



COMET

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

ANNUAL REPORT 2016/17



NERC
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ENVIRONMENT



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INTRODUCTION

THE CENTRE FOR OBSERVATION AND MODELLING OF EARTHQUAKES, VOLCANOES AND TECTONICS (COMET) PROVIDES NATIONAL CAPABILITY IN THE OBSERVATION AND MODELLING OF TECTONIC AND VOLCANIC HAZARDS.

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

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

We work closely with the British Geological Survey (BGS), with our sponsors the Natural Environment Research Council (NERC), with the European Space Agency (ESA), and with many other national and international partners. In addition, we are working with business, Government and the space agencies to ensure that the UK continues to invest in and benefit from satellite missions.

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

This report gives an overview of COMET's activities during 2016/17, highlighting major scientific achievements as well as progress against our key objectives. It covers the period 1 January – 31 December 2016 for publications, and 1 April 2016 – 31 March 2017 for all other outputs.



DIRECTOR'S WELCOME

THE PUBLICATION OF THIS THIRD ANNUAL REPORT SIGNIFIES THAT WE ARE NOW MORE THAN HALFWAY THROUGH THE CURRENT PHASE OF COMET (2014-2019) - A TIME TO TAKE STOCK OF OUR MANY ACHIEVEMENTS, AND ALSO TO ENSURE THAT WE ARE ON TRACK TO ACHIEVE OUR GOALS.

We have continued to make considerable progress against our overarching aims of measuring tectonic strain across the planet, measuring deformation and gas release at every active volcano, and building new models of hazardous processes.

Notably, December 2016 saw the launch of LiCSAR, a processing system specifically designed to handle the vast amounts of data generated by the European Space Agency (ESA) Sentinel-1 mission. LiCSAR is already providing high-resolution deformation data for the entire Alpine-Himalayan seismic belt, where most of the planet's deadly earthquakes occur, and we will be expanding LiCSAR to provide global coverage of the tectonic belts over the next few years.

With volcanoes, we now have the ability to monitor volcanic ash as well as SO₂ emissions via the Infrared Atmospheric Sounding Interferometer (IASI) Near Real Time website, and we have also made progress on using IASI to monitor smaller emissions of SO₂ into the troposphere.

In addition, a new system using Sentinel-1 data has been trialled to monitor volcano deformation in Iceland, and we are now rolling it out across Europe and parts of Asia. Next, we will extend this automated detection of ground deformation to Africa and Central and South America, regions with large explosive volcanoes that are currently covered only by limited ground surveys.

As well as this progress on our planned research, COMET's event response capabilities were tested in 2016 with the seismic events in Italy and New Zealand. In both cases, our investigations revealed surprising complexity in the fault ruptures, with ongoing work funded by NERC urgency grants now underway to fully interpret the events and improve seismic hazard assessment in the affected regions.

Our success in securing additional resources, particularly from the Global Challenges Research Fund (GCRF), is meanwhile positioning us to address some of the significant challenges faced by developing countries in relation to geohazards. Specifically, in China, Earth Observation (EO) will be used to assess and rapidly respond to large earthquakes and induced landslides, while in Chile we are using satellite imagery to construct a 3D model of the built environment and highlight active fault structures within the city of Santiago. In Ethiopia, we will produce a new high-resolution map of dynamic surface motions to help understand hazards associated with volcanism, earthquakes, and landslides, while in Nicaragua our scientists will be working on developing an early warning system for Masaya volcano. We will also be using citizen science to increase communities' resilience to environmental disasters.

Back in the UK, our partnership with the British Geological Survey (BGS) continues to evolve and we are engaged in strategic discussions on our long-term vision for COMET.

This includes establishing how COMET can support BGS in meeting its commitments to UK Government, inputting to strategic advice on geohazards worldwide and responding to natural disasters where UK interests are affected.

Overall, it has been year of building on previous achievements whilst remaining flexible and responsive to the dynamic Earth which we study. In the coming year we aim to build closer links with the Global Earthquake Model (GEM), which ultimately aims to reduce vulnerability to earthquakes, and have already held a joint workshop which highlighted synergies and identified how we can mutually benefit from our work on seismic hazard.

We also plan to further knowledge and share results on ground deformation across the Alpine Himalayan Belt, East African Rift, and Ethiopia, global volcano deformation, and volcanic gas and ash dispersal. At the same time we will continue to respond to events in partnership with BGS, whilst refining our work on low cost GPS receivers that can be deployed rapidly in the field.

I am confident that we will continue to deliver excellent science with real-world impact, and look forward to another year of progress.

Finally, I would like to thank the COMET review board for their valued contributions both throughout the year and, particularly, at our Annual Meetings where their feedback and guidance continues to both maximise the quality and rigour of our science, and to shape COMET as an organisation.



Professor Tim Wright
COMET Director

CHAIR'S FOREWORD

THROUGHOUT MY THIRD YEAR AS CHAIR OF THE COMET ADVISORY BOARD, I HAVE CONTINUED TO BE IMPRESSED BY THE QUALITY OF THE SCIENCE DELIVERED BY THE COMET COMMUNITY, AS WELL AS ITS COLLABORATIVE SPIRIT.

Speaking on behalf of the Board, we are especially pleased to note the progress made on COMET's processing of Sentinel-1 data. In particular, the launch of LiCSAR, which is translating huge volumes of raw satellite data into useful information, presents exciting new scientific and event response opportunities, as well as the potential for innovative applications based on the Sentinel-1 mission.

We are similarly pleased to see COMET's success regarding GCRF funding, a key topic of discussion at the 2016 Annual Meeting. The technology and science offered by COMET clearly has applications in developing resilience, taking action on short-term environmental shocks and monitoring long-term environmental change, and we look forward to seeing how this potential is realised now that resources have been secured.

