COMET

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

ANNUAL REPORT

2015/16

BGS 1835

NERC SCIENCE OF THE ENVIRONMENT

CONTENTS

DIRECTOR'S WELCOME

It is a great pleasure to introduce this second annual report for COMET 2014-19. COMET aims to make major advances in our understanding of tectonics and volcanology and deliver societal impact by combining the latest satellite earth observation techniques with ground-based observations and models.

This has been an important year for COMET. Our staff, students, and scientists have been working towards delivering some of the key goals set out in our proposal, including the building of routine satellite monitoring services that enable us to monitor tectonic and volcanic deformation, and to map the dispersion of volcanic gas and ash. We have been forging a closer partnership with the British Geological Survey (BGS) and we have used our combined expertise to lead coordinated responses to the Gorkha (Nepal) earthquake and Volcán Calbuco (Chile) eruption. Finally, we welcomed the COMET review board to our first full annual meeting and held focussed discussion meetings on modelling volcanic systems, measuring and using high-resolution topography, and satellite radar interferometry.

The EU's Copernicus program has led to a transformative increase in the availability of satellite imagery for the Earth's tectonic and volcanic belts. With the successful launch of Sentinel-1B in April 2016, joining its twin, Sentinel-1A, most tectonic and volcanic areas will be imaged with satellite radar at least 4 times in any 24 day period, and many places will be imaged 4 or more times every 12 days. This gives us the opportunity to respond to any sudden event within a few days, and the large volume of data for any given area means that we will soon be able to detect subtle changes at volcanic systems and the slow build up of tectonic strain around active faults. Building a routine system to handle the massive volume of data produced by the Sentinel-1 constellation remains a significant challenge for COMET and our partner project, LiCS. We now have a system that can process data on demand, and are working to automate the production of interferograms and time-series for all tectonic and volcanic areas. We are also working closely with the European Space Agency (ESA) to guide their acquisition strategy.

In Year 2 of COMET, we have also improved our volcanic ash and gas monitoring service that used data from the IASI instrument on the operational Metop satellites. We have launched an online volcano deformation database in association with the Global Volcano Model Work, Cornell University and the US Geological Survey. This acts as a source for all observations of volcanic deformation made by the international community, and will ultimately be a portal for the latest results from Sentinel-1. We are also building a database of active faults for Central Asia and are working towards the routine production and archiving of earthquake source models from Sentinel-1 data.

Two events in the past year demonstrated COMET's strength in event response. The April 2015 Gorkha (Nepal) earthquake ruptured part of the major thrust system underlying the Himalayas. COMET scientist Jean-Philippe Avouac coordinated our response, which included the rapid acquisition of information from Sentinel-1, the collection of ground-based GPS measurements of motion, the deployment of seismic stations, and considerable effort in modelling the earthquake so that we could understand what had happened and what might happen next. At the same time, BGS scientists used EO data to map the thousands of landslides triggered by the earthquake. James Jackson compiled and digested the scientific findings for the UK Department for International Development, who were responding to the event on the ground. DfID and NERC were able to provide rapid additional funding to fill in observational gaps.

Three days before the Nepal earthquake, Volcán Calbuco (Chile) erupted, emitting a plume of gas and ash that reached a height of 17 km. Several thousand people were evacuated and the eruption grounded air traffic over much of South America. This eruption tested our ability to respond on the ground and with satellites. Our automated IASI web portal was able to track the gas plume from the eruption in near-real time. Four days after the eruption, we were able to measure ground deformation with Sentinel-1 data. In conjunction with local scientists, and funded by a NERC urgency grant, COMET scientists worked in the field to measure the widespread distribution of ash deposits across the continent. They supplemented this information with innovative use of images from social media to put together one of the most comprehensive data sets showing the widespread impact of an eruption.

COMET's scientific community is thriving, particularly in terms of our postgraduate students and early career researchers. Our early career conference, held at the BGS Edinburgh offices in January, was attended by 65 researchers from across the COMET community, and the quality of the talks and posters produced by our PhD students continues to astound me. We have also benefited from 8 new associates with whom we share the latest research and develop joint initiatives.

Our PhD students and staff remain in high demand, and I offer my congratulations to some long-standing COMET students and staff who have moved on to new posts. In particular, I congratulate three of our COMET staff, John Elliott, Susi Ebmeier, and Richard Walters, who have taken up academic positions. Of course, we hope that they will all remain part of the COMET family as we move into the future.

Overall, it has been year of building on the significant achievements of our first year, and I look forward to COMET's continuing success in the future.

Professor Tim Wright
COMET Director

FOREWORD BY ROLAND BURGMANN, CHAIR, COMET ADVISORY BOARD

My first year as Chair of the COMET Advisory Board has been extremely positive, the highlight being the 2015 Annual Meeting in Shropshire where myself and other Board members learned about COMET's activities and achievements and, importantly, had the chance to provide input and advice to the COMET team.

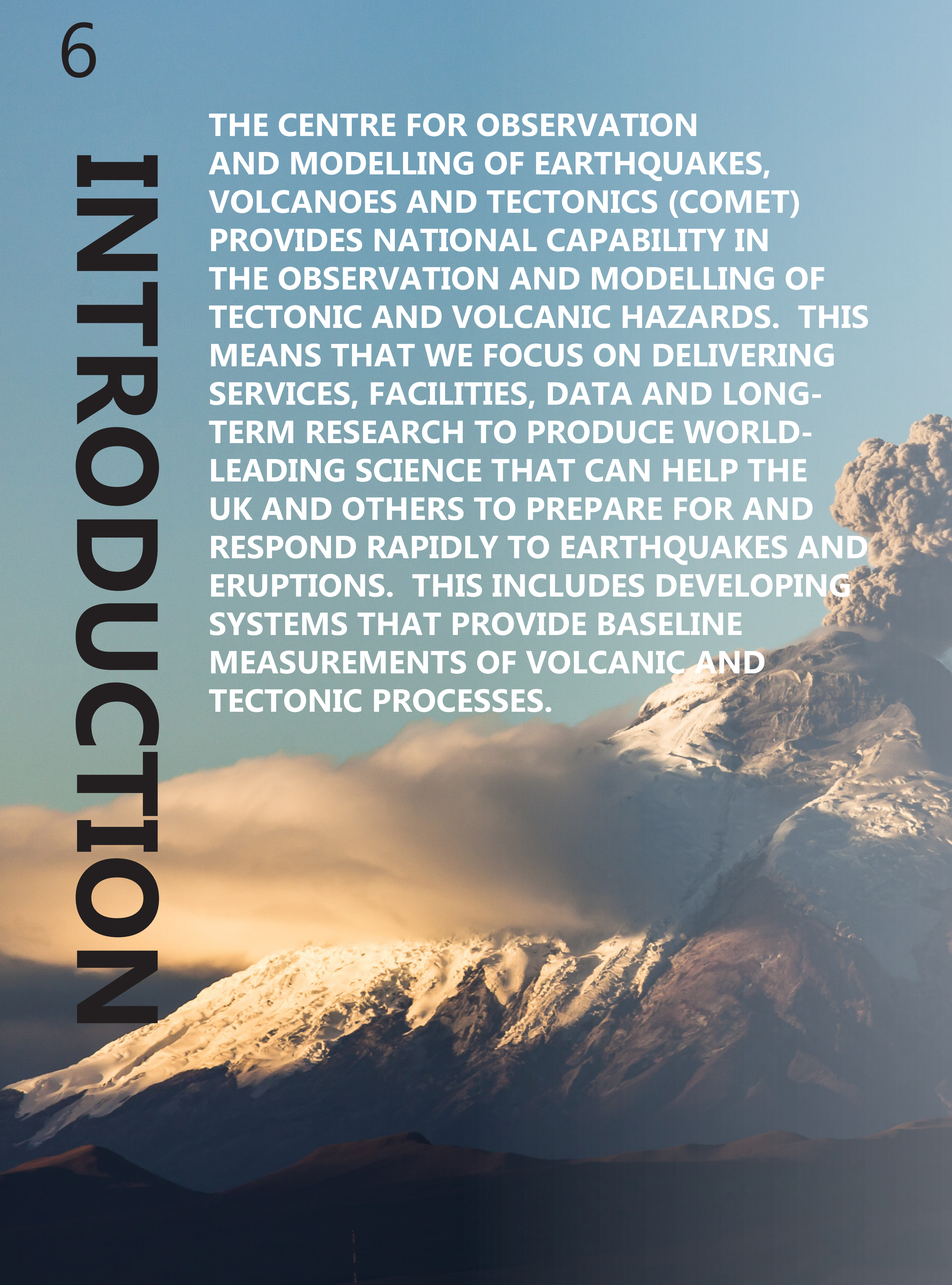
Our overall conclusion is that COMET scientists are working together on high quality, innovative and interdisciplinary projects, with their science catching the attention of both the scientific community and the public. COMET's enthusiasm and collaborative spirit is also evident.

COMET's publication record is equally impressive, reflecting the extent of their international collaborations. Just as importantly, COMET's activities have had a significant impact outside of the scientific community, including hazard and risk management, media engagement, education and outreach, much of which is detailed in this document.
One of COMET's highest priorities is the processing of data from Sentinel-1A, which will support a wide range of COMET researchers as well as others interested in using the data. This is a highly ambitious project, breaking new ground in terms of what can be achieved through satellite radar interferometry. I look forward to being involved in the planning and delivery of the service in an advisory capacity.

Speaking on behalf of the Board, we continue to be excited about the advances COMET is making in tectonics, seismology, geodesy, and volcanology. Their capability to effectively respond to earthquakes and volcanic events is evident, and COMET's partnership with the BGS can only further the achievements of both organisations in hazard monitoring and assessment.

Finally, we commend COMET on having established a vibrant and highly regarded research organisation with a strong community of faculty, postdocs and students, and look forward to continued involvement in its success. It will be good to have the opportunity to directly engage with the COMET community again at the 2016 Annual Meeting in Manchester.

Professor Roland Bürgmann
University of California, Berkeley, USA
Chair, COMET Advisory Board



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. THIS MEANS THAT WE FOCUS ON DELIVERING 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. THIS INCLUDES DEVELOPING SYSTEMS THAT PROVIDE BASELINE MEASUREMENTS OF VOLCANIC AND TECTONIC PROCESSES.

COMET brings together nationally- and internationally-recognised scientists to provide leadership in strategic and discipline-based Earth Observation (EO) research. Our researchers, based at the Universities of Oxford, Cambridge, Leeds, Bristol, Reading, Durham, Liverpool, Newcastle and University College London, use 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.

We work closely with the British Geological Survey (BGS) to deliver cutting-edge research on earthquakes and volcanoes and hazard monitoring services, with our sponsors the Natural Environment Research Council (NERC), with the European Space Agency (ESA) on EO missions and data, and with many other national and international partners.

As well as providing leadership across the EO community, we are growing a vibrant and excellent young research community who will form the next generation of COMET scientists. 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.

This report gives an overview of COMET's activities during 2015/16, highlighting major scientific advances and achievements. It covers the period 1 January – 31 December 2015 for publications, and 1 April 2015 – 31 March 2016 for all other outputs.

WELCOME

MIKE BURTON (CHAIR IN VOLCANOLOGY, UNIVERSITY OF MANCHESTER)

Mike's areas of research include measurements, experiments and modelling of magmatic processes, with a particular focus on measurements of volcanic gases from ground, air and space. His previous work has included remote sensing of gas emissions from Italian volcanoes, including the response to four major eruptions on Etna and Stromboli.

TIM CRAIG (1851 RESEARCH FELLOW, UNIVERSITY OF LEEDS)

Tim focuses on multidisciplinary studies of earthquakes and tectonics in intraplate settings. His expertise includes rare intraplate earthquakes in North America and Europe, their distribution in space and time, and how they relate to the concept of a 'seismic cycle' in plate interiors.

JOHN DOUGLAS (LECTURER, UNIVERSITY OF STRATHCLYDE)

John's research aims to improve earthquake risk evaluation for engineering purposes. He focuses on problems related to the power and energy sector such as the impact of earthquakes on nuclear power plants. One of his main interests is improving ground-motion prediction to provide better models of the shaking to expect at a site given a particular earthquake at a certain distance.

AKE FAGERENG (LECTURER, CARDIFF UNIVERSITY)

Ake's interests lie in how the Earth deforms and how this is recorded in the rocks at the Earth's surface. He uses field investigations alongside a range of geochemical and imaging techniques to investigate both plate boundaries and plate interiors; specifically the range of seismic styles in subduction zones, how rifts form and are controlled (or not) by pre-existing structures, and why there are large earthquakes far from plate boundaries.

WELCOME TO OUR NEW ASSOCIATES

COMET associates are UK-based researchers working on complementary topics, often in collaboration with our existing members. Our associates join us at meetings and receive COMET communications, meaning they can keep up with the latest research and are well-placed to develop joint partnerships and projects with us.

EVGENIA ILYINSKAYA (UNIVERSITY ACADEMIC FELLOW, UNIVERSITY OF LEEDS)

Evgenia's research focuses on volcanic gases and aerosol particles. Her work involves sampling and measurement campaigns at active volcanoes alongside laboratory analyses, and includes investigations of volcanoes in Iceland (Hekla, Eyjafjallajökull, Grímsvötn and Holuhraun), Central America, Hawaii, Antarctica, and Japan.

MIKE KENDALL (PROFESSOR OF SEISMOLOGY, UNIVERSITY OF BRISTOL)

Mike's work covers pure and applied seismology, with connections to mineral physics, geodynamics and engineering. His main interests lie in microseismicity and passive seismic monitoring, rock-fracture characterization, and linked geophysics, geomechanics and fluid-flow modelling.

ANDY NOWACKI (LEVERHULME EARLY CAREER FELLOW, UNIVERSITY OF LEEDS)

Andy is a seismologist interested in global and local seismic phenomena, including how the interior of the Earth moves around, where and how molten material is created, and the history of our planet. His current project, 'The Secret History of the Earth's Mantle', aims to investigate the structure of the lowermost mantle.

MAX WERNER (LECTURER, UNIVERSITY OF BRISTOL)

Max's research centres on earthquake processes and seismic hazard assessment. Specifically, he aims to better understand earthquake physics and to improve estimates of seismic hazard using numerical modelling alongside seismological observations. He is particularly interested in better understanding the mechanisms by which earthquakes trigger other earthquakes and in improving models of future earthquake potential.

OUR RESEARCH

COMET IS SIGNIFICANTLY IMPROVING THE UNDERSTANDING OF TECTONIC AND VOLCANIC PROCESSES. WE ALSO USE OUR RESEARCH TO SUPPORT RISK REDUCTION AND HAZARD MANAGEMENT BY, FOR EXAMPLE, INFLUENCING POLICY AND INFORMING EMERGENCY PROCEDURES.

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.

To meet these aims, we are pursuing a number of research challenges, including:

Identifying changes in volcanic activity, and what they might mean, using ground-based measurements alongside new high-spatial resolution optical and radar imagery.

Developing methods that enable us to use high-resolution InSAR data from ESA's Sentinel-1 satellites to measure tectonic strain.

Using deformation data from Sentinel-1 to estimate the fault location and mechanism for every continental earthquake above magnitude 6.0.

Improving our knowledge of time-dependent surface deformation to make significant progress in understanding the 3D strength distribution in the continents.

Collecting and interpreting information on magma composition, gas emissions, and the "plumbing system" of a volcano to both understand its internal state and predict future behaviour.

Using InSAR data alongside the Infrared Atmospheric Sounding Interferometer (IASI) to observe volcanic activity on a global scale, develop better measurements and models of volcanic deformation and degassing, and establish volcano monitoring and automated alert systems.

RESEARCH HIGHLIGHTS

CREEPY FAULTS

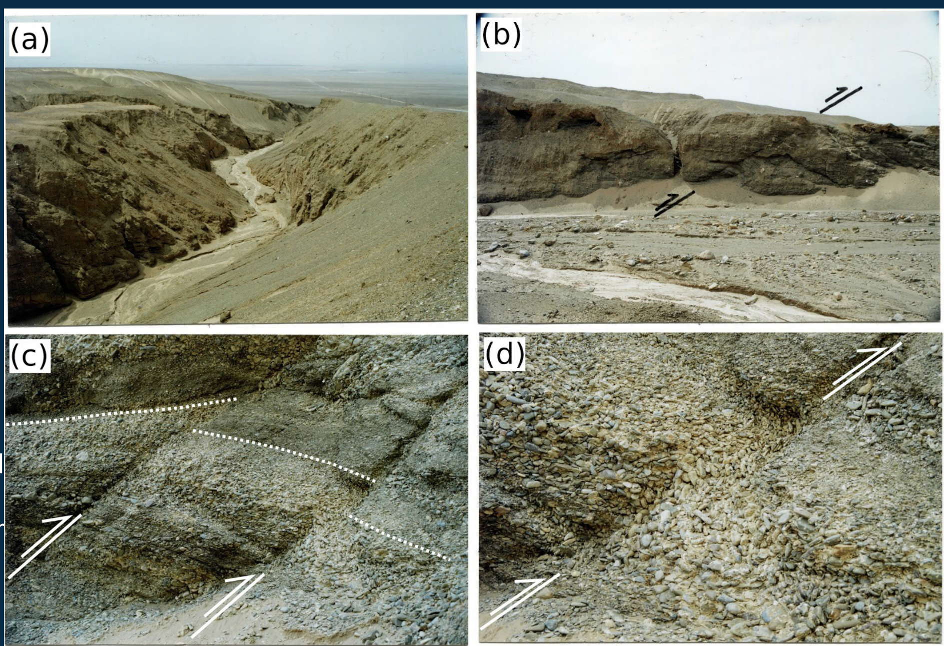
ALEX COPLEY

Alex Copley is a lecturer at the University of Cambridge. His work focuses on observing and modelling active tectonics.

New constraints on the material properties of creeping faults

New satellite observations from Iran have provided a glimpse of the properties and behaviour of active faults. A major goal in active tectonics is to understand the material properties of active faults, which has clear implications for hazard assessment. Work on this subject has progressed down multiple, parallel avenues, including experimental work, theoretical calculations, and field and remote observations of natural faults. Lab measurements and modelling work have suggested a very non-linear relationship between the forces imposed on a creeping fault, and the rate it slips.

New observations from a thrust belt in eastern Iran have now provided a test of this model. The Shahdad thrust belt lies on the margin of the Lut desert in Iran. Rupture in a nearby earthquake in 1998 was known to have caused motion on the fault bounding the thrust belt, because of the stresses caused by the earthquake slip. Alex Copley and Romain Jolivet revisited this earthquake sequence, and used InSAR to measure fault slip occurring at a slower rate both before and after the rapid slip following the 1998 earthquake.



In order to examine how the fault slip rate depended on the forces acting on the faults, Copley and Jolivet constructed a mechanical model for the forces acting on the thrust belt, and calculated the stress changed from the 1998 earthquake. Their results show a very non-linear relationship between applied force and fault slip rate, appearing to confirm the applicability to natural faults of the laboratory-derived fault friction laws.

However, much work remains to be done in this field. Further work is necessary to establish whether the mechanisms of fault slip are the same in nature as in the lab experiments, or if the agreement seen in Iran is a coincidence. It also remains to be established to what extent natural faults vary in properties in location and through time. Combining new satellite data and methods, with the long archive of satellite data that now exists, provides a promising avenue for future progress.

