheimer	Professor of Volcanology	Oct 1994 – present
Madeleine Humphreys	Postdoctoral researcher	Apr 2010 – Sep 2010
Emma Liu	Postdoctoral researcher	May 2016 - Sep 2019
Period when the claimed impact occurred: August 2013 – August 2020		
Is this case study continued from a case study submitted in 2014? Y		

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

University of Cambridge researchers developed the first automated network of ultra-violet sensors to monitor volcanic gases at active volcanoes. Since the initial work on prototype instrumentation in 2002, the design has been implemented on 42 volcanoes across 18 countries and five continents. Sensors have been developed to be mounted on unmanned aerial vehicles, which allows monitoring of highly active and difficult-to-access volcanoes. Worldwide, 500 million people live in areas at risk from volcanic eruptions. The impact of this research has been to:

I. Protect life, property and livelihoods through:
   - enhancing the capability of volcano observatories worldwide to forecast eruptive activity in order to provide warning of imminent eruptions
   - providing critical input into government decisions leading to a) evacuations and b) mandatory exclusion zones

II. Allow safe industrial re-development (e.g. geothermal on Montserrat)

III. Allow the people of Manam to stay on their own land, rather than being permanently displaced, through developing the ABOVE project community-led resilience programme

2. Underpinning research (indicative maximum 500 words)

Up to the mid-2000s, volcanoes were monitored largely using the occurrence of earthquakes and displacements of the ground surface, because these data were available at a high temporal resolution (several measurements every second) and were a reliable indicator of magma movement. Geochemical monitoring, which yields the only direct indication of magma close to the surface, was in its infancy, yet increases in gas fluxes from volcanoes often preceded eruptions and so provided a tantalising yet untapped source of information about eruptive activity. Gas flux data were available so infrequently (once per day or per week, using cumbersome instrumentation) that their utility was severely limited, despite their potential to track magma ascent and forecast eruption style.

Sulfur dioxide (SO_2) fluxes are a critical part of volcano monitoring. When magma ascends towards the surface and decompresses, sulphur exsolves from silicate melt and enters the gas phase. This process is analogous to removing the cork from champagne, which results in CO_2 bubbles forming. The gas phase may migrate to the surface ahead of the magma, through permeable bubble networks. Increases in gas flux (SO_2 is one of the primary gas species, the others are H_2O and CO_2) therefore indicate the impending arrival of magma to the surface, i.e. they can be used, in tandem with seismicity and ground displacements, to forecast eruptions [R1].

The impact described in this case was underpinned by research that took place within the Department of Earth Sciences at the University of Cambridge between 2002-2019, during which time a miniaturised UV spectrometer was developed for measurement of volcanic sulphur dioxide [R2] and the first network of scanning UV spectrometers was installed at volcanoes by **Edmonds, Oppenheimer** and co-workers [R3, 4]. A network of three UV spectrometers was developed and installed in Montserrat during the eruption of the Soufriere Hills Volcano in 2002 [R2, 3], whereby the spectrometers were connected to a scanning optical assembly and fibre optic cable, with power and telemetry, and code – which was made widely available - was written to both acquire spectra and to retrieve SO_2 column amounts. SO_2 column amounts were combined with meteorological data to derive SO_2 fluxes every few minutes through the day, allowing the geochemical and geophysical data to be compared and interpreted on similar timescales, revolutionising the integrated monitoring of volcanoes [R1, R5].

This development provided the model and basis for UV spectrometer networks elsewhere [e.g. R3]. 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’. Scanning spectrometer networks were installed on 42 volcanoes (for context, around 50-60 volcanoes erupt every year) across five continents between 2002 and 2020 (**27 since 2013**, the period covered by this impact case) by a number of research groups (e.g. EU-funded NOVAC, led by PI B. Galle, Chalmers University, co-I **Oppenheimer**) and volcano observatories, based on the design of the first installation in Montserrat, West Indies in 2002.