COMET's relationship with BGS is meanwhile fundamental to its future success and longevity. We are pleased to see that strategic discussions are underway, with both organisations taking a proactive approach to long-term planning.

Overall, we continue to be excited about the advances COMET is making in both modelling and Earth Observation at all career levels. Importantly, it is clear that COMET's PhD students and early career researchers are its greatest asset, boding well for the future. Finally, we look forward to hearing more of COMET's progress, and to continued involvement in its success.



Professor Roland Bürgmann
Chair, COMET Advisory Board



OUR NEW MEMBERS



Jonathan Weiss, COMET Researcher, Leeds

Jonathan's current research focuses on using geodetic data to study interseismic strain accumulation across the Alpine-Himalayan Belt. Specifically, he is working with COMET and Earthquakes without Frontiers (EwF) scientists on refining methods to integrate (Sentinel-1) InSAR and GNSS data to create high-resolution crustal velocity and strain rate fields, which will be used to improve estimates of seismic hazard across the region.

Jonathan is also interested in the link between mountain building and the earthquake cycle and explores this connection using a combination of field, geodetic, and numerical approaches while primarily targeting the Central Andes.



David Ferguson, COMET Associate, Leeds

David uses geochemical and geochronological methods to investigate magmatic and volcanic processes. He is particularly interested in understanding the role of magmatism within the Earth system, including exploring the links between magmatism and tectonic processes such as continental rifting, and the potential role of the climate system in modulating volcanic/magmatic activity.



Philip Benson, COMET Associate, Portsmouth

Philip specialises in the relatively new discipline of rock physics, but with broad research interests in areas as diverse as geophysics, volcano-tectonics, and structural geology. His particular focus is to apply modern laboratory rock deformation techniques to simulate active tectonic areas such as deep subduction zones and active volcanoes, recording induced seismicity that acts as a diagnostic to these deep crustal processes.



Fabien Albino, COMET Researcher, Bristol

Fabien's research focuses on understanding the physical processes that lead to an eruption. This includes characterising the external processes that can mechanically trigger an eruption by using numerical modelling, studies of Icelandic subglacial volcanoes, and the effect of lake discharge or icecap retreat on the occurrence of eruptions. He has developed elastic mechanical models to quantify the critical overpressure inside a magma reservoir before an eruption, which may help for eruption forecast, and considered more realistic crust rheology in ground deformation models.

More recently, Fabien has used InSAR techniques to obtain valuable information about how the Earth's surface changes before, during, and after an eruption, including studies of the 2011-2012 eruption of Nyamulagira Volcano (Democratic Republic of Congo) using TanDEM-X interferometry. This provided a high-resolution thickness map of the lava flows and derived with accuracy the volume of the eruption. Such results have proven important in understanding the dynamics of the magmatic system, as well as improving hazard assessment.



A LOOK BACK AT 2016/17

AS WELL AS OUR PLANNED SCIENTIFIC RESEARCH, DURING 2016/17 COMET MEMBERS WERE INVOLVED IN ACTIVITIES RANGING FROM RESPONDING TO SEISMIC EVENTS AND ADVISING GOVERNMENTS ON VOLCANIC HAZARDS TO TRAINING THE NEXT GENERATION OF EO SCIENTISTS AND INFORMING THE PUBLIC ABOUT THE DYNAMIC EARTH.

EVENT RESPONSE

Apennines (Italy) earthquakes (Laura Gregory, Leeds/Richard Walters, Durham)

In 2016, a sequence of devastating earthquakes struck central Italy, starting on the 24th August 2016 with a Mw 6.2 event near the medieval village of Amatrice.

COMET scientists responded remotely and in the field, by rapidly identifying the causative faults using Sentinel-1 InSAR data at the same time as the field team investigated surface ruptures and installed short-baseline low-cost GNSS monitoring equipment. Despite the relatively low magnitude of this event, significant lives were lost due to the shallow nature of rupture on a rather complicated system of normal faults.



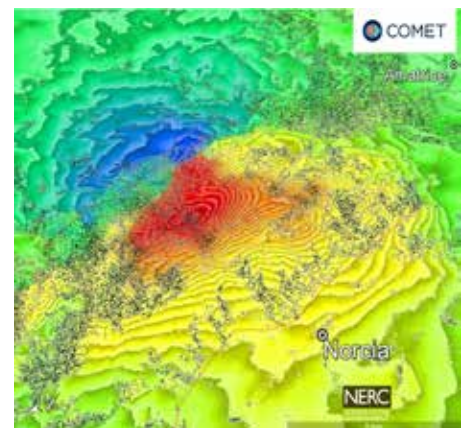
COMET PhD student Huw Goodall contemplates the surface rupture that resulted from the 30th Oct M6.6 event. The rupture strikes across the side of Mt Vettore in the distance

COMET scientists won a NERC urgency grant to continue investigating the earthquake. The field team returned to central Italy in late September in order to continue monitoring the surface ruptures using terrestrial laser scanning (TLS), when a second (Mw 6.1) and finally third (Mw 6.6) earthquake struck.

This final large earthquake levelled many of the mountain villages that had already been damaged by the previous earthquakes. The field team were able to reach the new surface ruptures within around 5 hours of the earthquake, and immediately began using TLS to develop a high-resolution near-field dataset of the post-seismic movement along the faults involved.

The combination of satellite radar data with field geological and geophysical data has revealed an incredibly complex pattern of fault rupture, both at the surface and at depth. The frequency of radar data obtained by the Sentinel-1 satellite has allowed us to separate out the sub-surface slip distributions for each of the three main earthquakes.