Reference: Copley, A., Jolivet R. (2016), Fault rheology in an aseismic fold-thrust belt (Shahdad, eastern Iran), Journal of Geophysical Research: Solid Earth doi:10.1002/2015JB012431

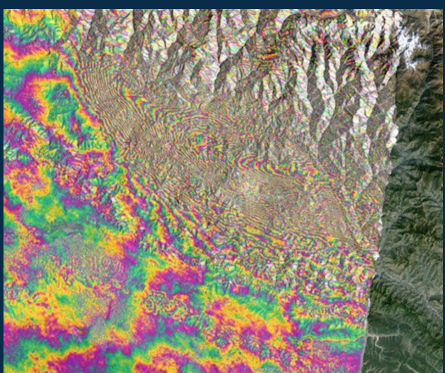
SENTINEL-1A IMAGES GORKHA (NEPAL) 2015 EARTHQUAKE

JOHN ELLIOTT

John Elliott is an Independent Research Fellow at the University of Leeds. He works on modelling earthquakes using deformation data.

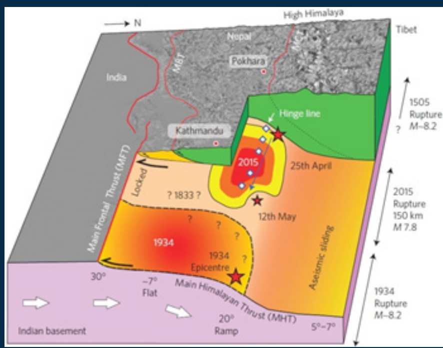
Images from ESA's Sentinel-1A satellite clearly show effects of earthquakes

On 25 April 2015, a 7.8 magnitude earthquake struck Nepal, claiming over 8,000 lives and affecting millions of people. Images from ESA's Sentinel-1A satellite clearly showed the effects of the earthquake, including the maximum land deformation only 17 km from Nepal's capital, Kathmandu. This explained the extremely high damage to the area. By combining Sentinel-1A imagery from before and after the quake, COMET scientists were able to study the rainbow-coloured interference patterns in the interferogram below and interpret them as changes on the ground.



Interferogram of the Nepal earthquake April 2015. Credit: Copernicus data (2015)/ESA/Norut/PPO. labs/COMET–ESA SEOM INSARAP

The interferogram, produced by Pablo González as part of the **INSARAP**[1] study, confirms that an area of 120 km by 50 km around Kathmandu lifted up with a maximum of at least 1m. Further north, the ground subsided, which is to be expected following slip along a shallow thrust.



Location of the 2015 earthquake and its aftershock on the resolved Main Himalayan Thrust geometry (with the upper plate removed to reveal the slip zone). High-frequency seismic sources are marked as diamonds running along the hinge line between the ramp and flat. The Mw 7.2 aftershock occurred at the eastern end of the main rupture.

It was also possible to see how the fault ruptured east from the epicentre, around 80 km northwest of Katmandu, and did not break the surface. This suggested that not all the strain built up in the rocks prior to the earthquake had been released.

This was evident from the subsequent magnitude 7.3 earthquake that shook Nepal on 12 May, whose epicentre lay directly beneath one of the most landslide-prone parts of the country, around 80 km east-northeast of the capital. This large aftershock occurred at the eastern end of the fault segment that had slipped earlier, and was almost certainly triggered by stress changes caused by the first earthquake.

The data also suggests there are still large segments of the fault under strain, giving a focus to resilience planning through initiatives such as the Earthquakes Without Frontiers (EWF) project. The hope is that such analysis can point to areas at greatest risk from future ruptures and assist with disaster planning. Importantly, COMET has been working on speeding up the production of the interferograms themselves. In this case, Sentinel-1A passed over Nepal shortly after midnight, Tuesday into Wednesday. The data was then downlinked and put in the hands of scientists within a matter of hours.

The results of this study were published in Nature Geoscience. In order to test the ideas presented in this study, the postseismic deformation following the earthquake is undergoing subsequent analysis by COMET researchers making use of the regular acquisitions by Sentinel-1. This will be used to examine the growth of topography in the months following the earthquake, as well as look for any shallower slip on the unruptured upper portion of the fault.

Reference: Elliott, J. R., Jolivet, R., González, P., Avouac, J.P., Hollingsworth, J., Searle, M., Stevens, V. (2016) Himalayan megathrust geometry and relation to topography revealed by the Gorkha earthquake, Nature Geoscience doi:10.1038/NGEO2623

[1]http://insarap.org

PROGRESS AGAINST OUR AIMS FOR 2015/16:

LAUNCH AN AUTOMATED INSAR SYSTEM FOR TECTONIC AND VOLCANIC REGIONS USING SENTINEL-1 DATA

During 2014-2015, most of our work was related to capacity building; the adaptation of existing technology to the TOPS (Terrain Observations by Progressive Scans) processing capabilities of Sentinel-1; and application to events such as the 2014-2015 Fogo (Cape Verde) eruption and April 2015 Gorkha (Nepal) earthquake.

In 2015-2016, we focused on the development and testing of the automation of Sentinel-1 SAR data processing products. By early 2016, the Looking inside the Continents from Space (LiCS) team was deploying the system in **CEMS/JASMIN**[2], the computing facility that allows COMET to process the astonishingly large volume of data from Sentinel-1. Realistic scenarios have now been produced for COMET's key areas of tectonic interest such as Turkey, and for several volcanoes including Sakurajima (Japan) and Tunguragua (Ecuador).

For the remainder of 2016, the output from the automation in these regions will provide a first batch of time-series products and large area velocity maps. We will carry out an analysis of the output and performance of the processor during this phase, with the results feeding into the next iteration. In parallel, work will begin to process data from across the globe with the goal of producing a global assessment of interferometric coherence, which can influence ESA's future acquisition plan.

In addition, as part of the LiCS project, the Newcastle COMET team is assessing (i) the performance of numerical weather models (NWM) in describing the spatio-temporal variability of tropospheric water vapour, and (ii) the feasibility of using NWM products to reduce water vapour effects on InSAR measurements. And researchers at UCL are working with ESA to improve orbit determination models for Sentinel-1.

LAUNCH A VOLCANIC SO2 MONITORING SYSTEM USING DATA FROM IASI. UPGRADE THE SERVICE IN RESPONSE TO USER FEEDBACK, AND ADD A VOLCANIC ASH RETRIEVAL

The Infrared Atmospheric Sounding Interferometer (IASI), carried on board the MetOp satellite, provides a wealth of data on various components of the atmosphere. These in turn further our understanding of atmospheric processes and the interactions between atmospheric chemistry, climate and pollution. The instruments make measurements at 9.30 am/pm (IASI-A) and 10.15 am/pm (IASI-B) local time, each providing twice daily global coverage.

A volcanic SO2 monitoring website[3] has now been launched displaying near real time (NRT) data from both IASI instruments within 3 hours of measurement. The analysed NRT data, with different assumed plume altitudes, are also available for download. A number of larger volcanic eruptions have been monitored via the website, including Volcán Calbuco, Chile (April 2015), Wolf Island, Galápagos (May 2015), Mount Etna, Sicily (December 2015) and Popocatépetl, Mexico (January 2016).

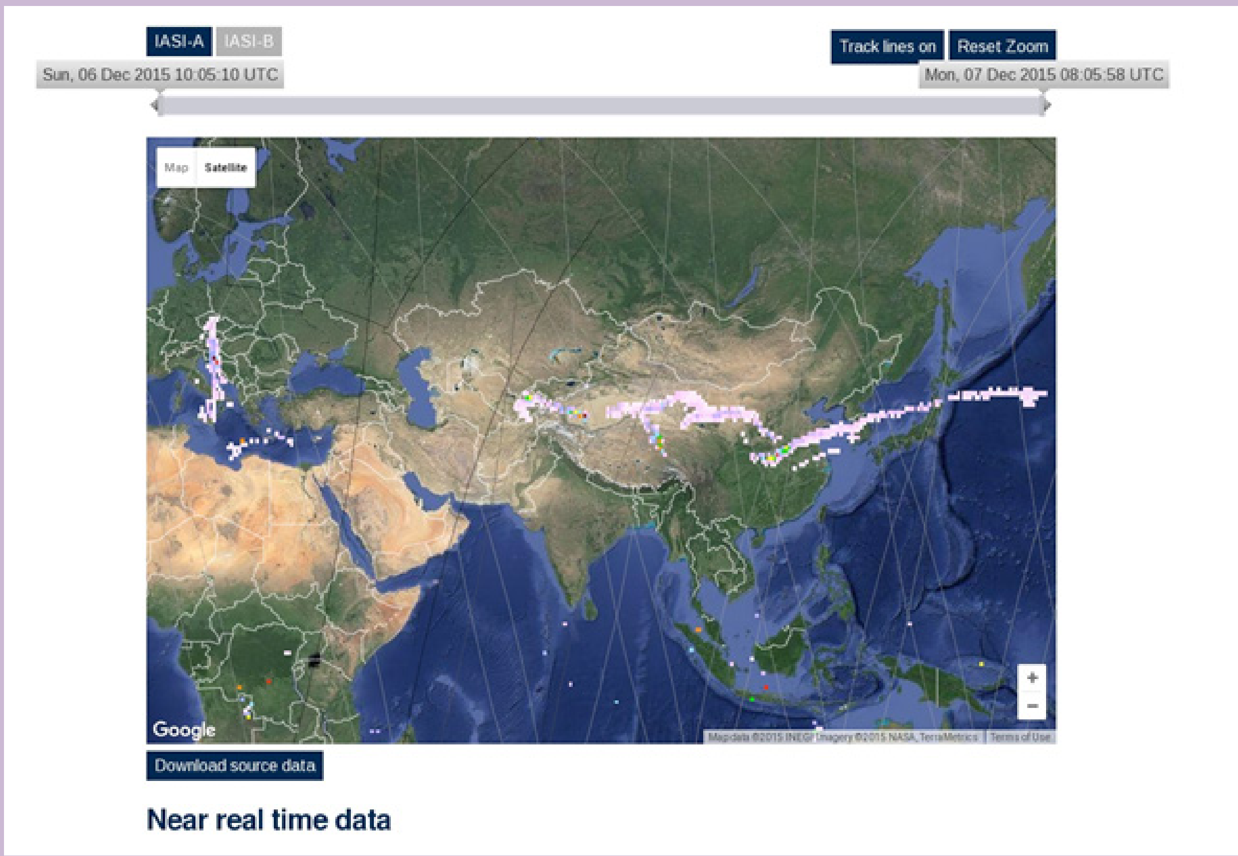
An archive of previous data is also available (quantitative estimates of SO2 column amount and plume altitude), covering both the global scale and specific areas of interest.

The primary objective of this service is to to provide NRT notification of a range of atmospheric anomalies. A volcanic ash flag, sensitive to aerosol optical depths of 0.5 at 550 nm, will be added to the website in the near future while biomass burning and Saharan dust flags are in development. The archive will also be expanded in line with the new NRT flags. This diversity of products differentiates us from other satellite based NRT websites.

Importantly, disseminating results through a website is the London Volcanic Ash Advisory Centre's (VAAC) preferred method of receiving information. A website also has the benefit of providing timely results to a wider number of VAACs, other stakeholders (including COMET scientists) and the general public.

[2] http://www.ceda.ac.uk/services/analysis-environments/

[3] http://www.nrt-atmos.cems.rl.ac.uk/



Screenshot from IASI NRT webpage 7 December 2015 showing Etna's plume travelling from Sicily to Asia

BUILD AND LAUNCH AN ONLINE GLOBAL VOLCANO DEFORMATION DATABASE TO PROVIDE A SUMMARY OF PAST DEFORMATION AND, ULTIMATELY, QUICK-LOOK SENTINEL-1 IMAGES FOR SCIENTISTS AND DECISION MAKERS IN VOLCANO OBSERVATORIES

Significant progress has been made on the COMET volcano deformation database over the past 12 months and it is now operating through a **dedicated website**[4]. Two thirds of the world's volcanoes have a database entry detailing past geodetic surveys, any deformation observations, and interpretations of significant results. Sample quick-look Sentinel-1 interferograms are also available for target volcanoes across Latin America, providing easily accessible results for volcano observatory staff.

Over the next year the aim is to populate the remaining volcano entries and utilise the COMET automatic Sentinel-1 processing facility to provide updated quick-look interferograms for every volcano globally. Through collaboration with the BGS and using NERC Impact Accelerator funding (£6.5k awarded in December 2015) at the University of Bristol, steps are also being taken to map archived information into a fully-relationable database. This will improve functionality and facilitate future statistical comparisons.

These steps are being developed in collaboration with the Global Volcano Model and Smithsonian Institution to ensure that COMET's contribution is complementary to other volcano databases.

[4]http://volcanodeformation.blogs.ilrt.org/

COMPLETE THE DEVELOPMENT OF VOLCANO DEFORMATION INVERSION SOFTWARE, INCLUDING A MODULE FOR THE GENERATION OF PRESSURE/VOLUME CHANGE TIME-SERIES, AND RELEASE A TRIAL VERSION TO THE COMMUNITY

We now have a beta version of the software that is able to invert InSAR and Global Positioning System (GPS) data but can also be easily adapted for the use of other geodetic datasets, such as Digital Elevation Models (DEM). The InSAR module has been adapted to Sentinel-1 data to take into account variations in the line-of-sight vector, including variable squint angle (one peculiarity of TOPS interferometry). This approach led to the results described in González *et al*. (2015)[5].

The inversion software is able to retrieve best-fitting source parameters and estimates of the uncertainties associated with each parameter by calculating their multivariate probability distribution using a Bayesian approach. This is based on a Markov-chain Monte Carlo algorithm, incorporating the Metropolis algorithm.

The software is written as a suite of Matlab scripts and can be run on any standard PC/Unix machine. The current version ingests pre-prepared .mat files containing InSAR data (latitude, longitude, line-of-sight displacement, heading, incidence and squint angle at each measurement point) and GPS data (latitude, longitude, 3D displacements and associated uncertainties). Further Matlab scripts are being developed to ingest different data formats and prepare the necessary input files.

The current version of the modelling software uses forward models for magmatic and tectonic sources from dMODELS (Battaglia et *al*., 2013)[6], as well as other sources. A beta version of Matlab scripts to plot results is also available.

The module for the generation of time-series of pressure/volume change is still under development (Marco Bagnardi is working on this with Dr. Michelle Parks of the University of Iceland), with the aim of releasing the update by the end of 2016. Future developments will include pre-processing routines to ingest different data formats, plotting routines to produce publication quality figures, and the time-series module.

The software is currently being used internally within COMET and by a few collaborators. The aim is for a wider release in late 2016.

CONTINUE TO RESPOND TO EVENTS AS THEY OCCUR, IN COLLABORATION WITH LOCAL PARTNERS, AND DEVELOP A JOINT RESPONSE PROTOCOL WITH BGS

Following a joint BGS-COMET workshop and further discussion with the COMET Advisory Board, we have developed draft guidelines on how COMET and BGS will work together regarding event response. Although the details will vary from event to event, the guidelines describe which events COMET[7] will respond to, and outline COMET-BGS roles and responsibilities for these events. COMET will, for example:

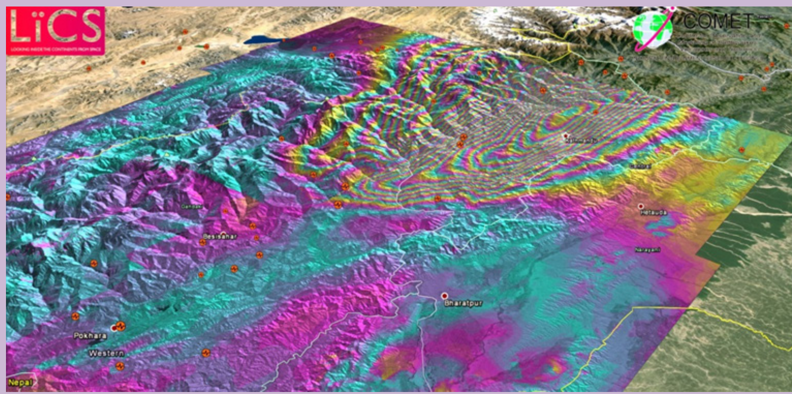
- Produce information/models that add value to raw data (e.g. precise locations, nature of faults, rupture direction etc.) within the shortest possible timeframe.
- Share datasets and results as they become available
- Manage COMET's relationships with international space agencies where its data is used.

During 2015/16, COMET responded to the April 2015 Gorkha (Nepal) earthquake (see below), April 2015 Volcán Calbuco (Chile) eruption and December 2015 Mount Etna (Sicily) eruption, described in the **Responding to Events** section.

[5]Gonzalez, P., Bagnardi, M., Hooper, A.J., Larsen, Y., Marinkovich, P., Samsonov, S.V., Wright, T.J. (2015) The 2014- 2015 eruption of Fogo volcano: Geodetic modeling of Sentinel-1 TOPS interferometry, Geophysical Research Letters doi:10.1002/2015GL066003
[6]Battaglia, M., Cervelli, P.F., Murray, J.R. (2013) DMODELS: A MATLAB software package for modeling crustal deformation near active faults and volcanic centers, Journal of Volcanology and Geothermal Research 10.1016/j.jvolgeores.2012.12.018
[7]Events where we have scientific expertise or interest in the affected area plus appropriate data coverage. Other events (e.g. where our involvement is requested) will be assessed on a case-by-case basis.

EVALUATE COMET'S RESPONSE TO THE GORKHA (NEPAL) EARTHQUAKE, 25 APRIL 2015

COMET's Jean-Philippe Avouac (Cambridge, now Caltech), John Elliott (Oxford, now Leeds), Pablo González (Leeds, now Liverpool), Tom Ingleby (Leeds), James Jackson (Cambridge), Colm Jordan (BGS), Andy Hooper (Leeds), and Tim Wright (Leeds) contributed to the international scientific response to the earthquake that devastated Nepal in April 2015.



Satellite radar images of ground deformation across Nepal resulting from the 2015 Gorkha earthquake. Each coloured fringe is equivalent to 10 cm of motion, indicating the city of Kathmandu rose by over a metre whilst the highest mountains in the north sank by over 60 cm.

Sentinel-1A passed over Nepal shortly after midnight on Tuesday 28 into Wednesday 29 April 2015. Because of the development work being undertaken within the LiCS project, the team was able to download and process the data within a matter of hours, creating an interferogram representing the displacement occurring on the earthquake fault. This quickly confirmed that an area of 120 km by 50 km around Kathmandu lifted up, with a maximum uplift of at least 1 m. The interferogram was subsequently refined and used to assist in mapping damage and landslides.

Subsequent research using data from Sentinel-1A (see **Research Highlights)** has allowed the team to precisely measure ground movement across the entire eastern half of Nepal.

Immediately following the earthquake, it was clear from our analyses, and those of our overseas partners and collaborators, that the event had ruptured a smaller fault area than we had anticipated, and the unruptured parts could still fail in future large earthquakes. James Jackson was in constant communication with DFID (Department for International Development), GO-Science (Government Office for Science) and SAGE (Scientific Advisory Group in Emergencies), advising them on the evolving international scientific understanding of the event. During this time, COMET also gave over 60 interviews to the international media.

