Institution: University of Sheffield		
Unit of Assessment: C-14 Geography and Environmental Studies		
Title of case study: Transformative Gas Sensing Technology in Volcano Monitoring		
Period when the underpinning research was undertaken: 2005–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:**
Andrew McGonigle	Reader in Volcano Remote Sensing	2005–present
Tom Pering	Lecturer	2016–present
Robert Bryant	Reader in Dryland Processes	1999–present
Period when the claimed impact occurred: August 2013–2020		
Is this case study continued from a case study submitted in 2014? N		

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

McGonigle's research has impacted on volcano monitoring agencies across the globe, expediting their purpose to enhance the safety of those living and working near volcanoes. His work focuses on development of novel techniques for monitoring volcanic gases, providing vital data for diagnosing activity and eruption forecasting. Relative to previous instrumentation, this technology delivers enhanced portability, user-friendly operability and accuracy and reduced cost. These units are now internationally adopted standards, with deployment to almost all degassing volcanoes globally thereby increasing access to valuable monitoring data. McGonigle has partnered with NASA to adapt his technology for a Moon lander sensing application. In 2020 McGonigle won the £50,000 first prize in the Aspect Success programme, in recognition of the enterprise, impact and innovation of this work.

2. Underpinning research (indicative maximum 500 words)

McGonigle's research is focused on inventing technologically innovative and low-cost UV volcano sensing techniques, suitable for widespread dissemination in the global south, and applying them to gain new insights into how volcanoes behave [R1, R2]. This is focused on spectroscopic [R3] and UV camera technologies [R4], in particular McGonigle's pioneering of the world's first smartphone sensor-based UV camera [R5, R6], by developing a novel technique for removing the UV absorbing layers from the surface of these detector units. This technology enables capture of gas release data once every few seconds in units as lightweight as 1 kg and with build costs as low as £600, in contrast to 20 kg and £50k, respectively, from the traditionally adopted technology. McGonigle's sensors also enable direct and accurate measurement of the speed at which the gases are transported from the summit craters. Such data are required in the gas emission rate computation but were hitherto obtained using unreliable proxy data from anemometers. Flux uncertainty has thereby been reduced from ~50% to ~10%. In addition, the UV camera approach's imaging capacity allows tracking of degassing from one vent to another, such that this technology provides far greater scope to resolve spatially and temporally the trends in behaviour which presage eruptions.

Ultraviolet (UV) sensors measure light intensity at wavelengths from 250 to 400 nanometres, using sources such as the sun, fluorescent lights or germicidal lamps. In volcano monitoring these units are used to measure the rates of gas release from craters to the atmosphere in order to help forecast eruptions. The sensors do this by measuring, at a safe distance from the crater, how much background UV skylight is absorbed by the released gases, from which emission rates can be quantitatively determined. As volcanic gases are sourced from underground magmas, their release rates provide a direct proxy for the rise and fall of magmas within the conduit, enabling diagnosis of activity conditions and prediction of future eruptions. Without such sensors pre-eruptive changes in gas emission rates cannot be identified, severely limiting attempts to predict eruptions and hence issue evacuations which can save human lives.

Until recently UV monitoring approaches were based on outdated technology rendering them bulky, expensive, non-user friendly and unreliable. The reach of captured gas emission data was severely limited, therefore, especially in the global south, where risks are high, but monitoring budgets are restrictive. Furthermore, the acquired data had very poor time resolutions and large errors (typically 2-3 measurements per week, and > 50%, respectively), significantly limiting their utility in resolving changes in behaviour.

The underlying research has been conducted by McGonigle at the University of Sheffield since 2005, supported multiple PI grants, e.g., from The Royal Society (2007-2009; £10k), the Italian Istituto Nazionale di Geofisica e Vulcanologia (2008-2013; £80k), the AXA Research Fund (2010-2011; £51k), Google (2013-2014; £6k), The Leverhulme Trust (2016-2017; £44k) and the Rolex Institute (2008-2020; £102k).