The fortunate timing of the return field campaign is providing unique insights into the rate and pattern of near-field afterslip in the immediate aftermath of a large earthquake. COMET investigation into the 2016 Amatrice sequence has thus far revealed that the distribution of faults in the region is surprisingly complex, and this complexity is likely to be controlling the spatial distribution of slip, and thus the magnitude, of each event in the sequence.



Satellite radar (InSAR) measurements of ground deformation from the 30th October 2016 Mw 6.6 earthquake in Central Italy. Colour shows total ground displacement towards (blue) or away from (red) satellite, with bands corresponding to 2.8 cm contours. Red lines show mapped faults

Mw 7.8 Kaikoura (New Zealand) earthquake (John Elliott/Tim Wright, Leeds)

When a major magnitude 7.8 earthquake struck the north-eastern half of the South Island of New Zealand on 14th November 2016, the existence of now two Sentinel-1 spacecraft in the constellation meant that COMET could generate a coseismic interferogram within two days of the event.

We provided the interferogram to local partners in New Zealand, and to the wider community via twitter, around 5.5 hours after the satellite overpass.

Calculation of ground offset displacements in a relatively rapid timeframe revealed the dramatic breadth and number of fault segments involved in this complex rupture. By providing these timely data to GNS, New Zealand's research institute focusing on geology, geophysics and nuclear science, COMET was able to assist with decision making concerning deployment of field instruments and targeting of field observations, as well as input to the early fault slip models that led to one of the first publications on this event.

Following on from the earthquake, COMET investigators and associates also submitted and won a NERC urgency grant to fully capture the surface offset rupture displacements with fieldwork and aerial surveying, as well as deployment of low-cost Global Navigation Satellite System (GNSS) equipment to test capturing postseismic deformation following major earthquakes.

This is recording some of the temporary landscape features created by the earthquake before they are destroyed by surface processes, and using a number of semi-permanent Global Positioning System (GPS) recorders to capture the rate and timing of post-seismic movement. This research will allow us to record the maximum amount of data useful for understanding the earthquake, which will in turn help in interpreting other earthquakes, and improving seismic hazard assessment.



The Situation Room at GNS, Wellington, two days after the earthquake, examining the Sentinel-1 offsets data derived by COMET, indicating the scale of the earthquake segmentation and deformation across the whole northern half of New Zealand's South Island. Credit: Sigrun Hreinsdottir

SCIENTIFIC DEVELOPMENTS

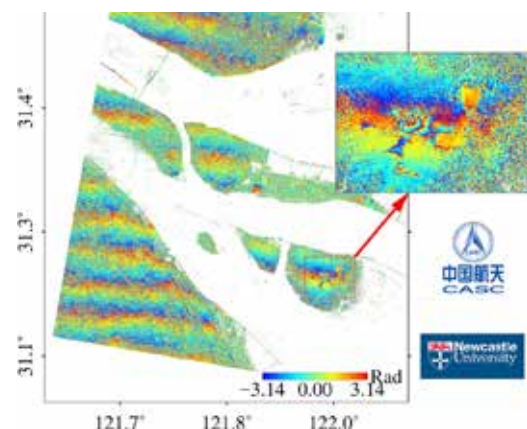
First interferograms from Chinese SAR satellites (Zhenhong Li, Newcastle)

A collaboration between Newcastle University and the China Academy of Space Technology has generated interferograms using Chinese Gaofen-3 (GF-3) imagery for the first time. These are also the first interferograms from Chinese Synthetic Aperture Radar (SAR) missions.

GF-3 was launched from the Taiyuan Satellite Launch Centre on 10 August 2016, and has been in operation since January 2017. The figure below shows the first GF-3 interferogram of approximately 50 x 50 km around Shanghai, China. Two fringes (equivalent to c. 5.6 cm of subsidence, likely to be caused by groundwater extraction) can be observed in the GF-3 interferogram with a time span of 116 days.

The GF-3 phase quality is of a high standard with a high spatial resolution (3.5 m in azimuth and 5.5 m in range), leading to high coherence even for interferograms with a spatial baseline of c. 600 m and a temporal baseline (time span) of nearly 4 months.

The team will continue to acquire GF-3 imagery over selected areas with scientific and/or engineering interests, focusing on improving data quality, refining the satellite orbits, and further developing interferometric processing algorithms (e.g. for automatic processing chains).



GF-3 interferogram around Shanghai, China (20161114-20170310). Two fringes are observed in the area indicated by a red rectangle, implying c. 5.6 cm of subsidence during the 116-day period

Web-based atmospheric correction toolbox released (Zhenhong Li, Newcastle)

The Iterative Tropospheric Decomposition (ITD) model separates stratified and turbulent signals from tropospheric total delays, and generates high spatial resolution zenith total delay and/or precipitable water vapour maps to be used for correcting InSAR measurements and other applications.

The research has been published in the Journal of Geophysical Research¹. This research also forms the basis of the InSAR atmospheric correction model being developed by the Looking inside the Continents from Space project (LiCS), incorporating continuous and global tropospheric delay datasets (e.g. numerical weather models).

A web-based toolbox (GACOS: Generic Atmospheric Correction Online Service for InSAR) has been developed, in which ITD is employed to generate high-resolution water vapour or tropospheric delay maps for InSAR correction. GACOS was released online at the 2017 FRINGE workshop in Helsinki, Finland on 6 June 2017².

