Institution: University of Liverpool

Unit of Assessment: 7 (Earth Systems and Environmental Sciences)

Title of case study: Liverpool volcanology research improves monitoring practice, influences decision making, and prevents loss of life in Guatemala

Period when the underpinning research was undertaken: 2014 - 2020

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:
Dr. Silvio De Angelis	Lecturer - Reader in Geophysics	2012 - present
Prof. Yan Lavallée	Chair of Volcanology	2012 - present

Period when the claimed impact occurred: January 2014 - July 2020

Is this case study continued from a case study submitted in 2014? No

1.Summary of the impact

Frontier research at the University of Liverpool has informed the implementation of operational volcano monitoring systems in Guatemala by developing techniques and practices that utilise seismic and acoustic data for real-time assessment of volcanic activity. In 2018, the adoption of these new methods by INSIVUMEH, the governmental agency responsible for monitoring of geological hazards in Guatemala, **changed volcano monitoring practice** and **influenced decision making** for the management of hazard areas near active volcanoes in the country. On 19 November 2018, the timely detection of intensifying activity by the new monitoring systems informed an evacuation, and **protected 3,925 people whose lives were under threat by eruptive activity** at Volcan de Fuego in Guatemala.

2. Underpinning research

World-class research in volcanology has been conducted in the School of Environmental Sciences at Liverpool under the leadership of Dr. Silvio De Angelis (Reader in Geophysics) and Prof. Yan Lavallée (Professor and Chair of Volcanology and Magmatic Processes). Their research focusses on characterizing the geophysical fingerprint of volcanoes to inform and develop operational frameworks for real-time volcano monitoring.

Liverpool research into volcano geophysics conducted between 2014 and 2020 has focussed on Official Development Assistance (ODA) countries, particularly Guatemala. In these countries volcanic activity has significant and long-lasting economic and societal impacts through the severe disruption to the lives and livelihoods of individuals. Communities in ODA countries are disproportionally vulnerable to volcanic hazards, as a high percentage live in potentially affected areas; scarce access to monitoring infrastructure, a lack of local know-how to implement solutions to the challenges posed by volcanic disasters and extreme poverty are aggravating factors. Understanding and managing the threat of volcanic activity is key to the economic development and welfare of these countries. De Angelis' and Lavallée's research was supported by grants from the academic, government, and private sectors. Relevant to this impact, those include funders such as the European Research Council**,** Natural Environment Research Council (NERC)**,** Society of Exploration Geophysics and the Foreign and Commonwealth Office UK (FCO).

Research published by the team led by De Angelis and Lavallée has provided new and robust frameworks for the interpretation of quantitative field observations and geophysical data monitored during volcanic unrest and eruption **[3.1, 3.2, 3.3].** At Santiaguito volcano, in Guatemala, the occurrence and causes of volcanic unrest were investigated to demonstrate links between volcanic processes, and the timing of changes in eruption intensity **[3.1]** as observed in seismic and acoustic (infrasound) data **[3.2, 3.3]**. This body of work established methodologies to characterize the state of unrest at volcanoes such as in Guatemala, where eruptions last for

periods as long as decades. Long-lived eruptions can undergo sudden and hazardous transitions, from nearly continuous, low-level eruptions to sudden and vigorous peaks in activity. These shifts can occur without clear long- or short-term precursors in the traditionally monitored geophysical signals such as seismic or ground deformation.

Liverpool's work at Santiaguito and other volcanoes **[3.2, 3.4, 3.5, 3.6**] highlighted the value and potential of infrasound data as a powerful diagnostic for volcanic unrest and as a real-time monitoring tool during volcanic crises. Work published in 2019-2020, led by De Angelis, focussed on investigating the mechanisms of infrasound generation and propagation at active volcanoes **[3.4, 3.5]**, and successfully explored the use of acoustic data for real-time monitoring of eruptive activity **[3.6]**. The team demonstrated that infrasound holds potential to inform early warning over periods of hours to minutes before the onset of the peak phase of activity at volcanoes **[3.6]**.