In May 2015, helped by decisive action from Duncan Wingham (NERC Chief Executive) and Chris Whitty (Science Advisor, DFID), a joint NERC-DFID initiative was funded to respond to the remaining threat. The project is monitoring the regions south and west of Kathmandu that remain unruptured, and which are known to have failed in earlier large earthquakes, with GPS instruments and broad-band seismometers. Our preliminary conclusion, that the earthquake's job was only half-done, has stood the test of time, and several publications have now confirmed that analysis. One possibility, and a reason for monitoring the situation, is that the unruptured parts of the fault could have slipped slowly and silently following the April mainshock, thereby relieving the stress without requiring a future earthquake. That is, unfortunately, not the case: InSAR and GPS analysis show that the threatened regions remain locked, and will slip in a future earthquake, but we don't know when. This is a clear example of how, without scientific insight and analysis, a proper assessment of the outstanding severe hazard would be impossible.

We are continuing to monitor the situation, briefing DFID, GO-science and SAGE regularly. Because of the continuing threat, NERC and DFID are allowing the project to continue until the end of September 2017, a year beyond its originally anticipated end date.

The project continues to be a great success, particularly regarding our high-profile interactions with the UK Government, DFID and Nepal. At the moment the Nepalese have no experience of running or analysing the data from broadband seismometers, but this is changing - in January 2016 we leveraged UNESCO support, as a result of the NERC-DFID grant, for a Nepalese postdoctoral researcher who we are training in disciplines ranging from instrument installation and maintenance to data analysis. This will ensure an enduring legacy for Nepal, with the training of local scientists in line with the **Earthquakes Without Frontiers**[8] (EWF) project.

[8]http://ewf.nerc.ac.uk/

Colm Jordan (BGS) and his team played a leading role building landslide inventories and advising on the associated hazards following the earthquake. BGS was called in by UK Government directly after the earthquake and was in constant contact with SAGE, DFID, GO-Science and the Foreign and Commonwealth Office (FCO). BGS staff provided regular updates on the situation, including the location of landslides and their impact on infrastructure. The results helped UK Government plan a concerted response, and also directly assisted relief efforts by showing where roads or rivers were blocked and where villages were affected by landslide debris.

A combination of optical and radar satellite imagery was used to very rapidly identify and characterise over 3000 landslides triggered by the earthquake. Various types of satellite data (obtained via the International Charter "Space and Major Disasters" and directly from data suppliers) were used, including WorldView, UK-DMC2, SPOT, Pleiades and RADARSAT-2. The UK team (including Durham University) also worked alongside, and compiled the landslide maps from, other agencies such as NASA, the National Geospatial Intelligence Agency (NGA), MDA Space and Robotics and the International Centre for Integrated Mountain Development (ICIMOD) to produce a comprehensive map of the post-earthquake landslides. The maps were made available as widely as possible including via the **International Charter website**[9], **UNOSAT**[10], **Nepal Earthquake Support**[11], Humanitarian Data Exchange, MapAction and **Earthquakes Without Frontiers**. The results were used on the ground by several relief agencies.

This work recognised that the terrain had been destabilised by the seismic events and therefore the approaching monsoon could result in a greater number of landslides than usual. DFID agreed to fund a project to continue monitoring through the monsoon, with imagery supplied via ESA Third Party Missions, UNOSAT, the Committee on Earth Observation Satellites (CEOS) and MDA (supported by the Canadian Space Agency). The success of the emergency response and subsequent monsoon monitoring project is demonstrated by the invitation to present the results to a Landslide Forum in Kathmandu and the continued calls on BGS by UK Government and international agencies when similar events happen worldwide. Maps and further information can be found on the **BGS website**[12].

CONTINUE TO WORK WITH ESA TO EVOLVE THE ACQUISITION SCHEDULE FOR SENTINEL-1, PARTICULARLY IN RESPONSE TO THE LAUNCH OF 1B IN EARLY 2016

Scientists in COMET have continued to work closely with ESA to ensure that the Sentinel-1 data being acquired are suitable for tectonic and volcanic research. We have been pleased with the volume of data acquired by Sentinel-1A and are looking forward to working with data from Sentinel-1B (launched on 22 April 2016). We have been asked by ESA to evaluate interferometric coherence from the Sentinel constellation, with the aim of using these results to reduce or increase the number of acquisitions for certain areas. In addition, Andy Hooper and Tim Wright were awarded an extension to their ESA-funded INSARAP collaboration with Norut (Norway) and PPO.Labs (The Netherlands) to investigate the interferometric performance of Sentinel-1B.

Sentinel-1B lifts off. Credit: ESA - Manuel Pedoussaut

[9]https://www.disasterscharter.org/web/guest/activations/-/article/landslide-in-nep-2
[10]https://data.humdata.org/user/login?came_from=http%3A%2F%2Fdata.humdata.org%2Fdataset%2Funosat-damage-assessment-nepal-earth-quake
[11]http://nga.maps.arcgis.com/apps/PublicGallery/index.html?appid=33f0a2b77ebe45c0a31a4b9a7b8a6d96
[12]http://www.bgs.ac.uk/research/earthHazards/epom/Nepalearthquakeresponse.html

DEVELOP A COLLABORATION WITH THE GLOBAL EARTHQUAKE MODEL ON THE INCORPORATION OF INSAR DERIVED VELOCITIES IN THE GLOBAL STRAIN RATE MODEL

In 2015, Richard Walters was awarded ~£3K from Climate and Geohazard Services at the University of Leeds to support the development of closer links between COMET and the Global Earthquake Model, via the Global Strain Rate Model (GSRM) project. These funds were used to support a month-long research visit to work with Prof. Corne Kreemer, the scientific lead on GSRM, at the University of Nevada, Reno, on methods to integrate InSAR data into GSRM.

During this visit, we considered both incorporating InSAR line-of-sight velocity data into the existing GSRM strain-rate inversion, and also developed a new methodology to optimally combine both GPS and InSAR data into consistent velocity and strain-rate fields.

The current GSRM approach explicitly assumes a null vertical velocity field, and only solves for the 2D horizontal strain-rate tensor, which is problematic as InSAR data are sensitive to vertical motions. We decided that the best way to add constraint from InSAR into the current GSRM is to decompose InSAR line-of-sight velocities into horizontal and vertical components and then incorporate the horizontal velocities alone into GSRM.

However, since this approach is limited by the original design of GSRM to the production of 2D velocity fields, we have also started developing a new method of strain-rate inversion that fully exploits both the information on vertical velocities and the high spatial resolution inherent in InSAR datasets. Unlike existing approaches, this is based on Bayesian methods and can adapt to the varying spatial resolution and coverage of global GPS and InSAR datasets.

These two prototype methods are currently being developed further and tested with synthetic data, and will enable both the incorporation of InSAR data into the existing GSRM, as well as the production of new 'optimal' 3D crustal velocity fields that fully exploit InSAR data from Sentinel-1.

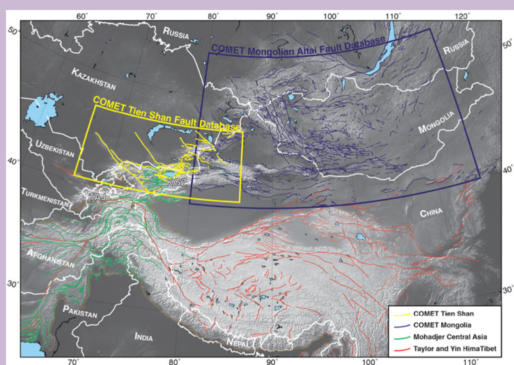
BEGIN TO BUILD A FORMAL COMET DATABASE OF ACTIVE FAULTING IN THE ALPINE-HIMALAYAN BELT, BEGINNING WITH CENTRAL ASIA

We have begun to structure and populate a database of active faults in Central Asia based on substantial recent work by COMET and LiCS researchers mapping and measuring these structures. The aims of this project are threefold:

1. Consolidate and disseminate the considerable previous research of these structures undertaken by COMET researchers and students as well as other groups.
2. Provide a unified source of information on fault locations, geometries, slip rates, and paleoseismic data throughout the region.
3. Construct a holistic view of deformation kinematics in the Tien Shan and north of the Tibetan Plateau—low strain-rate regions with widely distributed seismic hazard. We have shapefiles for active faults across Mongolia, Southern Kazakhstan, and Kyrgyzstan.

We have translated a few of these into detailed database entries with additional metadata, and are continuing to assemble this information. Entries include medium-scale fault geometries, dip, dip direction, sense of slip, slip rate, timing of slip, and any paleoseismic information.

Choices of attributes and decisions about the scale of mapping have been guided by the results of a three day workshop on fault rupture mapping, hosted by CNRS France (the French National Centre for Scientific Research) and attended by Austin Elliott and Richard Walker. The next phase of activity will involve continuing to populate the database attributes, including ascribing existing entries with names, segment divisions, and accuracy or quality ratings. The geographical scope of our database lies generally north of, and is complementary to, the **new database of Mohadjer et al., 2016[13].**

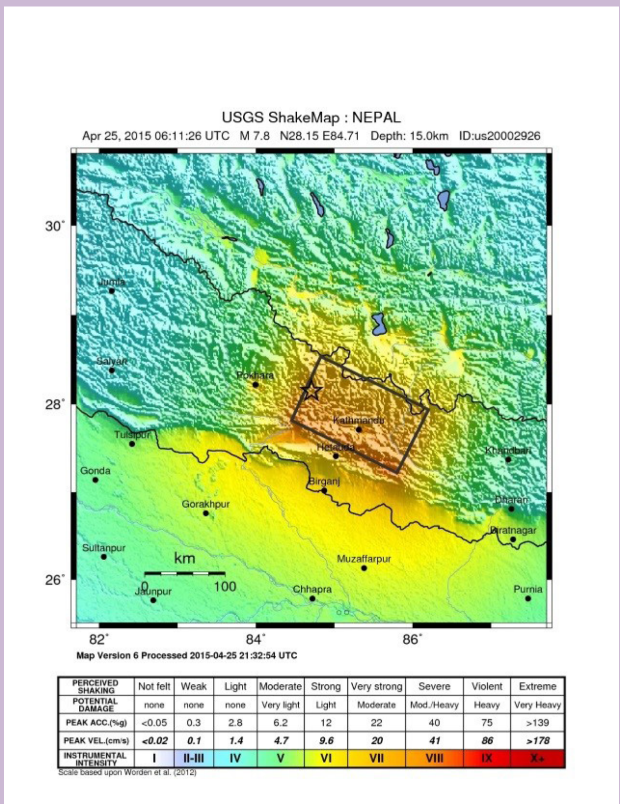


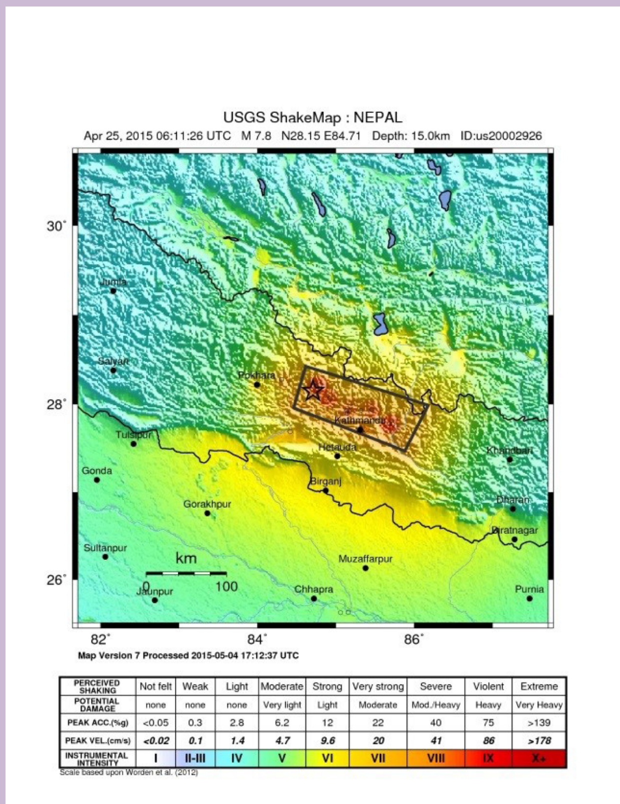
Regional fault mapping that forms the basis of the COMET fault database. A subset of the major faults have additional attributes including names, senses of motion, and geological slip rates. We are continuing to populate this information for the others, and our geographic scope complements that of the neighbouring regional fault databases depicted on the map.

[13] http://www.geo.uni-tuebingen.de/projekte/faults/index.php

WORK WITH THE USGS ON INCORPORATING COMET GEODETIC RESULTS FROM SENTINEL-1 IN THEIR RAPID SOURCE MODELLING AND 'SHAKEMAP' ESTIMATES OF STRONG MOTION

We have worked on an ad hoc basis with Gavin Hayes (USGS), Richard Briggs (USGS) and Bill Barnhart (Iowa) to incorporate geodetic observations made by COMET in rapid-response finite source models for several earthquakes, including the 2015 Gorkha (Nepal) and Illapel (Chile) earthquakes. For the Nepal earthquake, the inclusion of radar observations significantly changed the USGS's shakemap distribution, resulting in a higher prediction for shaking in Kathmandu.





USGS "ShakeMaps" for the 2015 Gorkha (Nepal) earthquake from seismology alone (version 6; left) and incorporating geodetic observations (version 7, right). The inclusion of geodetic data results in stronger shaking over a smaller area, and increased intensity in Kathmandu.

EMPLOY A PDRA AT UCL TO CONTINUE WORK ON JOINT GNSS-SEISMIC INSTRUMENTATION

Chris Atkins started as a Postdoctoral Research Assistant in August 2016. He will be working on the development/application of a new Global Navigation Satellite System (GNSS) Seismometer which will help us to measure the dynamic ground displacements caused by earthquakes. These displacements are essential to improving earthquake early warning and emergency response mechanisms.

EMPLOY A PDRA IN BRISTOL TO WORK ON VOLCANO INSAR

James Hickey started as a Postdoctoral Research Assistant in Volcano InSAR in October 2015. His work focuses on the monitoring of volcanic deformation, through the use of satellite InSAR. He is responsible for processing and analysing InSAR data for volcanic unrest and eruption across the globe, and combining satellite and ground-based observations to develop new monitoring strategies. He is also taking a lead role in developing the volcano deformation database above.

CONTINUE TO DEVELOP THE CONTENT AND STYLE OF THE COMET WEBSITE

The **COMET website**[14] is regularly updated with news stories and research highlights. Launched in March 2015, it has received more than 25,000 views to date with a peak of 3,000 in May 2015, coinciding with coverage of the Nepal earthquake.

A new COMET logo has also been developed which aims to represent all aspects of our work and provide an easily recognisable brand.

[14]http://comet.nerc.ac.uk

RESEARCH HIGHLIGHTS

OVER WHAT DISTANCES DO VOLCANOES INTERACT?

JULIET BIGGS

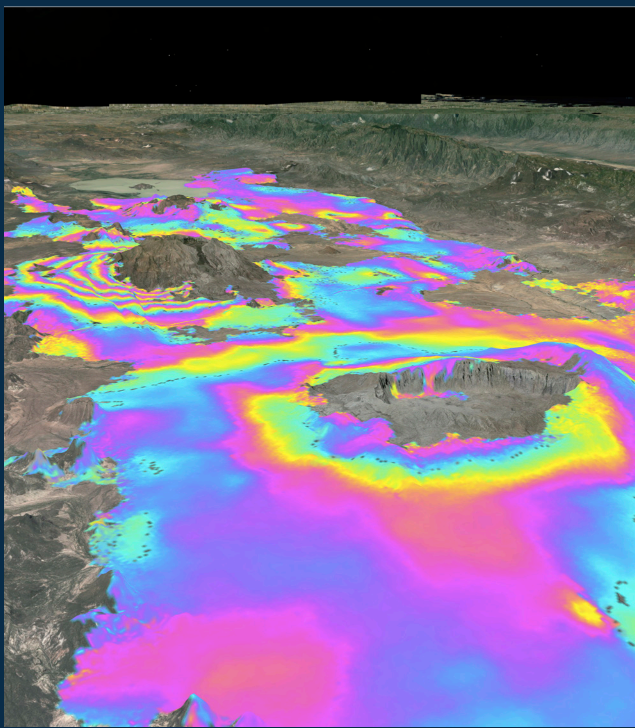
Juliet Biggs is a Reader in the School of Earth Sciences at the University of Bristol. Her research focuses on using InSAR to understand the physics of the processes that deform the Earth's surface.

Restless magmatic plumbing systems mapped using satellite imagery

In the geological past, large eruptions have often occurred simultaneously at nearby volcanoes. To investigate this, scientists from the University of Bristol used satellite imagery to study the distances over which restless magmatic plumbing systems interact. Using deformation maps from the Kenyan Rift, they monitored pressure changes in a sequence of small magma lenses beneath a single volcano. Importantly, these showed that active magma systems were not disturbed beneath neighbouring volcanoes less than 15 km away.

The satellite data showed that unrest in Kenya was restricted to an individual system. Inter-bedded ash layers at these same volcanoes, however, showed that they have erupted synchronously in the geological past. This led to a comparison of observations of lateral interactions based on recent geophysical measurements with those from petrological analyses of much older eruptions.

Observations from around the world were then compared with simple scaling laws based on potential interaction mechanisms. This showed that stress changes from very large eruptions could influence volcanoes over distances of up to 50 km, but that smaller pressure changes associated with unrest require a different mechanism to explain the interactions.



The results highlighted volcanology's current scientific revolution – the concept of a large vat of liquid magma beneath a volcano is being replaced by that of a crystalline mush that contains a network of melt or gas lenses. The interactions patterns observed in Kenya support this view, and help to constrain the geometry and location of individual melt and gas lenses.

Alongside COMET, this study was funded by RiftVolc which is investigating the past, present and future behaviour of volcanoes in the East African Rift.

Reference: Biggs, J., Robertson, E., Cashman, K. (2016) The lateral extent of volcanic interactions during unrest and eruption, Nature Geoscience doi:10.1038/ngeo2658

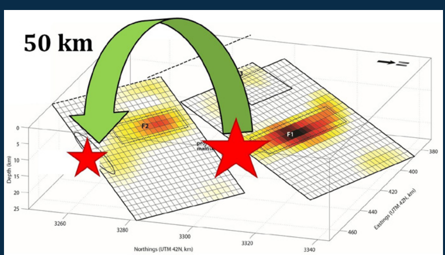
JUMPING EARTHQUAKES

JOHN ELLIOTT, BARRY PARSONS, TIM WRIGHT & TIM CRAIG

This work, involving COMET members John Elliott, Barry Parsons and Tim Wright, and COMET Associate Tim Craig, was part-funded by COMET, Earthquakes without Frontiers (EwF) and Looking Inside the Continents from Space (LiCS) projects.