1. Yu, C., N. T. Penna, and Z. Li (2017), Generation of real-time mode high-resolution water vapor fields from GPS observations, J. Geophys. Res. Atmos., 122, 2008–2025 <http://onlinelibrary.wiley.com/doi/10.1002/2016JD025753/full>
2. <http://ceg-research.ncl.ac.uk/v2/gacos/>

Digital Elevation Model of the epicentral area of the 2016 Amatrice earthquake, Italy (Richard Walters, Durham)

New Pleiades tri-stereo imagery of the epicentral area of the 2016 Amatrice, Italy, earthquake acquired through the Committee on Earth Observation Satellites (CEOS) Seismic Risk Pilot was used to construct a high-resolution (~1 m) Digital Elevation Model (DEM).

The DEM was provided to groups at the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Rome) and COMET (Leeds) to aid investigators working in the field in the epicentral area of the earthquake. The intention is to make the DEM publicly available in due course.



Aerial images show the extent of the damage in Amatrice following the 2016 earthquake. Credit: AP/BBC



Surveying damage on the road

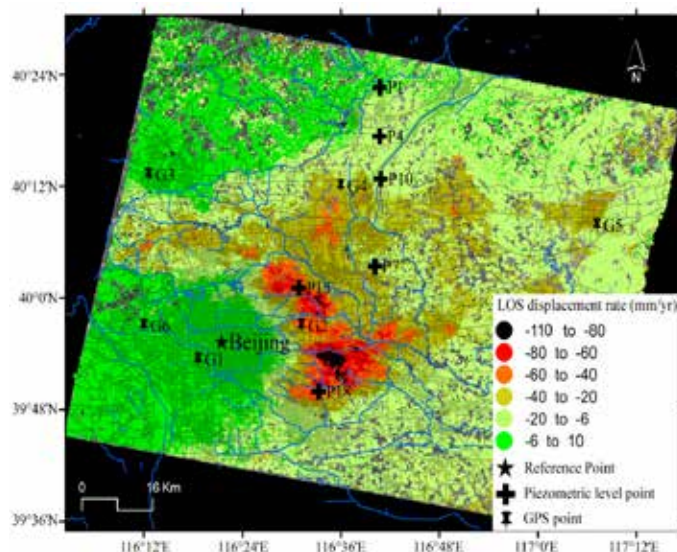
IMPACT AND INFLUENCE

COMET continues to work with governments, Non-Governmental Organisations (NGOs) and other partners to ensure that our science has real impact, shaping policy decisions and managing natural hazards.

Locko Neuberg, Professor of Physical Volcanology at Leeds, focuses on the monitoring, modelling and interpretation of volcanic signals. He has developed several conceptual models to explain volcanic seismicity, and since 2014 has been chairman of the Scientific Advisory Committee (SAC) that advises the British Government and the Government of Montserrat on volcanic activity on Montserrat. Further details are set out in the Research Highlight "**Montserrat continues to inflate**" on page 40.

COMET also contributes to the Committee on Earth Observation Satellites (CEOS) working group on disasters³, helping to establish and implement both the volcano and seismic risk pilot projects. We used the CEOS seismic pilot to obtain vital high-resolution topographic data for the 2016 Amatrice, Italy earthquake.. We have used data from the CEOS volcano pilot in collaboration with volcano observatories in Latin America to investigate the relationship between uplift and a moderate earthquake during unrest at Chiles-Cerro Negro volcanoes (Ecuador-Colombia), to investigate topographic change associated with the long-lived eruption of Monserrat (West Indies) and to study the decaying extrusion rate at Reventador (Ecuador).

We are also working closely with scientists in the Global Earthquake Model (GEM), in particular on developing methodologies for incorporating InSAR data into the Global Strain Rate Model (GSRM), which currently only uses GNSS data, on simulations of the impact of earthquake scenarios, and on the incorporation of COMET's fault data from Central Asia. As part of the Global Volcano Model (GVM) we have set up a Global Volcano Deformation Task Force to collate observations of volcano deformation.



Mean line-of-sight displacements derived from Envisat (2003-2010) in the Beijing Basin

Elsewhere, the tools and techniques developed by COMET researchers are being applied more widely to address societal challenges. Beijing is one of the most water-stressed cities in the world. Due to over-exploitation of groundwater, the Beijing region has been suffering from land subsidence since 1935. Newcastle's Zhenhong Li contributed to a study which used the Small Baseline InSAR technique to process satellite images acquired between 2003 and 2011, allowing investigation of land subsidence in the Beijing region⁴.

Maximum subsidence was seen in the eastern part of Beijing (over 100 mm/year), with a good correspondence between both the two sets of satellite measurements (Envisat and TerraSAR-X), and InSAR and GPS derived subsidence rates. This shows how InSAR is a powerful tool for monitoring land subsidence, as well as identifying the main triggering factors of land subsidence: there were some interesting relationships between land subsidence and groundwater level, active faults, accumulated soft soil thickness, and different aquifer types and distances to pumping wells.

This work has attracted the attention of a wide range of prestigious international media (e.g. The Guardian, The Telegraph, Huffington Post, Forbes and the BBC), and is ranked in the top 5% of all research outputs tracked by [Altmetric](https://www.altmetric.com/)⁵, with a score of 378 at the time of writing.



It was also selected by the Multidisciplinary Digital Publishing Institute (MDPI) as one of the top ten published articles in 2016⁶. The score reflects all conversations surrounding the research, from social media sites, newspapers, blogs and many other sources.

3. <http://ceos.org/ourwork/workinggroups/disasters/>

4. Chen, M., Tomás, R., Li, Z., Motagh, M., Li, T., Hu, L., Gong, H., Li, X., Yu, J., Gong, X. (2016) Imaging Land Subsidence Induced by Groundwater Extraction in Beijing (China) Using Satellite Radar Interferometry, Remote Sens. <http://www.mdpi.com/2072-4292/8/6/468>

5. <https://mdpi.altmetric.com/details/8441790#score>

6. <http://blog.mdpi.com/2017/02/20/mdpi-altmetrics-top-10-published-articles-in-2016>

COMET InSAR Training Workshop (Jonathan Weiss, Leeds)

October 2016 saw the first COMET InSAR training workshop, held at the University of Leeds. The workshop was aimed at postgraduate students and early career scientists interested in incorporating InSAR data into their research.