De Angelis introduced new numerical schemes for acoustic wavefield modelling, and novel waveform inversion methods for infrasound data **[3.4, 3.5]** akin to methods employed in seismology to characterize the source mechanisms of earthquakes. Numerical modelling of the infrasonic wavefield, including the effects of terrain topography and atmospheric effects, provides a valuable tool for planning the deployment of acoustic sensor networks **[3.5, 3.6]**; infrasound data inversion allows evaluation of the source mechanisms of explosions and assessment of the magnitude of volcanic activity in terms of the rate at which gas and pyroclasts are ejected from erupting vents **[3.5, 3.6].** These are key input parameters into models of atmospheric dispersal of volcanic material as used by aviation authorities to dispatch warnings during eruptions **[3.4]**. Work published by De Angelis in 2020 introduced new algorithms and their open source software implementation for analysis of infrasound array data **[3.6].** These algorithms allow detection, quantification and tracking of the evolution of volcanic unrest in real-time, including the associated uncertainties. This work demonstrated that the deployment of microphones in small clusters is an efficient, robust and cost-effective solution to provide information that can be readily exploited to inform volcano surveillance operations and early warning protocols.

3. References to the research

3.1 Wallace, P. A., Lamb, O. D., **De Angelis, S.**, Kendrick, J. E., Hornby, A. J., Díaz-Moreno, A., González, P. J., von Aulock, F. W., Lamur, A., Utley, J. E. P., Rietbrock, A., Chigna, G., and **Lavallée, Y.** (2020). Integrated constraints on explosive eruption intensification at Santiaguito dome complex, Guatemala. Earth and Planetary Science Letters, 536, doi:10.1016/j.epsl.2020.116139.

3.2 Lamb, O. D., Lamur, A., Diaz-Moreno, A., **De Angelis, S.**, Hornby, A. J., von Aulock, F. W., and **Lavallee, Y.** (2019). Disruption of Long-Term Effusive-Explosive Activity at Santiaguito, Guatemala. Frontiers in Earth Science, 6, doi:10.3389/feart.2018.00253

3.3 De Angelis, S., Lamb, O. D., Lamur, A., Hornby, A. J., von Aulock, F. W., Chigna, G., and Rietbrock, A. (2016). Characterization of moderate ash-and-gas explosions at Santiaguito volcano, Guatemala, from infrasound waveform inversion and thermal infrared measurements. Geophysical Research Letters, 43(12), doi:10.1002/2016GL069098

3.4 De Angelis, S., Diaz-Moreno, A., and Zuccarello, L. (2019). Recent Developments and Applications of Acoustic Infrasound to Monitor Volcanic Emissions. Remote sensing, 11(11), doi:10.3390/rs11111302

3.5 Diaz-Moreno, A., Iezzi, A. M., Lamb, O. D., Fee, D., Kim, K., Zuccarello, L., and **De Angelis, S.** (2019). Volume Flow Rate Estimation for Small Explosions at Mt. Etna, Italy, from acoustic waveform inversion. Geophysical Research Letters, 46(20), doi:10.1029/2019GL084598

3.6 De Angelis, S., Haney, M., Lyons, J. J., Wech, A., Fee, D., Diaz-Moreno, A., and Zuccarello, L. (2020). Uncertainty in Detection of Volcanic Activity Using Infrasound Arrays: Examples From Mt. Etna, Italy. Frontiers in Earth Sciences, 8, doi: 10.3389/feart.2020.00169

4. Details of the impact

Research at Liverpool has informed the implementation of operational volcano monitoring systems in Guatemala by developing techniques for the real-time assessment of volcanic activity. The adoption of these new methods by INSIVUMEH in 2018 has:

- **changed volcano monitoring practice** in Guatemala
- **influenced decision making** for management of hazard areas near active volcanoes in Guatemala
- detected intensifying activity at Volcan de Fuego in November 2018 which informed an evacuation, and **protected 3,925 people whose lives were at risk** from eruptive activity

4.1 Volcano monitoring and local capacity building in Guatemala

In 2014 Liverpool researchers recognized that risk mitigation in Guatemala required a long-term commitment. Funding from European Research Council, Natural Environment Research Council, and Society of Exploration Geophysics initiated a collaboration with INSIVUMEH to improve monitoring of Santa Maria-Santaguito. De Angelis and Lavallée designed a program centred on four elements:

i) research at Guatemalan volcanoes, in particular Santiaguito and Fuego
ii) technical support in the implementation of a volcano monitoring system based on seismic and infrasound data
iii) advisory roles to assist with the development of a volcano monitoring programme
iv) training of local scientific and technical staff in Guatemala

The U.S. Geological Survey Volcano Disaster Assistance Program (VDAP) confirmed that *"one critical role of Dr. De Angelis is his ability to provide Guatemalan scientists with educational opportunities … that cannot be offered by a governmental organization"* **[5.2],** that *"the primary focus of his work has been to increase the understanding of volcanoes and volcanic unrest"* **[5.2],** and that Dr De Angelis *"has carried out his studies with a strong, consistent emphasis on simultaneously improving the capabilities of our Guatemalan colleagues"* **[5.2].**