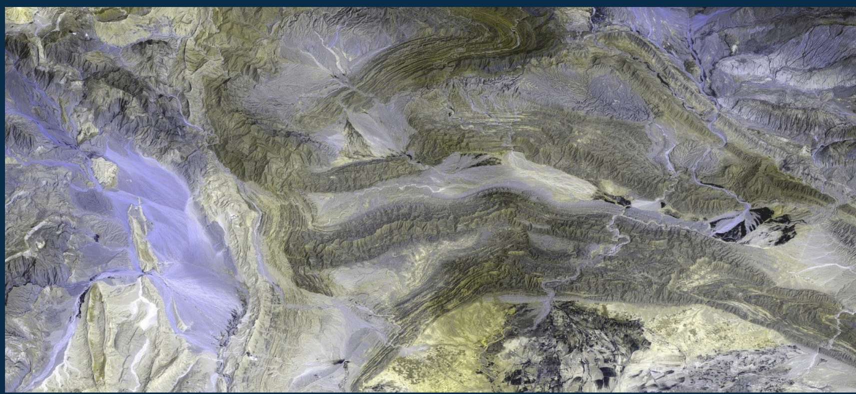
Limits to rupture forecasting exposed by instantaneously triggered earthquake doublet

An important question in understanding the potential magnitude of earthquakes, and consequently the hazard certain faults may pose, is the distance over which earthquakes can jump during rupture. This is because a critical observation of earthquake scaling which holds true is that the longer a fault rupture, the larger the earthquake. In a bigger earthquake, the ground shaking is more severe, it occurs over a wider area and lasts longer; exposing more buildings and people to a greater level of hazard.



The 50 km jump imaged between the two fault planes which ruptured in the 1997 Pakistan earth-quake. This leap between faults is 10 times larger than the previously though maximum.

The previous consensus on the control of the maximum likely leap in an earthquake was that an offset between faults of 5 km would probably be enough to stop a rupture - the gap being too much of a physical barrier for the earthquake to jump across. This limit of 5 km is used in some standard seismic hazard assessments.



Fold and thrust belt of the western Sulaiman mountains of Pakistan. Hidden beneath these folds is the pair of large fault planes that ruptured in the 1997 Harnai earthquake, jumping 50 km between segments. Image: Landsat 8 false colour image

However, an international team of researchers, including current and ex- members of COMET, have forensically unpicked from a seismic event that struck Pakistan in 1997, a pair of large earthquakes that had been previously catalogued as one. In a study publishedearlier this year in Nature Geoscience, they combine satellite observations with seismology, to show that this pair of earthquakes involved a massive jump of 50 km between fault segments during the rupture – this is 10 times larger than the current accepted rule that is used in assessing earthquake hazard.

This finding will fundamentally change the way in which earthquake hazard scenarios are run in regions of distributed faulting, because the network of faults which could potentially be triggered as the rupture proceeds would be greatly expanded. Therefore, not only is it crucial to determine the range of jumps feasible in earthquakes, such as in this study, it is also critical to establish the distribution of faults within the crust which could be potentially triggered. This will be no easy task, given that many faults, such as the pair involved here, are hidden underground and lack a clear surface expression to give away their presence. There are large regions of the world, some with huge cities, which have these buried faults beneath them - places such as Southern California, Iran and east China. The goal of identifying active faults is one of the major research avenues for COMET & LiCS.

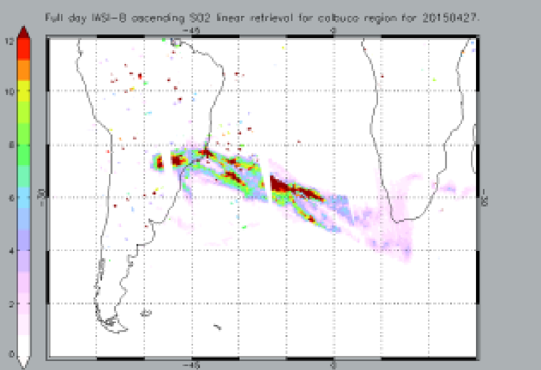
Reference: Nissen, E. K., Elliott, J.R., Sloan, R.A., Craig, T.J., Funning, G.J., Hutko, A., Parsons, B.E., Wright, T.J. (2016) Dynamic triggering of an earthquake doublet exposes limitations to rupture forecasting, Nature Geoscience doi:10.1038/NGEO2653

RESPONDING TO EVENTS

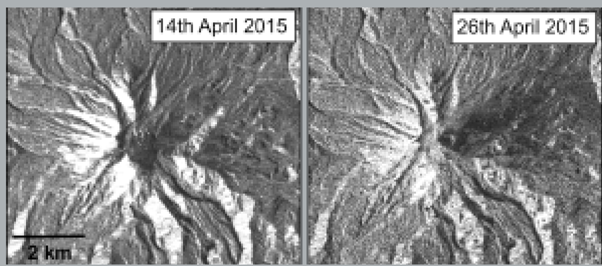
VOLCÁN CALBUCO (COMET LEADS - SUSI EBMEIER, DAVID PYLE, TAMSIN MATHER)

THIS WORK WAS FUNDED BY A NERC URGENCY GRANT

On 22 April 2015, an explosive eruption began at Calbuco volcano, Chile, 54 years after its last major eruption. This was the third largest explosive eruption in Southern Chile in the past decade, and resulted in the deposition of tephra over a wide area of southern Chile and Argentina. The eruption was preceded by only a few hours of seismicity and no evidence of pre-eruptive deformation was detected in the years or days before the eruption. The eruption of Calbuco provided an opportunity to examine the pre-eruptive conditions associated with rapid eruption onset as well as the impact of this type of explosive eruption that is not well represented in the geological record.



Sulphur dioxide retrieval (Dobson units) for 27th April 2015. Large volumes of SO2 were released during the eruption - first estimations are that the Calbuco eruption released 0.2 -0.4 million tonnes of SO2.



Radar backscatter images of Calbuco volcano on 14 and 26 April 2015. Differences between the two images are due to changes in the scattering and reflecting properties of the ground, caused by the deposition of explosive deposits and removal of material at the volcano's crater.

A NERC urgency grant awarded to David Pyle, Tamsin Mather, Karen Fontijn and Harriet Rawson (Oxford) allowed the collection and analysis of tephra samples from the eruption. These were then analysed in combination with InSAR measurements of co-eruptive subsidence (Bagnardi, Ebmeier & González) and satellite observations of ash and SO2 emission (Carboni, Hayer & Ventress). Both petrological and geological constraints place a magma reservoir in the mid-crust at 10-15 km. The relatively low ratio of erupted magma volume to modelled magma reservoir volume change suggests that magma was not volatile saturated – consistent with the lack of amphibole phenocrysts. However, the large amount of SO2 released during eruption demonstrates significant vesiculation and degassing during the ascent of magma. The 2015 Calbuco eruption is therefore likely to have been driven by internal processes, such as the gradual development of a volatile rich cap during the differentiation of magma not wholly water-saturated.

ONGOING WORK AT SOUFRIÈRE HILLS VOLCANO, MONTSERRAT (COMET LEAD - LOCKO NEUBERG)

Locko Neuberg also continues to chair the Scientific Advisory Committee (SAC) for Montserrat, providing advice on a strategic level to the Foreign and Commonwealth Office and the Government of Montserrat regarding the ongoing eruption of Soufrière Hills Volcano. The SAC's advice is used in the compilation of risk maps, designation of evacuation zones and access regulations for agriculture, tourism and commerce. Importantly, this work relies on the Montserrat Volcano Observatory who monitor unrest, activity and hazards at Soufrière Hills and use this data to advise both the SAC and the Government of Montserrat; and the Seismic Research Centre who run the Observatory.

MOUNT ETNA (COMET LEADS - ELISA CARBONI, DON GRAINGER)

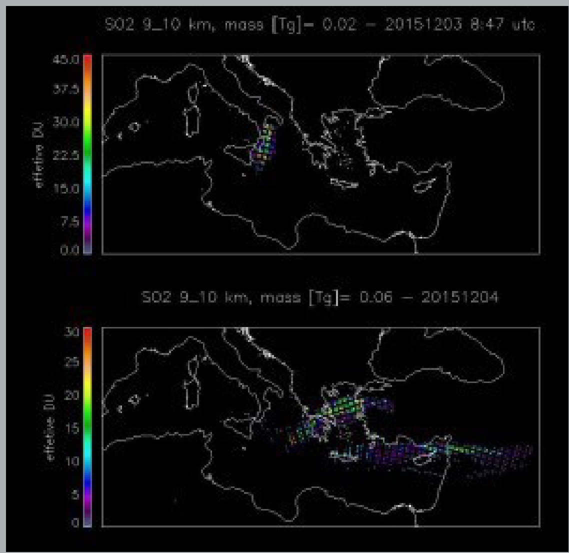
On the evening of 2 December 2015, meanwhile, Sicily's Mount Etna began to erupt for the first time in over two years, reaching a brief but violent climax in the early hours of 3 December which included lava fountains as well as a column of gas and ash several kilometres high. The event was among the most violent seen at Etna over the last twenty years.

Luckily, good weather meant that the eruption could be monitored with visual and thermal cameras. According to reports, activity peaked between 02:20 and 03:10 GMT when a continuous lava fountain reached heights well over 1 km, with some jets of volcanic material reaching 3 km into the sky. Although the eruption had more or less ceased by dawn, the volcanic cloud had blown northeast, causing ash to be deposited on the nearby towns of Taormina, Milazzo, Messina and Reggio Calabria.

COMET scientists tracked the volcanic plume's progress using data from the Infrared Atmospheric Sounding Instruments (IASI) on board ESA's MetOp-A and MetOp-B satellite platforms. These instruments can detect the presence of volcanic SO2 in the atmosphere. The results, which were displayed on the **IASI NRT web page**[15], showed that by Friday 4 December the plume had reached an area between Crete and Iraq, containing 0.06 Tg (1012g) SO2.

By the morning of 7 December, the plume had travelled from Sicily to Asia, reaching as far as Japan and the Pacific Ocean. This is an excellent example of how we can track volcanic plumes using the near real time IASI service.

Ash cloud from Mount Etna's Voragine crater lights up the sky.
Credit: Marco Restivo/Demotix/Corbis



Estimate of SO2 amount from IASI-A overpass on the morning of 3 and 4 December 2015, assuming the SO2 between 9 and 10 km altitude.

[15]http://www.nrt-atmos.cems.rl.ac.uk/

PUBLICATIONS

COMET HAS A STRONG PUBLICATION RECORD. SINCE JANUARY 2014, WE HAVE PUBLISHED 110 ARTICLES IN SCIENTIFIC JOURNALS. 27% OF THESE WERE IN THE TOP 10% OF ARTICLES CITED WORLDWIDE, WITH 80% BEING THE RESULT OF INTERNATIONAL COLLABORATIONS.

We published 59 articles between 1 January and 31 December 2015 (see Annex 1 - 2014 articles are covered in our previous report).

Some of the main scientific advances from last year are described below.

Work involving **Alex Copley** and **John Elliott** helped to unravel a complex seismic sequence using a combination of techniques, explaining not only the August 2014 Murmuri (Iran) earthquake sequence but also the formation of the Zagros mountain range where it occurred[16].

Pablo González and colleagues were the first scientists to use ESA's Sentinel-1A satellite in its new standard radar acquisition mode, Terrain Observation by Progressive Scans (TOPS) for geophysics on the investigated 2014-15 eruption at Fogo, the most active volcano in the Cape Verde archipelago[17].

Alex Copley and COMET alumnus **Roman Jolivet** used multidisciplinary techniques to provide new insights into the material properties of active faults (p.12). They found that there was a very non-linear relationship between the forces imposed on a creeping fault and the rate that it slips, which has important implications for hazard assessment[18].

John Elliott led work to establish the effects of the 2015 Gorkha (Nepal) earthquake (p.13). The research, which also involved **Romain Jolivet, Pablo González**, and COMET Associate **Jean-Philippe Avouac**, showed that an area around Kathmandu of 120 km by 50 km lifted up by at least 1 m, whereas ground further north subsided as a result of the event[19].

COMET Associate **Anja Schmidt**, working with COMET scientists **Elisa Carboni**, **Roy Grainger** and **Tamsin Mather**, studied the 2014 Bárðarbunga eruption in Iceland. They showed how the volcano emitted three times as much of a toxic gas as all European industry combined[20].

Shuttle image of the Zagros Mountains, Iran. Credit: NASA

John Elliott, **Alastair Sloan**, **Barry Parsons** and **Tim Wright**, alongside COMET Associate **Tim Craig**, contributed to research establishing the distance over which earthquakes can jump during rupture (p.23). This work is highly relevant to the many regions of the world that have large faults buried beneath them, especially those with huge cities such as Iran, Eastern China and Southern California[21].

Tamsin Mather, **David Pyle** and **Roy Grainger** investigated the complex refractive index of volcanic ash at 450.0 nm, 546.7 nm and 650.0 nm from eruptions in Japan, Iceland, Chile, Italy, New Zealand, Greece and Alaska, using remote sensing techniques to monitor volcanic clouds and return information on their properties. This is extremely important to the aviation industry, civil defence organisations and those in peril from volcanic ash fall[22].

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[16]Copley, A., Karasozen, E., Oveisi, B., Elliott, J.R., Samsonov, S., Nissen, E. (2015) Seismogenic faulting of the sedimentary sequence and laterally-variable material properties in the Zagros Mountains (Iran) revealed by the August 2014 Murmuri (E. Dehloran) earthquake sequence, Geophysical Journal International doi: 10.1093/gji/ggv365

[17]Gonzalez, P., Bagnardi, M., Hooper, A.J., Larsen, Y., Marinkovich, P., Samsonov, S.V., Wright, T.J. (2015) The 2014- 2015 eruption of Fogo volcano: Geodetic modeling of Sentinel-1 TOPS interferometry, Geophysical Research Letters doi:10.1002/2015GL066003

[18]Copley, A.,Jolivet R. (2016), Fault rheology in an aseismic fold-thrust belt (Shahdad, eastern Iran), Journal of Geophysical Research: Solid Earth doi:10.1002/2015JB012431

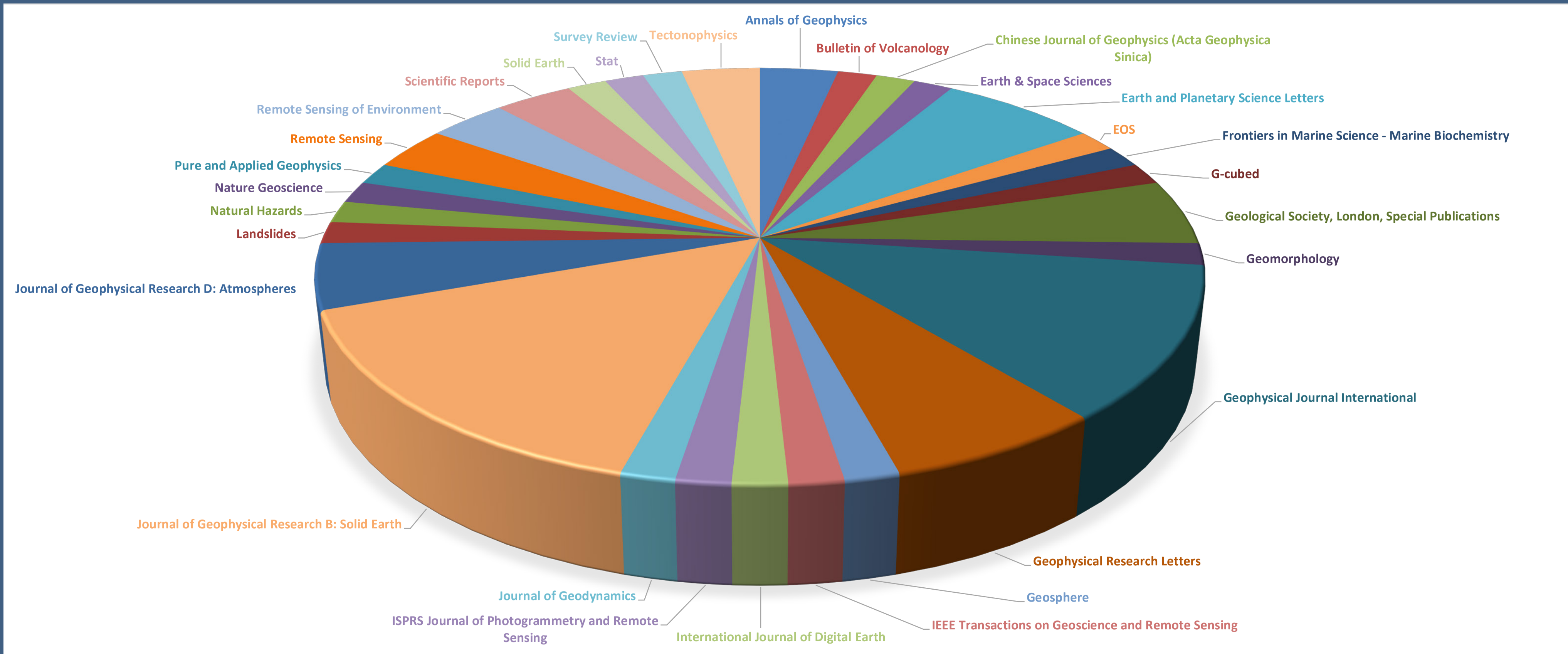
[19]Elliott, J. R., Jolivet, R., González, P., Avouac, J.P., Hollingsworth, J., Searle, M., Stevens, V. (2016) Himalayan Megathrust Geometry and Relation to Topography Revealed by the Gorkha Earthquake, Nature Geoscience doi:10.1038/NGEO2623

[20]Schmidt, A., Leadbetter, S., Theys, N., Carboni, E., Witham, C.S., Stevenson, J.A., Birch, C.E., Thordarson, T., Turnock, S., Barsotti, S., Delaney, L., Feng, W., Grainger, R.G., Hort, M.C., Höskuldsson, Á., Ialongo, I., Ilyinskaya, E., Jóhannsson, T., Kenny, P., Mather, T.A., Richards, N.A.D., Shepherd, J. (2015) Satellite detection, long-range transport, and air quality impacts of volcanic sulfur dioxide from the 2014-2015 flood lava eruption at Bárðarbunga (Iceland), Journal of Geophysical Research: Atmospheres doi:10.1002/2015JD023638

[21]Nissen, E. K., Elliott, J.R., Sloan, R.A., Craig, T.J., Funning, G.J., Hutko, A., Parsons, B.E., Wright, T.J. (2016) Dynamic triggering of an earthquake doublet exposes limitations to rupture forecasting, Nature Geoscience doi:10.1038/NGEO2653

[22]Ball, J.C.G., Reed, B.E., Grainger, R.G., Peters, D.M., Mather, T.A., Pyle, D.M. (2015) Measurements of the complex refractive index of volcanic ash at 450, 546.7, and 650 nm, Journal of Geophysical Research doi:10.1002/2015JD023521

SPREAD OF JOURNALS IN WHICH COMET PUBLISHED ITS 59 PAPERS IN 2015



FUNDING SUCCESSES

THE LONG-TERM FUNDING THAT COMET RECEIVES FROM NERC UNDERPINS A MUCH BROADER SPECTRUM OF RESEARCH ACTIVITIES FUNDED THROUGH OTHER SOURCES. MAJOR COLLABORATIONS ARE DESCRIBED IN THE NEXT SECTION, BUT IN 2015 COMET SCIENTISTS WERE SUCCESSFUL IN WINNING A NUMBER OF OTHER AWARDS:

NERC IRNHIC GRANT: ACTIVE TECTONICS AND SEISMIC HAZARD ASSESSMENT IN SHAANXI, GANSU, AND NINGXIA PROVINCES, CHINA (PHILIP ENGLAND)
Value: £501K
Duration: January 2016 - January 2019

NERC IRNHIC GRANT: PAN-PARTICIPATORY ASSESSMENT AND GOVERNANCE OF EARTHQUAKE RISKS IN THE ORDOS AREA (PAGER-O) (PHILIP ENGLAND)
Value: £501k
Duration: January 2016 - January 2019

NERC URGENCY GRANT: IMPACTS OF THE CALBUCO ERUPTION, CHILE (DAVID PYLE)
Value:£51K
Duration: July 2015 - March 2016

ESA LIVING PLANET FELLOWSHIP (SUSI EBMEIER)
Value: €86K
Duration: April 2015 - March 2017

KAUST COMPETITIVE RESEARCH GRANT CALL [KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY] (PAOLA CRIPPA)
Value: US$436k
Duration: April 2016 - April 2019

L'ORÉAL-UNESCO UK AND IRELAND FELLOWSHIP FOR WOMEN IN SCIENCE (PAOLA CRIPPA)
Value: £15k
Duration: August 2015 - August 2016

INCREASING RESILIENCE TO NATURAL HAZARDS IN EARTHQUAKE-PRONE REGIONS IN CHINA (IRNHIC) [NERC, ESRC AND THE NATIONAL NATURAL SCIENCE FOUNDATION OF CHINA] (ZHENHONG LI)
Value: £123k
Duration: January 2016 - January 2019

LEVERHULME RESEARCH FELLOWSHIP: HOW DO GASES DRIVE VOLCANISM (ANDREW MCGONIGLE)
Value: £43k
Duration: July 2016 - Sep 2017

EXPLORING THE POTENTIAL FOR PRECISION NUTRIENT MANAGEMENT IN CHINA [STFC NEWTON AGRI-TECH FUND] (ZHENHONG LI)
Value: £375k
Duration: April 2015 - March 2016

ROYAL SOCIETY RESEARCH GRANT: MEASURING VOLCANIC POLLUTION USING SMARTPHONES - PROOF OF CONCEPT AND CITIZEN SCIENCE (EVGENIA ILYINSKAYA/ANJA SCHMIDT)
Value: £10k
Duration: April 2016 - March 2017

DETECTING GEOHAZARDS WITH GPS

MAREK ZIEBART & CHRIS ATKINS

Marek Ziebart is Professor of Space Geodesy at UCL. His work focuses on using satellites in orbit around planets to measure dynamic characteristics including plate tectonics. Chris Atkins is a COMET researcher (and PhD student at the time of the research), also based at UCL. He is working on a new Global Navigation Satellite System (GNSS) Seismometer which will help us to measure dynamic ground displacements caused by earthquakes.

