COMET

CENTRE FOR THE OBSERVATION AND MODELLING OF EARTHQUAKES, VOLCANOES AND TECTONICS

ANNUAL REPORT 2017 / 2018

NERC SCIENCE OF THE ENVIRONMENT

BGS 1835

CONTENTS

DIRECTOR'S WELCOME

Our fourth annual report comes at a time of celebrating success whilst we plan COMET's future.

Earlier this year I had the honour of accepting, on behalf of COMET, the Royal Astronomical Society Group Acheivement Award in Geophysics. This recognised the efforts of the entire COMET family, of whom I remain immensely proud. I would like to formally thank everyone involved in COMET, past and present, for their contributions.

Although the award acknowledged the full scope of our research, our work on satellite geodesy was singled out for commendation. LiCSAR, our processing system designed to handle the vast amounts of data from the Sentinel-1 satellites, is now providing high-resolution deformation data for the entire Alpine-Himalayan seismic belt, where most of the planet's deadly earthquakes occur. We are expanding LiCSAR to provide global coverage, as well as developing a system to allow rapid response to seismic and volcanic events.

Our new system using Sentinel-1 to monitor volcano deformation, LiCSAR-volcano, is also now operational, allowing us to monitor ground deformation on 929 volcanoes worldwide, including Africa and Central and South America - regions with large explosive volcanoes currently only covered by limited ground surveys.

Our capacity to monitor volcanic ash as well as SO_2 emissions in near-real time using the Infrared Atmospheric Sounding Interferometer (IASI) continues to improve, and in particular we have made progress on using IASI to monitor smaller and lower altitude emissions as well as ongoing activity.

We have also remained responsive to the dynamic Earth, responding to events in Agung (Indonesia), China and the Galapagos Islands amongst other places, all of which are described in this report.

Our partnership with the British Geological Survey (BGS) now includes a joint long-term vision, ensuring that COMET supports BGS's commitment to UK Government on disaster response.

Our success in securing Global Challenges Research Fund (GCRF) support is meanwhile helping to address significant challenges faced by developing countries in relation to environmental hazards, ranging from volcanic emissions in Nicaragua to earthquakes in Chile and crustal movements in Ethiopia, and from seismic hazard in Malawi to global volcano alert systems based on satellite data.

As all of this suggests, COMET is part of a global community working to improve understanding of seismic hazard. We also have a growing cohort of young researchers who are vital not only to delivering all of this, but also to steering COMET into its next phase. Their work features throughout this report, and I am sure that some of their names will become increasingly familiar in coming years.

In the meantime, during the next year, we will continue to produce research into seismic and volcanic hazard which has real-world impact whilst planning a vibrant and successful future.

Professor Tim Wright
COMET Director

CHAIR’S FOREWORD

As Chair of the COMET Advisory Board, I am delighted to reflect back on another successful and stimulating year, the highlight of which was the well-attended COMET annual meeting.

COMET’s enthusiasm for scientific discovery and its community spirit were evident throughout the event, continuing to build its reputation as a collaborative, world-leading research organisation.

Speaking on behalf of the Board, we are particularly encouraged by the strong scientific contributions from COMET’s students and early career researchers. With their expertise and commitment to the organisation, COMET’s future is clearly in good hands.

In future, as well as hearing about new scientific developments and responses to recent events, we look forward to seeing COMET’s progress on integrating observations and models, and increasing their application to seismic hazard forecasting.

All of these elements are described in this document, and we hope that you find the content as interesting and informative as we have.

On behalf of the COMET Advisory Board,

Professor Ramon Arrowsmith
Chair, COMET Advisory Board

1000-m high Bordeira (caldera wall) of the Cha das Caldeiras Caldera in Fogo (Cape Verde)
Credit: Pablo J González, March 2018, University of Liverpool

INTRODUCTION

The Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) provides national capability in the observation and modelling of tectonic and volcanic hazards.

We deliver services, facilities, data and long-term research to produce world-leading science that can help the UK and others to prepare for, and respond rapidly to, earthquakes and eruptions.

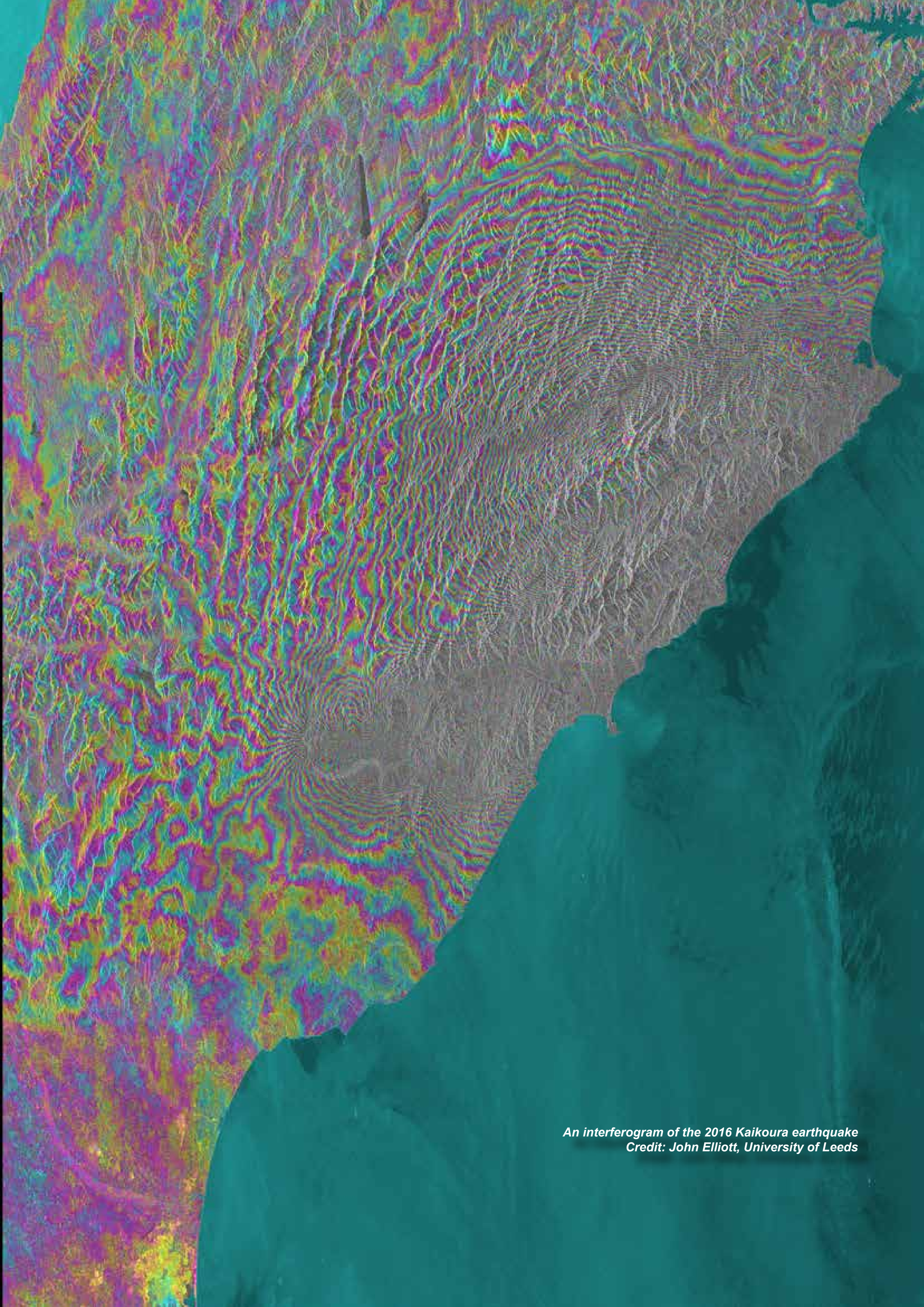
Based at the Universities of Oxford, Cambridge, Leeds, Bristol, Reading, Durham, Liverpool, Newcastle and University College London (UCL), we use satellite Earth Observation (EO) techniques such as Synthetic Aperture Radar Interferometry (InSAR) alongside ground-based observations and geophysical models to study earthquakes and volcanoes, and understand the hazard they pose. As well as providing scientific leadership in EO, we have a vibrant young community of postgraduate students and early career researchers.

We work closely with the British Geological Survey (BGS), with our sponsors the Natural Environment Research Council (NERC), with the European Space Agency (ESA), and with many other national and international partners.

In addition, we are working with business, Government and the space agencies to ensure that the UK continues to invest in and benefit from satellite missions.

COMET has three main aims for 2014-2019: to measure tectonic strain with unprecedented resolution for the entire planet, to measure deformation and gas release at every active volcano, and to combine these data with ground-based observations to build new models of hazardous processes that can be used to mitigate risk.

This report gives an overview of COMET's activities during 2017-18, highlighting major scientific achievements as well as progress against our key objectives. It covers the period 1 January – 31 December 2017 for publications, and 1 April 2017 – 31 March 2018 for all other outputs.



An interferogram of the 2016 Kaikoura earthquake
Credit: John Elliott, University of Leeds

OUR NEW MEMBERS

Milan Lazecky, COMET Scientific Programmer (Leeds)

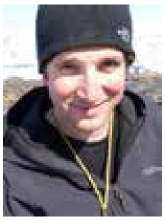
Milan joins COMET in the key post of Scientific Programmer, focusing on the development and maintenance of the LiCSAR facility, which is automatically producing InSAR products with Sentinel-1 data. Milan is working closely with the wider COMET and Looking inside the Continents from Space (LiCS) teams to implement new developments in the system and extend its coverage.

Matthew Fox, COMET Associate[1], (UCL)

Matthew's research focuses on understanding landscape evolution to deconvolve complex feedbacks amongst climate and tectonics. In doing so, he combines geomorphic and geophysical data with novel numerical methods to study surface processes at a range of spatial and temporal scales, addressing questions such as how do changes in climate modulate the processes or rates of erosion; how do tectonic processes respond to this redistribution of mass; and how quickly does CO_2 in the Earth's climate decrease due to increased silicate weathering driven by tectonic activity.

Ekbal Hussain, COMET Associate (BGS)

Following completion of his PhD at Leeds, Ekbal is now a Remote Sensing Geoscientist at BGS where he is continuing his work on applying InSAR techniques to understand ground deformation around active tectonic faults. He also works with optical satellite imagery to produce digital elevation models, mapping faults and surface geomorphology, and uses satellite imagery to map landslides and provide the groundwork for landslide susceptibility modelling. In addition Ekbal works closely with the Global Earthquake Model to calculate the seismic risk to cities from potential distant and near-field earthquake sources.



Dylan Rood, COMET Associate (Imperial College London)

Dylan applies cosmogenic isotopes and accelerator mass spectrometry (AMS) to studying active tectonics, Earth surface processes, climate change, and earthquake hazards. Currently Director of the CosmIC Laboratory at Imperial College London, his expertise in Quaternary geochronology using cosmogenic isotopes can be applied to a wide breadth of problems within the COMET remit.

1 Associates are normally UK-based researchers working on complementary topics, often in collaboration with our existing members. Please contact us if you are interested in becoming a COMET associate.

A LOOK BACK AT 2017/18

As well as our planned research, over the past year COMET members were involved in activities ranging from responding to seismic events and advising governments on volcanic hazards to training the next generation of EO scientists and informing the public about the dynamic Earth.

Event response

Intrusive activity at Cerro Azul volcano, Galápagos Islands

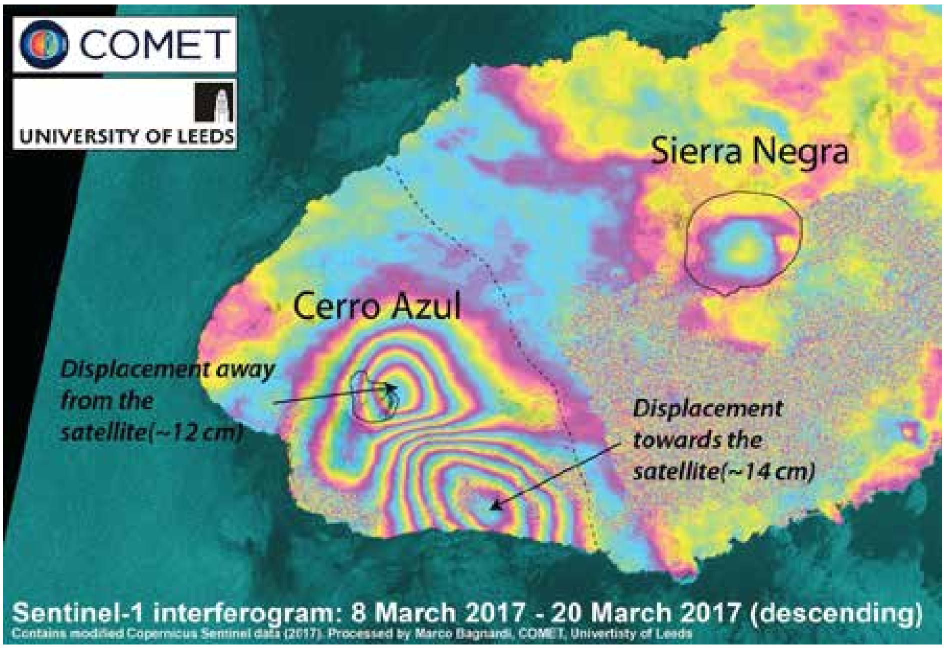
Cerro Azul is the southernmost active volcano on Isabela Island, Galápagos (Ecuador). On 18-19 March 2017, seismic activity increased on the south eastern flank of the volcano. On the same day, the Instituto Geofisico Escuela Politécnica National (IGEPN), the organisation responsible for the monitoring of Ecuadorian volcanoes, issued a warning for a possible imminent eruption.

The recorded seismicity was composed of volcano tectonic (VT) earthquakes, consistent with processes of rock fracturing, with the majority of events having magnitudes between 2.4 and 3. There were also sporadic events of magnitude up to 3.6.

Sentinel-1 acquired synthetic aperture radar data on 7 and 8 March, prior to the onset of the seismic activity, and on 19 and 20 March, once seismicity started to exceed background levels both in terms of the number of earthquakes and of energy release.

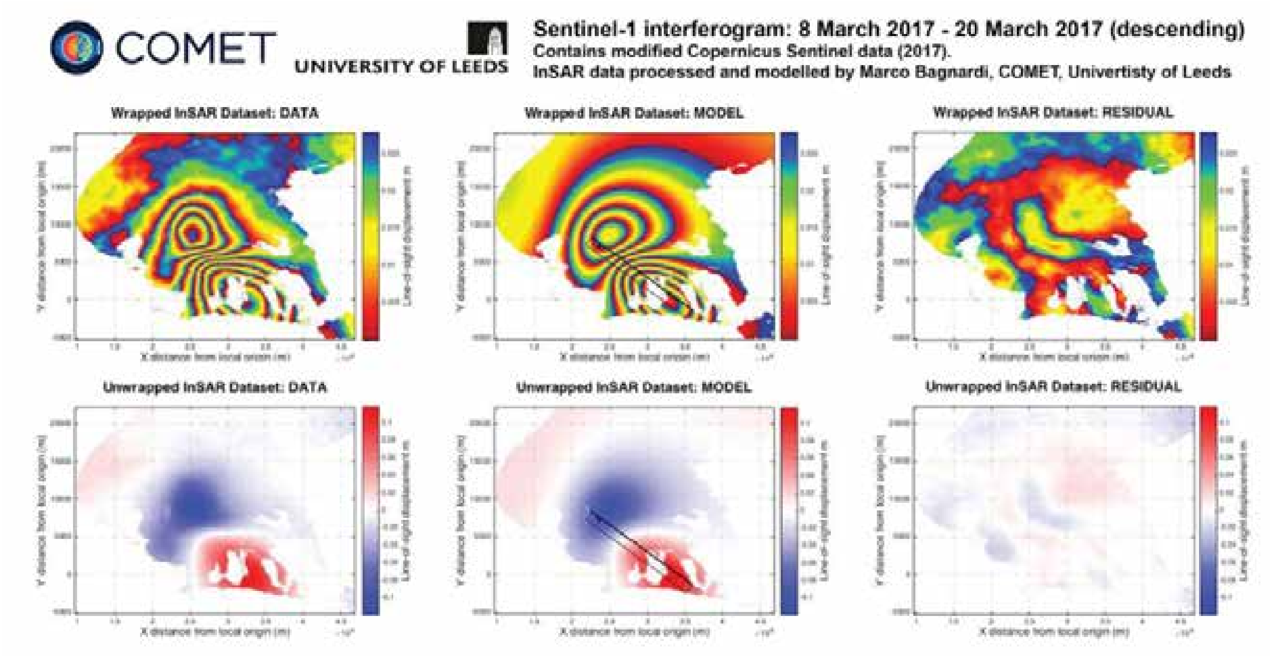
Within ten hours of receiving the warning from IGEPN, COMET was able to get hold of the most recent Sentinel-1 data for the area, process it into differential interferograms, invert the data to infer the source of the observed deformation, and pass the information back to IGEPN.

The results showed significant deformation (up to 14 cm) in the region affected by the seismic swarm. More specifically, the InSAR data showed uplift at the south eastern flank of the volcano and contemporary subsidence centred at the summit of the volcano.



Sentinel-1 interferogram showing deformation caused by the magmatic intrusion as of 20 March 2017. Each colour fringe corresponds to ~2.8 cm of displacement in the direction between the ground and the satellite

COMET researcher Marco Bagnardi[2], working with the IGEPN, carried out a preliminary analysis of the InSAR data and found that the deformation could be explained by the intrusion of a 20-40 million cubic metres sill at a depth of ~5 km beneath the surface of the volcano.

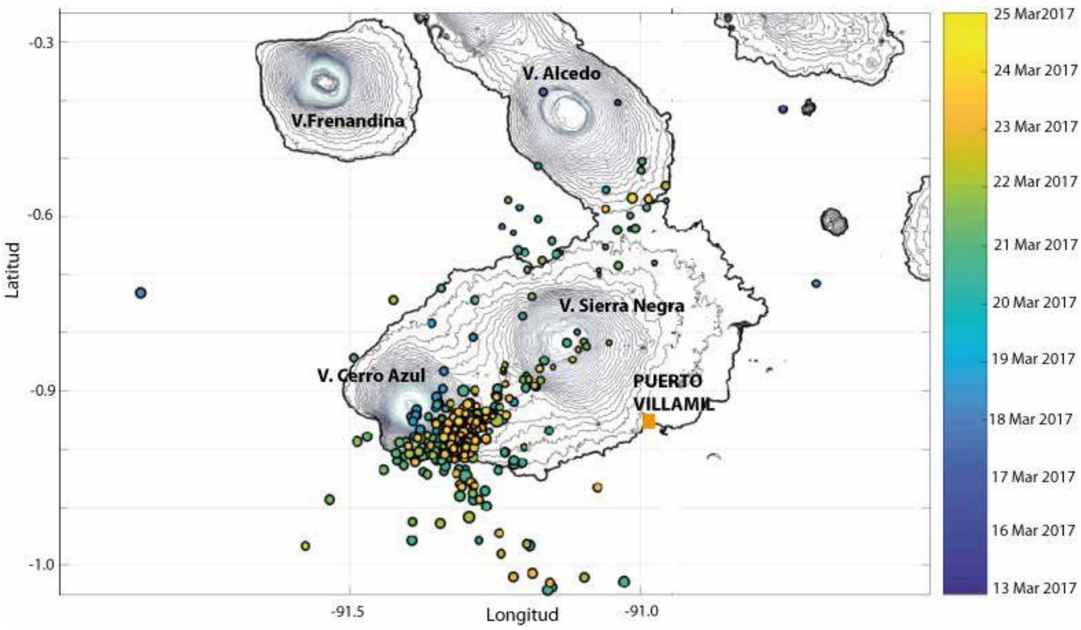


Modelling results from the inversion of InSAR data. The proposed model is composed of a horizontal sill intrusion at ~5 km depth (black rectangle) fed by a deflating source at ~6 km depth (black star)

2 Now Postdoctoral Fellow at NASA's Jet Propulsion Laboratory

A LOOK BACK AT 2017/18

Such intrusion is likely to be fed by a 6 km deep reservoir, cantered beneath the summit of the volcano. The location of the intrusion well matches the location of the seismicity recorded by IGEPN.