Over 50 people attended the 3-day event, which combined informal lectures with practical exercises covering a variety of InSAR-related topics. Around half of the attendees were associated with COMET, with others coming from a variety of UK and EU institutions, as well as Taiwan and Japan. Most of the attendees were PhD students, researchers/technicians and postdoctoral researchers.

The opening lecture on InSAR background and basics was followed by a practical exercise in using recently acquired Sentinel-1 SAR imagery to create a coseismic interferogram for the region affected by the 2016 Amatrice earthquake.

This was followed by a lecture on InSAR data preparation, processing, and software. Day two began with InSAR time series analysis and a practical exercise using Sentinel-1A data acquired over Mexico City between late 2014 and early 2015, plus a lab exercise on modelling and reducing atmospheric InSAR noise using both empirical and weather model-based techniques.

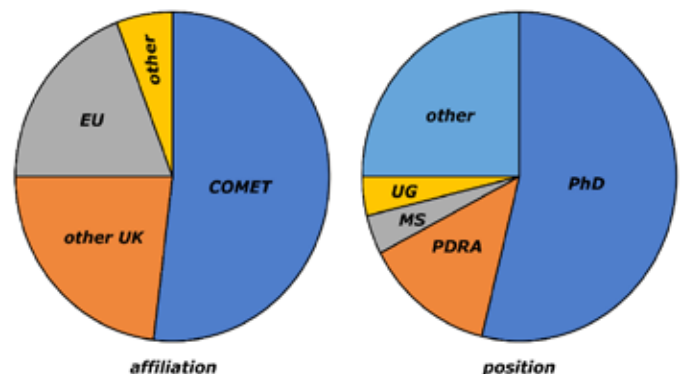
The third day included modelling InSAR-derived displacement fields, with modules on interseismic, coseismic, and volcano deformation. The workshop concluded with an introduction to Bayesian modelling of InSAR-derived surface displacement fields.

Feedback on the workshop was overwhelmingly positive. Perhaps unsurprisingly, one of the most popular events was the curry on the second night! Participants also particularly enjoyed the practical exercises related to modelling of surface displacement fields and Sentinel-1 data processing. The consensus was that they would be able to incorporate their learning into their own research, aided by all the material being made available online.

Many thanks to all who attended and helped organise the workshop. We plan to hold similar InSAR-related training events in October 2017.

COMET researchers also contributed to several other training courses during 2016/17, including ESA's Advanced Training Course on Remote Sensing of the Cryosphere, which covered SAR and InSAR theory, the UNAVCO InSAR course, which covered basic and advanced InSAR theory as well as several InSAR processing techniques (both Andy Hooper, Leeds), and the first Tenerife International Training Course in Volcano Monitoring, sponsored as an official course for La Laguna University (Spain)⁷ (Pablo González, Liverpool).

COMET InSAR Training Workshop Attendance



Left: Approximately half of the attendees were associated with COMET; others came from a variety of UK and EU institutions, with two participants from Taiwan and one from Japan. Right: The majority of attendees were PhD students, researchers/technicians (other), and postdoctoral research associates (PDRA). Two undergraduate (UG) and two Masters (MS) geophysics students also attended



Interferogram creation tutorial on day 1. Yu Zhou (Oxford) is pleased with his newly created Sentinel-1 derived Amatrice earthquake coseismic interferogram

7. <http://www.involcan.org/tenerife-international-training-course-on-volcano-monitoring/>

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BGA-COMET GPS Training Workshop (Juliet Biggs, Bristol)

COMET and the British Geophysical Association (BGA) sponsored a training course in May 2017, hosted by the University of Bristol, on using the GAMIT/GLOBK software suite to process raw GPS data. This was the second time this course had been run in the UK, following requests for a repeat of the successful 2015 event, which attracted participants from all over Europe.

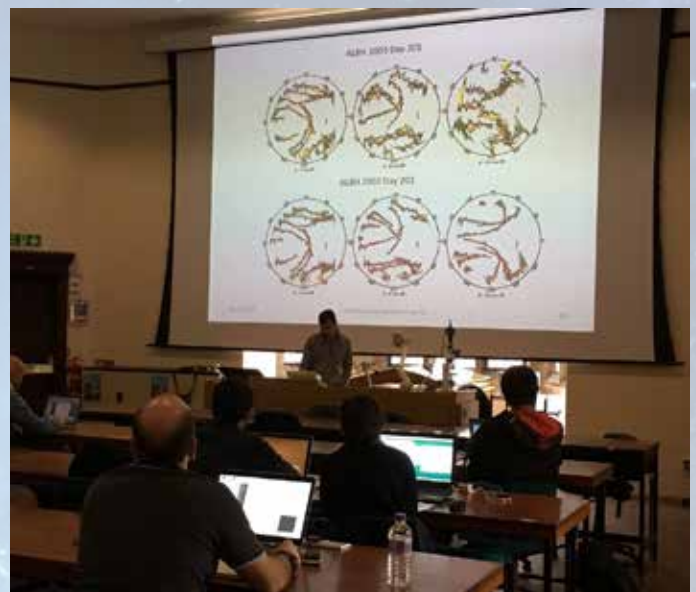
The course was led by Dr Michael Floyd, a Research Scientist at the Massachusetts Institute of Technology (MIT) in the United States, where the software is maintained and developed.