Using sidereal filtering to detect geohazards in near real time

Geodetic quality GPS data – high precision range measurements made between orbiting spacecraft and tracking stations, often rigidly attached to bedrock – are a key parameter in analysing the earthquake cycle. These tracking stations often make measurements at 1 Hz or higher, enabling us to calculate high rate position time-series and revealing various kinds of motion related to seismic waves and other forms of deformation.

Earthquakes often cause a change in ground shape that is retained after the earthquake is over, and which can be determined from a time-series. This in turn can be used to estimate the size of the earthquake, how much energy was released and the epicentre location.

Figure 2 below shows an estimate of the GPS antenna movement in a north-south direction during the 2011 magnitude 9.0 Tohoku earthquake over a period of 25 minutes, calculated by a standard processing method called PPP (precise point positioning). Seismometers can provide similar information, but one drawback is that they can 'clip' when the seismic waves become too large. A GPS antenna, on the other hand, has no such limitations. Because of this, GPS antennas are sometimes called broadband GPS seismometers.

In practice, we combine information from both GPS antennas and seismometers, with thousands of GPS antennas installed around the world, connected to the internet and taking measurements 24 hours a day.

Fig. 1 - Deep braced GNSS tracking antenna at the Aleutian Islands, Cape Sarichef, Alaska (AV24-WestdahlNWAK2008). Photo: UNAVCO.org

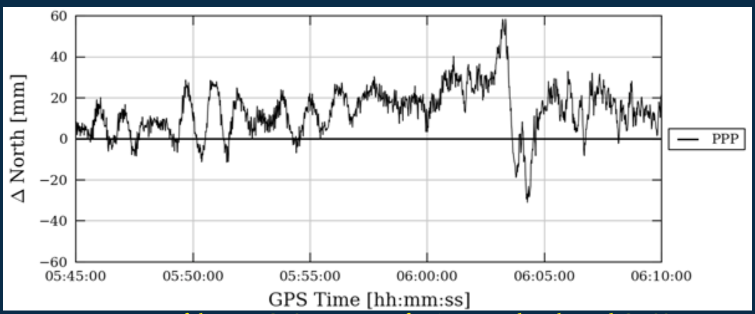


Fig. 2 - 25 minutes of the 1Hz GPS time series for AV24 - a deep braced GNSS antenna on the Aleutian Islands, Cape Sarichef, Unimak Island, Alaska at the time of the 2011 Tohoku earthquake (WestdahlNWAK2008).

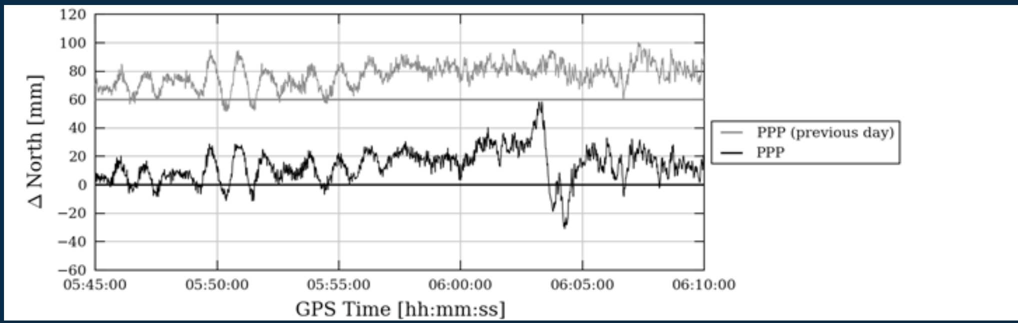


Fig. 3 - The GPS time series (North-South component) for station AV24 on the day of the earthquake and on the day before. The time series on the vertical axis are offset by 60mm for clarity.

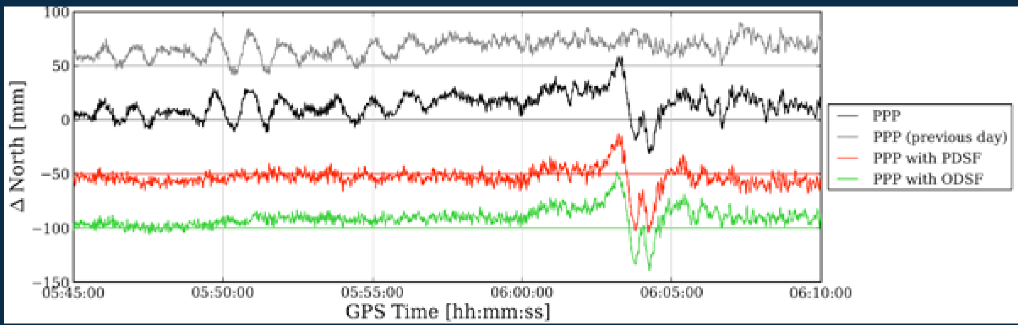


Fig. 4 - The same GPS time series for station AV24, but with the time series resulting from the two types of sidereal filter also shown. The time series on the vertical axis are offset by 50mm for clarity.

However, one problem with the GPS data is multipath. This is like radio interference, where the signals transmitted by satellites have more than one way of getting to the antenna. The strongest direct signal is distorted by those bouncing off adjacent reflecting surfaces, causing spurious patterns of motion in the receiver time-series. These can vary rapidly over a few seconds in a noise-like way (with amplitudes of a few mm), or they can be a slowly varying position error (with changes of a few cm). Both of these effects limit our ability to use GPS data for seismometry.

Figure 3 again shows the day of the Tohoku earthquake (black time-series) and the arrival of the largest seismic waves at around 6:03:00. A similar signature is also visible around 5:50:00. However, that same signature (an apparent ground movement of some 25 mm over a few minutes, shaking and then reducing in magnitude) is visible at almost the same time on the previous day (grey time-series).

It doesn't mean the earthquake was repeating – these are multipath distortions, indistinguishable from seismic waves. Our problem, then, is how to remove the spurious data whilst retaining the earthquake's actual signature.

Sidereal filtering is a technique used to reduce errors caused by multipath. It relies on the receiver remaining static from one day to the next relative to the surrounding environment, and takes advantage of the ground track repeat time of GPS satellites, which is just less than a sidereal day (usually around 23 hours, 55 minutes, 55 seconds). The repeating multipath error can thus be identified and largely removed from the following day.

A conventional position-domain sidereal filter (PDSF) identifies and removes this repeating pattern from a position time-series. However, the ground track repeat time of individual GPS satellites can differ from each other by a few seconds, whereas a

PDSF has to assume that all satellites have the same repeat time. This can cause problems for the PDSF, especially when the frequency of the oscillations caused by multipath interference is high.

To account for this we have developed an observation-domain sidereal filter (ODSF) that identifies and removes multipath errors from the GPS phase measurements. Unlike the PDSF, it can account for small differences in the ground track repeat times of the GPS satellites. This makes it more effective at removing the effects of high-frequency multipath error and less sensitive to satellite outages.

For each phase measurement, the ODSF algorithm searches for an appropriate correction based on the azimuth and elevation of the relevant satellite. That correction is derived from the measurement residuals on the previous day that most closely correspond to that azimuth and elevation. The precision of these measures of azimuth and elevation needs to be high – a hundredth of a degree or better.

Figure 4 shows the same 25-minute time-series after applying the PDSF and ODSF sidereal filters.
Both the PDSF and the ODSF are largely successful at removing these oscillating errors. They reveal a surface wave arrival time of about 06:00:00 with the largest Love waves arriving at around 06:03:00, easily distinguishable from the original unfiltered time-series.

Figure 5 shows 1 Hz displacements at station AV27 which is only 11 km from AV24, where a very similar displacement signal might be expected.
The standard PPP time-series (black and grey) are clearly severely affected by strong short-period (~11 s) multipath error. In this case, the PDSF was unable to remove such a high-frequency error and instead increased the amplitude of these oscillations, whereas the ODSF was far more effective as it could take into account the differing repeat times of the satellites.

Overall, while the precision of GPS technology has improved dramatically, data processing and interpretation must still be handled carefully. Multipath effects on position time-series can introduce spurious signatures that resemble seismic events, but sidereal filtering offers a very effective way to clean up GPS positioning time-series to reveal geophysical events clearly in near-real time.

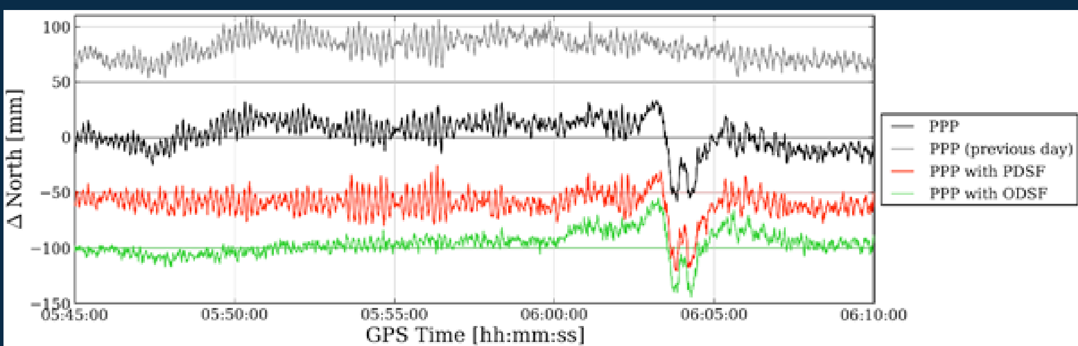


Fig. 5 - GPS time series for station AV27 including those resulting from the two types of sidereal filter. The time series on the vertical axis are offset by 50mm for clarity.

COLLABORATIONS & PARTNERSHIPS

COMET CONTINUES TO STRENGTHEN ITS SCIENTIFIC COLLABORATIONS AND LINKS WITHIN THE UK AND OVERSEAS. SINCE APRIL 2014, WE HAVE BEEN WORKING IN PARTNERSHIP WITH THE BRITISH GEOLOGICAL SURVEY (BGS) TO DELIVER CUTTING-EDGE RESEARCH ON EARTHQUAKES AND VOLCANOES AS WELL AS HAZARD MONITORING SERVICES.WE ALSO WORK CLOSELY WITH THE NATURAL ENVIRONMENT RESEARCH COUNCIL (NERC), NATIONAL CENTRE FOR EARTH OBSERVATION (NCEO) AND EUROPEAN SPACE AGENCY (ESA), AS WELL AS MANY OTHER NATIONAL AND INTERNATIONAL PARTNERS.

OUR PARTNERSHIP WITH THE BGS INCLUDES FUNDING JOINT STUDENTSHIPS ON TOPICS SUCH AS MONITORING VOLCANIC PROCESSES USING INSAR, FORECASTING EARTHQUAKE SEQUENCES, AND INVESTIGATING LANDSLIDES USING SATELLITE AND GROUND-BASED RADAR.
OUR STAFF ALSO WORK ON A RANGE OF PROJECTS WITH NATIONAL AND INTERNATIONAL PARTNERS WHICH ENHANCE OUR SCIENCE PROGRAMME NOT ONLY THROUGH THE ADDITIONAL FUNDING BUT ALSO DATA, IDEAS AND, MOST IMPORTANTLY, PEOPLE:

EARTHQUAKES WITHOUT FRONTIERS (EWF)[23]

EWF is an international partnership bringing together Earth scientists, social scientists working on community vulnerability in disaster-prone regions, and experts in communicating scientific knowledge to policy makers. It aims to increase knowledge of earthquake hazards in affected regions and improve resilience.

The EwF team was closely involved in the scientific response to the 2015 Nepal earthquake and is continuing to investigate the mechanisms behind the event. The team has also been working with colleagues in Nepal with a view to improving resilience to future earthquakes, not just in Nepal and neighbouring countries, but also for earthquake-prone nations across the globe.

Other research areas include the Suusamyr Valley in Kyrgyzstan, where a 1992 earthquake left more than 70 people dead. The EwF team has produced high-resolution digital elevation models (DEMs) of the entire valley, analysed the available satellite data, mapped surface ruptures and measured offsets with differential GPS. Using a drone, thousands of aerial photos were also collected and will be used to compute a DEM using the structure-from-motion technique.
The most recent investigations have been into the Tien Shan in Central Asia, one of the largest mountain belts on Earth, where deformation due to the collision of India with Eurasia is leading to some of the strongest known intracontinental earthquakes. Fieldwork in Kazakhstan has meanwhile focused on the M8.3 1889 Chilik earthquake and the Dzhungarian Fault which reaches hundreds of kilometres from Eastern Kazakhstan into China.

[23]http://ewf.nerc.ac.uk/

FUTUREVOLC[24]

FutureVolc, led by the University of Iceland and Icelandic Meteorological Office, is a long-term monitoring experiment looking at geologically active regions of Europe that are prone to natural hazards. It is developing the "supersite" concept, integrating space- and ground-based observations to improve monitoring and evaluation of volcanic hazards.

Outcomes have included the development of a **web-portal**[25] for Icelandic volcanoes, where scientific users can access data and operational users, such as airliners and civil protection agencies, can find the information they need for decision-making processes.

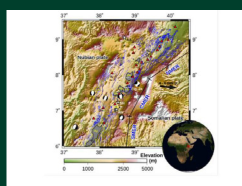
Monitoring has meanwhile been improved by the installation of new seismic and GPS stations, including around Bárðarbunga where they played a major role in analysing dyke intrusion and the subsidence of the caldera, and modelling magma migration and volume change. Other developments have included new software which helped to map the progress of magma during the Bárðarbunga rifting event, and an automatic processing algorithm for InSAR which allowed the mapping of deformation associated with the rifting event in near real time.

FutureVolc as an EC sponsored project ended in March 2016, although the collaboration between COMET and the FuturevVolc partners continues.

LOOKING INSIDE THE CONTINENTS FROM SPACE (LICS)

Looking inside the Continents from Space (LiCS) is a NERC large grant that is using data from the Sentinel-1 constellation to revolutionise our knowledge of how continents deform, how strain accumulates during the earthquake cycle, and how seismic hazard is distributed. The team consists largely of COMET scientists and aims to combine satellite data with ground-based observations to map tectonic strain at high spatial resolution throughout the Alpine-Himalayan Belt and East African Rift, and to use the results to inform new models of seismic hazard. The project has potential to deliver widespread benefits in many sectors, from geospatial services and government policy to the insurance/re-insurance industry and meteorological offices.
To date, the primary focus has been on developing the automatic Sentinel-1 processing system, and on the collection of new field and satellite observations of active faulting in Central Asia. Both of these have been conducted in close step with COMET, with much of the work carried out by project scientists jointly funded by COMET and LiCS. The next year will see the publication of the first country-scale InSAR deformation maps from Sentinel-1.

RIFTVOLC[26]



RiftVolc, 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. The research will help to develop new methods to assess and forecast volcanic hazards from high risk central volcanoes, active rift segments and volcanic fields.

Fieldwork in the Main Ethiopian Rift Valley is well underway and has included dynamic microgravity surveys, allowing investigations of the mass change beneath the volcanoes, and also the servicing of several GPS stations.

RiftVolc scientists from the University of Bristol have also used satellite imagery to investigate the distances over which restless magmatic plumbing systems interact, using deformation maps from the Kenyan Rift to monitor pressure changes in a sequence of small magma lenses beneath a single volcano.

[24]http://futurevolc.hi.is/

[25]http://futurevolc.vedur.is/

[26]https://riftvolc.wordpress.com/

SPECTRALLY HIGH RESOLUTION INFRARED MEASUREMENTS FOR THE CHARACTERISATION OF VOLCANIC ASH (SHIVA)[27]

SHIVA is studying the properties of volcanic ash using ground- and space-based high resolution infrared spectrometer measurements. The project will look at changes in ash composition during an eruption in order to better understand volcanic processes, particularly shedding light on processes of magma ascent and fragmentation in volcanic eruptions.