Earthquake locations between 13 and 25 March 2017. Credit: IGEPN "Informe Especial Cerro Azul No. 2 – 2017"

Deformation and associated seismic activity continued to occur during the following days, with surface displacements measured by InSAR of up to 38 cm by 1 April.

Modelling of data spanning the entire event suggests the intrusion of 80-100 million cubic metres beneath the south eastern flank of Cerro Azul and withdrawal of an equivalent volume from the magma reservoir. With this information, IGEPN were able to assess and mitigate the hazard associated with this episode of unrest.

Dyke intrusion between neighbouring arc volcanoes responsible for 2017 pre-eruptive seismic swarm at Agung, Bali

On 21 November 2017, Agung volcano in Indonesia erupted, ending more than 50 years of quiescence. As the previous eruption in 1963 killed several thousand people, monitoring and interpretation of the pre-eruptive signals in 2017 was important to manage the crisis and prevent fatalities. Sentinel-1 InSAR data and 3D numerical modelling, led by Fabien Albino and Juliet Biggs at the University of Bristol, showed that the seismic crisis recorded two months before the eruption resulted from an emplacement of a large and deep magma intrusion between Bali's Agung and Batur volcanic systems.

In September 2017, a seismic swarm had triggered the evacuation of over 150,000 people from Agung. At that time, COMET was involved in the InSAR response for the volcanic crisis, working closely with the Volcano Disaster Assistance Program led by the US Geological Survey (USGS). The first goal was to perform a systematic analysis of the most recent Sentinel-1 SAR scenes (1 image every 12 days for both orbits).

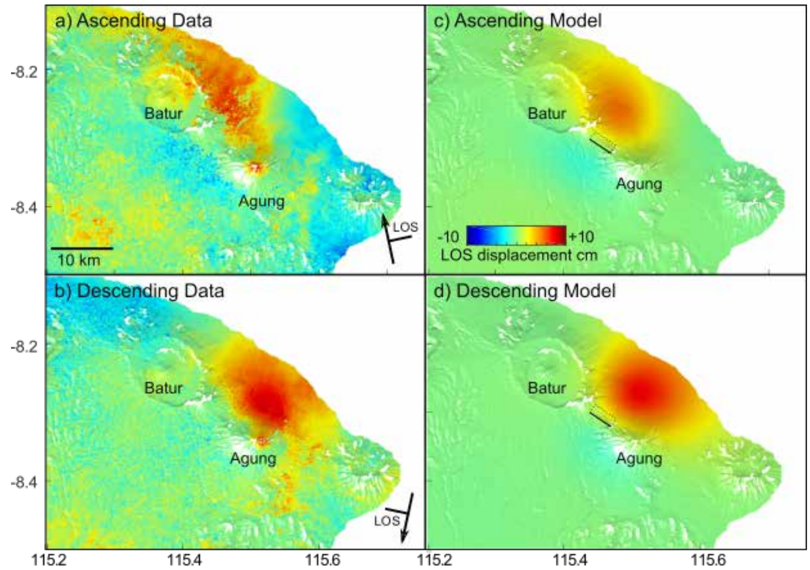
The tropical climate in Bali is a challenge for InSAR techniques, as radar waves are slowed by water vapour in the atmosphere causing false signals, unless corrections are applied. The team therefore used the atmospheric corrections provided by GACOS (see Scientific Developments) to produce an InSAR time series from April to November 2017.

This showed a persistent 5 km radius uplift signal of 8-10 cm on the north flank of the edifice starting in late September 2017, in both ascending and descending tracks (Figure a-b).

The inversion of InSAR data using 3D Finite Element Model shows that the ground deformation signal is consistent with a deep sub-vertical magma intrusion located between Agung and its neighbour Batur caldera (Figure c-d). Using stress modelling confirmed that the N129º strike of the inferred dyke is not related to the regional tectonic stresses, but it can be explained by the topographic load of the volcanic centres.

The interpretation is that the transport of magma below Agung is controlled by the emplacement of large and deep mafic intrusions that likely propagate between Agung-Batur systems. For the first time, the geodetic observations revealed ongoing interactions between Agung and Batur which have important implications for interpretation of distal seismicity, the links between magmatic systems of closely spaced arc volcanoes, and the potential for cascading hazards as the occurrence of simultaneous eruptions at neighbour volcanoes.

This work is helping to assess how useful satellites can be in responding to major volcanic events, alongside ground-based networks, to ensure that decision-makers have access to the best possible information.



a-b) Sentinel-1 stacked unwrapped interferogram showing ground uplift at Agung for the period August-November. c-d) Ground deformation associated with the optimal model: a deep magma intrusion located midway between Agung and Batur volcanoes

A LOOK BACK AT 2017/18

Sentinel-1 satellites reveal pre-event movements and source areas of the Maoxian landslides, China

At about 5:38am local time on 24 June 2017, a massive landslide struck Xinmo Village, Maoxian County, Sichuan Province in China. Sichuan Province is prone to earthquakes, including the 2008 Mw 7.9 Wenchuan earthquake that killed over 70,000 people, as well as the 1933 Mw 7.3 Diexi earthquake with a death toll of up to 9,300. The landslide swept away 64 homes in Xinmo village, blocking a 2 km section of river and burying 1,600 metres of road. The collapsed rubble was estimated to be about thirteen million cubic metres (Figure 1a). Three days later, on 27 June 2017, a second landslide hit Xinmo Village; at almost the same time, another landslide occurred in Shidaguan Town, 20 km away (Figure 1b).

Figure 1 The Maoxian landslides: (a) Xinmo Village; (b) Shidaguan Town

A joint team from Newcastle University (led by COMET scientist Zhenhong Li), Chengdu University of Technology, Tongji University, China Academy of Space Technology and Wuhan University (China) raced against time to respond to these two events by combining Sentinel-1 and Chinese Gaofen-2/3 satellite images with field observations.

Sentinel-1 acquired a post-event image thirteen and half hours after the Xinmo event, and provided the first interferogram for the Xinmo landslide. This first Sentinel-1 interferogram, together with its corresponding coherence and amplitude maps, not only helped identify the source area of this massive landslide, but also assisted with mapping the landslide boundary (Figure 2).

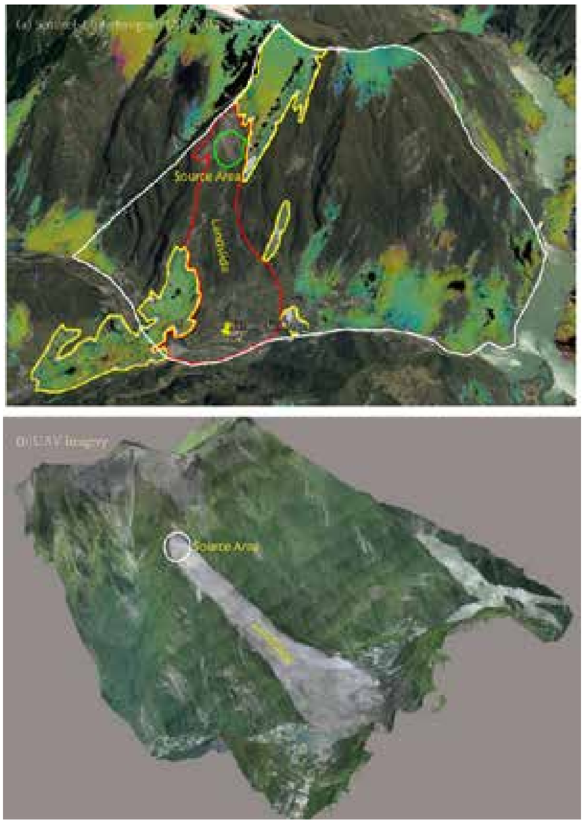


Figure 2 The Xinmo landslide: (a) the first Sentinel-1 interferogram; (b) UAV imagery. Note: (1) Red lines represent the landslide boundary derived from InSAR observations; (2) Yellow lines indicate relatively stable areas; and (3) Green and white circles imply the source area of this massive landslide

More importantly, through the analysis of the archived Sentinel-1 data, the team found that pre-event movements appeared in the source area from 14 May to 19 June 2017. Pre-event signals were even clearer for the Shidaguan landslide, suggesting it had been sliding for a while. Although landslides are hard to predict, this study convincingly demonstrates that InSAR can be used to detect and map active landslides, with possible applications in landslide early warning systems.

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Scientific developments

COMET - GBIS

The open source COMET Geodetic Bayesian Inversion Software (GBIS), led by COMET researcher Marco Bagnardi[3], allows users to perform inversions of InSAR and/or Global Positioning System (GPS) data to estimate deformation source parameters.

GBIS was officially released to the scientific community on 31 May 2017, and version 1.0 of the software is available from its dedicated webpage[4]. The software comes with a detailed user manual describing installation, data preparation, and use of the inversion algorithm. A full update can be found under Progress Against Our 2016/17 Objectives.

GACOS

The Generic Atmospheric Correction Online Service for InSAR[5] (GACOS), developed by the COMET team at Newcastle University, uses the Iterative Tropospheric Decomposition (ITD) model (Yu *et al*., 2017[6]) to separate stratified and turbulent signals from tropospheric total delays, and generate high spatial resolution zenith total delay maps to be used for correcting InSAR measurements and other applications.

GACOS has the following key features: (i) globally available; (ii) operational in near real-time; (iii) easy to implement; and (iv) users informed how the model performs and whether the correction is recommended.

GACOS was launched at the June 2017 ESA FRINGE workshop in Helsinki, and since then has been widely used for correcting atmospheric effects on SAR interferograms - over 100,000 correction maps were freely generated up to 28 Feb 2018.

Multi-GNSS high precision deformation monitoring

Also at Newcastle University, a prototype multi-Global Navigation Satellite System (GNSS) high precision deformation monitoring system has been developed by Professor Zhenhong Li and his team. Five multi-GNSS receivers have been installed on the roof of the Urban Sciences Building, and are able to continuously monitor the surface movements of the building.

Key system features include: precision (horizontal 1-2 mm, vertical 2-5 mm); extended Kalman filter with filter information recorded, leading to higher efficiency; high ambiguity fixing rates; high sensitivity to both small transient and long-term deformations; compatible with GPS, and the Russian GLONASS and Chinese Beidou systems; and operational under all weather conditions.

Potential applications include monitoring earthquakes, active faults, volcanoes, landslides, and the stability of man-made infrastructure (e.g. buildings, dams and bridges). The system is also being incorporated into the development of landslide early warning systems.

3 Now Postdoctoral Fellow at NASA's Jet Propulsion Laboratory
4 http://comet.nerc.ac.uk/gbis/
5 http://ceg-research.ncl.ac.uk/v2/gacos
6 Yu *et al*., (2017) Interferometric synthetic aperture radar atmospheric correction using a GPS-based iterative tropospheric decomposition model, Remote Sensing of Environment doi:10.1016/j.rse.2017.10.038

Impact and influence

COMET works closely with governments, Non-Governmental Organisations (NGOs) and other partners to ensure that our science has real-world impact, shaping policy decisions and improving how we, as a society, manage natural hazards.

We are participating in the volcano and seismic risk pilot projects developed by the Committee on Earth Observation Satellites (CEOS) Working Group on Disasters[7], including the response to the eruption of Mount Agung, Indonesia described earlier.

COMET is also a participant in the CEOS Geohazards Lab initiative, which is increasing the use of EO data on geohazards and their impacts. The initiative focuses on sharing EO resources for disaster risk reduction and response, including InSAR products from COMET's LiCSAR service. This should help to ensure that LiCSAR reaches more users, including volcano observatories, national disaster response agencies and other government bodies involved in planning for and mitigating risk.

Our collaboration with the Global Earthquake Model (GEM) continues to develop methods for incorporating InSAR data into the Global Strain Rate Model (GSRM), simulating the impact of earthquake scenarios, and including COMET's fault data from Central Asia. A 2017 joint meeting with BGS and GEM established the collaboration along with best practice in developing a regional fault model. COMET and GEM are now collaborating on a regional seismic hazard model, based on our growing set of observations in this complex deforming region.

As part of the Global Volcano Model (GVM) we have set up a Global Volcano Deformation Task Force[8]. Led by COMET scientist Juliet Biggs, alongside Professor Matt Pritchard of Cornell University, this brings together researchers studying volcano deformation worldwide, along with organisations that compile information on global volcanic activity. The Task Force is leading a two year project to compare global volcano deformation measurements with satellite thermal and gas observations, and make these data more available to volcano observatories. All of this will hopefully promote the use of InSAR and volcano deformation research in hazard assessment.

Elsewhere, COMET researchers are sharing their expertise with a new generation of Earth scientists.

In April 2017, COMET scientist Pablo J. González contributed to the Tenerife International Training Course on Volcano Monitoring, hosted by the Instituto Volcanológico de Canarias (INVOLCAN). The course was a hands-on introduction to volcano monitoring, alternating lectures with practical laboratory and field activities in disciplines including seismology, geodesy, thermal imaging, volcano infrasound and methods for eruption forecasting.

In August 2017, COMET scientist Juliet Biggs participated in a pre-IAVCEI workshop called 'Promoting the Use of Satellite Observations at Volcano Observatories', funded by the STREVA project. This aimed to facilitate two-way communication between volcano observatory staff members and the volcano remote sensing community, using both case studies and practical demonstrations of satellite data.

In October, COMET ran its InSAR course in Leeds, now a regular feature on the COMET calendar. This 3-day workshop for early career researchers was aimed at improving InSAR processing and analysis capabilities, combining informal lectures and practical exercises on topics such as InSAR theory, data access and processing, and time series analysis. A further workshop took place in November 2018.

COMET associate Susi Ebmeier also ran an introduction to InSAR specifically for volcanologists at the Volcanic and Magmatic Studies Group (VMSG) Conference held in Leeds in January 2018[9]. The workshop aimed to help those new to InSAR but interested in understanding the method better, either to make use of global displacement data, or to examine interferograms of volcanic deformation.

At the same event, COMET scientist Jurgen (Locko) Neuberg led a workshop on the seismic signals that are particularly important in volcanic environments. These can shed light on magma properties and conduit geometry as well as playing a role in the forecasting of dome collapse and dome eruptions.

7 http://ceos.org/ourwork/workinggroups/disasters/
8 http://globalvolcanomodel.org/gvm-task-forces/volcano-deformation-database/
9 https://vmsg2018.leeds.ac.uk/

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In March 2018, COMET scientist Zhenhong Li contributed to an InSAR Meteorology Workshop in Miami, sponsored by NASA[10]. This brought together meteorologists, geodesists and InSAR engineers to explore the potential applications of InSAR to meteorology, focusing on data from Sentinel-1 as well as NASA's forthcoming NISAR mission. Zhenhong presented the Generic Atmospheric Correction Online Service for InSAR (GACOS) described earlier.

Zhenhong also contributed to the China Academy of Space Technology (CAST) Radar Training Course, which demonstrated how to collect observations with radar satellites such as Sentinel-1 and TanDEM-X, and reviewed the Chinese Gaofen-3 satellite's observational plan.

Finally, COMET scientists Tim Wright, Juliet Biggs and Colm Jordan provided training in Addis Ababa as part of the Geohazards workshop run by BGS and RiftVolc.

10 https://insarmeteorologymiami2018.org

Communication, outreach and engagement

We want people from across society to understand our science and how it applies to everyday life, sharing our enthusiasm for and expertise on this dynamic planet. Here are some highlights from the past year.

September 2017 saw the launch of the COMET webinar series[11] with Director Tim Wright speaking on what geodesy can tell us about the continental lithosphere. His talk, *Probing the rheology of the continental lithosphere in the new era of big data geodesy,* has now had over 300 views on YouTube. This was followed in spring 2018 by COMET scientists Tamsin Mather on *Integrating satellite and ground-based measurements to understand volcanic behaviour,* and Alex Copley on *Exploring the controls on earthquakes and tectonics: from the plains of India to the greatest mountain range on Earth*.

These initial webinars have been lively and informal affairs, with ample time for discussion, including questions from a remote audience. The recordings are also made available on YouTube for later viewing, attracting a global audience with viewers in over 40 countries including Ethiopia (5.5% of the audience), Japan, Italy and Mexico.

We are now planning the 2018/19 webinar series, to include presentations in Spanish, reflecting the fact that 11% of our twitter followers have Spanish as their first language, allowing us to share our science even more widely.

October 2017 saw Tim Wright deliver the Royal Astronomical Society Harold Jeffreys Lecture, *Monitoring our dynamic planet using satellite geodesy*[12]. This public event explained how we can use satellite EO to respond to and prepare for earthquakes and volcanic eruptions, with examples from recent events in Nepal, New Zealand, Ethiopia and South America, and again has been made available online.

In January 2018, COMET scientist Juliet Biggs was one of three speakers at the Cabot Institute's 2018 Annual Lecture. *Watching the world's volcanoes* described the challenges of monitoring and predicting eruptions from the Earth's 1,500 land-based volcanoes, and how COMET's volcano deformation database is transforming the way we respond to volcanic risk. With the Cabot Institute being the University of Bristol's flagship cross-disciplinary research centre, Juliet's talk reached a diverse audience interested in a broad range of social and environmental challenges.

Making our work more widely accessible online remains a priority. In his article for PreventionWeb, the knowledge platform for disaster risk reduction[13], COMET scientist Zhenhong Li explained how satellites might be used in early warning systems for landslides. Although it is still hard, if not impossible, to detect a landslide using traditional techniques, especially in mountainous areas, Zhenhong explained how satellite radar makes it possible to efficiently detect and map active landslides over a wide region. In future, this information could be used to set up real-time monitoring systems for key sites or wherever abnormal behaviour is detected.

Other online articles described work on carbon dioxide fluxes from the East African Rift[14] (Deep Carbon Observatory), the potential to monitor geothermal power from space[15], how a rapidly populating coastal region from the Gulf to Pakistan faces a huge tsunami risk[16] (both in The Conversation), using ESA's Sentinel satellites to monitor the eruption at Mount Agung[17] and using drones to provide insights into volcanic activity[18].

In print, Tamsin Mather and Tim Wright contributed to New Scientist's feature *Taking Earth's pulse: How to predict eruptions from space*[19]. The article explained how InSAR could be used to monitor ground deformation globally. Another article by Tim Wright appearing in Catalyst magazine[20] set out the same principles for GCSE and A-level pupils.