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

R1. Pering, T. D., Liu, E. J., Wood, K., Wilkes, T. C., Aiuppa, A., Tamburello, G., Bitetto, M., Richardson, T., & McGonigle, A. J. S. (2020). Combined ground and aerial measurements resolve vent-specific gas fluxes from a multi-vent volcano. *Nature Communications*, *11*(1), 3039. https://doi.org/10.1038/s41467-020-16862-w

R2. Pering, T. D., Ilanko, T., Wilkes, T. C., England, R. A., Silcock, S. R., Stanger, L. R., Willmott, J. R., Bryant, R. G., & McGonigle, A. J. S. (2019). A Rapidly Convecting Lava Lake at Masaya Volcano, Nicaragua. *Frontiers in Earth Science*, *6*, 241. https://doi.org/10.3389/feart.2018.00241

R3. McGonigle, A. J. S. (2007). Measurement of volcanic SO2 fluxes with differential optical absorption spectroscopy. *Journal of Volcanology and Geothermal Research*, *162*(3–4), 111–122. https://doi.org/10.1016/j.jvolgeores.2007.02.001

R4. McGonigle, A. J. S., Pering, T. D., Wilkes, T. C., Tamburello, G., D'Aleo, R., Bitetto, M., Aiuppa, A., & Willmott, J. R. (2017). Ultraviolet Imaging of Volcanic Plumes: A New Paradigm in Volcanology. *Geosciences*, *7*(3), 68. https://doi.org/10.3390/geosciences7030068

R5. Wilkes, T., McGonigle, A., Pering, T., Taggart, A., White, B., Bryant, R., & Willmott, J. (2016). Ultraviolet Imaging with Low Cost Smartphone Sensors: Development and Application of a Raspberry Pi-Based UV Camera. *Sensors*, *16*(10), 1649. https://doi.org/10.3390/s16101649

R6. Wilkes, T., Pering, T., McGonigle, A., Tamburello, G., & Willmott, J. (2017). A Low-Cost Smartphone Sensor-Based UV Camera for Volcanic SO2 Emission Measurements. *Remote Sensing*, *9*(1), 27. https://doi.org/10.3390/rs9010027

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

McGonigle's research has led to: 1) transformation of volcano observation by the global reach of these technologies; 2) significantly enhanced monitoring capacity, to the benefit of governmental volcano observatories and citizens living in the vicinity of active volcanoes; 3) the development of next generation space exploration instrumentation, through partnering with NASA. The innovation and transformational impact of his technology was recognised in 2020 when he was awarded first prize, £50,000, in the Aspect Success programme.

1) Transforming volcano observation globally

Global reach has been delivered, since August 2013, through McGonigle's team training >50 personnel from monitoring agencies in countries including Italy, Papua New Guinea, Ecuador, Mexico, Costa Rica, and Nicaragua, in the use of these technologies, including free distribution of the operating software and hardware protocols developed by this team to ensure the widest possible impact. This has involved invited presentations at key international gatherings of the volcanic gas monitoring community in Ecuador (2017), Perú (2018) and Chile (2019), involving translation of the smartphone UV camera technology into monitoring operations in five Latin American countries with EPSRC Impact Acceleration funding. This led to follow on contracts for McGonigle to instrument volcanoes in northern Chile (£94k; 2019; local government project) [S1, S2] and Perú (£61k; 2019; governmental Geophysical Institute of Perú project) with UV camera and spectrometer units [S3]. More widely McGonigle's techniques are now *'used as standard in volcano observatories across the globe'*, [S4; Institute of Sustainable Development, France]. Since 2013 more than 100 spectrometer and camera units have been operated on almost every (n>40) degassing volcano on the planet, in more than 30 countries on every continent, resulting in of over 20,000 survey days of data.