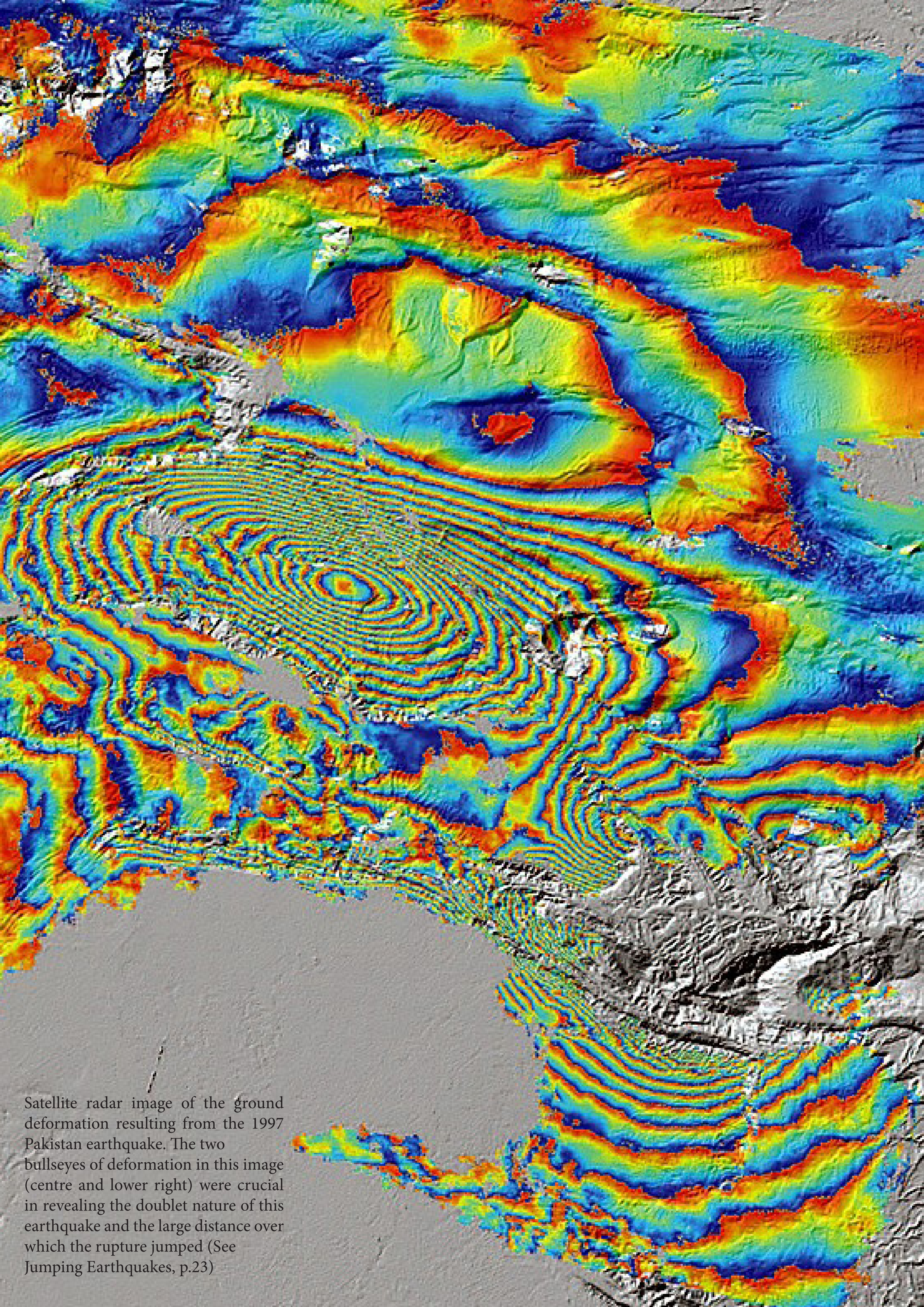
Monserrat. Credit:: BGS

STRENGTHENING RESILIENCE IN VOLCANIC AREAS (STREVA)[28]

STREVA is an innovative interdisciplinary project aiming to develop and apply 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. Led by the University of East Anglia, the project brings together researchers from universities and research institutes from across the UK with those from areas affected directly by volcanic activity. Work to date has mainly involved investigating past case studies and primary data gathering, sharing this information with partners, and looking at developing new ways of analysing and ultimately managing risk. Future work will focus on Tungurahua volcano, Ecuador, where there is a very good opportunity for further strengthening collaborations between geodesy, seismology and modelling on different timescales.

[27] https://volcano.atm.ox.ac.uk/index.php/SHIVA

[28] http://streva.ac.uk/



Satellite radar image of the ground deformation resulting from the 1997 Pakistan earthquake. The two bullseyes of deformation in this image (centre and lower right) were crucial in revealing the doublet nature of this earthquake and the large distance over which the rupture jumped (See Jumping Earthquakes, p.23)

RESEARCH HIGHLIGHTS

EARTHQUAKE TRIGGERS DANGEROUS LANDSLIDES IN THE PAMIRS

AUSTIN ELLIOTT

Austin Elliott is a postdoctoral scientist at the University of Oxford. He works on measuring topographic change due to historical, prehistoric, and contemporary earthquakes using high resolution topography, and is co-funded by COMET and the Looking inside the Continents from Space (LiCS) project.

Satellite stereo-imagery captures 3d displacements from an earthquake and its effects

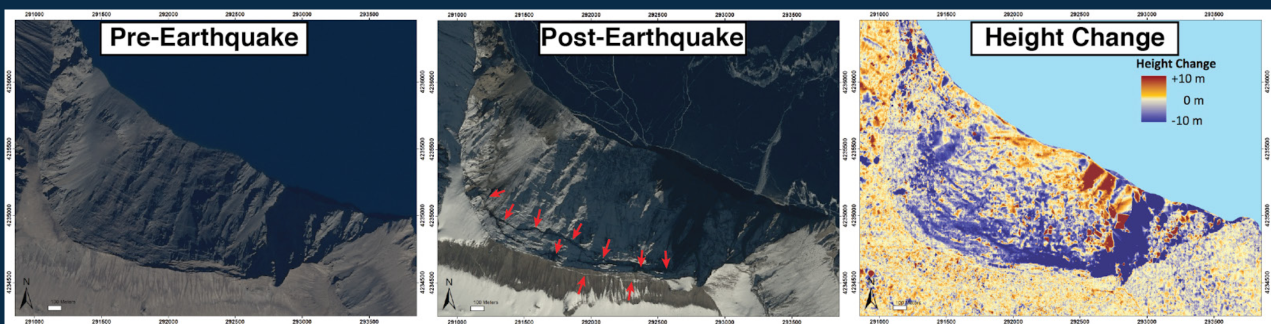
Elevation data derived from high resolution satellite imagery reveals ground deformation in remote and rugged landscapes that are difficult to access by foot and costly to survey by other methods like lidar. Austin's work used pre-and post-event stereo-imagery to measure the displacement and landslides caused by a MW7.2 earthquake that struck the high Pamir Mountains of Tajikistan on 7 December, 2015.

The earthquake struck near Sarez Lake, a massive body of water threateningly dammed behind a quake-triggered landslide in 1911. Potential overtopping of this natural dam represents a profound risk to the Tajik and Afghan populations downstream along the Murghob/Bartang River. Immediately after the earthquake, the COMET team ordered an acquisition of tri-stereo 1.5-m SPOT (Satellite for the Observation of the Earth) imagery covering the source fault, which were used to construct DEMs. Existing tri-stereo imagery from earlier in the year provided a pre-earthquake reference from which to measure topographic shifts caused during the earthquake.

Calculating the differences between these DEMs revealed that the earthquake broke along a seismic gap in the major Karakul-Sarez Fault between parts of the fault that have ruptured more recently. The maps of height change also revealed numerous large avalanches around the fault break and allowed their volumes to be quantified.

Importantly, landslides into Sarez Lake during the 2015 earthquake did not generate a dam-overtopping seiche, sparing downstream populations from a cascading catastrophe.

This measurement of the earthquake and the relatively modest landslides it caused show that Sarez Lake remained stable during a possible worst-case-scenario of rupture on the nearest portion of the Karakul-Sarez fault—promising news for local risk assessment.



MAGMA ACCUMULATING FASTER THAN ERUPTION AT AIRA CALDERA

JAMES HICKEY

James Hickey is a postdoctoral scientist at the University of Bristol. He works on observing and modelling volcanic deformation using satellite and ground-based methods, and is co-funded by COMET and the STREVA (STRENGTHENING RESILIENCE IN VOLCANIC AREAS) consortium.

Continued inflation and intrusion indicate extensive magma accumulation despite ongoing eruptive activity

The Aira caldera system is home to Japan's most active volcano – Sakurajima – and has a rich volcanic history dating back millions of years. Understanding its evolution is essential to facilitate eruption forecasting, and reduce the risk posed to over 600,000 people in the adjacent city of Kagoshima.

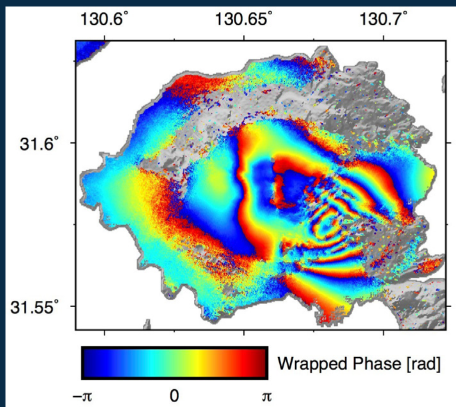
Sakurajima has daily Vulcanian-style eruptions with a propensity for spectacular displays of volcanic lightning. Its past is also littered with larger events, including a Plinian eruption in 1914 that killed 58 people and connected the volcano to the mainland with extensive lava flows.

A photograph of a typical eruption of Sakurajima, taken in July 2013. Small-scale pyroclastic flows descend the flanks. Credit: James Hickey

The 1914 eruption was also important for scientific endeavours – it was one of the world's first measurements of co-eruptive deformation. Levelling surveys dating back to 1892 indicated that over a metre of subsidence accompanied the event. This levelling time-series now highlights how the present day inflation is approaching the level inferred prior to the big 1914 eruption. Continuous and campaign GPS and satellite InSAR have also been used to monitor the ongoing uplift, and provide improved spatial and temporal coverage of the deformation pattern. The data delineate an axi-symmetric area of inflation extending wider than the caldera limits.

Analysis of the spatial deformation pattern and temporal inflation rate using numerical models indicates that the source of the uplift is a large, deep magma reservoir beneath the caldera. Magma is likely supplied in batches through incremental addition of horizontal planar bodies, or sills.

Given the continued activity at Sakurajima, these results indicate that magma is amassing faster than it can be



Sentinel-1 TOPS interferogram showing the deformation associated with the intrusion of a vertical planar body of magma, or dyke, in August 2015. Each colour cycle represents 2.8 cm of ground motion in the satellite line-of-sight, with the maximum deformation on the eastern side of the intrusion reaching ~14 cm

erupted. Comparisons of magma eruption and supply rates highlight a ~130 year timeframe to re-accumulate enough magma for another 1914-sized eruption (~ 2044).

Interestingly, the lava of the 1914 eruption was emitted from the flanks, rather than a summit vent. The same location experienced a shallow magma intrusion in the summer of 2015, which accompanied an escalation in volcanic unrest and prompted a dramatic increase in the alert level. Fortunately the intrusion stalled before reaching the surface. Continued monitoring will determine whether this was a lucky escape or the start of a build-up to a larger eruption.

SHARING OUR SCIENCE

COMET IS VERY ACTIVE WITHIN THE SCIENTIFIC COMMUNITY, WITH STRONG REPRESENTATION AT SOME OF THE MOST PRESTIGIOUS INTERNATIONAL EARTH SCIENCE EVENTS.

COMET members gave a total of 16 presentations at the December 2015 American Geophysical Union (AGU) Fall Meeting - the world's largest Earth and space science conference. A further 8 talks included work involving COMET researchers. Presenting our work at the AGU was an opportunity to showcase COMET's achievements to the entire Earth science community prior to publication. This attracted interest not only from Earth Observation scientists but also those working in the broader fields of volcanology and tectonics.

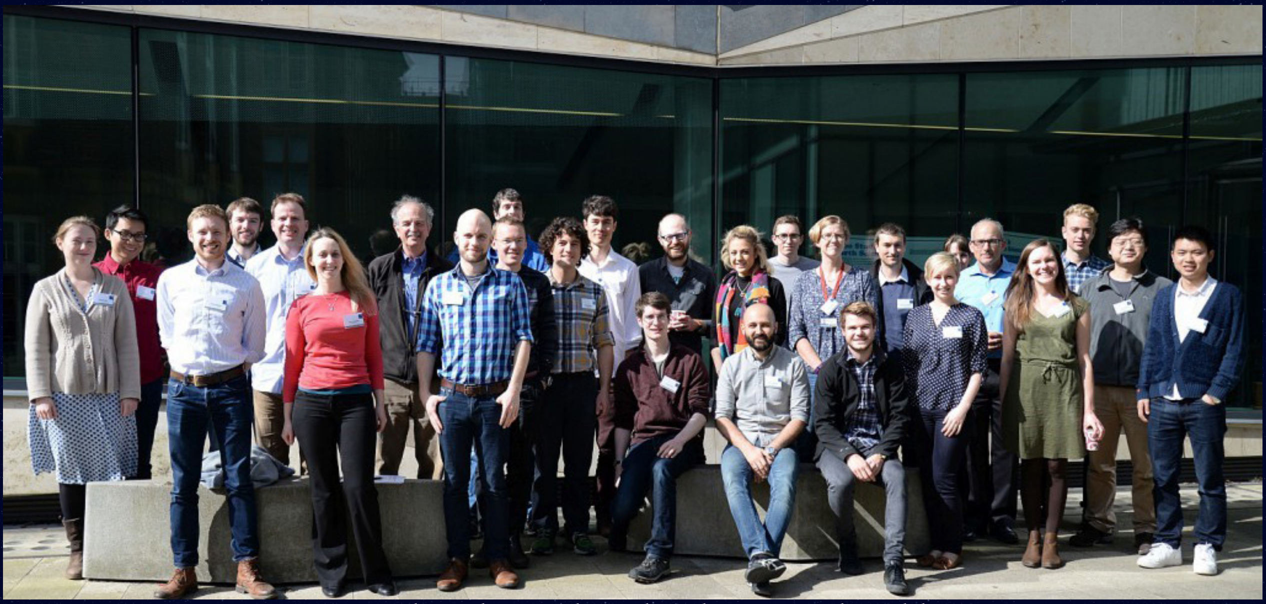
Our contributions covered topics ranging from forecasting flood basalt eruptions at Bárðarbunga volcano, Iceland, through magma-earthquake interaction at Chiles-Cerro Negro volcanoes on the Ecuador-Colombian border, to constraining the geometry of the Main Himalayan Thrust from space geodesy.

At the European Geophysical Union (EGU) meeting in Vienna in April 2015, we gave 10 talks covering subjects ranging from flank instability at Fogo volcano, Cape Verde to the 2005 Tarapaca and 2014 Iquique earthquakes in Spain. Tim Wright gave the 2015 Bullerwell Lecture, firstly at the 2015 EGU meeting, and again in early September at the British Geophysical Association Postgraduate Research in Progress meeting. His talk focused on measuring surface deformation in fault zones using satellite geodesy, current work on the North Anatolian Fault, Turkey, and the future of geodetic observation. Also at the EGU, Greg Houseman gave the 2015 Augustus Love Medal Lecture, *Some problems of the lithosphere*, in recognition of his contributions to the field of geodynamics.

Christoph Grutzner presenting his research at EGU 2016 in Vienna. Credit: Alex Copley

Many of our members present their work throughout the year at prestigious conferences and events. Marek Ziebart was invited to give a lecture at NASA's Goddard Space Flight Centre titled *Space vehicle non-conservative forces: historical perspectives, recent progress and next steps*, while as the current Mineralogical Society Hallimond Lecturer David Pyle gave his talk at the Society's January 2016 Annual Meeting. Tamsin Mather is also a 2016 Mineralogical Society Distinguished Lecturer, aiming to promote interest and discussions across the broad field of mineral sciences to undergraduates, research students as well as more advanced scientists. She is speaking about the lifecycle of volcanoes in the Main Ethiopian Rift, volcanic activity at Santorini, Greece, and the role of volcanoes in global change.

Closer to home, COMET held several specialist meetings with experts from across the globe joining us to share their latest findings. The University of Oxford hosted a COMET Topography Workshop from 31 March to 1 April 2016, focusing on high-resolution data derived from stereo satellite imagery and Structure-from-Motion. The aims were to provide practical training with



COMET members and guests at the March/April 2016 Topography Workshop

ERDAS Imagine and Agisoft Photoscan software, to discuss best practice and to talk about strategies and problem solving. Speakers included COMET Board Member Ramon Arrowsmith from Arizona State University. Earth Observation is meanwhile one of several techniques used to study magmatic processes at a global scale. Although each technique can shed light on one or more volcanic processes, the highest chance of truly understanding what controls magmatic activity happens when all the measurements and information are analysed together.

In November 2015, the University of Leeds hosted a meeting to discuss how magmatic activity can be better understood and reproduced by models of volcanic processes. Fourteen COMET members were joined by experts from other world-leading institutions such as the USGS, the University of Geneva and the University of Liverpool to consider the numerous challenges associated with replicating natural volcanic processes. This included the ability to observe what happens at the surface of the volcano but only indirectly infer what goes on beneath it.

Using a multidisciplinary approach was the key element of the discussions, with several future projects identified, including using different disciplines to classify active volcanoes across the globe on the basis of their deformation and gas emissions. Much effort will also be put in understanding the characteristics of magma reservoirs, moving from conceptual models of simple liquid-filled cavities to complex, multi-phase dynamic systems. Specific volcanoes where COMET already has access to long records of geophysical, geochemical and petrological data (for example Soufrière Hills in Montserrat and Kilauea Volcano in Hawaii) will be used as natural laboratories.

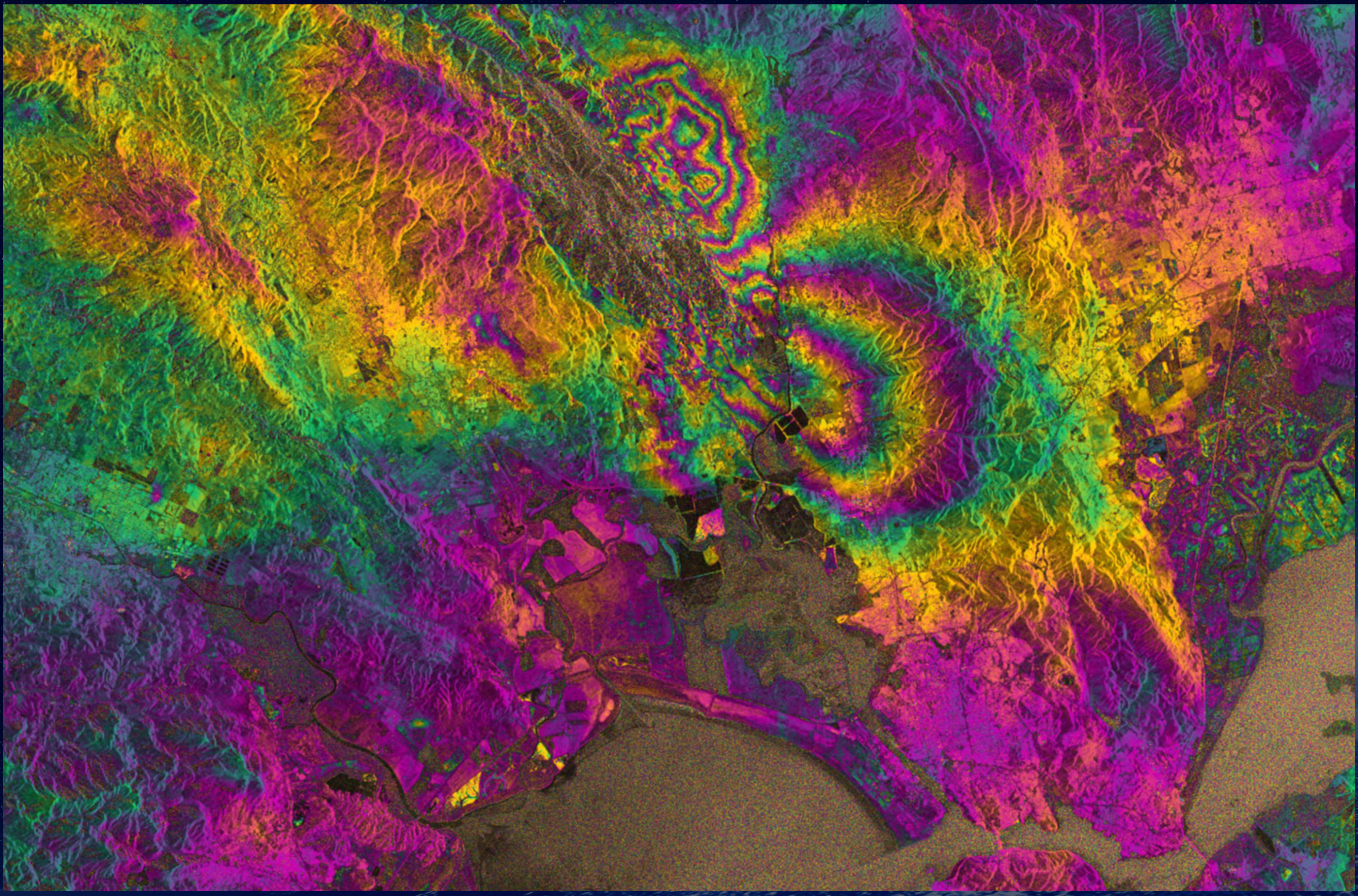
We also contribute to training young researchers and other partners in the countries that we work in, with 2015 seeing earthquake hazard workshops held for scientists in Jammu (India) and Tehran (Iran). COMET scientists from the University of Cambridge shared their knowledge and expertise on the fundamentals of earthquake seismology and building awareness to seismic hazard through lectures, tutorials and field training, as well as a series of open talks on earthquake hazard and preparedness.