In total, 12 people participated in the course, of whom five are graduate students in geophysics at UK universities, with the rest being researchers at institutions in the UK, France, Italy and the Czech Republic.

The course consisted of a series of lectures on the theoretical fundamentals of GPS data processing and the practical use of the software, plus hands-on tutorial sessions where the participants progressed towards their own scientific goals using their own GPS data. The lectures covered GPS data file formats and translations for input to GAMIT, basic GPS phase data processing using GAMIT, time series and velocity product generation using GLOBK, and the principles of error analysis at each of these stages. There was also an opportunity to view and experiment with GPS field equipment.

The week was a resounding success – Dr Floyd commented on the strong progress by the course participants, and the immediate verbal feedback from the participants was very positive. We have already received enquiries about similar courses in the future, with several participants expressing an interest in sending their colleagues and students.

The course schedule and lecture material can be accessed online⁸.



BGA-COMET GPS Training Workshop

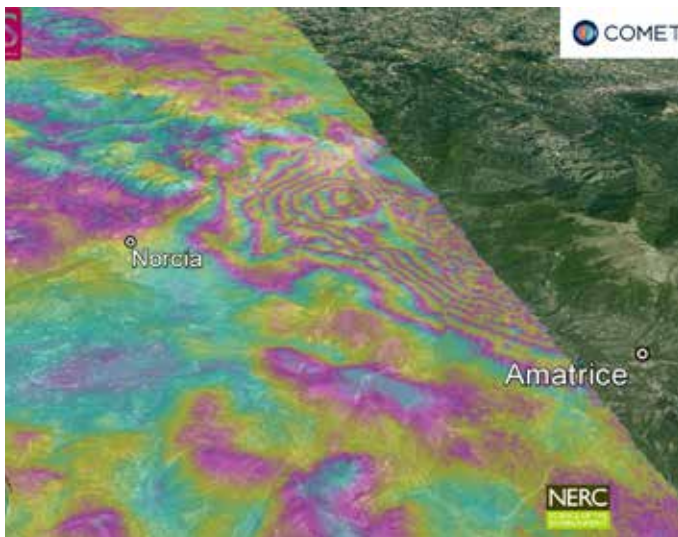
8. http://web.mit.edu/mfloyd/www/courses/gg/201705_Bristol/

COMMUNICATION, OUTREACH AND ENGAGEMENT

We want people from all parts of society to understand our science and appreciate the direct role that it can play in their lives. We also want to share our enthusiasm for studying this dynamic planet, inspiring the next generation of Earth scientists.

We work closely with the mainstream media to explain how our research is shedding light on seismic events: coverage of our work on the Apennines earthquakes, led by Laura Gregory (Leeds) and Richard Walters (Durham) appeared in the mainstream media and was featured regularly on the BBC website, as well as being the subject of BBC radio interviews.

Work by John Elliott and Tim Wright (both Leeds) on the Kaikoura earthquake in New Zealand, one of the most complex and comprehensively recorded earthquakes in history, also received significant media attention. A key message was the need for a rethink on how earthquakes are expected to behave in high-risk regions.



Sentinel-1 interferogram of the ground deformation around Norcia and Amatrice due to the 24 August earthquake



Ground uplifted by the Kaikoura earthquake. Credit: John Elliott

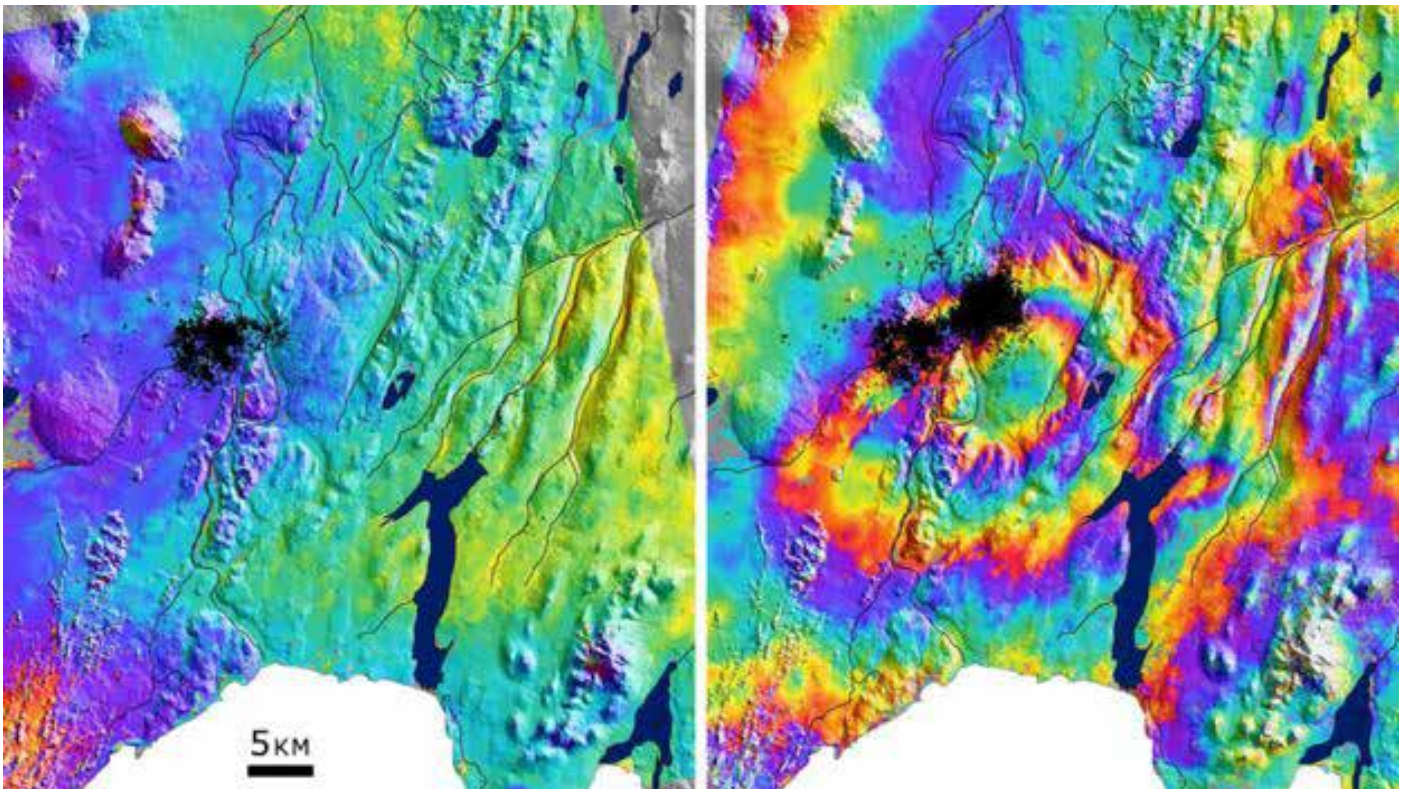
According to Altmetric, the Hamling *et al.* paper on complex multifault rupture during the 2016 Mw 7.8 Kaikoura earthquake, New Zealand⁹, published in March 2017, has a score of 328, placing it in the top 5% of all research outputs scored by Altmetric, including coverage by 28 news outlets¹⁰. COMET's use of Sentinel-1 data to monitor global volcano deformation, led by Andy Hooper and Juliet Biggs, meanwhile featured on BBC News at Ten, as well as Radio 4's Inside Science and The World Tonight, the World Service's Science in Action and Science Hour, and numerous international science websites.