2) Significantly enhancing volcano monitoring capacity to the benefit of local populations

Enhanced monitoring capacity has the potential to benefit citizens living in the vicinity of volcanoes. The developed sensors have been deployed to capture pre-eruptive signals on volcanoes near major urban conurbations e.g., the Greater Mexico City region, Mexico (21M people; Popocatépetl volcano), Managua, Nicaragua (1M; Masaya), Quito, Ecuador (1.4M; Reventador), Catania Italy (1M; Etna), Pasto, Colombia (0.4M; Galeras), Goma, DRC (0.4M; Nyiragongo) and San José, Costa Rica (0.3M; Poás).

Furthermore, McGonigle *"has pioneered highly significant improvements in the capacity of governmental volcano monitoring agencies across the globe"* [S4], by delivering technology with:

a) Improved portability; the lightweight, easily portable nature of the units means they are easy to transport, even to the *'most challenging field destination'* [S5; Fredy Apaza, Instituto Geológico Minero y Metalúrgico, Perú]. Previously, deploying gas sensors to many volcanic regions, e.g., in Papua New Guinea, Ethiopia and DRC would have been dangerous, expensive and in some cases impossible.

b) User friendly operability, enabling non-experts to straightforwardly deploy the units and process the resulting data [S6; Andrea Rizzo, Istituto Nazionale di Geofisica e Vulcanologia, Italy].

c) Reduced cost, that has enabled the technology to be distributed globally, particularly across the Global South where resources are limited, thereby vastly increasing the *“valuable data that we now have available for monitoring and forecasting”* [S4].

d) Improved data accuracy and spatio-temporal resolution, which enables the volcanic process to be scrutinised in much more detail, leading to new knowledge and understanding [S4].

Overall, this has led to enhanced understanding and forecasting, through increased capacity to resolve transitions from non-eruptive to eruptive activity [S6], directly impacting people living nearby by reducing associated potential volcanic risks to livelihoods and health, including respiratory issues and impact injury.

3) Developing new technologies for space exploration

McGonigle’s UV smartphone sensors have been identified by NASA as a technology suitable for measurement of water in Lunar rocks. This data is key to advancing our grasp of the evolution of the planets and moons of the solar system, and in terms of harvesting this resource for life support in NASA’s planned Artemis program lunar station. Collaboratively McGonigle and NASA have created a novel sensor for lunar rover deployment. Previously, NASA were unable to progress this work, which must be performed on the lunar surface, as there was no market-available UV sensor compact enough for installation on board the proposed shoebox sized ‘puffer’ lunar rovers, yet sensitive enough for this highly challenging measurement. Since 2018 McGonigle has been subcontracted to NASA to co-develop a prototype 60g UV spectrometer for this application, based on his sensor module.

“Although it seems there may be multiple options for detectors, there are few viable, effective detector technologies that meet our requirements. Dr. McGonigle’s research enabled us to develop low-cost, lightweight, and high sensitivity UV sensors using off-the- shelf technology for our breadboard instrument” Research and Instrument Scientist, NASA [S6].

This prototype has already rapidly escalated through NASA’s Technology Readiness Levels (TRL); TRLs are now widely used classification characterising the maturity of technology, ranging from 1- ‘Basic principles observed and reported’ to 9 ‘Actual system "flight proven" through successful mission operations’. The spectrometer has now passed rigorous proof of concept tests, demonstrating sufficient sensitivity for this application, reaching TRL4. In 2020 funding was confirmed, by NASA, for development up to TLR6 'prototype demonstration in a relevant space environment' [S6].

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

S1. Contract paperwork to evidence our working relationships with the Universidad Católica del Norte in Chile. Contract dated 140519.

S2. Contract paperwork to evidence our working relationship with the Instituto Geofisico del Perú. Contract dated 141119.

S3. Chargé de Recherche; Institute of Research for Development, Laboratoire Magmas et Volcans; Université Blaise Pascale, Clermont Ferrand, France.

S4. Istituto Nazionale di Geofisica e Vulcanologia; Sezione di Palermo, Italy.

S5. Instituto Geológico Minero y Metalúrgico; Arequipa, Perú.

S6. Testimonial Research and Instruments Scientist, NASA.