11 http://comet.nerc.ac.uk/comet-webinar-series/
12 Available at https://youtu.be/zB9EeAZnZf8
13 https://www.preventionweb.net/news/view/54209
14 https://deepcarbon.net/feature/researchers-track-sneaky-carbon-dioxide-flux-estimate-eastern-rift-emissions#.WpgkvjZFAyC
15 https://theconversation.com/how-to-turn-a-volcano-into-a-power-station-with-a-little-help-from-satellites-86566
16 https://theconversation.com/the-rapidly-populating-coastal-region-from-the-gulf-to-pakistan-faces-a-huge-tsunami-risk-75569
17 https://earth.esa.int/web/sentinel/missions/sentinel-1/news/-/article/sentinels-monitor-volcanic-mount-agung
18 http://iopscience.iop.org/article/10.1088/2058-7058/30/7/45/meta
19 https://www.newscientist.com/article/mg23531410-500-earths-pulse-how-to-predict-disasters-by-watching-the-surface/
20 http://magazines.stem.org.uk/catalyst-edition-30.html?b=1&p=18

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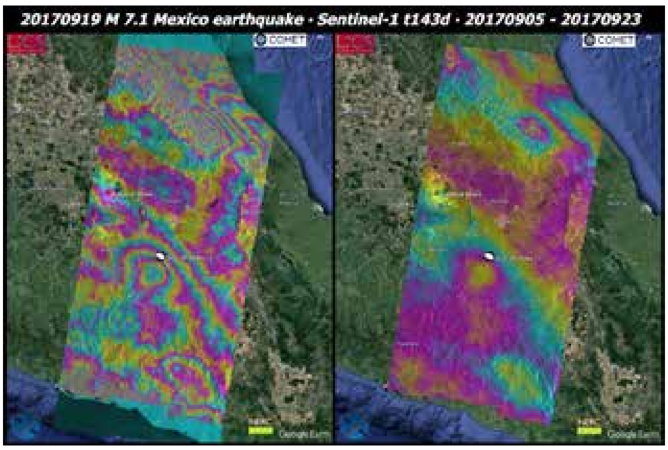
Tamsin Mather also appeared on BBC Radio 4's The Life Scientific[21], explaining what volcanic plumes reveal about our planet and how volcanoes have shaped the Earth. Alongside fellow COMET scientist Clive Oppenheimer, Tamsin also took a more lighthearted look at volcanoes on BBC Radio 4's The Infinite Monkey Cage[22], considering how technology can be used to predict the next big volcanic eruption, as well as the history and importance of volcanoes around the world.

COMET scientist Andy Hooper, along with Juliet Biggs, joined the BBC science team to discuss COMET's ambition to monitor every land volcano on Earth using Sentinel-1, allowing alerts to be issued automatically if deformation – a potential sign of eruption – is detected[23]. This will be particularly useful in Central and South America and Africa, regions with several large, explosive volcanoes but where ground surveys are limited.

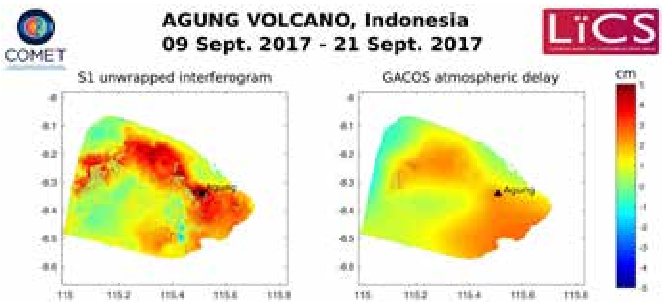
Throughout the year, COMET has also provided the mainstream media with insights into recent and ongoing earthquakes and eruptions. Scientist Jurgen (Locko) Neuberg explained to The Guardian how GPS data and modelling is being used to monitor the eruption risk on Montserrat[24], Andy Hooper discussed a recent Mount Etna eruption on BBC Radio 5's Drive programme, and COMET associate Laura Gregory commented on the earthquake which hit central Mexico in September 2017 to BBC News 24.



Descending interferogram for the September 2017 Puebla, Mexico earthquake

Social media remains important, particularly when it comes to sharing data on eruptions and earthquakes: our tweet of the descending interferogram for the M7.1 Mexico earthquake, showing 6 cm of subsidence in a 50 km-radius signal, was seen by over 12,000 users and liked or retweeted almost 500 times.

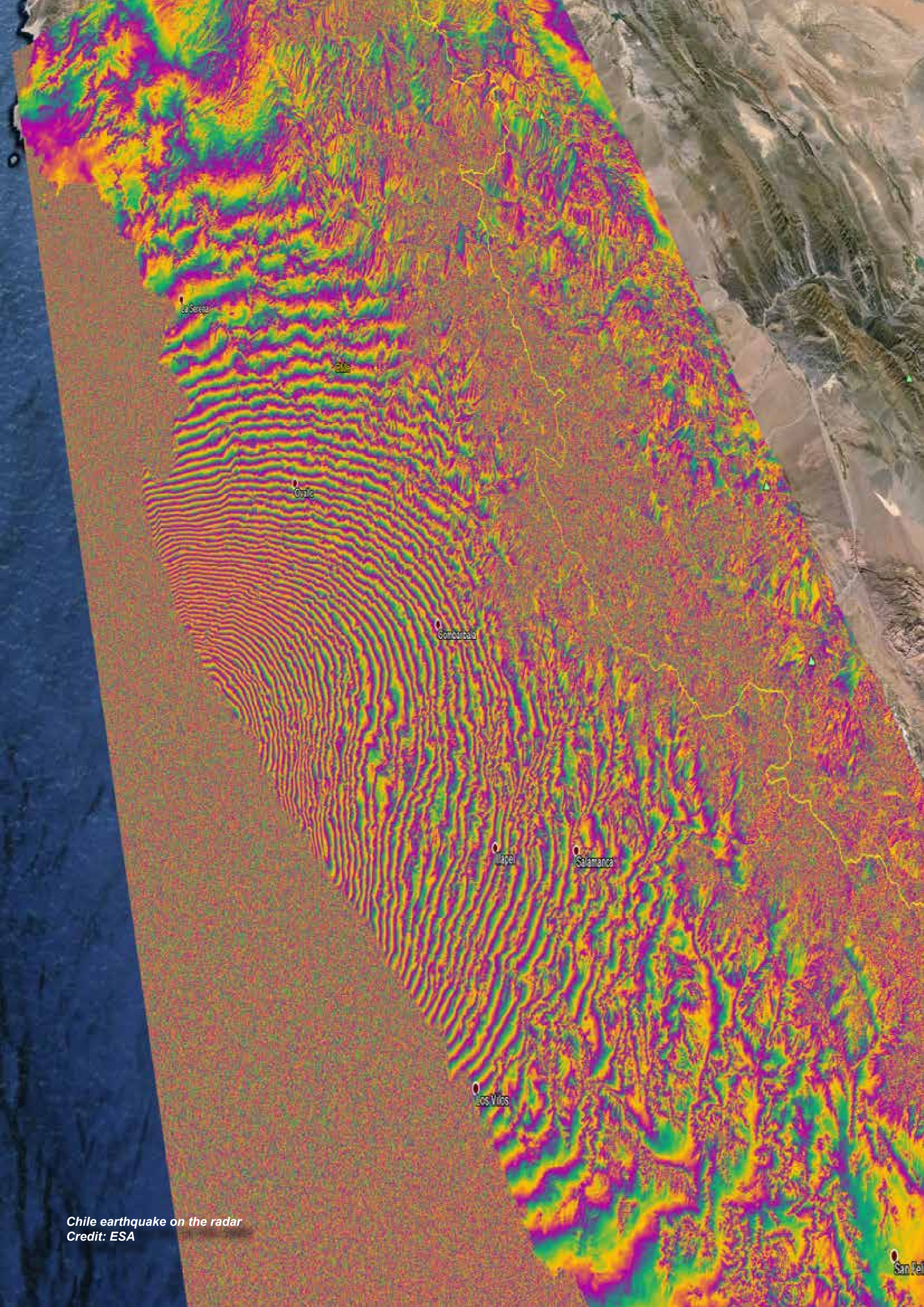
Tweets about work on the atmospheric errors at Agung received more than 17,000 twitter impressions.



Weather models showing that the Agung InSAR fringes are due to atmospheric errors rather than deformation. Credit: @julietbiggs

Finally, our website views increased from 20,000 in 2015, when the new website was launched, to 30,000 in 2017. We are continuing to expand the website content, which now includes our webinars and a range of datasets and services.

21 http://www.bbc.co.uk/programmes/b08t0d3w
22 https://www.bbc.co.uk/programmes/b09r47j1
23 http://www.bbc.co.uk/news/science-environment-39642372
24 https://www.theguardian.com/world/2018/mar/06/terrawatch-montserrats-volcano-remains-a-risk



Chile earthquake on the radar
Credit: ESA

PROGRESS AGAINST OUR 2016/17 OBJECTIVES

Continue the development of the COMET/LiCS InSAR processing system to include unwrapped interferograms and linear time series, and average LOS velocities. Share results via the ESA GTEP and EPOS portal

Nick Greenall/Karsten Spaans, Scientific programmers, Leeds

We have tested and implemented unwrapping on the automated system, and have been producing unwrapped interferograms consistently since December 2017, which are served through the LiCSAR portal[25] (Figure 1).

Since this time, we have been testing time series and velocity estimation methods, and expect to integrate these into the system over the summer. These products will be delivered through the portals. Besides the portal, we have been in ongoing discussion with EPOS about data format, delivery and ingestion methods into their system.

Unwrapped interferogram from frame 044A_05235_131005, covering Etna. The unwrapped interferogram is rewrapped to 10 cm fringes

Establish an automatic fast response system within LiCSAR that prioritises rapid data processing of earthquakes and eruptions

Nick Greenall/Karsten Spaans, Scientific programmers, Leeds

We have been working on a prototype fast response system, which allows rapid response to seismic and volcanic events. The framework for this system is working, but requires better integration with the CEMS computing facility. We have been working with CEMS engineers to set up this integration, and expect this to be completed before the end of the year.

Screengrab of the COMET-LiCS InSAR portal, showing the current coverage of data over the Alpine-Himalayan belt. Each coloured polygon represents one scene, and the colour indicates the number of interferograms in that scene. Yellow coloured polygons have more scenes than red coloured ones

25 http://comet.nerc.ac.uk/COMET-LiCS-portal/

Both Images taken from Fieldwork in Hawaii
Credit: Evgenia Ilyinskaya, University of Leeds

PROGRESS AGAINST OUR 2016/17 OBJECTIVES

Make time series and velocity fields available for the Alpine-Himalayan belt and East African rift. Share results via the ESA GTEP and EPOS portal

Jonathan Weiss, COMET researcher, Leeds

Sentinel-1 line-of-sight (LOS) velocities from the COMET/LiCS InSAR processing system are being converted to East, North, and Up velocities by stitching together adjacent frames and jointly inverting LOS and GNSS information to create high-resolution velocity fields for large portions of the Alpine-Himalayan Belt and East African Rift.

Results will be presented at the 2018 Fall American Geophysical Union (AGU) Meeting in Washington, D.C. and will be shared via the ESA GTEP and EPOS portal as they become available.

Produce the first strain map for the Alpine-Himalayan belt from GNSS and InSAR, and deliver a country-scale deformation map for Ethiopia. Continue to evaluate methods for deriving continuous velocity and strain rate fields

Jonathan Weiss, COMET researcher, Leeds

An evaluation of methods for deriving continuous velocity and strain rate fields were presented at the 2017 Fall AGU Meeting in New Orleans, and an associated manuscript is currently being prepared. Work is ongoing towards making small improvements to the method of choice (VELMAP; e.g. Walters *et al.*, 2014; Wang and Wright, 2012), which jointly inverts InSAR and GNSS measurements to construct high-resolution velocity and strain rate fields. These include introducing spatially dependent weighting to improve the interpolation and also implementing a Bayesian approach in the velocity field inversion to minimize the importance of Laplacian smoothing on the velocity and strain rate fields.

Strain rate maps for rapidly straining COMET priority areas across the Alpine-Himalayan belt and Ethiopia will be derived as Sentinel-1 line-of-sight velocities become available via the COMET/LiCS InSAR processing system, and the first strain rate map for the Alpine-Himalayan belt based on GNSS and InSAR will be presented at the 2018 Fall AGU Meeting in Washington, D.C.

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Refine and further populate the database of active faults in central Asia using collective expertise and up-to-date scientific results about each studied fault, and make it publically available

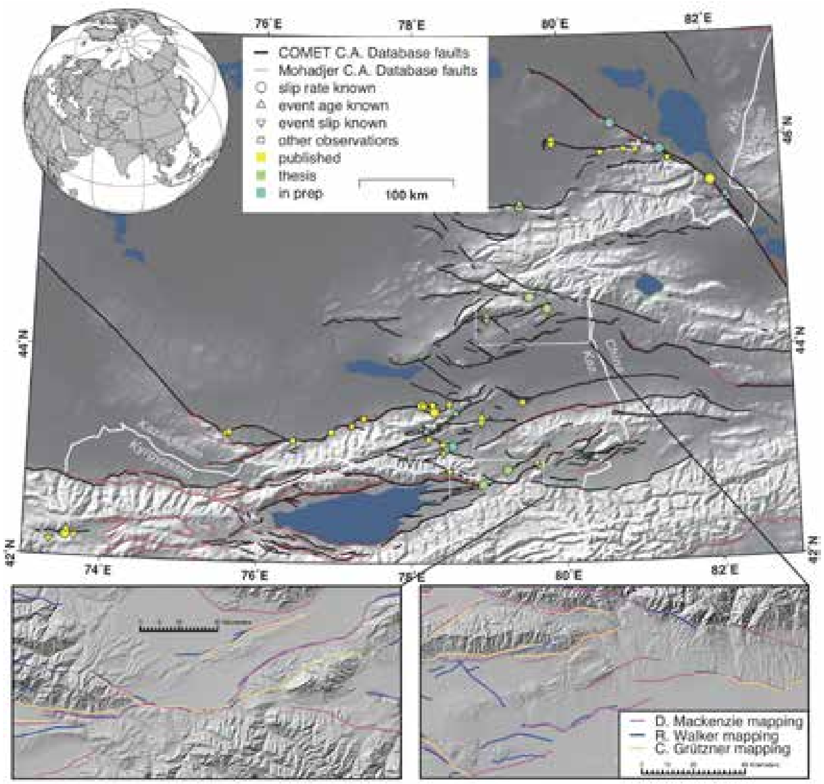
Austin Elliott, COMET researcher, Oxford

COMET researchers have carried out extensive paleoseismic fieldwork and remote mapping of seismic faults in the slowly deforming but high-hazard Tien Shan. We are compiling these observations in a database of active faults and earthquake surface ruptures to map out strain accommodation in conjunction with geodetic measurements.

The map below shows faults in the northern Tien Shan mapped by COMET, and identifies sites at which earthquake ages, seismic slip, and/or long-term slip rates have been measured in the course of our research. These observations form an integral part of the active fault database we are developing.

As we compile data from various studies, consolidation and unification of mapping are required to accurately and uniformly represent the fault system, with refinements to fault traces as shown in the figure sub-panels here.

In addition, in 2017 COMET hosted a joint meeting with members of the BGS and the Global Earthquake Model (GEM) Foundation in order to establish collaboration and best practices developing a regional fault model. COMET and GEM researchers are now collaborating on a regional seismic hazard model, based on our growing set of observations in this complex deforming region.



Map of fault observations by COMET researchers which are being incorporated into a regional fault database of Central Asia. Lower panels illustrate one of the tasks in unifying a database of detailed mapping from multiple sources

PROGRESS AGAINST OUR 2016/17 OBJECTIVES

Develop and implement tools to populate the volcano deformation database with the most recent processed InSAR image using data from Sentinel-1

Fabien Albino, COMET researcher, Bristol

LiCSAR-volcano – a system for automatic operating of ground deformation signals on Holocene active volcanoes - is now operational, enabling us to monitor ground deformation on 929 volcanoes. Since November 2017, 32,681 interferograms have been processed on different volcanic regions, and we are currently using Machine Learning techniques to detect ground deformation signals automatically.

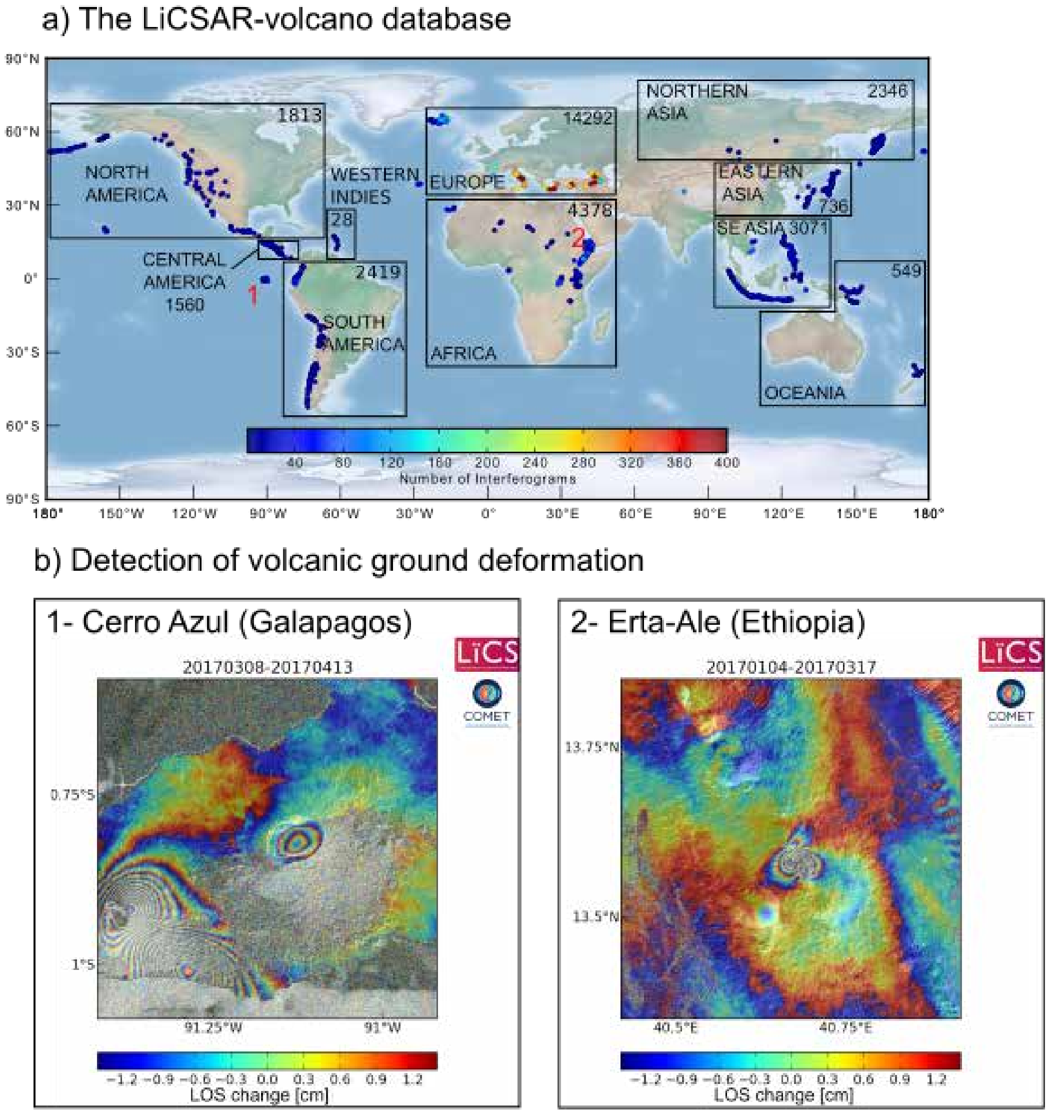
We have been working to develop automatic processing of Sentinel-1 SAR data to deliver InSAR products for all Holocene land-volcanoes (~1300). The raw data are processed through the LiCSAR system and available through the web portal[26].