Long-term sustainability was at the core of the Liverpool-INSIVUMEH cooperation from its inception, as evidenced by the INSIVUMEH Director General, *"Local capacity building in Guatemala is a central objective of […] INSIVUMEH; in this respect the role played by Dr. De Angelis has been central"* **[5.1a]**. In January 2016, Lavallée co-led a ten-day workshop to train local staff and academics on monitoring instrument deployment and data analysis, specific to Guatemalan volcanoes **[5.1b]**.

4.2 Responding to an eruption of Volcan de Fuego with technical advice and support

On June 3, 2018, an eruption of Volcan de Fuego "*killed 110 people, and 332 remain missing to date. Over 10,000 had to be relocated, and about 3,600 permanently lost their homes"* **[5.3]**. Almost overnight Guatemala became dependent on outside expertise, requiring technical advice and support **[5.4]**. The Liverpool team led by De Angelis was the first in the country after the June 2018 eruption. The UK's Foreign and Commonwealth Office (FCO) provided funds *"to install seismic and acoustic monitoring equipment and to implement some of their recent research into a real-time system for automatic detection of volcanic activity"* **[5.3]**. According to the Director General of the European Civil Protection and Humanitarian Aid Operations (ECHO), De Angelis was *"instrumental in the assessment of the situation on the ground in the aftermath of the eruption"* **[5.5]**.

The Guatemalan government's Coordinadora Nacional para la Reducción de Desastres (CONRED) issued a request for assistance **[5.4]** to ECHO through its Emergency Response Coordination Centre (ERCC), and a team of experts was deployed to Guatemala. De Angelis' name was *"put forward for the ERCC mission by the UK Civil Contingencies Secretariat (Cabinet Office) based on his extensive body of research and work"* **[5.5].** He joined the ERCC mission on July 3, 2018 **[5.5]**. The mission concluded on 13 July having implemented a preliminary real-time

monitoring system *"directly derived from research published by Dr. De Angelis and colleagues"* **[5.5].**

4.3 Developing a real-time volcanic monitoring system in Guatemala

De Angelis later returned to assist VDAP colleagues with the installation of additional equipment, which became the core of what is now an increasingly developing volcano monitoring program in Guatemala **[5.1a, 5.2]**. A framework for the analysis of acoustic data later published by De Angelis **[3.6]** had been implemented at INSIVUMEH as early as September 2018 to provide *"for the first time a system … capable of detecting and alarming on volcanic explosions, pyroclastic flows and lahars at Fuego"* **[5.1a].** In 2019 a Volcanic Scientific Advisory Committee (VSAC) was established to advise INSIVUMEH on volcanic risk assessment and strategic planning for volcano monitoring in Guatemala. Based on his world-class track record, De Angelis was nominated as a member of the Volcanic Scientific Advisory Committee **[5.7]**.

In 2019, the Head of Volcanology at INSIVUMEH visited Liverpool to work on the implementation of new volcano monitoring tools through funding from the Society of Exploration Geophysics. De Angelis and INSIVUMEH developed additional software for the real-time calculation of monitoring parameters based on research published in **[3.3, 3.4, 3.5, 3.6]**. According to the Director General of INSIVUMEH, the *"new workflow at INSIVUMEH is based on research by Dr. De Angelis and colleagues, including improved processing to detect and track volcanic activity, assessment of explosion magnitude and evaluation of the volume of ash injected in the atmosphere during volcanic explosions"* **[5.1a]**. In January 2020, De Angelis organized a workshop in Guatemala funded by the UK Foreign and Commonwealth Office to train 25 members of INSIVUMEH staff and civil protection officials on the new monitoring tools **[5.1a, 5.2, 5.3].**

4.4 Changing practice, influencing policy and saving lives in Guatemala

To date, the new volcano monitoring systems at INSIVUMEH have detected over 30,000 events, including volcanic explosions, lahars, and pyroclastic flows at Fuego. The work of the Liverpool team between 2014 and 2020 has significantly contributed to transforming volcano monitoring capacity in Guatemala **[5.1a, 5.2, 5.3]**. Liverpool research provided new tools for timely detection of eruptive activity, which have already influenced early warning practice and civil protection response during volcanic crises in Guatemala **[5.1a, 5.5, 5.6, 5.7]**.