The advent of unmanned aerial vehicle (UAV) technology provided the opportunity for the ABOVE project, led by University of Cambridge researchers **Liu** and **Edmonds**, funded by the Alfred P Sloan Foundation, and including collaborators from the University of Bristol, USA, New Zealand, Germany, Sweden, Papua New Guinea and Costa Rica. The project developed cheap and portable sensors that could be mounted on UAVs to be flown into dangerous, highly active and difficult-to-access volcanoes [R6]. The data from these sensors showed previously unrecognised patterns in gas emissions related to bubble bursting, puffing and conduit dynamics [R6]. Subsequently, field campaigns to Guatemala, Montserrat and Papua New Guinea (places with active volcanoes and particularly vulnerable populations) in 2017-2019 have established these UAV-based methods, through training and sharing knowledge, as part of the regular toolkit of local volcano observatories for monitoring and hazard assessment.

Following the eruption of the White Island volcano in New Zealand in December 2019, and the tragic loss of life that followed, Edmonds was asked in August 2020 to provide consultant expert advice on gas monitoring data to the New Zealand Health and Safety Executive (Worksafe).

3. References to the research (indicative maximum of six references)
The following peer-reviewed papers were all published in broad, high impact Earth Science journals, and are of a quality that is excellent/world-leading in terms of originality, significance and rigour.

R1 2010 Christopher T, **Edmonds M**, **Humphreys M**, Herd RA. Volcanic gas emissions from Soufrière Hills Volcano, Montserrat 1995–2009, with implications for mafic magma supply and degassing. Geophysical Research Letters. 2010 Oct 1;37(19). https://doi.org/10.1029/2009GL041325

R2 2003 Galle B, **Oppenheimer C,** Geyer A, McGonigle AJ, **Edmonds M**, Horrocks L. A miniaturised ultraviolet spectrometer for remote sensing of SO_2 fluxes: a new tool for volcano surveillance. Journal of Volcanology and Geothermal Research. 119(1-4):241-54. https://doi.org/10.1016/S0377-0273(02)00356-6

R3 2003 **Edmonds M,** Herd RA, Galle B, **Oppenheimer CM**. Automated, high time-resolution measurements of SO_2 flux at Soufrière Hills Volcano, Montserrat. Bulletin of Volcanology. 65(8):578-86. https://doi.org/10.1007/s00445-003-0286-x

R4 2003 McGonigle AJ, **Oppenheimer C**, Hayes AR, Galle B, **Edmonds M**, Caltabiano T, Salerno G, Burton M, Mather TA. Sulphur dioxide fluxes from Mount Etna, Vulcano, and Stromboli measured with an automated scanning ultraviolet spectrometer. Journal of Geophysical Research: Solid Earth. 108(B9). https://doi.org/10.1029/2002JB002261

R5 2008 Rodríguez LA, Watson IM, **Edmonds M**, Ryan G, Hards V, **Oppenheimer CM**, Bluth GJ. SO_2 loss rates in the plume emitted by Soufrière Hills volcano, Montserrat. Journal of Volcanology and Geothermal Research. 2008 Jun 1;173(1-2):135-47. https://doi.org/10.1016/j.jvolgeores.2008.01.003

R6 2019 **Liu EJ**, Wood K, Mason E, **Edmonds M**, Aiuppa A, Giudice G, Bitetto M, Francofonte V, Burrow S, Richardson T, Watson M. Dynamics of outgassing and plume transport revealed by proximal Unmanned Aerial System (UAS) measurements at Volcán Villarrica, Chile. Geochemistry, Geophysics, Geosystems. 20(2):730-50. http://dx.doi.org/10.1029/2018GC007692

Grants:

- 2007: PI Edmonds, Royal Society Grant – installation of gas sensors, GBP15,000
- 2010: PI Edmonds, Deep Carbon Observatory DECADE grant for development of gas sensors, USD15,000
- 2014-2017: Co-I Edmonds, Centre for the Observation and Modeling of Earthquakes and Tectonics (NERC, COMET) GBP1.2M total, GBP153,757 to Cambridge
- 2018-2019: PI Liu, Co-I Edmonds, Alfred P Sloan Foundation GBP180,000, 'ABOVE': to use sensors mounted on unmanned aerial vehicles to quantify volcanic gas emissions from Papua New Guinea.
- 2005-2010: participant Oppenheimer (PI Galle, Chalmers University), FP6: Network for Observation of Volcanic and Atmospheric Change (NOVAC), GBP112,280.