Aerial view of the Earthquake Faultline and slips in a Mountain Valley behind the town of Kaikoura, New Zealand



9. Hamling *et al.* (2017) Complex multifault rupture during the 2016 Mw 7.8 Kaikōura earthquake, New Zealand, *Science* <http://science.sciencemag.org/content/356/6334/eaam7194>
 10. <https://www.altmetric.com/details/18042703>

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



This image shows a volcanic region in the north of Iceland. Sentinel-1 senses ground movement as magma rises up from deep in the Earth, and surface bulging becomes apparent by comparing images taken in a sequence. The left hand picture shows a time just as activity is about to get underway; on the right, the ground is lifting and quakes are increasing (black dots). Credit: ESA/Sentinel-1/COMET

As well as the mainstream media, our work is highlighted in review articles aimed at informing undergraduate students and more specialist audiences of the latest findings and new perspectives. The February 2017 issue of *Elements on Volcanoes: From Mantle to Surface*¹¹ included articles by Juliet Biggs and Matt Pritchard (Bristol) on monitoring volcano deformation with InSAR, and Marie Edmonds (Cambridge) on the role of volatiles in magma dynamics and eruption style. The April 2017 issue on Sulfides¹² meanwhile included an article by Marie and Tamsin Mather (Oxford) on volcanic sulfides and outgassing.

Other review articles were published in *Nature Communications* (see “**The golden age of tectonic remote sensing**” on page 32) and *Eos*, the American Geophysical Union’s Earth and Space Science news journal (on the origins of Kazakhstan’s 1889 Chilik earthquake¹³).

11. <http://elementsmagazine.org/past-issues/volcanoes-from-mantle-to-surface/>

12. <http://elementsmagazine.org/past-issues/sulfides/>

13. <https://eos.org/research-spotlights/tracking-down-elusive-origins-of-kazakhstans-1889-chilik-quake>

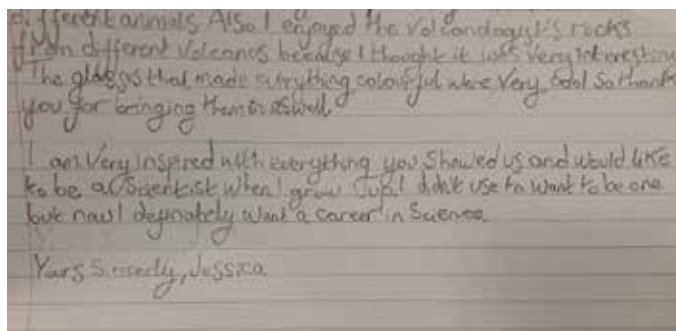
We want to raise scientific aspirations in schools, and bring scientific innovation to public audiences. Here are just a few of our efforts:

COMET's Laura Gregory, Marco Bagnardi and Ruth Amey took part in the 2016 Leeds Pint of Science Festival, where they presented the latest research on the dynamic Earth in a most accessible setting – the pub. Topics included the unpredictable nature of earthquakes, with Laura explaining how tracking past earthquakes can help to forecast them in the future; and Marco describing how we can look inside magma chambers lying several kilometres beneath the Earth's surface from space. Ruth Amey also worked with the [ParsQuake](#)¹⁴ team to produce a video explaining the relationship between faults and earthquakes. ParsQuake develops, implements, and distributes earthquake education packages all around Central Asia and beyond.

And across COMET, our researchers visit local schools to share our enthusiasm for volcanoes and earthquakes at all stages of the curriculum.

In Oxford, David Pyle curated an [exhibition on volcanoes at the Bodleian Libraries](#)¹⁵ accompanied by his book, [Volcanoes: encounters through the ages](#)¹⁶.

The exhibition pulled together eyewitness accounts, scientific observations and artwork to demonstrate how our understanding of volcanoes has evolved over the past two millennia. It was chosen by The Guardian as one of the best art and design exhibitions of 2017.