Several COMET scientists are involved in editing academic journals, significantly influencing their content. Examples include Tamsin Mather, editor of Earth and Planetary Science Letters, the leading journal in its field, and Andy Hooper, editor of the Journal of Geodesy, which covers the whole range of geodetic science including theoretical and applied studies. Zhenhong Li is meanwhile editor of Advances in Space Research, an open journal covering all areas of space research and Jurgen

Neuberg is an Editor-in-chief for the Journal of Volcanology and Geothermal Research.

We also make efforts to attract scientific readership beyond traditional journal publications. Our work on the 2014 Napa Valley and 2015 Gorkha (Nepal) earthquakes, and on the 2014 Fogo eruption has been featured in Eos, the AGU publication for news and perspectives about the Earth and space sciences. Eos has a broad international readership and is freely available to anyone with an interest in these subject areas.

Similarly, Phys.org, the leading web-based science, research and technology news service, with a readership of 1.75 million every month, featured our work on how one earthquake can trigger a second large event, as well as the fault that caused the 2015 Gorkha (Nepal) earthquake.



Credit: Copernicus data (2014)/ESA/PPO.labs/Norut/COMET-SEOM Insarap study

IMPACT AND INFLUENCE

COMET RECOGNISES THE IMPORTANCE OF WORKING WITH GOVERNMENTS, NGOS AND OTHER PARTNERS TO ENSURE THAT OUR SCIENCE HAS REAL IMPACT, USING OUR WORK TO SHAPE POLICY DECISIONS AND MANAGE NATURAL HAZARDS. CRUCIALLY, OUR WORK ON THE NEPAL 2015 EARTHQUAKE AND ITS AFTERMATH, WHICH IS DESCRIBED ABOVE, CONTINUES TO DELIVER SOCIETAL BENEFITS TO THOSE AFFECTED.

Our work on the 2015 Gorkha (Nepal) earthquake continues to deliver societal benefits. In particular, our joint NERC-DFID project, funded to respond to the remaining threat, has monitored the regions south and west of Kathmandu that remain unruptured, and which are known to have failed in earlier large earthquakes, providing a proper assessment of the outstanding hazard. We are continuing to monitor the situation, briefing DFID, GO-science and SAGE regularly, and using UNESCO funding to support a Nepalese scientist whom we will train to work on all aspects of the project, from instrument installation and maintenance to data analysis.

We are meanwhile continuing to work closely with BGS to provide co-ordinated and rapid responses to seismic events. BGS is the primary contact for the UK Government and media, and COMET contributes by assembling and analysing the data, and helping BGS to develop briefing notes and information for decision makers and the public.

Internationally, COMET continues to be involved with a number of initiatives to ensure that our work has the highest possible societal impact. We have been leading players in the development and implementation of the Committee on Earth Observation Satellites (CEOS) working group on disasters, helping to establish and implement both the volcano and seismic risk pilot projects. Through these projects, the space agencies have committed to providing data that enable us, and other scientists around the world, to respond to volcanic and seismic disasters, and to prepare for them by assessing the hazard in certain key areas. COMET scientists are also currently involved in the establishment of the CEOS landslide risk pilot project.

We are working closely with scientists in the Global Earthquake Model, in particular on developing methodologies for incorporating InSAR data into the global strain rate model, which currently only uses GNSS data. Also, as part of the Global Volcano Model we have set up a Global Volcano Deformation Task Force to collate observations of volcano deformation. Furthermore, the response to the Nepal earthquake has opened up a dialogue with the USGS over the use of InSAR in their rapid response source models and "shakemap" predictions of strong ground motions.

COMMUNICATION AND ENGAGEMENT

COMMUNICATING OUR RESEARCH TO A WIDE AUDIENCE AND EXPLAINING WHY IT IS IMPORTANT IS KEY TO OUR SUCCESS. WE WANT BOTH THE PUBLIC AND DECISION MAKERS TO BE INFORMED ABOUT WHAT WE DO, BUILDING CONFIDENCE IN OUR SCIENCE AND ALSO INSPIRING THE NEXT GENERATION.

We work closely with the national and international media to get our messages across. Highlights include our work on the April 2015 Nepal earthquake being featured by the **BBC website**[29] as well as interviews with BBC TV, the BBC World Service, BBC Radio 4 Science Hour, Channel 4 and the Discovery Channel, and the story being picked up by international media outlets including the Washington Star, Wall Street Journal, Toronto Post and El País.

Andy Hooper meanwhile wrote pieces for **CNN**[30] and **The Guardian**[31] on why the eruption of the Bárðarbunga volcano in Iceland poses significant risks in terms of pollution, although massive disruption of air travel is unlikely. David Pyle and Tamsin Mather were also interviewed for an episode of BBC Radio 4's **Costing the Earth, Lava: A Dangerous Game**[32], which explored volcanic risks and their potential global impacts.

In addition to scientific publications, our members write blog posts. David Pyle's piece on why we can't predict when a volcano will erupt was published in **The Conversation**[33], a collaboration between editors and academics to provide informed news analysis and commentary. David also has his own blog, **Volcanic Degassing**[34], which is part of the EGU network. Austin Elliott blogs regularly for the AGU on **Trembling Earth**[35], which highlights developments in earthquake science and international mitigation efforts around the world, and Christoph Gruetzner is a major contributor to Palaeoseismicity.org, a blog about the latest research into geologic records of past earthquakes. Our partner projects also have their own blogs, such as the Earthquakes without Frontiers blog which provides updates on the latest project activities.

We continue to reach a wide audience through our website, via twitter (over 500 followers) and by issuing press releases on topics such as the fault which caused Nepal earthquake, the hazard posed by volcanic ash, and potential early warning signals for volcanic eruptions.

For younger audiences, Tamsin Mather was a scientific essay contributor to George and the Blue Moon by Lucy and Stephen Hawking, the latest in a series of books designed to explain complex science to young readers through the background of adventure travels.

[29] http://www.bbc.co.uk/news/science-environment-32515059
[30] http://edition.cnn.com/2014/11/20/opinion/icelandic-volcano-hooper/
[31] https://www.theguardian.com/science/blog/2014/aug/28/iceland-volcano-2010-flight-chaos
[32] http://www.bbc.co.uk/programmes/b055g73y
[33] http://theconversation.com/why-cant-we-predict-when-a-volcano-will-erupt-53898
[34] http://blogs.egu.eu/network/volcanicdegassing/
[35] https://blogs.agu.org/tremblingearth/

Face-to-face contact is also important, particularly when it comes to the younger generation. To help celebrate NERC's 50th anniversary and their 2015 Summer of Science, the London Volcano model created for our partner project, STREVA, went on tour.

Credit: Sarah Lloyd

The volcano was the focus of activities and events for 14 days across 4 different locations, run by a team of 25 volunteers including COMET researchers from all career stages, and with much support from education and outreach teams at BGS, Diamond Light Source and Oxford University Museum of Natural History. Highlights included the Diamond Light Source Open Day, where 4,000 people came to the exhibit; the Green Man Festival in Wales, which saw four days of painting and hands-on activities for children; and the Oxford Museum of Natural History, where the volcano took up a residency on the lawn for two weeks, had 2500 visitors, and an explosive finale.

Engaging the general public is also important. In early 2016 COMET Director Tim Wright gave a talk, *When continents collide*, to the Leeds Geological Association. This aimed to promote and further interest in the geological sciences, both amongst LGA members and within the wider community, with the talk being widely publicised and open to all.

Painting volcanoes at the Green Man Festival for NERC's summer of science. Credit: Danielle McLean

RESEARCH HIGHLIGHT

A TEN-YEAR SURVEY OF EMISSIONS AT ANATAHAN VOLCANO

BRENDAN MCCORMICK

Dr Brendan McCormick is a postdoctoral scientist at the University of Cambridge. He uses satellite spectroscopy to monitor volcanic gas emissions, and is co-funded by COMET, the BGS, and the Isaac Newton Trust.

Ten years of satellite observations reveal highly variable sulfur dioxide emissions at Anatahan volcano, Mariana Islands

Volcanic gas emissions vary widely according to the level of activity, and at remote volcanoes, Earth Observation proves a reliable way to monitor this variability. Long-term monitoring of these emissions is critical for gauging levels of unrest—many eruptions are preceded by increasing degassing—and to quantify the impact of volcanoes on Earth's atmosphere and climate.

The most sensitive measurements of volcanic emissions are made at the Earth's surface, using a combination of remote and direct techniques. However, emissions from many highly active but remote volcanoes are only measured infrequently. If their activity is highly variable, intermittent measurements will not accurately quantify the volcano's emissions.

Ground-based measurements at Anatahan volcano (Mariana Islands) shortly before a major eruption in 2005 led to suggestions that it was among the largest sources of sulfur dioxide worldwide. However, reports compiled by the Smithsonian Global Volcanism Program describe Anatahan's activity as intense but short-lived eruptions separated by longer intervals of quiescence.

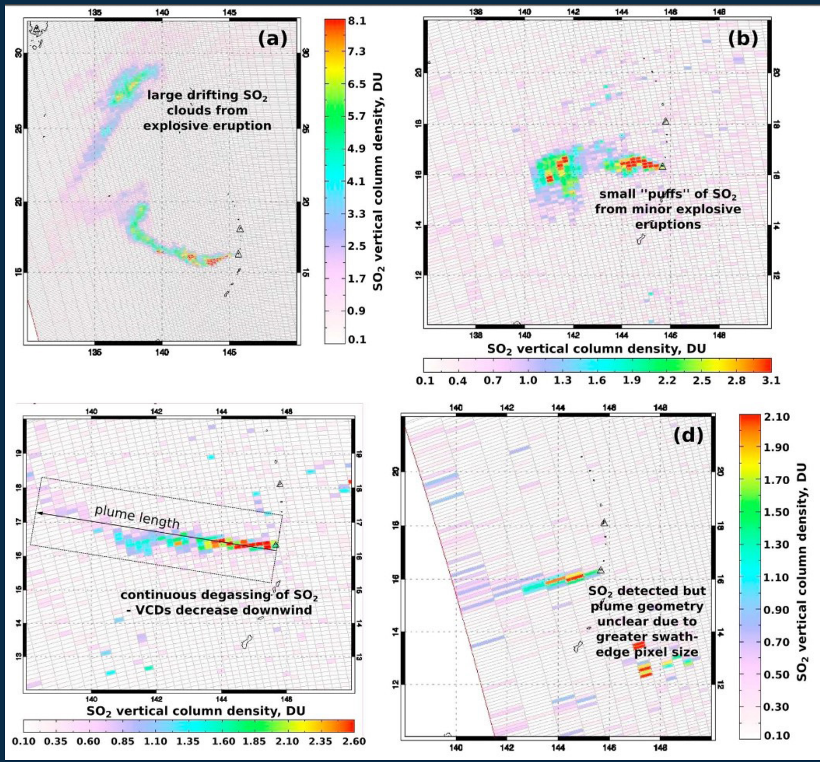
To investigate, Brendan's team used data from four satellite-based spectrometers (OMI, GOME-2, SCIAMACHY, AIRS) to construct a ten-year timeseries of SO2 emissions from Anatahan. They confirmed that emissions during Anatahan's 2005 eruption were among the largest seen worldwide in that year, and that since it reawakened in 2003, Anatahan has dominated volcanic emissions in the region. However, the data also showed that SO2 emissions over ten years were highly variable, peaking during eruptive activity, but falling sharply while the volcano was quiescent.

Many volcanoes worldwide exhibit persistent passive degassing, which is widely held to be the dominant component of long-term volcanic emissions. By comparison, these findings suggest that certain volcanoes, like Anatahan, may only emit substantial SO2 during eruptions, with negligible passive emissions.

In summary, although simulations of volcanic climate forcing depend on accurate emissions budgets, most of these are currently drawn from sporadic ground-based datasets and use time-averaging to extrapolate total annual degassing.

This work has shown that satellite observations are essential for building more accurate emissions budgets—being highly complementary to ground-based datasets in their longer duration and broader scope—and should therefore be more fully integrated into global studies of volcanic degassing.

Reference: McCormick, B., Popp, C., Andrews, B., Cottrell, E. (2015) Ten years of satellite observations reveal highly variable sulphur dioxide emissions at Anatahan Volcano, Mariana Islands, Journal of Geophysical Research: Atmospheres doi:10.1002/2014JD022856



Representative daily snapshots of SO2 vertical column density over Anatahan volcano as measured by the satellite-based UV spectrometer OMI. From the geometry of SO2 clouds, we can track broad changes in style of activity. The mass of SO2 in each cloud can be computed and a timeseries of daily observations of this so-called atmospheric loading can be used as a proxy for degassing flux

Anatahan Volcano. Credit: Smithsonian Institute

POSTGRADUATE COMMUNITY

COMET SUPPORTS A VIBRANT COMMUNITY OF AROUND 50 RESEARCH STUDENTS. AS WELL AS CREATING A NEW GENERATION OF EARTH SCIENTISTS, WE AIM TO EQUIP THEM WITH THE SKILLS THEY NEED TO DEVELOP SCIENTIFIC AND POLICY SOLUTIONS FOR TACKLING GLOBAL ENVIRONMENTAL CHALLENGES.

THE 2016 COMET STUDENT MEETING WAS HELD AT BGS EDINBURGH IN JANUARY, AND WAS ATTENDED BY AROUND 50 COMET MEMBERS AND COLLABORATORS. WE HEARD EXCELLENT TALKS FROM OUR RESEARCH STUDENTS, AS WELL AS NEW STAFF AND ASSOCIATES, ON TOPICS RANGING FROM THE SEISMICITY AND KINEMATICS OF THE HELLENIC SUBDUCTION ZONE TO THE FATHER'S DAY ERUPTION AT KĪLAUEA VOLCANO, HAWAII.

OUR STUDENTS' WORK ALSO FORMS THE BASIS OF MANY COMET PAPERS AND SEVERAL WITH STUDENT FIRST AUTHORS, INCLUDING:

• Barišin, I., Hinojosa-Corona, A., Parsons, B. (2015) Co-seismic vertical displacements from a single post-seismic lidar DEM: example from the 2010 El Mayor-Cucapah earthquake Geophysical Journal International doi:10.1093/gji/ggv139

• Bekaert, D., Walters, R.J., Wright, T.J., Hooper, A.J., Parker, D.J. (2015) Statistical comparison of InSAR tropospheric correction techniques, Remote Sensing of Environment doi:10.1016/j.rse.2015.08.035

• Bekaert, D., Hooper, A., Wright, T. (2015) A spatially-variable power-law tropospheric correction technique for InSAR data, Journal of Geophysical Research doi: 10.1002/2014JB011558

• Bekaert, D., Hooper, A., Wright, T. (2015) Reassessing the 2006 Guerrero slow slip event, Mexico: implications for large earthquakes in the Guerrero Gap, Journal of Geophysical Research doi:10.1002/2014JB011557

• Hodge, M., Biggs, J., Goda, K., & Aspinall, W. (2015) Assessing infrequent large earthquakes using geomorphology and geodesy: the Malawi Rift, Natural Hazards doi:10.1007/s11069-014-1572-y

• Howell, A., Jackson, J., England, P., Higham, T., Synolakis, C. (2015) Late Holocene uplift of Rhodes, Greece: Evidence for a large tsunamigenic earthquake and the implications for the tectonics of the eastern Hellenic Trench System, Geophysical Journal International doi:10.1093/gji/ggv307

• Parker, A.L., Biggs, J., Walters, R.J., Ebmeier, S.K., Wright, T.J., Teanby, N.A., Lu, Z. (2015) Systematic assessment of atmospheric uncertainties for InSAR data at volcanic arcs using large-scale atmospheric models: Application to the Cascade volcanoes, United States, Remote Sensing of Environment doi:10.1016/j.rse.2015.09.003

• Penney, C., Copley, A., Oveisi, B. (2015) Subduction tractions and vertical axis rotations in the Zagros-Makran transition zone, SE Iran: The 2013 May 11 Mw 6.1 Minab earthquake Geophysical Journal International doi: 10.1093/gji/ggv202

• Reynolds, K., Copley, A., Hussain, E. (2015) Evolution and dynamics of a fold-thrust belt: The Sulaiman Range of Pakistan, Geophysical Journal International doi:10.1093/gji/ggv005

• Spaans, K., Hreinsdóttir, S., Hooper, A., Ófeigsson, B.G. Crustal movements due to Iceland's shrinking ice caps mimic magma inflow signal at Katla volcano (2015) Scientific Reports doi:10.1038/srep10285

• Zhou, Y., Parsons, B., Elliott, J.R., Barisin, I., Walker, R.T. (2015) Assessing the ability of Pleiades stereo imagery to determine height changes in earthquakes: A case study for the El Mayor-Cucapah epicentral area, Journal of Geophysical Research B: Solid Earth doi:10.1002/2015JB012358

• Zhou, Y., Elliott, J.R., Walker, R.T., Parsons, B. (2015) The 2013 Balochistan earthquake: an extraordinary or completely ordinary event? Geophysical Research Letters doi:10.1002/2015GL065096

NEXT DESTINATIONS

Recent Bristol COMET graduate **Amy Parker**, now a Research Associate at Curtin University in Perth, Australia, will have her thesis, *Developing semi-automated processing of Sentinel SAR data with a focus on volcanoes in Latin America*, published as part of the Springer Theses series which recognises outstanding PhD research.