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

Worldwide, 500 million people live in areas at risk from volcanic eruptions [E1]. The spectrometer networks first developed by Edmonds and colleagues at the University of Cambridge have been adopted by volcanological observatories on 42 volcanoes (27 since 2013) across 18 countries and five continents [E2, E3]. They are used to protect life, property and livelihoods through forecasting eruptive activity and informing critical decisions on evacuations and exclusion zones; to allow safe industrial re-development; and – through the ABOVE project resilience programme (Aerial-Based Observations of Volcanic Emissions) - to allow the Manam islanders to remain on their island.

Forecasting Eruptive Activity and providing warning of imminent eruptions

The Institute of Geological & Nuclear Sciences (GNS), New Zealand, were among the first government bodies to develop a spectrometer system based on the design Edmonds and colleagues pioneered. Senior Scientist at GNS, Dr Craig Miller, states [E4]:

'*the UV scanning spectrometer network installed by Edmonds, Oppenheimer and colleagues in Montserrat provided the template for GNS volcanologists to develop a similar system at White Island, New Zealand. It is used for monitoring volcanic activity at this hazardous and unpredictable volcano. An increase in gas flux, along with increased levels of seismicity and ground deformation, would significantly increase the probability of eruption and consequently* *the alert level at the volcano, which is used for decision-making surrounding issues such as restricting access and warnings to the public*'.

In October 2019, SO_2 fluxes measured by the scanning spectrometers (and accompanying tremor) at White Island increased to the highest levels since 2016, suggesting an eruption was imminent over the coming weeks and months [E5, 6]. On 18 November 2019, the alert level was raised to '2' (the highest before eruption) signalling 'heightened volcanic unrest' and 'potential for eruption hazards' [E7].

Tragically, an eruption on 9 December 2019 killed 19 people. In this case, clear warnings were not heeded, and preventative action which could have saved lives was not taken.

At Volcán Tungurahua (Ecuador), 30,000 people live in areas at risk from pyroclastic flows and lahars. A spectrometer system based on the Cambridge design was installed in 2004. Eruptions in 2013, 2014 and 2016 have had considerable impacts on livelihoods, particularly agricultural activities (with crops damaged and land made unusable due to the deposition of volcanic ash). The scanning spectrometer stations provide SO_2 flux data for the assessment of risk and early warning of eruptions. In February 2014 >600 people were evacuated after alert levels were raised in response to increasing SO_2 flux (to over 2000 tonnes per day), as well as increased rates of earthquakes and ash venting at the summit:

'*The automatic scanning DOAS stations as first developed at Soufriere Hills Volcano, and which nice results have been shown by Edmonds and colleagues in 2003, have been widely adopted by volcanological observatories over the past 15 years…At Tungurahua, we installed 2 DOAS systems directly based on the Montserrat UV spectrometer system, the UV scanning spectrometer network yielded important data which, when used in combination with other monitored parameters as seismic activity, allowed us to assess hazard levels and advise local authorities on the general level of volcanic activity'* [E3, Instituto Geofisico, Ecuador].

Providing critical input into mandatory exclusion zones

In Montserrat, the eruption of the Soufriere Hills Volcano ceased in 2011, yet it remains restless. One key characteristic is continued high flux of SO_2, as measured by the spectrometer network, leading the government to retain an exclusion zone around the volcano. The Montserrat Volcano Observatory (MVO) and Scientific Advisory Committee (British Foreign Office) continue to rely on the SO_2 flux data to assess whether the eruption is over or has merely paused. The March 2019 MVO Scientific Report [E8] states:

'*the potential for continuing activity has been considered against the following three criteria:*

1. *Seismicity*
2. *Gas – daily SO_2 emission rates above 50 tonnes per day*
3. *Ground deformation*

Criteria 2 and 3 are currently being met.'