At the time of writing, more than 900 volcanoes located on six different continents are covered and our database is composed of 32,681 interferograms (a).
Final outputs of the most recent InSAR products (e.g. unwrapped interferograms and coherence maps) are generated automatically and can be accessed via the COMET Volcano Database[27](b). Such information is dedicated to the scientific community as well as the Volcano Observatories.

Our final goal is to develop an alert system which will activate each time a new ground deformation signal is detected in the InSAR database. To achieve this objective, we have started to use Machine Learning techniques (Convolutional Neural Network) to automatically detect ground deformation signals on unwrapped interferograms. By providing ground deformation signals as ground truth, the system is able to recognize patterns which have similar characteristics.

Our preliminary study ran over 30,000 interferograms and flagged hundreds that could contain potential ground deformation signals. After eye-check by an expert, about 35 among them show actual ground deformation associated with volcanic unrest, such as the intrusive events at Erta-Ale or Cerro Azul (b).

26 http://comet.nerc.ac.uk/COMET-LiCS-portal/
27 https://volcanodeformation.blogs.ilrt.org



a) Map showing the total number of interferograms calculated over different geographical regions. b) Examples of final outputs available online at the COMET Volcano Database. Interferograms show significant volcanic unrest at Cerro-Azul and Erta-Ale

PROGRESS AGAINST OUR 2016/17 OBJECTIVES

Further refine IASI SO_2 and ash retrieval techniques for monitoring low level volcanic emissions as well as specific eruptions

Elisa Carboni, COMET researcher, Oxford

Thermal infrared spectrometers such as the Infrared Atmospheric Sounding Interferometer (IASI) are valuable instruments for detecting and quantifying volcanic emissions of sulphur dioxide (SO_2) and volcanic ash. Particular strengths of IASI are that it can operate at night, during high latitude winters, and the spectral measurements contain information of plume altitude.

Taylor *et al*. (2018) explored the potential of IASI for detecting and quantifying SO_2 emissions from smaller and lower altitude emissions or for the assessment of ongoing activity.

Figure 1 shows the monthly average IASI SO_2 masses retrieved at Tungurahua in Ecuador, compared with the Ozone Monitoring Instrument (OMI) and ground based Differential Optical Absorption Spectroscopy (DOAS) flux data. These data demonstrate that the satellite instruments are capable of capturing relative changes in volcanic activity. There is generally good agreement here between the OMI and the IASI results. These match the periods of enhanced volcanic activity (shaded in grey). Similarly, good agreement was found between IASI and OMI measurements of SO_2 emissions in Kamchatka.

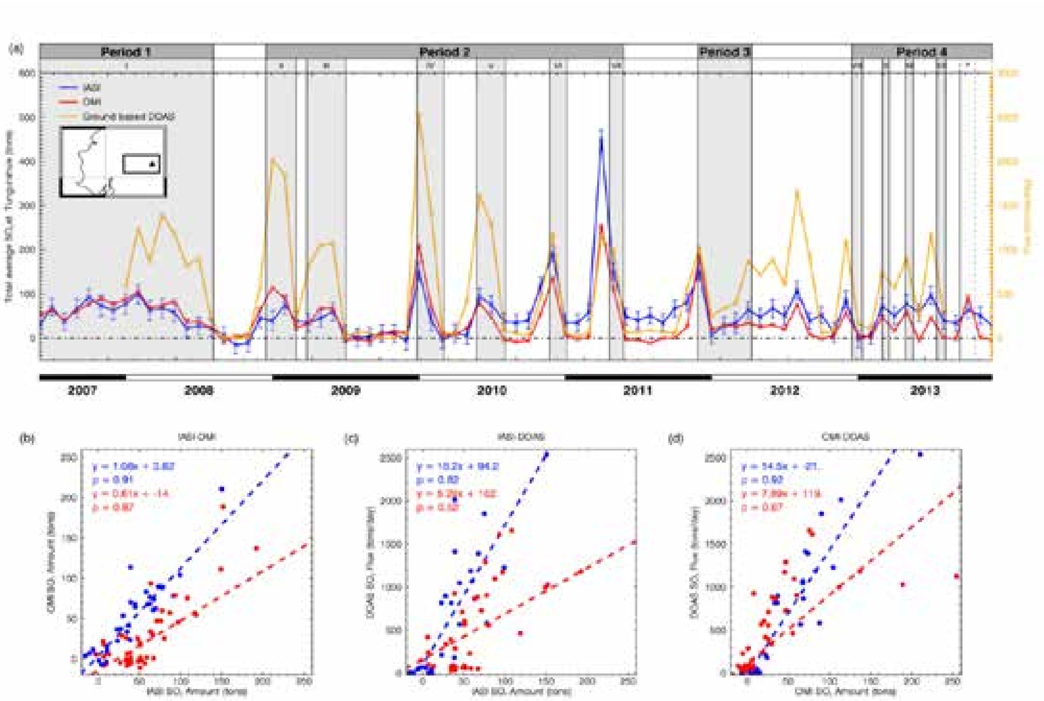


Figure 1 (from Taylor et al., 2018): (a) Time-series of total monthly average of SO_2 around Tungurahua from IASI and OMI for June 2007 to December 2013, and the monthly average SO_2 flux recorded with a ground based DOAS network and published in Hidalgo et al. (2015). Average total masses of SO_2 at Tungurahua were calculated from the monthly SO_2 column amounts using the box area shown in the map. Shaded in grey are episodes of activity. The error bars on the IASI average total SO_2 masses incorporate the instrumental error, and errors associated with the forward model, meteorological data and non-perfect representation of gas absorption and errors due to the presence of a cloud

IASI data have been used to derive the first time-series of daily SO_2 mass and vertical distribution over the six-month-long 2014-2015 Holuhraun eruption. A new optimal estimation scheme is used to calculate daily SO_2 fluxes and average e-folding time every twelve hours. The SO_2 mass present between two altitude levels was estimated using the method of Carboni *et al*. (2016) to produce the vertical distribution of SO_2. Both the young emitted plume as well as the mature plume that had been transported around in the Northern Hemisphere for few days are included in the distribution.

The time-series of the centre-of-mass of the plume closest to the vent can be used as rough estimate for the injection height. Figure 2 shows the time-series of: (i) the IASI SO_2 vertical distribution: (ii) the IASI altitude of the centre-of-mass of the SO_2 values within 500 km of the vent; (iii) plume altitude from Icelandic MetOffice (IMO) measurements. The altitude of the centre-of-mass is less than 4 km for the majority (96%) of the measurements.

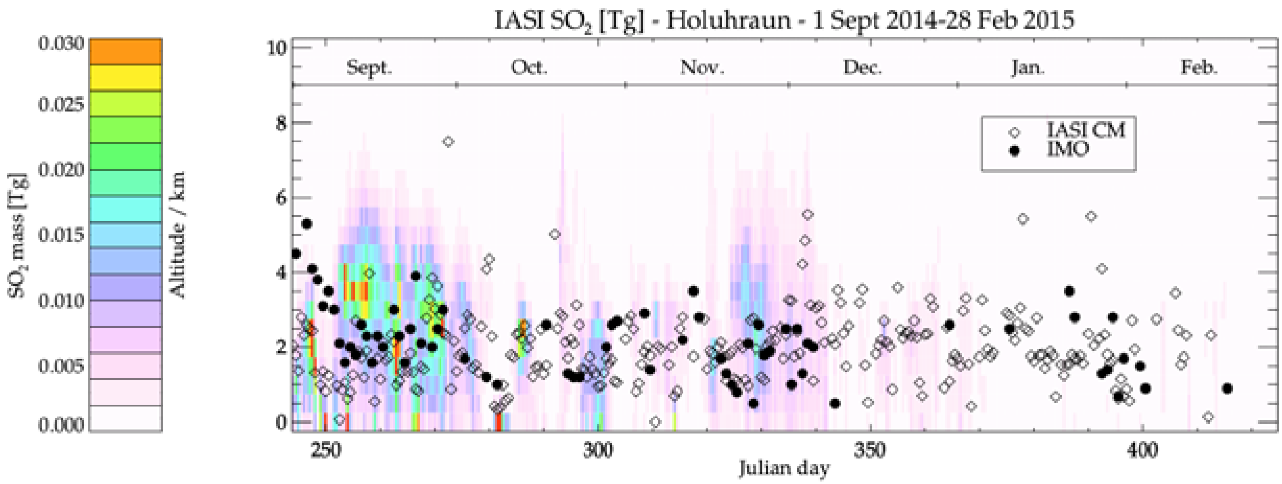


Figure 2 (from Carboni et al. 2018): SO_2 vertical distribution in km above sea level. The colour represents the mass of SO_2, dark-red represents values higher than the colour-bar. Every column of the plot is generated from an IASI map (one every 12 hrs). The black diamonds show the altitude of the centre-of-mass computed with the IASI pixels within 500 km from the vent, the black dots show the altitude from IMO measurements

One of the main uncertainties in volcanic ash radiative transfer models is the assumption of ash optical properties.

We used measured complex refractive index of different ash samples (Reed *et al.* 2018), together with the corresponding ash compositions, to develop a new parameterization that allows the complex refractive index of volcanic ash to be determined from the ash SiO_2 content or its ratio of non-bridging oxygens to tetrahedrally-coordinated cations (NBO/T). The parameterization for the thermal infrared spectral region is show in Figure 3.

PROGRESS AGAINST OUR 2016/17 OBJECTIVES

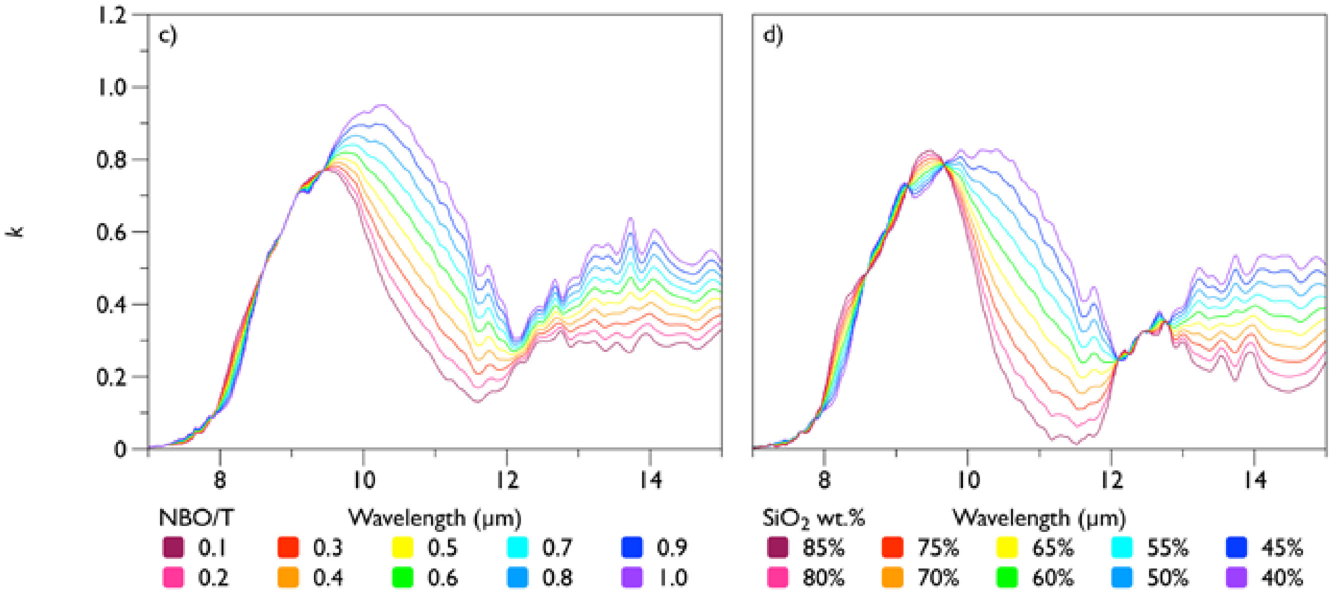


Figure 3: (from Prata et al., in review): Modelled imaginary part of refractive indices showing the effect of varying parameters NBO/T and SiO_2

We used this parameterization to study different volcanic plumes including Chaitén (2008), Okmock (2008), Grimsvotn (2011), and Puyehue-Cordon Caulle (2011). Satellite mass loading retrievals of volcanic ash using the parameterization show significant differences compared to those using an assumed complex refractive index, and there is generally a corresponding better fit between measurements and model.

A new IASI ash dataset including this parameterization and a new ash altitude scheme will be submitted to the WMO SCOPE-Nowcasting Inter-comparison of Satellite-derived Volcanic Ash Products (2018) to assess the volcanic ash product generate from satellite measurements.

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Continue the development of the COMET Bayesian deformation modelling software, including routines to account for the topographic effect on surface displacements and new analytical and numerical forward models

Marco Bagnardi[28], Comet researcher, Leeds

Since it was first released to the scientific community in May 2017, more than 250 users have downloaded the COMET Geodetic Bayesian Inversion Software (GBIS) from the COMET website[29]. Results obtained using GBIS v1.0 were presented in two recent publications (Albano *et al*., 2017; Temtime *et al*., 2018), where the users estimated source parameters for tectonic, magmatic and geothermal sources of deformation.

A scientific manuscript describing the methodology and principles upon which the GBIS software is based has now been published (Bagnardi and Hooper, 2018). In this work we applied the inversion algorithm to InSAR data measuring co-seismic displacements associated with the 2015 Mw 6.4 Pishan earthquake, China. Our results coincide with those presented in previous publications (e.g. Ainscoe *et al*., 2017) and validate the applicability of our approach to the study of tectonic processes.

The development of GBIS continues and a new enhanced version is being released to the scientific community. This version will include new analytical solutions for the compound dislocation model (CDM) (Nikkhoo *et al*., 2017), and for triangular dislocations (Nikkhoo and Walter, 2015), will contain bug fixes, and will have an improved, extended user manual.

We are also currently testing the use of the Boundary Element Method to accurately account for the effect of topography on surface displacements, and to simulate sources of deformation with complex geometries.

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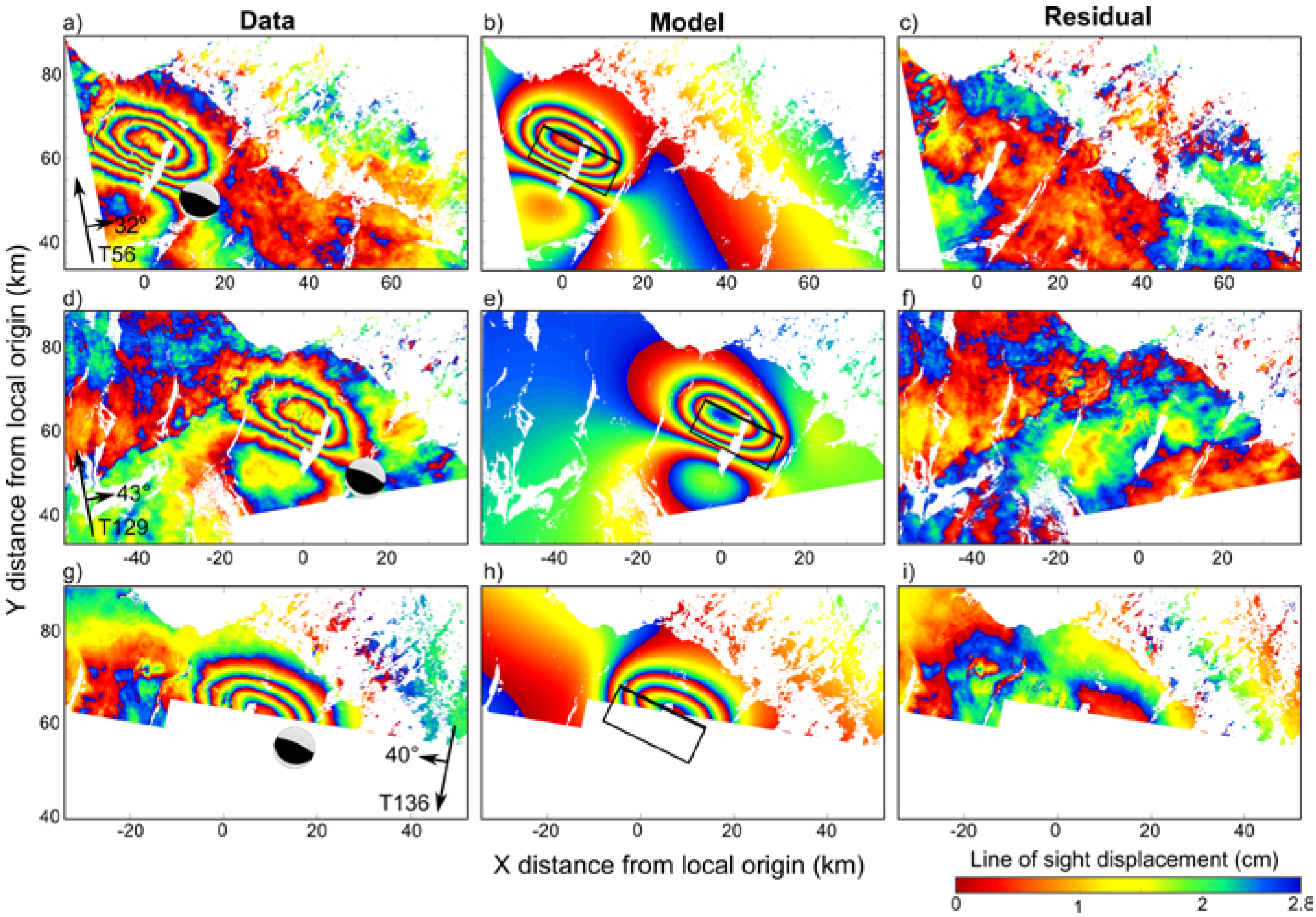
28 Now Postdoctoral Fellow at NASA's Jet Propulsion Laboratory
29 http://comet.nerc.ac.uk/gbis/

PROGRESS AGAINST OUR 2016/17 OBJECTIVES



Sentinel-1 TOPS interferograms for the 2015 Mw 6.4 Pishan earthquake, (middle) forward model using the maximum a-postereori probability (MAP) solution, and (right) residual maps. Black arrows on data plots show the flight direction of the satellite, the look direction with the incidence angle in degrees, and the track number. The beach ball represents the fault plane solution from gCMT catalogue and marks the epicentral location. The black rectangle on model plots represents the outline of the optimal fault plane, with the thicker line outlining the up-dip edge of the fault. Differential interferograms show co-seismic displacements measured between (top row) 30/06/2015–24/07/2015, (middle row) 11/06/2015–05/07/2015, and (bottom row) 24/06/2015–18/07/2015. From Bagnardi and Hooper, 2018

Further develop a low-cost GNSS sensor network for autonomous real-time deformation monitoring, focusing on assessing the performance of two prototype sensors in terms of precision over different baseline lengths and power consumption

Chris Atkins, COMET researcher, UCL

Global Navigation Satellite Systems (GNSS) such as Global Positioning Systems (GPS) can be used to measure ground displacements with sub-centimetre precision. To achieve this, it used to be necessary to use geodetic-quality equipment typically costing thousands of pounds. In recent years, low-cost single-frequency 'mass-market' receiver modules and antennae have become available. With careful data processing, these offer similar levels of precision at a fraction of the price. This makes it feasible to deploy several high-precision sensors without being precluded by cost.