During the last episode of intensification of volcanic activity at Fuego, in November 2018, the new monitoring systems at INSIVUMEH, based on Liverpool research, detected an early escalation in eruptive activity. This information was instrumental for INSIVUMEH to advise the Guatemalan national civil protection authorities and to jointly recommend the evacuation of 3,925 people, whose life was under threat from the ongoing eruption **[5.6]**.

The significance and reach of this impact is reinforced by the high levels of volcanic hazards across Guatemala, with 1,341,000 people living within 10 km of one of three active volcanoes. The 1902 eruption of Santa Maria claimed the lives of about 8,700 people and "*activity at Fuego could potentially affect an area populated by nearly 1,000,000 people, which includes rural areas where poverty frequently represents an aggravating factor*" **[5.1a].**

4.5 Improving volcano monitoring practice in Italy, Ecuador and New Zealand

In the future, new monitoring systems similar to those implemented at INSIVUMEH will provide surveillance at other volcanoes instrumented with similar equipment. Liverpool has already instrumented the Santa Maria volcanic complex with a network of sensors integrated within the new systems and volcano monitoring protocols through funding from the Society of Exploration Geophysics. Based on the impact of the work in Guatemala and a successful track record, the Liverpool research team received invitations in 2020 from the Instituto Nazionale di Geofisica e Vulcanologia, Italy to work on monitoring Mount Etna **[5.8]**, the Instituto Geofisico, Ecuador **[5.9],** and the Institute of Geological and Nuclear Sciences, New Zealand **[5.10]** to collaborate on the development of infrasound monitoring systems. This is a powerful testament to the significant impact and international reputation of research in volcanology and geophysics at Liverpool.

5. Sources to corroborate the impact

5.1a Director of INSIVUMEH**.** Factual Statement that describes contributions to developing new monitoring systems at INSIVUMEH based on Liverpool research, and confirms advisory roles undertaken by De Angelis during and after the 2018 eruption of Fuego volcano.

5.1b Professor of Geophysics at Boise State University (USA) and the leader of the first Workshop on Volcanoes (WoV). Factual statement that describes the efforts of Lavallée and his team at Liverpool, towards volcano monitoring strategies and shared best practices during WoV2016.

5.2 Geophysicist, U.S. Geological Survey Volcano Disaster Assistance Program (VDAP). Factual statement that describes the quality of training delivered by Liverpool and the collaboration with US Geological Survey in developing a volcanic monitoring system in Guatemala.

5.3 Her Majesty's Ambassador to the Republic of Guatemala. Factual statement describing work of De Angelis as part of a rapid response team in the aftermath of eruption and role in initiating building a modern monitoring system in Guatemala.

5.4 Coordinadora Nacional para la Reducción de Desastres, Guatemala. *In Spanish*. Request for assistance to the Directorate General for European Civil Protection for qualified experts to help develop rapid response and monitoring systems in Guatemala and to advise on risk and hazard.

5.5 Acting Team Leader (Unit 2) at the Directorate General for European Civil Protection and Humanitarian Aid Operations (DG ECHO). Leader of the EU-ECHO mission in Guatemala in the aftermath of the June 2018 eruption of Volcan de Fuego. Factual statement confirming the advisory role undertaken by De Angelis during the EU-ECHO eruption response mission.

5.6 Coordinadora Nacional para la Reducción de Desastres, Guatemala. *In Spanish*. Informative Bulletin from 19 November 2019 confirming the evacuation of residents in Guatemala: https://web.archive.org/web/20201119163459/https://conred.gob.gt/boletin-informativo-no-3992018-actividad-de-volcan-de-fuego-continua-generando-flujos-piroclasticos/ [Accessed 01/12/2020]

5.7 Director of INSIVUMEH**.** Letter of invitation to join the Volcanic Scientific Advisory Committee to establish volcano monitoring systems in Guatemala in the future.

5.8 Coordinator of Seismological Research and Monitoring, Istituto Nazionale di Geofisica e Vulcanologia, Catania, Italy. Letter of invitation to collaborate towards development of volcano infrasound monitoring systems in Italy.

5.9 Director of Instituto Geofisico, Ecuador. Letter of invitation to collaborate towards development of volcano infrasound monitoring systems in Ecuador.

5.10 Science Operations and Data Team lead, GNS Science, New Zealand. Letter of invitation to collaborate towards development of volcano infrasound monitoring systems in New Zealand.