Consequently, the volcano remains in an elevated state of unrest, with an exclusion zone including over half the island.

Allowing safe industrial re-development

However, on Montserrat, the monitoring networks are now making economic recovery possible. The Government has permitted a geothermal plant to be established in the exclusion zone, a decision informed by advice from the MVO, based partly on gas flux information. The Director of the MVO [E9] states:

'In 2014 the Government of Montserrat gave permission for a geothermal company, the Iceland Drilling Company*, to begin operations generating two boreholes from which it was projected that much of the island's energy needs would be provided. A third well is planned for 2020. This permission was based on advice from the Montserrat Volcano Observatory on volcanic risk; gas fluxes were one part of the critical evidence upon which the low risk level for that particular area was assigned.'*

Test results indicate that geothermal power could generate more electricity than is needed by the island, freeing it from reliance on diesel-powered generators – among the most expensive electricity in the world – and reducing CO_2 emissions by replacing fossil fuel generated electricity [E10].

Allowing islanders to remain on their land

The ABOVE project, led by University of Cambridge researchers Liu and Edmonds, involves field campaigns to Papua New Guinea volcanoes Rabaul and Manam to deploy UAV gas sensors and train local people in these techniques. Manam is a small island with > 2000 people, who are regularly evacuated to the mainland during eruptions every few years (there have been nine since 2000). Islanders live with extreme volcanic risk, as permanent relocation is unacceptable because the island is essential to their way of life and rehoming on the mainland brings risk of conflict. The UAV technology and training provided by the ABOVE project offers a means for them to remain. An ABOVE project video includes interviews with local people:

'*Those major eruptions [in 2004] were never addressed properly by the government… we have been waiting for 15 years and nothing is happening… We are regarded as IDPs – Internally Displaced Persons - on our own land*.'[E11].

The ABOVE project provides equipment and training to the local volcano observatory to continue measurements of gas fluxes using UAVs. One representative from each province in Papua New Guinea came to the training workshop in February 2019 and, thereafter, successfully lobbied provincial governments for additional funding [E1]. The islanders had relied on visual monitoring, but now fly UAVs over the volcano to monitor gas flux and activity to see what and who is most at risk, allowing them to remain on their own land.

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

[E1]. 'Above and Beyond': the story of the ABOVE project https://www.cam.ac.uk/stories/activevolcano

[E2]. Excerpt from NOVAC web page, showing the number of volcanoes with UV scanning spectrometers installed https://novac-community.org/volcanoes

[E3]. Testimonial from Instituto Geofisico, Ecuador

[E4]. Testimonial from Senior Scientist, Natural Hazards Division, GNS Science, New Zealand

[E5]. New Zealand news article describing elevated unrest at White Island, New Zealand, in October 2019, with details of high SO_2 fluxes.

[E6]. A second Zealand news article describing elevated unrest at White Island, New Zealand, in October 2019, with details of high SO_2 fluxes.

[E7]. Geonet, Volcanic Alert Bulletin, 18 November 2019. Geonet is the Volcano Monitoring Arm of GNS Science, the principal geological Government Agency in New Zealand.

[E8]. MVO Scientific Report for Volcanic Activity between 1 October 2018 and 31 March 2019, Open File Report OFR 19-01, *7 June 2019.* Montserrat Volcano Observatory. See page 37.

[E9]. Testimonial from the Director of the Montserrat Volcano Observatory

[E10]. The Iceland Drilling Company https://www.jardboranir.is/drilling-project-starting-in-montserrat/

[E11]. The ABOVE project page https://deepcarbon.net/project/above#Overview