COMET's initial aim is to develop a pool of simple GNSS data loggers for use by COMET scientists. Our first prototype was based around a Raspberry Pi Zero single-board computer. This enabled us to easily gather GNSS measurements to confirm that centimetre-level precision is indeed achievable after data processing.

Figure 1 shows a 1 Hz position time series (easting, northing and height) of a stationary sensor spanning about 1 hour 20 minutes calculated using GPS, GLONASS and Galileo measurements. These positions are relative to a second 'base' sensor about 15 km away. Notice that the standard deviation of each time series is just a few millimetres. The small oscillating errors present in each time series are a result of multipath interference and antenna phase centre variation. New data processing software is being written which will include algorithms to mitigate these errors, thereby increasing precision further.

However, the Raspberry Pi-based prototype used a relatively large amount of energy and suffered from the disadvantage of requiring a 'graceful' shutdown before the accompanying battery ran out of charge. Our current prototype does away with the need for a Raspberry Pi and simply logs data directly to an SD card when connected to a power supply, so no damage to the hardware is caused by a loss of power. It uses much less energy and is thus more suitable for integrating with a solar panel. We are now conducting tests to make sure the current configuration is reliable. The test bed used for the development of this sensor is shown in Figure 2.

The current configuration is designed to be very energy-efficient so that the sensor can log data continuously for several weeks if desired. In the longer-term, we intend to develop a wireless network of GNSS sensors, each capable of transmitting raw measurement data, ultimately forming part of a real-time monitoring system. It is also envisaged that each unit will be capable of hosting multiple sensors suitable for the required application.

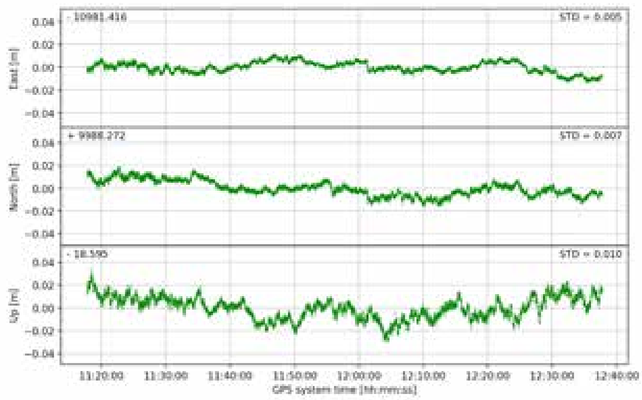


Figure 1: 1 Hz time series of the east, north and up components of a baseline of approximately 15 km calculated using data from two low-cost GNSS sensors

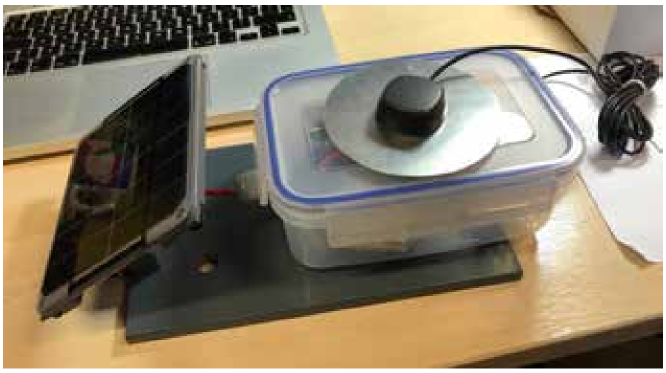


Figure 2: The test bed used for GNSS sensor development

PROGRESS AGAINST OUR 2016/17 OBJECTIVES

Formally sign the COMET-BGS memorandum of understanding, promoting the strategic and working relationship between the two organisations accordingly, including regarding event response

The memorandum was signed in autumn 2017 by COMET Director Tim Wright and BGS Director of Science for Earth Hazards and Observatories John Rees. It sets out the terms for collaboration between our two organisations, aiming to ensure that we work to the strengths of both partners, enhancing the value of the partnership. This will help COMET to benefit from greater exposure of its science to UK and international policy-makers through BGS-led operations; whilst BGS will benefit from greater involvement in fundamental science and rapid access to emerging data and information on seismic hazard.

Strengthen links between COMET and relevant national and international research organisations such as GEM and VMSG, facilitating collaboration and discussion

As event sponsor, many members of the COMET volcano community helped to organise, and contributed to, the January 2018 VMSG conference in Leeds. The event, attended by around 200 volcanologists of all career stages, highlighted the latest developments and advances in volcanology, including research undertaken by COMET. It also included workshops by COMET members on topics such as InSAR theory and practice, and volcano seismology.

COMET's work on volcanoes in Iceland, Indonesia, Nicaragua and Ethiopia was showcased alongside developments in the tools and techniques used to monitor and model volcanic activity. A highlight was former COMET student Will Hutchison's talk, as 2018 Willy Aspinall Prize Winner, on new geophysical and geochemical constraints on the plumbing of Ethiopian rift volcanoes.

Juliet Biggs and Susi Ebmeier meanwhile made links with the USGS John Wesley Powell Center for Analysis and Synthesis, which facilitates collaborative synthesis and analysis opportunities in Earth system science.

In addition, in 2017 COMET hosted a joint meeting with BGS and GEM in order to establish the collaboration and best practice in developing a regional fault model for Central Asia. COMET and GEM researchers are now collaborating on a regional seismic hazard model, based on our growing set of observations in this complex deforming region.

Develop and deliver a COMET webinar series aimed at sharing COMET research both within COMET and across the wider Earth observation community

As described earlier, September 2017 saw the launch of the COMET webinar series[30]. As of spring 2018, there have been three webinars, with more scheduled. Tim Wright presented on geodesy and the continental lithosphere, Tamsin Mather on satellite and ground-based measurements of volcanic behaviour, and Alex Copley on controls on earthquakes and tectonics. Streamed live and also available to view on COMET's YouTube channel, the webinars are proving a great way to share our research more widely and we will continue to expand our webinar offer throughout 2018/19.

Consult the wider COMET community on the future direction of COMET, identifying strategic goals and new opportunities for 2019 onwards

In March 2018, COMET and BGS held a joint open meeting on COMET's future. Discussions were structured around two main points: the key science questions regarding earthquakes, volcanoes and tectonics over the next 5 years; and new and future technologies and satellite missions that COMET should be exploiting.

The lively discussions resulted in a range of ideas on COMET's future, as well as a reflection on progress to date versus COMET's original goals. The outcomes are now being distilled into a new proposal setting out COMET's ambitions for the period 2019 onwards.

30 http://comet.nerc.ac.uk/comet-webinar-series/

RESEARCH HIGHLIGHT

A new paradigm for the evolution of faulting and uplift in mountain belts

Sam Wimpenny, COMET research student, Cambridge

In Cambridge, we have been using evidence of recent and past earthquakes in the Andes to investigate the change in the style of faulting within the high Andean plateau from shortening to extension. Combining our new chronology of faulting in the Andes with physical models has enabled us to study the forces supporting mountain ranges, and how these forces may change through time.

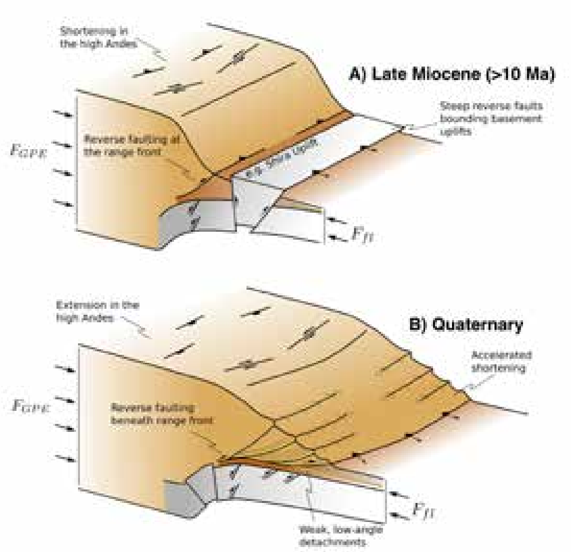
Mountain belts are formed through shortening and thickening of the lithosphere. However a number of Cenozoic mountain belts contain moderate-magnitude extensional earthquakes within their highest parts (e.g. Andes, Tibet, Albanides). As a result there must have been a change in the force balance within these mountain ranges to lead to the onset of extension.

We have been investigating the evidence for past and present faulting in the high Andes using observations from seismology, radar geodesy, gravity, satellite imagery, geomorphology and field studies, and relating the pattern of extension in the high regions to the kinematics and evolution of faulting in the eastern sub-Andean forelands of the mountain belt.

We found that extension in the high Andes began at the same time that shortening in the adjacent sub-Andean forelands became focused on low-angle detachment faults cutting the thick foreland basin sediments (~5-9 Ma). Low-angle detachment horizons in the eastern Andes are focused in highly overpressured, phyllosilicate-rich Paleozoic shales, which provide a weak base over which the toe of the Andean wedge can rapidly propagate.

As a result, since the late Miocene there has been a fourfold acceleration in shortening within the eastern Andes, and a reduction in the force transmitted between the forelands and the Andes, leading to the onset of extension in the high plateau.

More generally, the evolution of faulting in the Andes suggests that mountain belts may weaken their surroundings by causing subsidence and sedimentation within their bounding foreland basins. Therefore the vertically-stratified rheology of the foreland lithosphere plays a key role in modulating the deformation, uplift and lateral growth of mountain belts through time.



Cartoon depicting the evolution of faulting in the high Andes and its forelands over the last ~10 Ma

Fieldwork in Peru
Credit: Aisling O'Kane, Bullard Laboratories, Cambridge University

RESEARCH HIGHLIGHT

What lies beneath? Insights from normal-faulting in central Greece

Alex Copley, COMET scientist, Cambridge

A perennial question in tectonics concerns the material properties and behaviour of the ductile part of the lithosphere, beneath the earthquake-prone brittle upper layer. The degree to which tectonic motions are spatially distributed or concentrated into discrete bands, and the relationship between the applied tectonic stress and the resulting motions (i.e. the rheology) are all open to debate.

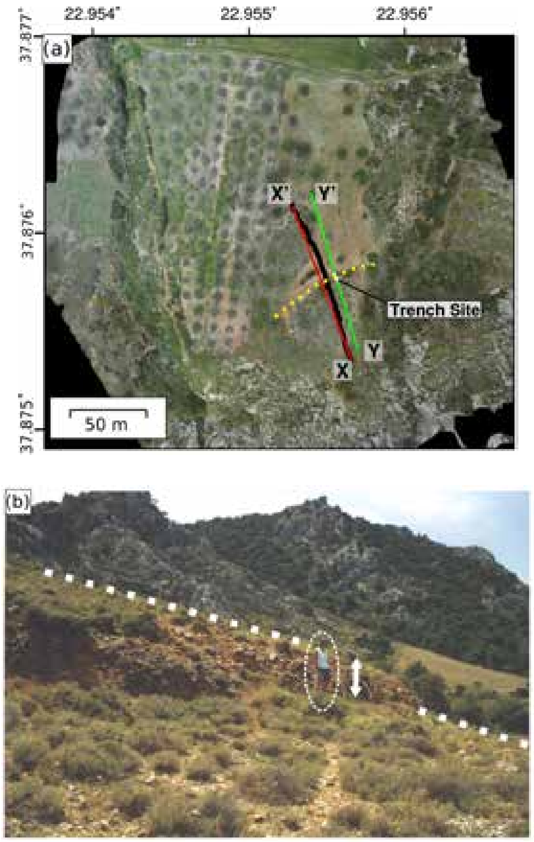
Recent years have seen contrasting views put forward based on the combination of mapping surface motions (with GPS or InSAR) and modelling the results. Some favour the presence of weak shear-zones beneath faults, motion on which loads the faults and causes earthquakes. Others favour laterally-homogeneous materials, but with material properties that result in both rapid transient motions after earthquakes, and also concentrated elastic loading in the intervening time periods.

Given that by tweaking poorly-known parameters both types of model can be made to be consistent with presently-available observations of surface motions, we decided to see if an alternative style of observation could be used to address this issue: the migration of activity within fault systems over million-year timescales.

The Gulf of Corinth in central Greece is rapidly-extending (~5 mm/yr at its eastern end, higher in the west), and is bounded by active normal faults. The majority of the extension is concentrated on faults that run along the coast, and are responsible for controlling the geometry of the coastline and the sedimentation in the adjacent basin. In the hinterland of these faults are other structures that are generally presumed to be inactive, but thick sequences of sedimentary rocks adjacent to them show that they were once the dominant rift-bounding faults.

We performed a detailed study of one of these structures: the Kenchreai Fault in the eastern Gulf of Corinth.

We produced high-resolution digital elevation models, using images captured by a camera mounted on a drone, kinematic GPS, and an Abney level. These elevation models show the presence of a scarp in multiple locations along the length of the fault. The offset of recent fan surfaces that are crossed by the scarp suggests it originates from faulting. We dug a trench in order to confirm the origin of the scarp. Truncated stratigraphy and an open fissure (now filled with sediment) attest to the presence of at least one recent surface-rupturing earthquake. Carbon-14 dating of the organic-rich fissure-fill shows the earthquake occurred within the past 1,500 years.



Measurements at Site 1 (37.876°N, 22.955°E). (a) Shows an ortho-photo produced by drone imagery. The white box shows the location of our palaeoseismological trench, and the dotted yellow line shows the scarp. (b) Shows the scarp (looking SW), with person circled for scale

Despite the recent earthquake activity at Kencreai, we know that it is not the most active fault in the region. The uplift of marine terraces on the downthrown side of the Kenchreai Fault shows that the Heraion and Pisia Faults, which are positioned across-strike from Kenchreai and ruptured in magnitude 6 earthquakes in 1981, dominate the vertical motions in the region and so accommodate most of the extension. However, the thick sedimentary section in the Corinth Isthmus shows that the Kenchreai Fault was previously the dominant structure. Activity has therefore migrated across-strike between parallel fault systems, but intriguingly the old faults retain some degree of activity.

There are multiple suggestions of why activity may migrate onto new fault systems during rift evolution. However, they all revolve around the new faults being able to break at lower differential stresses than the old faults, which drives the migration. However, why should the old faults remain active, when the newer faults are easier to break in earthquakes?

The key lies with the ductile lower crust, which can control the loading of the overlying faults, and produce significant enough stresses to break a fault that is no longer the weakest component of a system. If the location and rate of loading were controlled by a laterally-homogeneous material with a memory of previous events, then all loading would be concentrated on the presently-dominant faults that rupture most often.

However, if the faults are underlain by weak shear zones, then this persistent weakness in the ductile crust can continue to load old faults, even if they are harder to move than the dominant structures.

Our observation of recent earthquake activity on the Kenchreai Fault has therefore allowed us to probe the properties and behaviour of the ductile part of the crust, and address one of the long-standing questions in tectonics by showing that the earthquakes are the result loading by motion on a weak sub-fault ductile shear zone.

Reference

Copley, A. *et al.* (2018) Unexpected earthquake hazard revealed by Holocene rupture on the Kenchreai Fault (central Greece): Implications for weak sub-fault shear zones, Earth and Planetary Science Letters doi:10.1016/j.epsl.2018.01.014

Volcán de Acatenango and Volcán de Fuego (double peak in the left centre of the image), Volcán de Agua (next right, more distant) and Volcán de Pacaya (in the far distance)
Credit: Universities of Bristol, Birmingham and INSIVUMEH

Explaining volcano deformation by magma movement rather than pressurisation

Jurgen (Locko) Neuberg, COMET scientist, Leeds

Tungurahua volcano in Ecuador has provided evidence that certain spatial and temporal deformation patterns can only be explained by shear stress caused by the ascent of viscous magma rather than reservoir pressurisation.

Cyclic seismicity and ground deformation patterns are observed on many volcanoes worldwide where seismic swarms and the tilt of the volcanic flanks provide sensitive tools to assess the state of volcanic activity. Ground deformation at active volcanoes is often interpreted as pressure changes in a magmatic reservoir, and tilt is simply translated accordingly into inflation and deflation of such a reservoir. Tilt data recorded by an instrument in the summit area of Tungurahua volcano in Ecuador, however, show an intriguing and unexpected behaviour on several occasions: prior to a Vulcanian explosion when a pressurisation of the system would be expected, the tilt signal declines significantly, hence indicating depressurisation. At the same time, seismicity increases drastically (Figure 1).

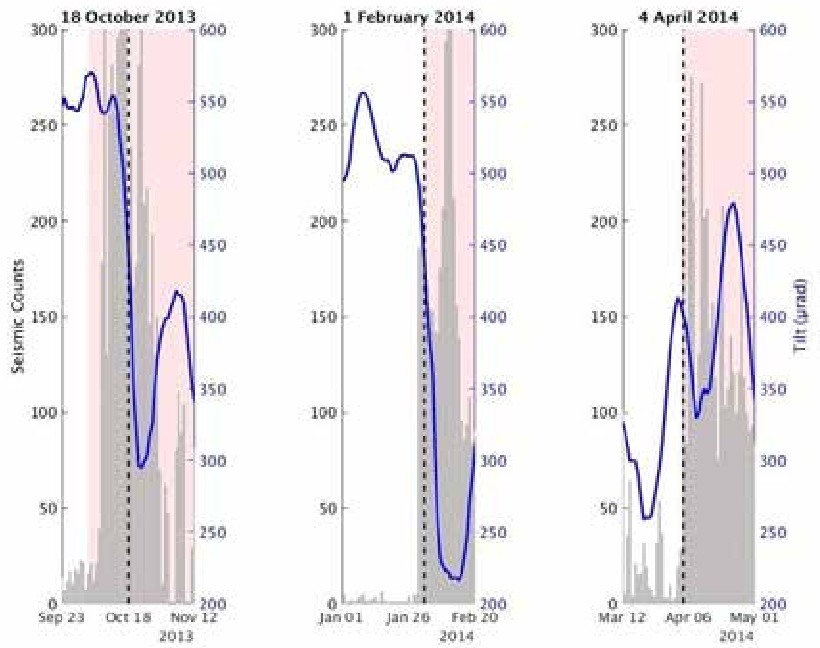


Figure 1: Radial tilt (solid line) and LP seismicity (histogram) at Tungurahua, Ecuador. Tilt decreases significantly before explosions (dotted lines) while seismicity increases. This can be explained by the stick-slip motion of the magma column reducing the overall shear stress by generating seismicity. This indicates shear stress partitioning and explains the anti-correlated behaviour between tilt and seismicity

RESEARCH HIGHLIGHT

Envisaging that such a pattern could carry the potential to forecast Vulcanian explosions on Tungurahua, we (Locko and Amy Collinson, postdoctoral researcher, Leeds) worked with colleagues from the Instituto Geofisico, Escuela Politécnica Nacional, Quito, Ecuador and used numerical modelling reproducing the observed tilt patterns in both space and time.