David Bekaert meanwhile completed his PhD on Interferometric Synthetic Aperture Radar for slow slip applications at Leeds in December 2015. One of the outputs from his thesis is the development of the open-source **Toolbox for Reducing Atmospheric InSAR Noise (TRAIN)**[36]. He is now a Caltech postdoctoral researcher at NASA's Jet Propulsion Laboratory. His current research interests include noise corrections for InSAR, subduction zone slow slip events, and subsidence along the Sacramento Delta and New Orleans region.

Finally, in the coming year, **Will Hutchison**, a COMET PhD student at Oxford Earth Sciences, will be taking up a postdoctoral research position as part of the HiTechAlkCarb consortium in St Andrews. Will's research focuses on volcanism in the Main Ethiopian Rift, using a range of methods to investigate active magmatic and hydrothermal processes, and understand the size and frequency of eruptive activity in the rift.

[36] http://davidbekaert.com/download/TRAIN_manual.pdf

AWARDS & RECOGNITION

COMET'S ACHIEVEMENTS WERE RECOGNISED IN SEVERAL WAYS DURING 2015/16:

APRIL 2015

Greg Houseman was awarded the Augustus Love Medal by the EGU, given to a distinguished scientist in the field of geodynamics He also received a CIRES Fellowship (honorary) at University of Colorado at Boulder (April 23 to June 23 2015).

Tim Wright gave the Bullerwell Lecture, an honour given by the British Geophysical Association (BGA) to an outstanding young British geophysicist, at the 2015 EGU in Vienna (repeated at the September 2015 BGA Postgraduate Research in Progress in Geophysics meeting).   He also received the Rosentiel Award from the University of Miami, which honours scientists who, in the past decade, have made significant and growing impacts in their field.

JUNE 2015

James Jackson received a CBE for his services to environmental science as well as the Geological Society Wollaston Medal - the society's highest award. James was one of the founding members of COMET and has been a major contributor to its success, pioneering a combination of earthquake source seismology, geomorphology, space geodesy and remote sensing to examine how the continents are deforming, looking at scales that range from single earthquakes to the vast continental areas of active plate movement such as Africa, Iran and the Aegean. He also leads the Earthquakes without Frontiers (EwF) project.

At the same ceremony, Geoff Wadge was awarded the society's Murchison Medal, which is given for research excellence in hard rocks. This recognised Geoff's contributions to geology and remote sensing, including research into volcanology, Caribbean tectonics, and volcanic hazards and risk assessment.

AUGUST 2015

Paola Crippa received a L'Oréal-UNESCO UK and Ireland Fellowship For Women In Science. The fellowship is part of an award scheme which encourages greater participation of women in science and recognises the achievements of exceptional female scientists across the globe.

OCTOBER 2015

Christoph Gruetzner was part of a research group that received the National Research Award of the Research Council of the Sultanate of Oman for their research on tsunamis in the Arabian Sea (Short- and long-term evolution along the coastline of Oman).

NOVEMBER 2015

Greg Houseman was elected a Fellow of Academia Europaea, the European Academy of Humanities, Letters and Sciences, membership of which is by invitation only and includes eminent scientists from across Europe.

The University of Bristol's Volcanology Research Group, including Matt Watson and Juliet Biggs, was awarded the Queen's Anniversary Prize for its internationally-recognised research into the risks posed by volcanoes to aviation. This has included developing an innovative computer model for predicting ash plume movement and helping to make airspace safer for the public.

JANUARY 2016

Philip England received the Royal Astronomical Society's Gold Medal for Geophysics, the society's highest honour, for his work on solid earth geophysics and improvements made in understanding the way the Earth's surface and interior operate.

Tamsin Mather was appointed as one of two Mineralogical Society Distinguished Lecturers, recognised as both good communicators and experts in their fields, to give lectures at universities and related institutions that appeal to undergraduates and research students as well as more advanced scientists.

David Pyle was also made the 2016 Mineralogical Society's Hallimond Lecturer, and will have the honour of delivering a lecture at the society's next annual meeting.

RESEARCH HIGHLIGHT

THE 2013 MW7.7 BALOCHISTAN EARTHQUAKE IN PAKISTAN: NOT SO UNUSUAL

YU ZHOU (OXFORD)

IN 2013, A MW7.7 EARTHQUAKE STRUCK BALOCHISTAN, CAUSED A HUGE SURFACE OFFSET AND TRIGGERED A SMALL TSUNAMI IN THE ARABIAN SEA. THE APPARENTLY STRANGE FAULT BEHAVIOUR ATTRACTED THE ATTENTION OF SCIENTISTS WORLDWIDE AND DISCUSSION IS STILL ONGOING. THIS AN INTERESTING CASE FOR PALEOSEISMOLOGISTS, NOT ONLY BECAUSE OF THE CASCADING EARTHQUAKE EFFECTS, BUT ALSO BECAUSE OF THE SURFACE RUPTURE DISTRIBUTION, FROM WHICH WE MIGHT LEARN SOME IMPORTANT LESSONS.

COMET student Yu Zhou and colleagues from Oxford University published research on this event[37], arguing that it might be not as unusual as it seems. Their research is based on the analysis of Pleiades stereo satellite imagery, which has proven to be a very useful data source. Yu describes the research in his own words below[38].

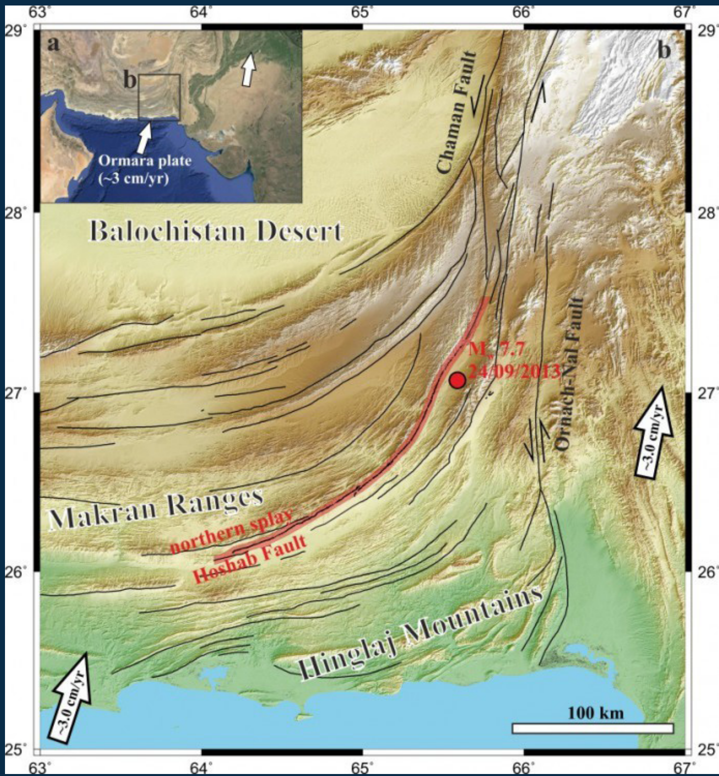
The 24 September 2013 Mw7.7 Balochistan earthquake in Pakistan is a very interesting event. It ruptured a 225-km long section of the curved and moderately dipping (50°-70°N) Hoshab fault whilst appearing to show consistent and predominantly strike-slip behaviour along its entire length, its slip vector rotating dramatically along-strike by 60°.

It is difficult to reconcile the largely strike-slip motion with the shortening to the west, which led to the argument that the fault kinematics switch between strike-slip and dip-slip motion in successive earthquakes[39 40]. Such kinematics is very unusual and has not been observed elsewhere. One way to test this hypothesis is to calculate the ratio of cumulative lateral to vertical displacements from past earthquakes. If the ratio of cumulative displacements is different from that in the 2013 event, it suggests that the fault kinematics do switch. The solution sounds simple, but field access is not possible yet.

Therefore we tasked Pleiades stereo imagery for the entire 225 km rupture and produced a 1-m resolution digital topography from it. By determining the vertical component of motion on the Hoshab fault for the first time, we found that the oblique motion in the 2013 earthquake is typical of this fault. A constant ratio of lateral to vertical motion over multiple earthquakes suggests that the Hoshab fault has experienced the same style of faulting throughout the Late Quaternary.

By further mapping of subparallel faults in the eastern Makran, we also show that failure occurs in a distributed fashion and is not constrained solely to the Hoshab fault, providing an explanation for long repeat times and hence a lack of seismic events in previous decades.
The Balochistan earthquake provides an example of distributed faulting in a remote and inaccessible area that has been made amenable to detailed near-field investigation by the new generation of very high-resolution satellite stereo imagery.

[37] Zhou, Y., Elliott, J., Parsons, B., Walker, R. (2015) The 2013 Balochistan earthquake: an extraordinary or completely ordinary event?, Geophysical Research Letters doi:10.1002/2015GL065096
[38] First featured on palaeoseismicity.org
[39] Avouac, J.-P., Ayoub, F., Wei, S., Ampuero, J.P., Meng, L., Leprince, S., Jolivet, R., Duputel, Z., Helmberger, D. (2014) The 2013 Mw7.7 Balochistan earthquake, energetic strike-slip reactivation of a thrust fault, Earth and Planetary Science Letters doi:10.1016/j.epsl.2014.01.036
[40] Barnhart, W., Briggs, R., Reitman, N., Gold, R., Hayes, G. (2015) Evidence for slip partitioning and bimodal slip behaviour on a single fault: Surface slip characteristics of the 2013 Mw 7.7 Balochistan, Pakistan earthquake, Earth and Planetary Science Letters doi:10.1016/j.epsl.2015.03.027



Fault map of the eastern Makran (Zhou et al., 2015)

3D view of the 2013 Balochistan earthquake rupture (Zhou et al., 2015)

FUTURE PLANS

COMET IS CONTINUING TO DELIVER HIGH-IMPACT NATIONAL CAPABILITY SCIENCE. IN 2016/17, OUR SPECIFIC OBJECTIVES ARE TO:

- Continue the development of the COMET/LiCS InSAR processing system and install at CEMS. Openly release first interferogram products.
- Influence ESA's acquisition strategy for the Sentinel-1A/1B constellation by examining current acquisitions and by characterising coherence in space and time.
- Evaluate methods for integration of InSAR and GNSS data for the derivation of high resolution crustal velocity and strain fields.
- Produce country-scale velocity and strain maps for parts of the Alpine-Himalayan Belt.
- Continue to populate the database of active faults in Central Asia. Tie fault mapping with forensic remote-sensing and ground-based studies for selected regions.
- Use observations of strain, for example along the North Anatolian Fault, to constrain models of the entire earthquake deformation cycle.
- Use the spatial distribution of strain and topography to map the spatial variations of lithosphere strength and basal tractions in eastern Tibet.
- Develop and implement a volcanic ash flagging routing within the COMET IASI Near Real Time system.
- Carry out a global assessment of SO2 volcanic degassing visible from space.
- Populate the remaining volcano entries in the COMET global volcano deformation database; add quick-look Sentinel-1 interferograms from the COMET/LiCS chain as they become available.
- Produce documentation, including a user manual, for the COMET Bayesian deformation modelling software, and provide a beta release to scientists outside COMET.
- For at least one volcano, develop a coupled model that predicts gas emissions, petrology and geophysical measurements, and invert to find probability distributions for the model parameters.
- Continue the development of a low-cost GNSS sensor network for autonomous real-time deformation monitoring.
- Continue to respond to significant events as they occur, in collaboration with local partners and the BGS.

- Continue to strengthen the COMET website, specifically focusing on research impact, expertise and engagement/outreach pages.
- Hold focused community meetings, for example on seismic hazard in collaboration with the global earthquake model.

In the past year we have said goodbye to a number of COMET early career researchers who have moved onto academic positions, including Richard Walters (Lecturer, University of Durham), Susi Ebmeier (Leverhulme Research Fellow, University of Leeds), John Elliott (University Academic Fellow, University of Leeds) and Pablo González (Lecturer, University of Liverpool). We wish them the best of luck with their future careers and trust that they will continue to play an active role in the wider COMET community.

We meanwhile look forward to welcoming new colleagues in the coming year. These include Mike Cassidy (University of Mainz) who will be joining the volcanology team at Oxford as a NERC Independent Research Fellow, focusing on using geochemistry, petrology and sedimentology as tools to understand the evolution of volcanic systems; and Jonathan Weiss (University of Hawaii) who will work on the integration of InSAR and GPS for mapping tectonic strain.

Finally, our national capability research underpins a wider range of scientific research that COMET staff and scientists will continue to undertake on a variety of research projects. We will also continue to write impactful publications, and work with end users to maximise uptake of and impact from the results.

Fieldwork in the Uzbekistan Mountains. Credit: John Elliott

GLOSSARY

AGU	American Geophysical Union
BGS	British Geological Survey
CEMS	Climate, Environment and Monitoring from Space
CEOS	Committee on Earth Observation Satellites
COMET	Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics
CNRS France	French National Centre for Scientific Research
DEM	Digital Elevation Model
DFID	Department for International Development
EGU	European Geosciences Union
EO	Earth Observation
ESA	European Space Agency
EwF	Earthquakes without Frontiers
FCO	Foreign and Commonwealth Office
GNSS	Global Navigation Satellite System
GO-Science	Government Office for Science
GPS	Global Positioning System
GSRM	Global Strain Rate Model
IASI	Infrared Atmospheric Sounding Interferometer
InSAR	Synthetic Aperture Radar Interferometry
LGA	Leeds Geological Association
LiCS	Looking inside the Continents from Space
Mw	Moment magnitude
NASA	US Space Agency (National Aeronautics and Space Administration)

NCEO	**National Centre for Earth Observation**
NERC	**Natural Environment Research Council**
NGO	**Non-Governmental Organisations**
NRT	**Near Real Time**
SAC	**Science Advisory Committee**
SAGE	**Scientific Advisory Group in Emergencies**
SAR	**Synthetic Aperture Radar**
SHIVA	**Spectrally High resolution Infrared measurements for the characterisation of Volcanic Ash**
SPOT	**Satellite Pour l'Observation de la Terre**
STREVA	**Strengthening Resilience in Volcanic Areas**
TOPS	**Terrain Observations by Progressive Scans**
UNESCO	**United Nations Educational, Scientific and Cultural Organization**
USGS	**US Geological Survey**
VAAC	**Volcanic Ash Advisory Centre**

ANNEX 1

COMET PUBLICATIONS JANUARY-DECEMBER 2015

Altuncu Poyraz, S., Teoman, M.U., Türkelli, N., Kahraman, M., Cambaz, D., Mutlu, A., Rost, S., Houseman, G.A., Thompson, D.A., Cornwell, D., Utkucu, M., Gülen, L. New constraints on micro-seismicity and stress state in the western part of the North Anatolian Fault zone: observations from a dense seismic array, Tectonophysics doi: 10.1016/j.tecto.2015.06.022

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Bekaert, D.P.S., Walters, R.J., Wright, T.J., Hooper, A.J., Parker, D.J. Statistical comparison of InSAR tropospheric correction techniques, Remote Sensing of Environment doi:10.1016/j.rse.2015.08.035

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Copley, A., Karasozen, E., Oveisi, B., Elliott, J.R., Samsonov, S., Nissen, E. Seismogenic faulting of the sedimentary sequence and laterally variable material properties in the Zagros Mountains (Iran) revealed by the August 2014 murmuri (E. Dehloran) earthquake sequence, Geophysical Journal International doi:10.1093/gji/ggv365

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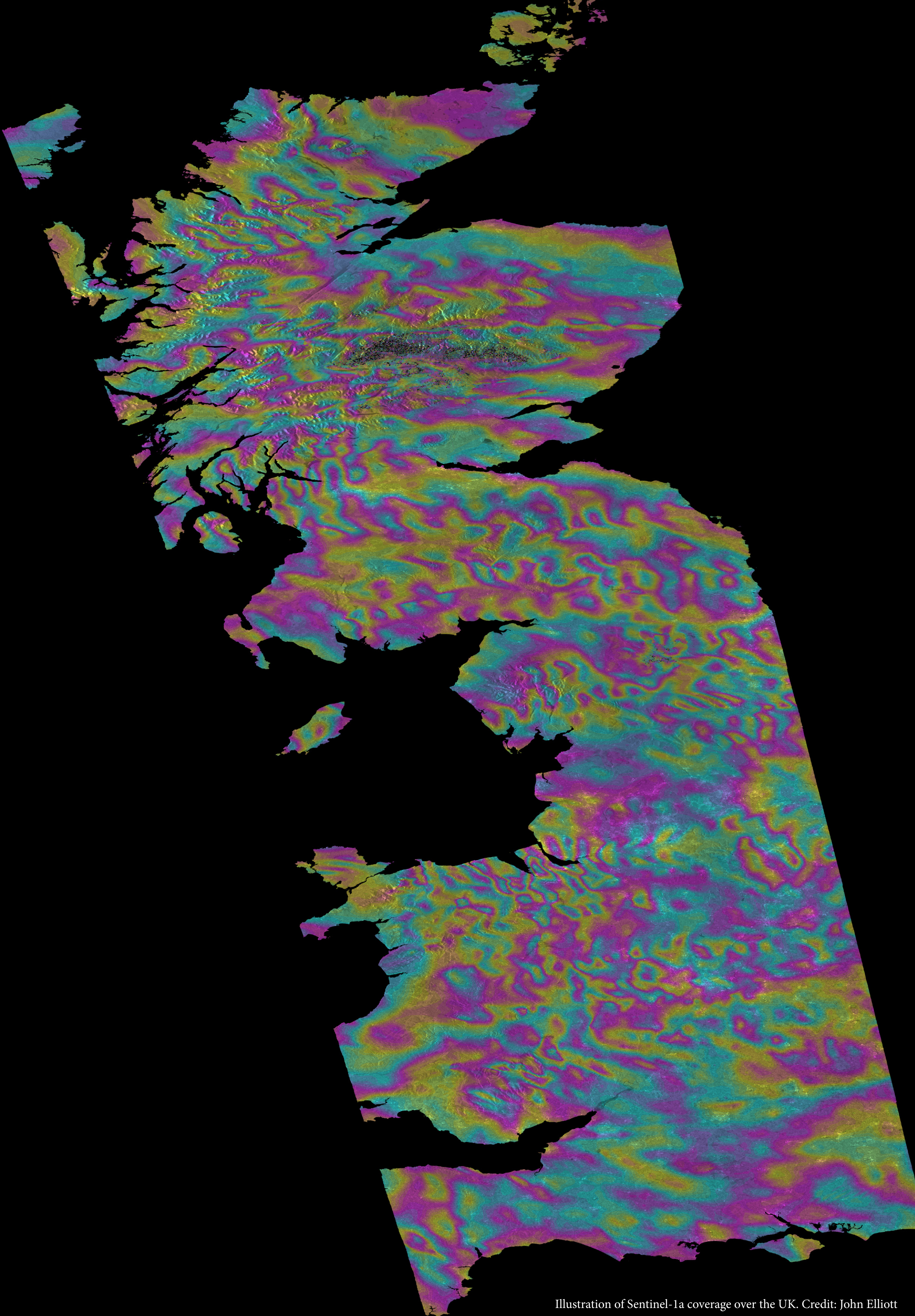

Illustration of Sentinel-1a coverage over the UK. Credit: John Elliott

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