They demonstrate that the tilt signal can be more easily explained as caused by shear stress due to viscous flow resistance, rather than by pressurization of the magmatic plumbing system. Furthermore, they investigated the interdependence of tilt and seismicity through shear stress partitioning and suggest that a joint interpretation of tilt and seismicity can help understanding the eruption potential of silicic volcanoes.

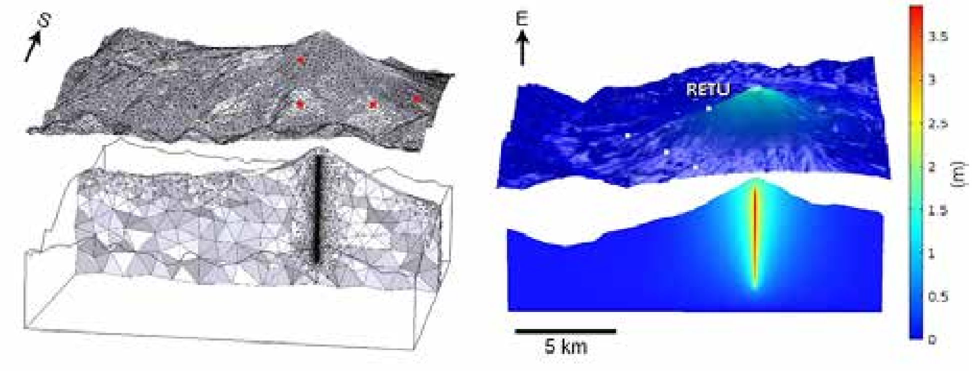


Figure 2: Digital elevation model of Tungurahua (left) and ground deformation induced by shear stress due to viscous flow resistance of ascending magma (right).Note that only the area close to the conduit is affected by this type of deformation (RETU station). Distal tiltmeters (white dots) do not pick this signal

These findings have several important implications for instrument deployment and data interpretation:

i. Tiltmeters should be deployed as close as possible to the conduit, however, topography can be used to enhance the amplitude of the signal.

ii. Tilt signal on silicic volcanoes might have to be interpreted in a very different way: as equivalent changes in magma ascent velocity. Hence, a decrease in tilt amplitude is not caused by deflation of a magma reservoir, but by the slowing ascent of magma that could lead to pressurisation and explosions.

iii. If changes in tilt are accompanied by seismicity a decrease in tilt could point to accelerating magma ascent where shear stress is converted into seismic slip rather than deformation and tilt. This is referred to as shear stress partitioning.

Future work will be dedicated to understanding the processes acting at the transition zone where magma ascent changes from a viscous-ductile regime into a friction controlled regime where seismicity is generated. Open questions include the amount of frictional heating that is generated and its potential role in lowering magma viscosity, and the exact amount by which shear stress is reduced by each seismic swarm. In order to address these question numerical models will be combined with laboratory experiments on synthetic and natural samples under simulated conduit conditions. This combination of experiments will help to quantify critical magma ascent rates which could be identified using tilt and seismic data in a volcanic forecasting tool.

Reference

Neuberg J.W., Collinson, A.S.D., Mothes, P.A., C. Ruiz, M, Aguaiza, S. (2018) Understanding cyclic seismicity and ground deformation patterns at volcanoes: Intriguing lessons from Tungurahua volcano, Ecuador, Earth and Planetary Science Letters doi: 10.1016/j.epsl.2017.10.050

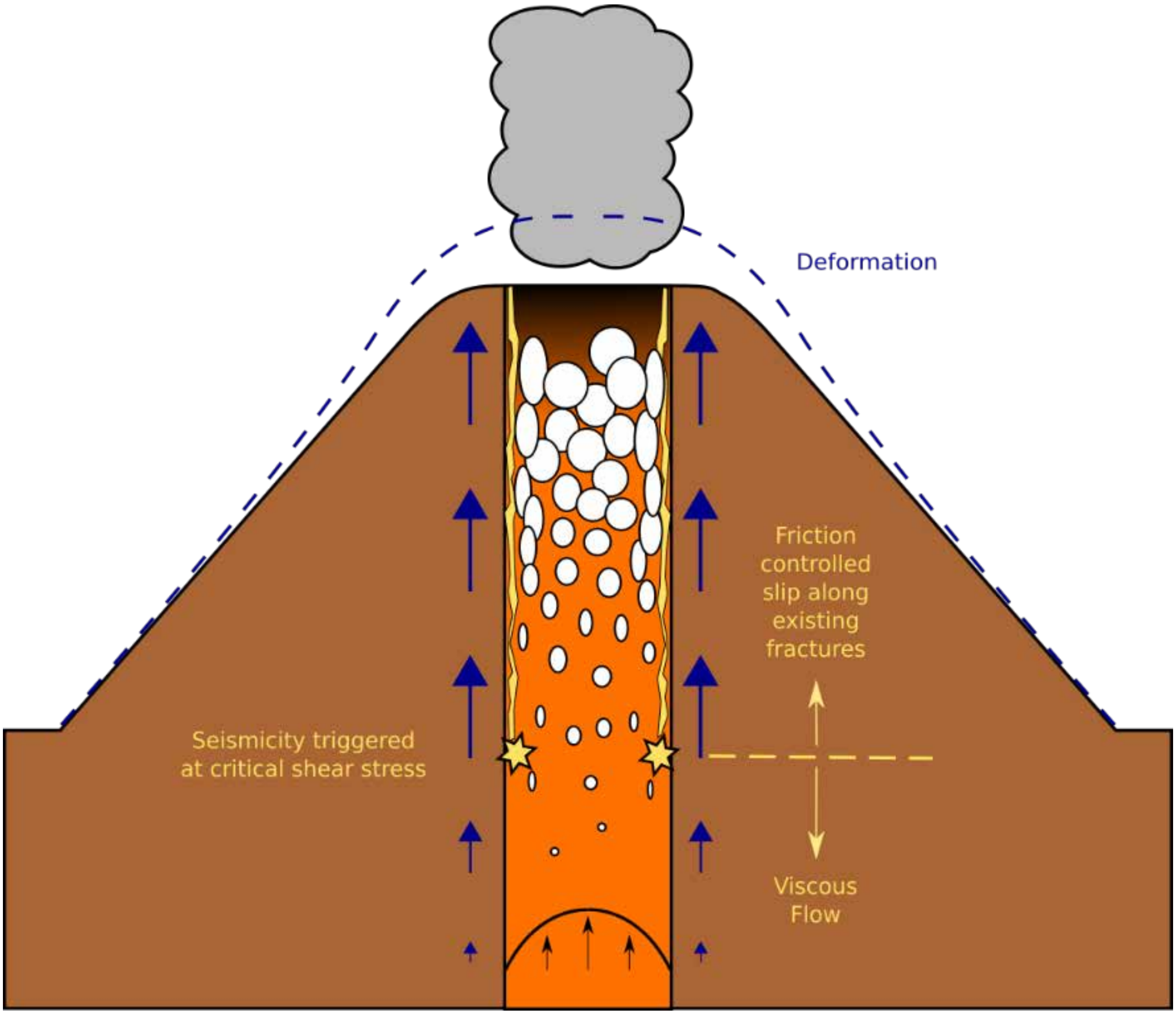


Figure 3: Shear stress due to viscous magma ascent acting at the conduit wall, causing deformation of the volcanic edifice (Regime 1). Once a critical stress is reached seismicity is generated by rupture and slip releasing energy such that less shear stress is exerted across the conduit wall reducing tilt (Regime 2). The narrow transition zone between regimes can be identified by the location of earthquakes

RESEARCH HIGHLIGHT

Synthesis of volcano InSAR datasets - implications for volcano monitoring and the lateral extent of magmatic domains

Susannah Ebmeier, COMET associate, Leeds

Satellite-based radar measurements (SAR and InSAR) have great potential for monitoring changes at volcanoes, both during and between eruptions. However, there are challenges in making the routine observations needed for the reliable operational assessment of hazard. We have analysed two global datasets of volcano deformation: the Smithsonian Institution Volcanoes of the World Database and the Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics Volcano Deformation Catalogue to assess the systematic characteristics of volcano deformation as detected by InSAR.

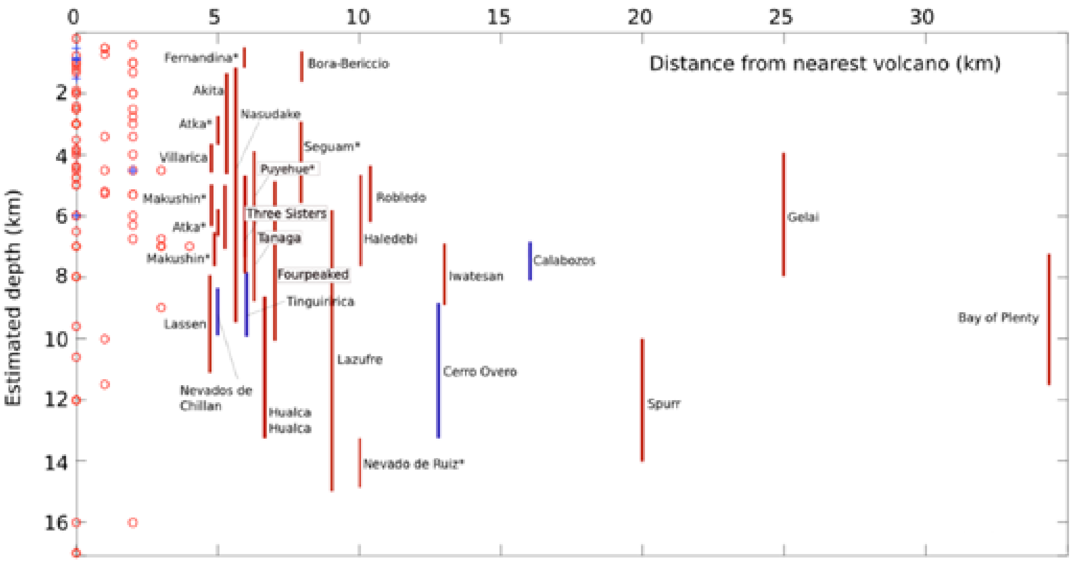
Satellite measurements have increased the spatial range of deformation that has been detected, at both ends of the spatial scale (~ 10 to > 1000 km_2). However, a higher proportion of InSAR observations capture non-eruptive and non-magmatic processes than those from ground-based instrument networks, and in particular, both transient (< month) and long-duration (> 5 years) deformation episodes are under-represented in global datasets.

Deformation is common (24% of all potentially magmatic events) at loci ≥5 km away from the nearest active volcanic vent, which has implications for monitoring network design, especially at poorly known volcanoes. As relatively few magmatic systems have been imaged tomographically, at many volcanoes InSAR observations provide the best evidence of the lateral extent of active magmatic domains. Global InSAR records therefore suggest that laterally extensive active magmatic domains are not exceptional, but can comprise the shallowest part of trans-crustal magmatic systems in a range of volcanic settings.

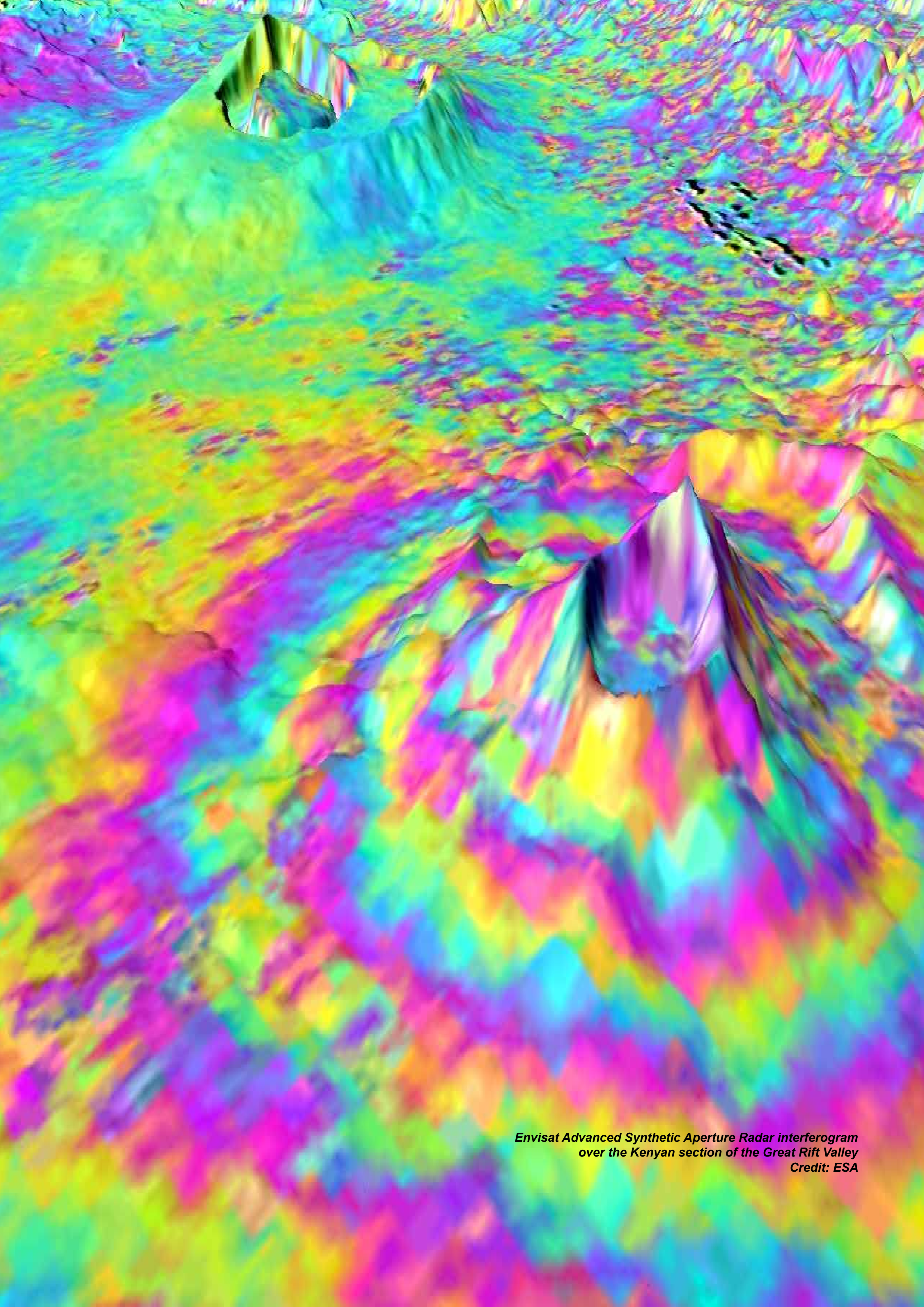
‘Baseline’ records of past InSAR measurements, including ‘null’ results, are fundamental for any future interpretation of interferograms in terms of hazard, both by providing information about past deformation at an individual volcano, and for assessing the characteristics of deformation that are likely to be detectable (and undetectable) using InSAR.

Reference

Ebmeier, S.K., Andrews, B.J., Araya, M.C., Arnold, D.W.D., Biggs, J., Cooper, C., Cottrell, E., Furtney, M., Hickey, J., Jay, J., Lloyd, R., Parker, A.L., Pritchard, M.E., Robertson, E., Venzke, E., Williamson, J.L. (2018) Synthesis of global satellite observations of magmatic and volcanic deformation: implications for volcano monitoring & the lateral extent of magmatic domains, Journal of Applied Volcanology doi: 10.1186/s13617-018-0071-3



Distances between the centre of deformation and the nearest edifice catalogued in the VOTW database are shown with respect to inferred source depth. For offsets greater than ~5 km, depths are shown as a range of values which correspond to the best-fit depths from different modelling methods, source geometries and time periods in different cases. Displacements < 5 km from the associated edifice are shown as circles. Red symbols correspond to deformation attributed to magmatic processes, while blue symbols were attributed, at least in part, to hydrothermal processes. The examples in this figure are limited to those sources interpreted to be associated with magma storage of some variety, normally modelled as a sill, point source or ellipsoid



Envisat Advanced Synthetic Aperture Radar interferogram over the Kenyan section of the Great Rift Valley
Credit: ESA

Sensing volcano structure using seismic anisotropy

Andy Nowacki, COMET associate, Leeds

Volcanoes are hazardous, but at the same time they can provide useful resources. This is the case at Aluto in the central Main Ethiopian Rift, which is the site of Ethiopia's only producing geothermal power station.

Volcanoes are the commonest sites of so-called 'high-enthalpy' geothermal resources, and at Aluto this is fed by meteroic water from the nearby rift flanks. It is of great interest, therefore, to understand whether the geo - and hydrothermal systems at Aluto are responsible for a potentially alarming rate of surface uplift and subsidence (up to 0.5 cm/day), observed since at least 2004, or whether this is seated deeper in a magmatic system. One way to address this is to probe the pattern of fracturing in the crust, since the presence of fluids and changes in stress may influence the surface.

We studied seismic recordings of local earthquakes made at the Aluto Regional Geophysical Observations (ARGOS) network, which was active from 2012 to 2014. Variations in the amount and orientation of fractures will lead to different styles of seismic anisotropy, which we inferred from measurements of shear wave splitting in shear waves from these local earthquakes. These observations are complimentary to a wealth of others which are now available at Aluto, including detailed geological mapping, gas flux measurements, seismicity, and resistivity and seismic tomography.

We find an exceptional spatial correlation whereby regions of very strong anisotropy occur almost exclusively within the inferred caldera limits, bounded by a mapped ring fault. This is likely because of a much higher density of fractures within the caldera than outwith, perhaps due to weakening or deformation during caldera formation. Furthermore, the fractures within the caldera do not align as expected from the regional stress field - the shear wave splitting observations are consistent rather with multiple sets of fractures. These fracture sets are hinted at again by surface mapping of faults and fissures.

The anisotropy is strongest near the surface, down to ~3 km below the edifice. Alongside existing observations of the spatial extent of surface deformation, low Vp/Vs ratios, and gas flux measurements, we believe there is a significant component of the downward surface deformation associated with the presence of large volumes of gas-rich fluid within and above the geothermal system at ~3 km depth. To fully test this hypothesis, however, we need a longer time-series of seismic and geodetic observations - something in progress as part of the RiftVolc project.

References

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Gleeson, M.L.M., Stock, M.J., Pyle, D.M., Mather, T.A., Hutchison, W., Yirgu, G., Wade, J. (2017) Constraining magma storage conditions at a restless volcano in the Main Ethiopian Rift using phase equilibria models, Journal of Volcanology and Geothermal Research doi:10.1016/j.jvolgeores.2017.02.026

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Samrock, F., Kuvshinov, A., Bakker, J., Jackson, A., Fisseha, S. (2015) 3-D analysis and interpretation of magnetotelluric data from the Aluto-Langano geothermal field, Ethiopia, Geophysical Journal International doi:10.1093/gji/ggv270

Wilks, M., Kendall, J.-M., Nowacki, A., Biggs, J., Wookey, J., Ayele, A., Bedade, T. (2017) Seismicity associated with magmatism, faulting and geothermal circulation at Aluto Volcano, Main Ethiopian Rift, Journal of Volcanological and Geothermal Research doi:10.1016/j.jvolgeores.2017.04.003

Data access

Seismic data are available from IRIS under the network code XM (ihttp://ds.iris.edu/mda/XM?timewindow=2012-2015).

RESEARCH HIGHLIGHT

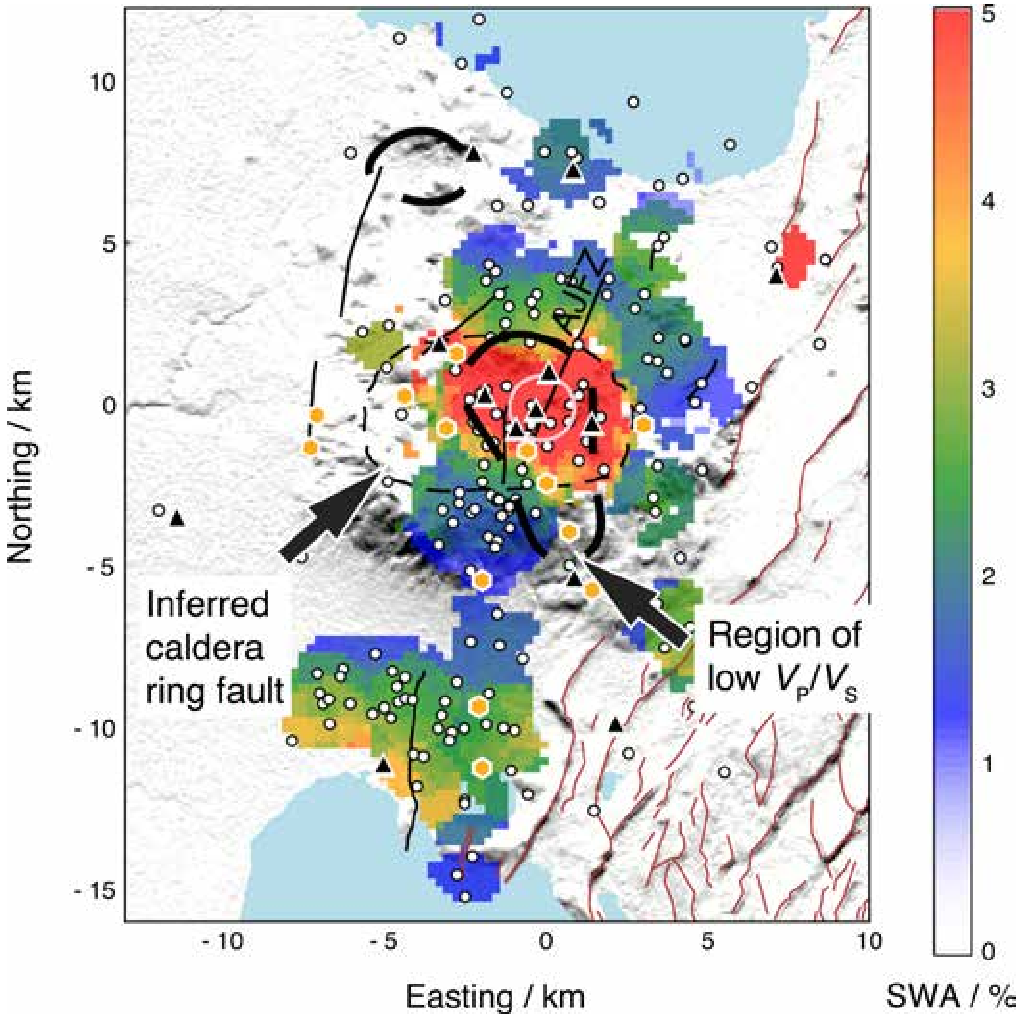


Figure 1: Results of shear wave splitting analysis of local earthquakes around Aluto, showing large anisotropy within the geothermal reservoir. Colour shows the strength of shear wave anisotropy (SWA). Colourless regions indicate no coverage. The region of tomographically-inferred low Vp/Vs (–25% contour) is shown by the thick black dashed lines, whilst the inferred caldera ring fault is the thin black dashed line. Thin unbroken lines are mapped faults, including the Artu Jawe Fault Zone (AJFZ) which is the primary pathway to the surface for geothermal fluids. White circles show midpoints of event–station paths used to create the map, orange hexagons are known hot springs and fumaroles, whilst black triangles are seismic stations. The pink circle in the centre is the location of the greatest geothermal alteration of rocks

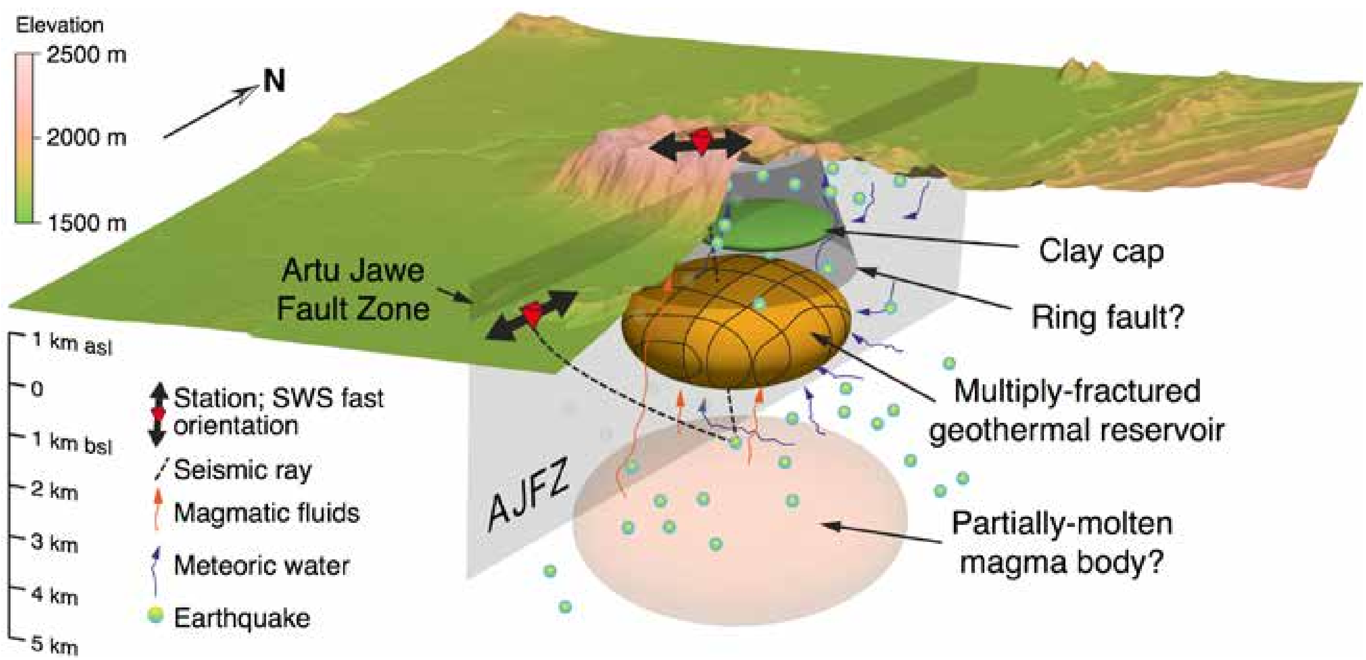


Figure 2: Cartoon describing our interpretation, showing an altered clay cap (which does not contribute much to anisotropy) above a heavily-, multiply- fractured geothermal reservoir, which is fed by a deeper magma body

RESEARCH HIGHLIGHT

Fault intersections exercise a dual control on stop-start earthquake rupture

Richard Walters, COMET scientist, Durham

COMET scientists have shown that both the timing and pattern of fault slip in earthquake sequences may be controlled by intersections of cross-cutting faults.

In continental interiors, the largest episodes of tectonic strain release involve failure of multiple fault segments. This takes place either as a single large earthquake, when all segments fail in just a few seconds, or as a protracted "seismic sequence" of clustered earthquakes, when the same failure instead spans hours to years. These two modes of strain release have very different implications for seismic hazard: either high hazard in a single event or moderate hazard over a much longer interval.

But why the same fault systems sometimes fail in one mode or the other, and what controls the relative timing of each earthquake in a seismic sequence has remained unknown, largely due to a lack of well-observed seismic sequences over the last two decades.

The Central Italy seismic sequence in 2016 presented the first opportunity to address these questions with modern datasets. From August to November 2016, a series of three M>6 earthquakes struck Central Italy, damaging towns across the region and killing several hundred people. The earthquakes represented the largest episode of strain release in the region in a century, since the 1915 Fucino earthquake, and the first major continental seismic sequence globally in the modern space-geodetic era.

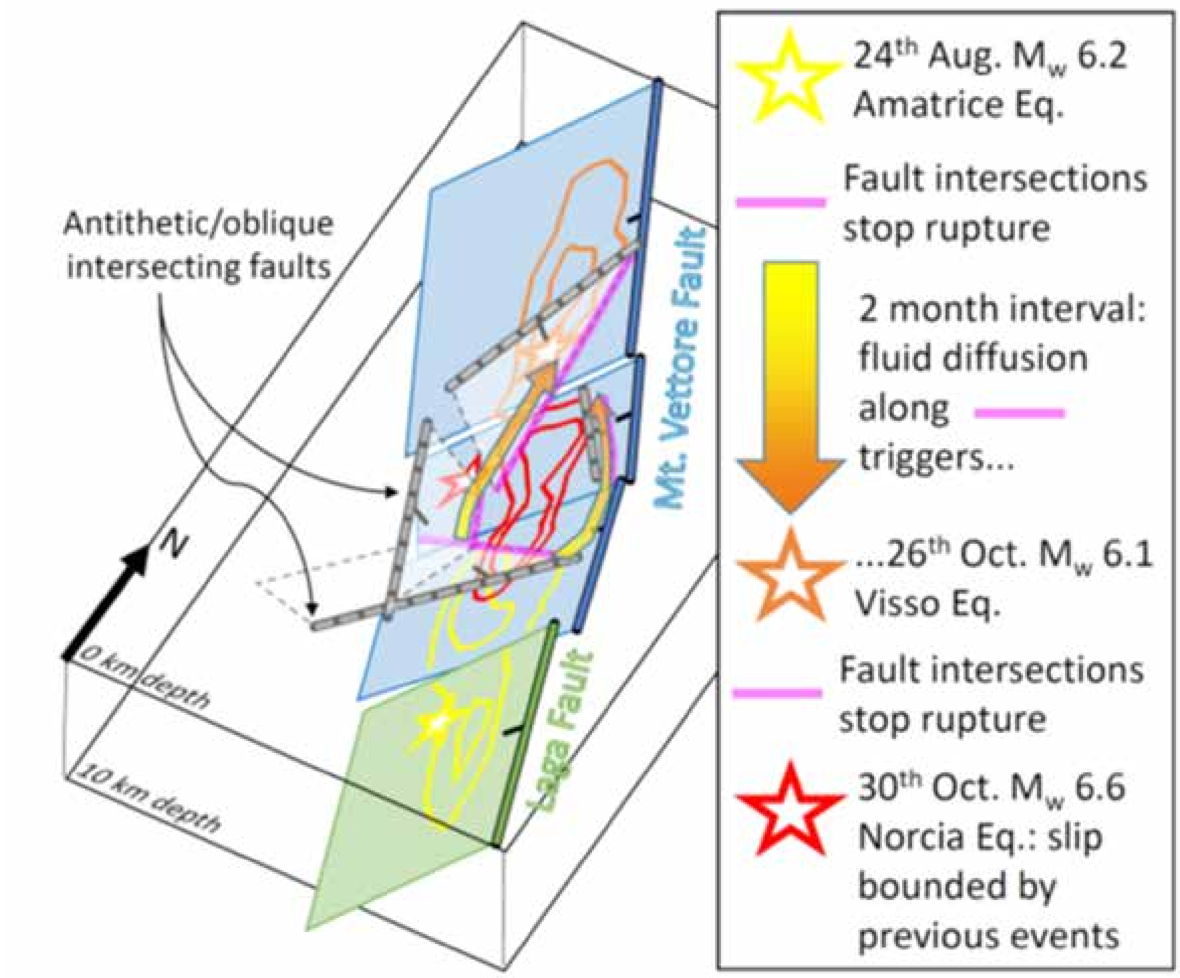
In work funded by a NERC Urgency Grant, COMET scientists and partners in the UK and Italy amassed a rich and varied geodetic, seismological and geological dataset on the earthquake sequence, in order to investigate why rupture stopped and why it started again. This included field measurements of surface ruptures and seismological data for each earthquake, measurements of deformation of the Earth's surface from GNSS instruments and from Sentinel-1 and ALOS-2 satellite systems throughout the sequence, and previously published aftershock locations.

By bringing together these varied datasets, the team were able to characterise the geometry of the complex array of faults that caused the earthquakes, including several faults oblique to the predominant NW-SE trending extensional structures. Furthermore, they were able to estimate how these faults slipped throughout the seismic sequence, and how this slip related to the spatial and temporal distribution of aftershocks.

What they found was both surprising and novel. Intersections of oblique and antithetic faults with the major fault system appear to separate the regions of slip from the three largest earthquakes. This strongly suggests these intersections exercise a first-order control on stopping the propagation of fault rupture, therefore preventing the fault system failing in a single large earthquake and instead favouring failure in a protracted earthquake sequence.

But in addition, the COMET scientists found that following the first earthquake, aftershocks migrated northwards away from this event along these same fault intersections. Two months later, the migrating front of aftershocks arrived at the hypocentre of the second earthquake, just as this earthquake nucleated. The temporal pattern of migration is consistent with diffusion of naturally-occurring water or carbon-dioxide along the fault intersections, suggesting that pressure-driven fluids triggered the second earthquake, starting the sequence again and controlling the relative timing of failure.

Fault intersections therefore appear to have exercised a dual control on the stop-start rupture throughout the 2016 Central Italy earthquake sequence, first preventing rupture in a single large earthquake, and second determining the temporal evolution of failure over the following two months. Investigation of future seismic sequences will reveal if this strong structural control is common to all such sequences. If it is, then characterising subsurface complexity in fault networks and modelling failure and fluid migration across these complex geometries could significantly improve future forecasts of seismic hazard.



Cartoon illustrating how fault intersections (magenta lines) controlled evolution of the 2016 Central Italy seismic sequence. These intersections of oblique and antithetic faults (grey dashed fault planes) with the major NE-SW fault system (blue and green fault planes) separate the major regions of slip in the three main earthquakes (yellow, orange and red contours of slip). The same intersections also channelled fluid migration (yellow-orange arrows), which triggered the second earthquake in the sequence and determined its timing in the sequence

Reference

Walters, R.J., Gregory, L.C., Wedmore, L., Craig, T.J., Wilkinson, M., McCaffrey, K., Elliott, J.R., Michetti, A., Vittori, E., Livio, F., Iezzi, F., Chen, J., Li, Z., Roberts, G., Goodall, H. (2018) Dual control of fault intersections on stop-start rupture in the 2016 Central Italy seismic sequence, Earth and Planetary Science Letters doi.org/10.1016/j.epsl.2018.07.043

PUBLICATIONS

COMET has a strong publication record: since January 2014, we have published 241 articles in peer-reviewed scientific journals covering both the Earth and atmospheric sciences. 56 were published between 1 January and 31 December 2017 (Annex 1), and, of these, 12 had COMET student first authors:

Arnold, D.W.D. *et al*. (2017) Decaying Lava Extrusion Rate at El Reventador Volcano, Ecuador, Measured Using High-Resolution Satellite Radar, Journal of Geophysical Research: Solid Earth doi:10.1002/2017JB014580

Braddock, M. *et al.* (2017) Satellite observations of fumarole activity at Aluto volcano, Ethiopia: Implications for geothermal monitoring and volcanic hazard, Journal of Volcanology and Geothermal Research doi:10.1016/j.jvolgeores.2017.05.006

Stephens, K.J. *et al.* (2017) Transient deformation associated with explosive eruption measured at Masaya volcano (Nicaragua) using Interferometric Synthetic Aperture Radar, Journal of Volcanology and Geothermal Research doi:10.1016/j.jvolgeores.2017.05.014

Yu, C. *et al.* (2017) Generation of real-time mode high resolution water vapor fields from GPS observations, Journal of Geophysical Research: Atmospheres doi: 10.1002/2016JD025753

Ingleby, T., Wright, T.J. (2017) Omori-like decay of postseismic velocities following continental earthquakes, Geophysical Research Letters doi: 10.1002/2017GL072865

Wimpenny. S. E. *et al.* (2017) Fault mechanics and post-seismic deformation at Bam, SE Iran, Geophysical Journal International doi: 10.1093/gji/ggx065

Hunt, J. *et al.* (2017) Spatially Variable CO_2 Degassing in The Main Ethiopian Rift: Implications For Magma Storage, Volatile Transport And Rift-Related Emissions, Geochemistry, Geophysics, Geosystems doi: 10.1002/2017GC006975

Ainscoe, E.A. *et al.* (2017) Blind Thrusting, Surface Folding, and the Development of Geological Structure in the Mw6.3 2015 Pishan (China) Earthquake, Journal of Geophysical Research: Solid Earth doi: 10.1002/2017JB014268

Hodge, M. *et al.* (2017) The role of coseismic Coulomb stress changes in shaping the hard-link between normal fault segments, Journal of Geophysical Research: Solid Earth doi: 10.1002/2017JB014927

Penney, C. *et al.* (2017) Megathrust and accretionary wedge properties and behaviour in the Makran subduction zone, Geophysical Journal International doi: 10.1093/gji/ggx126

Howell, A. *et al.* (2017) Subduction and vertical coastal motions in the eastern Mediterranean, Geophysical Journal International doi:10.1093/gji/ggx307

Hussain, E. *et al.* (2018) Constant strain accumulation rate between major earthquakes on the North Anatolian Fault, Nature Communications doi:10.1038/s41467-018-03739-2

Some of our major scientific advances from last year are described below.

COMET researchers at Oxford worked with colleagues from Addis Ababa University to estimate the total amount of carbon being emitted from the Eastern Rift – the eastern branch of the East African Rift, a zone near the horn of East Africa where the crust stretches and splits.

The study, led by COMET student Jonathan Hunt and published in *Geochemistry, Geophysics, Geosystems*[31], extrapolated from soil carbon dioxide surveys to estimate that the Eastern Rift emits somewhere between 3.9 and 32.7 million metric tons (Mt) of carbon dioxide each year. This demonstrates how, even near some seemingly inactive volcanoes, carbon dioxide from melted rock seeps out through cracks in the surrounding crust.

Hot spring bubbling with carbon dioxide near the Main Ethiopian Rift. Credit: Jonathan Hunt

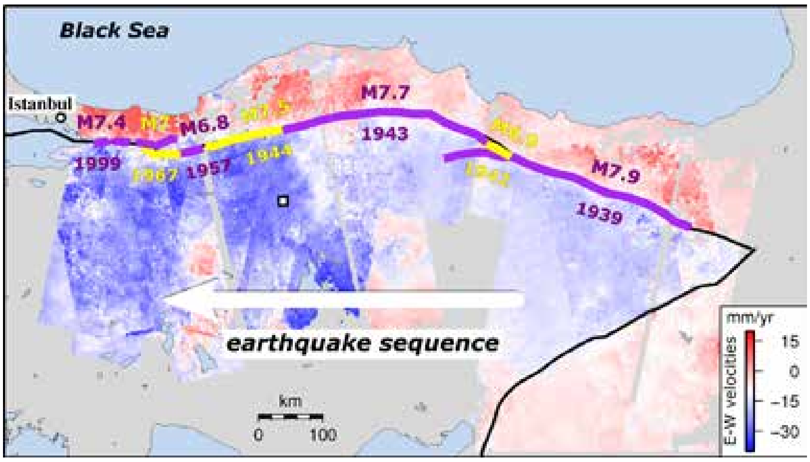
31 Hunt J.A. *et al.* (2017) Spatially variable CO_2 degassing in the Main Ethiopian Rift: Implications for magma storage, volatile transport and rift-related emissions, Geochemistry, Geophysics, Geosystems doi: 10.1002/2017GC006975

As part of the RiftVolc consortium, Bristol Masters student Mathilde Braddock first-authored a paper on geothermal monitoring and volcanic hazard at Aluto volcano in the Ethiopian Rift Valley, published in the *Journal of Volcanology and Geothermal Research*[32]. Working alongside Bristol COMET's Juliet Biggs and Matt Watson, as well as former Oxford COMET student Will Hutchison and COMET scientists David Pyle and Tamsin Mather, Mathilde used satellite images to show how the volcano's surface was inflating over a period of months and then deflating over several years, suggesting that magma, geothermal waters or gases are moving around below the surface.

Satellite thermal images also showed that Aluto's steam vents often coincided with fault lines and fractures on the volcano. The temperature of these vents has remained stable over several years of monitoring, with any changes resulting from a delayed response to rainfall on the higher ground of the rift margin: vents nearer the centre of the volcano were, by comparison, unaffected by rainfall and therefore a better representation of the geothermal waters.

This is one of the first times that anyone has monitored a geothermal resource from space, representing an inexpensive and risk-free way of assessing geothermal potential across the Rift Valley and beyond[33].

Satellite data also shed new light on seismic hazard in one of the world's deadliest earthquake zones. Led by COMET student Ekbal Hussain[34] and published in *Nature Communications*[35], the study describes how tectonic strain builds up along Turkey's North Anatolian Fault at a remarkably steady rate. This means that present-day measurements can not only reflect past and future strain accumulation, but also provide vital information on events still to come.



Strain rates along Turkey's North Anatolian Fault (past ruptures shown in purple/yellow) alongside westward progression of earthquakes since 1939

Strain builds up as Turkey is squeezed between three major tectonic plates. This process has caused almost the entire length of the fault to rupture since 1939, in a series of major earthquakes gradually migrating east-west towards Istanbul.

Satellite images from ESA's Envisat mission were used to identify tiny ground movements at earthquake locations along the fault. The 600-plus images, taken between 2002 and 2010, provided insights into the equivalent of 250 years of the fault's earthquake repeat cycle.

Remarkably, apart from the ten years immediately after an earthquake, strain rates levelled out at about 0.5 microstrain per year, equivalent to 50 mm over a 100 km region, regardless of where or when the last earthquake took place.

32 Braddock, M. *et al.* (2017) Satellite observations of fumarole activity at Aluto volcano, Ethiopia: implications for geothermal monitoring and volcanic hazard, Journal of Volcanology and Geothermal Research doi:10.1016/j.jvolgeores.2017.05.006
33 Adapted from an article in The Conversation by William Hutchison, Juliet Biggs and Tamsin Mather: https://theconversation.com/how-to-turn-a-volcano-into-a-power-station-with-a-little-help-from-satellites-86566
34 Now Remote Sensing Geoscientist at BGS.
35 Hussain, E. *et al.* (2018) Constant strain accumulation rate between major earthquakes on the North Anatolian Fault, Nature Communications doi:10.1038/s41467-018-03739-2

This means that strain rates measured over the short term can also reflect what's happening in the longer term, telling us how much energy is being stored on the fault and could eventually be released in an earthquake.

It also suggests that some existing hazard assessment models, which presume that strain rates vary over time, need to be rethought. This is especially true for regions where there are long gaps between earthquakes, such as the Himalayas.

A study led by COMET associate Evgenia Ilyinskaya, and published in *Earth and Planetary Science Letters*[36] found a previously undetected potential health risk from the high concentration of small particles found in the boomerang-like return of a volcanic plume.

The team, which also included associate Anja Schmidt and COMET's Tamsin Mather, Clive Oppenheimer, Brendan McCormick-Kilbride and Marie Edmonds, traced plume from the 2014-2015 Holuhraun eruption and found a second type of plume that impacts air quality.

This second plume had circled back to Icelandic cities and towns long after the health warning about the initial plume had been lifted.

This showed that while the plume's sulphur dioxide (SO_2) levels had reduced, it was very rich in fine particles which contained high concentrations of sulphuric acid and trace metals found in human-made air pollution that are linked to negative health effects.

It is estimated that short- and long-term exposure to this type of fine particle, from both human-made and natural sources, cause over three million premature deaths globally per year and remains the single largest environmental health risk in Europe.

The study recommends that in future, gas-rich eruptions both the young and mature plumes should be considered when forecasting air pollution and the dispersion and transport pattern of the plume[37].

36 Ilyinskaya, E. *et al*. (2017) Understanding the environmental impacts of large fissure eruptions: Aerosol and gas emissions from the 2014–2015 Holuhraun eruption (Iceland), Earth and Planetary Science Letters doi: 10.1016/j.epsl.2017.05.025

37 Adapted from https://www.leeds.ac.uk/news/article/4058/volcanic_plumerang_could_impact_human_health

The summit of Volcán de Fuego showing active vents
Credit: Universities of Bristol, Birmingham and INSIVUMEH

COLLABORATIONS AND PARTNERSHIPS

COMET continues to strengthen its scientific collaborations, both within the UK and overseas. Our partnership with BGS is delivering cutting-edge research on earthquakes and volcanoes as well as hazard monitoring services, whilst we are a key partner in several major international initiatives:

Earthquakes without Frontiers[38] (EwF) brought together Earth scientists, social scientists, and science communication experts to increase knowledge of earthquake hazards in affected regions, and improve resilience.

In its final year, the EwF team was involved in fieldwork, remote sensing, and seismological research in Turkmenistan, Albania, India, Kyrgyzstan, Kazakhstan, Macedonia, and Greece. Much of the recent work involved producing high-resolution Digital Elevation Models (DEMs), and performing geomorphological analysis, palaeoseismic trenching, and Quaternary dating to establish the earthquake history and behaviour of active faults.

This information forms the basis of our understanding of earthquake hazard in nearby population centres, and also provides new information to address underlying scientific questions regarding the controls on the properties and behaviour of active faults.

FutureVolc[39], led by the University of Iceland and Icelandic Meteorological Office, has been a long-term monitoring experiment looking at geologically active regions of Europe that are prone to natural hazards. It developed the “supersite” concept, integrating space- and ground-based observations to improve monitoring and evaluation of volcanoes.

Although FutureVolc officially ended in March 2016, the collaboration continues through a new initiative, EUROVOLC, which will further improve volcano monitoring, early warning, data sharing and eruption response on a global level.

The NERC-funded **Looking inside the Continents from Space** (LiCS) project is using Sentinel-1 data to revolutionise our knowledge of how continents deform, how strain accumulates during the earthquake cycle, and how seismic hazard is distributed. LiCS is combining satellite data with ground-based observations to map tectonic strain throughout the Alpine-Himalayan Belt and East African Rift, using the results to inform new models of seismic hazard.

The LiCSAR service is now providing Sentinel-1 InSAR products for download, with interferograms and coherence maps produced automatically using the LiCSAR processor, and new interferograms available within two weeks of data acquisition. The initial focus on the Alpine-Himalayan tectonic belt is also being expanded with the aim of producing a complete archive for tectonic and volcanic areas globally, as well as development of an rapid event response facility.

38 http://ewf.nerc.ac.uk/
39 http://futurevolc.hi.is/

RiftVolc[40], led by the Universities of Edinburgh and Bristol, focuses on volcanoes and volcanic plumbing systems in the East African Rift Valley. It is investigating what drives eruptions over geological timescales; what controls the active magmatic system and volcanic unrest; and what the potential threats from future volcanic activity are.

RiftVolc has led to a step change in our understanding of many Ethiopian volcanoes, with recently published research addressing topics such as post-caldera volcanism along the Main Ethiopian Rift, and seasonal patterns of seismicity and deformation at the Alutu geothermal reservoir.

Spectrally High resolution Infrared measurements for the characterisation of Volcanic Ash[41] (**SHIVA**), which ended in March 2017, aimed to study the properties of volcanic ash using information contained in infrared spectra and the change in composition during an eruption, in order to better understand the volcanic processes that control eruptive activity.

As well as publications, outputs from the project include a new optimal estimation retrieval scheme for ash/aerosol using IASI measurements in both clear and cloudy conditions, and measurements of ash that can be directly applied to improve the accuracy of satellite retrievals of ash column concentrations.

Strengthening Resilience in Volcanic Areas[42] (STREVA), led by the University of East Anglia, is aiming to develop a practical and adaptable volcanic risk assessment framework. The results will be used to develop plans to reduce the negative consequences of volcanic activity on people and assets. Work is focusing on volcanoes in Ecuador, Colombia and Montserrat, including Tungurahua, Reventador and Soufrière, where we are strengthening links between geodesy, seismology and modelling on different timescales. Recent outputs include work on meteorological controls on volcanic ash dispersal at Soufrière, as well as an analysis of the impacts of its 1902-1903 eruption.

40 https://riftvolc.wordpress.com/
41 https://volcano.atm.ox.ac.uk/index.php/SHIVA
42 http://streva.ac.uk/

AWARDS AND RECOGNITION

We are delighted that COMET's collective achievements, past and present, were recognised by the Royal Astronomical Society (RAS) in their latest round of awards.

The 2018 RAS Group Achievement Award in Geophysics acknowledged COMET's success in using satellite and ground-based observations and geophysical modelling to study earthquakes, volcanoes and tectonics across the globe. Their citation said:

The Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) receives this year's Group Award for its consistently high standard of insight into dangerous movements of the Earth's crust. It has exploited the revolution in satellite geodesy that allows position and changes in position to be measured accurately and frequently, as well as repeated detailed imaging of the Earth's surface.

Its members have revolutionised our understanding of crustal processes - magma and ground fluid movement connected with volcanism, and buckling of the crust before, during and after earthquakes - and have received awards for work on the faults causing disasters such as the Bam (Iran, 2003) and Gorkha (Nepal, 2015) earthquakes, and the swelling and eruption of volcanoes worldwide including in Montserrat, Chile and Iceland.[43]

Professor Tim Wright receiving the 2018 RAS Group Achievement Award on behalf of COMET

43 http://comet.nerc.ac.uk/comet-honoured-royal-astronomical-society/

There were also a number of individual successes:

Juliet Biggs (COMET scientist) received the AGU Geodesy Section Award at 2017's AGU Fall Meeting. The award recognises Juliet's outstanding contributions to the field of satellite geodesy and understanding of both active volcanism and faulting. On receiving the award, she said: *Many of the previous AGU Geodesy Section Award winners have been role models for me personally, and seeing my name among them is truly humbling.*

Tesfaye Temtime (COMET student) won an award for his poster at the Cabot Institute's Natural Systems and Processes Session.

Zhenhong Li (COMET scientist) won Best Guest Editor Award 2017 for the journal Remote Sensing's special issue *Earth Observations for Geohazards*. Along with fellow Guest Editor Professor Roberto Tomas, from the University of Alicante, the award recognised his efforts in attracting and publishing high-quality papers on remote sensing.

Chen Yu (COMET student) received Best Paper Award at the 2017 UK Next Generation Positioning, Navigation and Timing Conference, recognising his work on GACOS to enhance network GNSS real-time kinematic positioning and satellite radar observations.

Tamsin Mather (COMET scientist) was elected as non-officer director of the US Geochemical Society, representing Europe (2017-2019), recognising the broad remit of her research in volcanology and wide range of collaborations across the disciplines of geochemistry and geophysics.

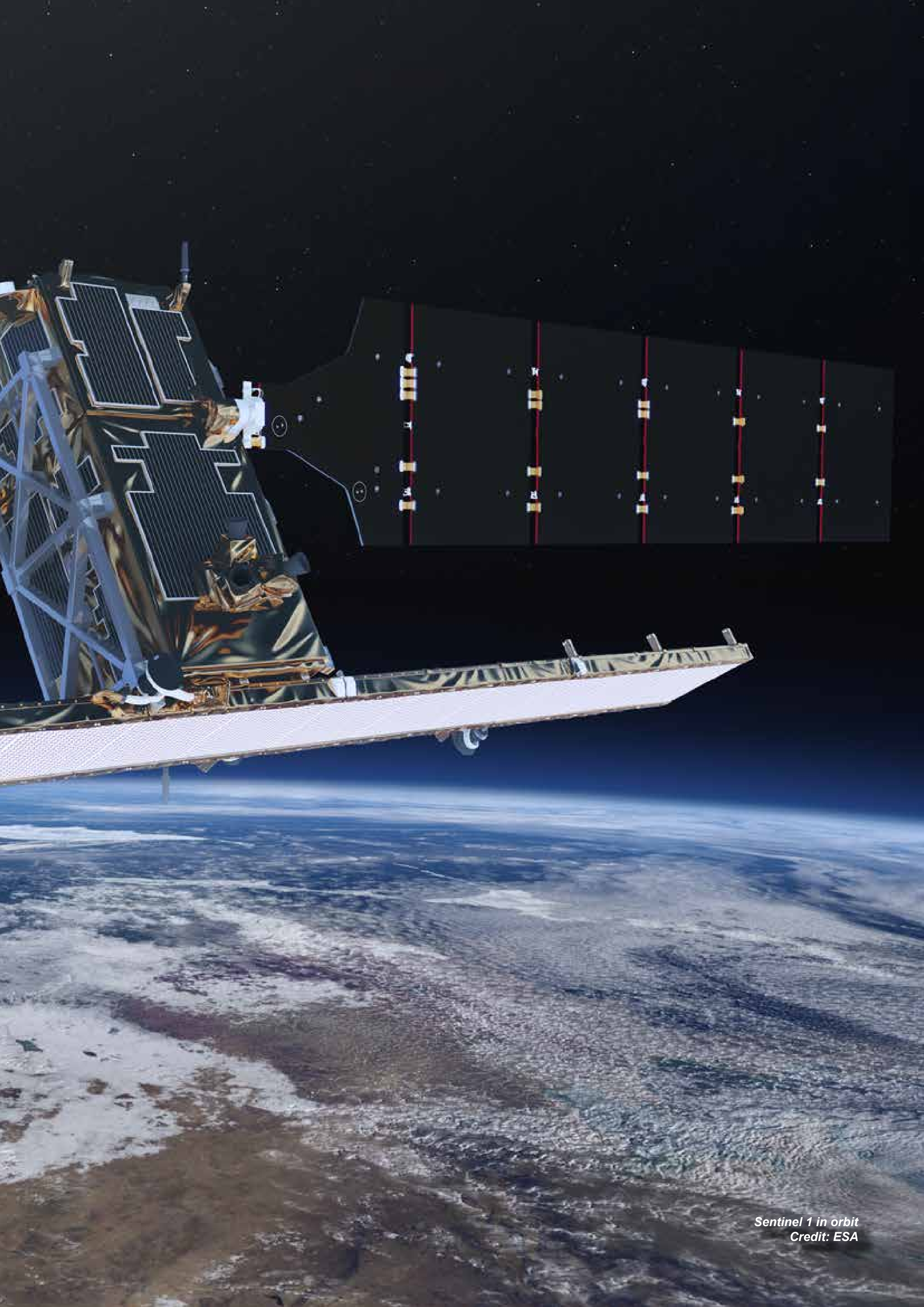
Will Hutchison[44] (former COMET student) received the 2018 Willy Aspinall Prize for his work on geophysical and geochemical constraints on Ethiopia's rift volcanoes. The prize is awarded to the author of an outstanding paper on applied volcanology published within three years of being awarded a PhD at a UK university.

The nomination was based on Will's 2016 paper in Geochemistry, Geophysics, Geosystems, on unrest at silicic calderas in the East African Rift[45] Alongside his previous publications, this work represents a significant advance in understanding volcanic processes and hazards on a regional scale, transforming our understanding of Aluto's eruptive history and its current unrest.

Colm Jordan (COMET scientist, BGS), on behalf of the International Charter 'Space and Major' Disasters, was presented with the 2017 NASA-sponsored William Thomas Pecora Project Manager Group Award for "outstanding support to the global community during times of crisis". As a Project Manager who has been involved in several activations, Colm said *I would like to recognise the input and contribution from BGS staff who have put in great effort on Charter activations to provide advice and support to UK and overseas governments, NGOs, aid agencies, and emergency responders when disasters have occurred.*

44 Now Research Fellow at the University of St Andrews

45 Hutchison, W. *et al* (2016) Causes of unrest at silicic calderas in the East African Rift: New constraints from InSAR and soil-gas chemistry at Aluto volcano, Ethiopia, Geochemistry, Geophysics, Geosystems doi: 10.1002/2016GC006395



Sentinel 1 in orbit
Credit: ESA

GLOSSARY

AGU	American Geophysical Union
BGS	British Geological Survey
CAST	China Academy of Space Technology
CEOS	Committee on Earth Observation Satellites
COMET	Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics
DEM	Digital Elevation Model
DOAS	Differential Optical Absorption Spectroscopy
EO	Earth Observation
EPOS	European Plate Observing System
ESA	European Space Agency
EwF	Earthquakes without Frontiers
GACOS	Generic Atmospheric Correction Online Service for InSAR
GBIS	Geodetic Bayesian Inversion Software
GCRF	Global Challenges Research Fund
GEM	Global Earthquake Model
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema (Russian for GNSS)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSRM	Global Strain Rate Model
GTEP	Geohazards Thematic Exploration Platform
GVM	Global Volcano Model
IASI	Infrared Atmospheric Sounding Interferometer
IMO	Icelandic Meteorological Office
IGEPN	Instituto Geofísico de la Escuela Politécnica Nacional
InSAR	Synthetic Aperture Radar Interferometry
ITD	Iterative Tropospheric Decomposition
LiCS	Looking inside the Continents from Space

LOS	Line of Sight
NASA	US Space Agency (National Aeronautics and Space Administration)
NCEO	National Centre for Earth Observation
NERC	Natural Environment Research Council
NISAR	NASA-ISRO Synthetic Aperture Radar
OMI	Ozone Monitoring Instrument
RAS	Royal Astronomical Society
SAR	Synthetic Aperture Radar
SHIVA	Spectrally High resolution Infrared measurements for the characterisation of Volcanic Ash
STREVA	Strengthening Resilience in Volcanic Areas
UCL	University College London
VMSG	Volcanic and Magmatic Studies Group

ANNEX 1 COMET PUBLICATIONS JANUARY TO DECEMBER 2017

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