Also tackling volcanoes, this time on screen, Clive Oppenheimer (Cambridge) collaborated with director Werner Herzog to create the Netflix original film *Into the Inferno*. The film follows the team to active volcanoes in Indonesia, Iceland, North Korea and Ethiopia as they explore the pivotal role that volcanoes have played in shaping societies. *Into the Inferno* had its world premiere at the Telluride Film Festival in September 2016, and also screened at the Toronto International Film Festival before being released on Netflix in October 2017.



Illustration of the 1783 eruption of Mount Asama from Illustrations of Japan by Isaac Titsingh



Clive Oppenheimer and Werner Herzog on Vanuatu's Mount Yasur. Credit: Clive Oppenheimer

We also reach a wide audience through our website¹⁷, which has had over 50,000 views, and via twitter¹⁸ (over 1,000 followers).

14. <https://www.youtube.com/watch?v=GOScTDipA6E>

15. <http://www.bodleian.ox.ac.uk/whatson/whats-on/upcoming-events/2017/feb/volcanoes>

16. <http://www.bodleianshop.co.uk/volcanoes.html>

17. <http://comet.nerc.ac.uk>

18. https://twitter.com/nerc_comet?lang=en - @NERC_COMET

OUR 2016/17 OBJECTIVES

In July 2016, COMET set out a number of objectives for the coming year, in consultation with our Advisory Board. Progress updates are provided below.

CONTINUE THE DEVELOPMENT OF THE COMET/LiCS InSAR PROCESSING SYSTEM AND INSTALL AT CEMS. OPENLY RELEASE FIRST INTERFEROGRAM PRODUCTS

Emma Hatton, InSAR Facility Manager, Leeds

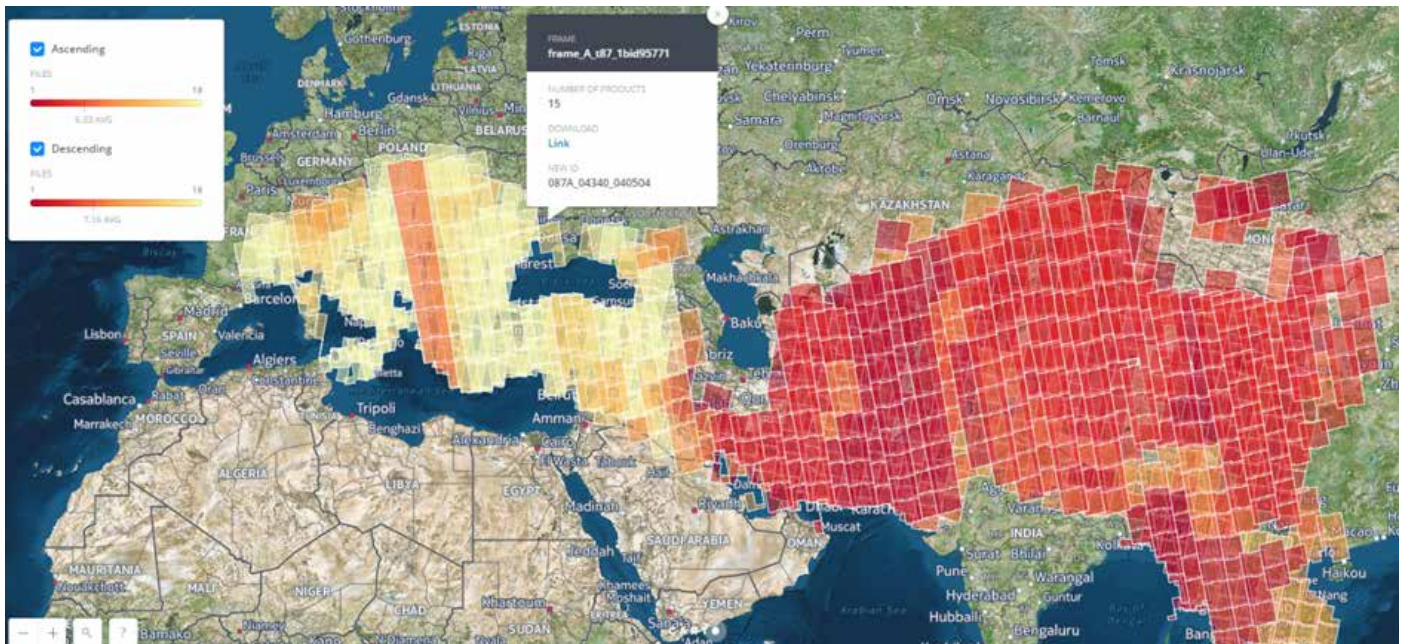
Significant progress has been made on the development of the COMET/LiCS InSAR processing system at CEMS¹⁹, The Climate, Environment and Monitoring from Space facility at the UK Satellite Applications Catapult.

One of the key obstacles to processing data automatically has been the image slicing strategy applied to the SAFE format products which sometimes results in different geographic coverage between repeat pass acquisitions.

This has been mitigated by recording details of all available Sentinel-1 data in a database. Bespoke images can then be formed from the bursts. A set of bespoke image frames has been defined globally and these can be “switched-on” for processing very easily.

The initial processing has been confined to approximately 1000 of these frames over the Alpine-Himalayan Belt and data are available from September 2016 at present. We are processing ~2000 interferograms per day. Interferograms and coherence images for the processed frames are available via the [COMET-LiCS Portal](http://comet.nerc.ac.uk/COMET-LiCS-portal/)²⁰.

Work continues on the development of the processor, but the but the complex database and daemons required to automate the process are now implemented.



Screenshot of the COMET-LiCS Portal, focusing on the Alpine-Himalayan Belt

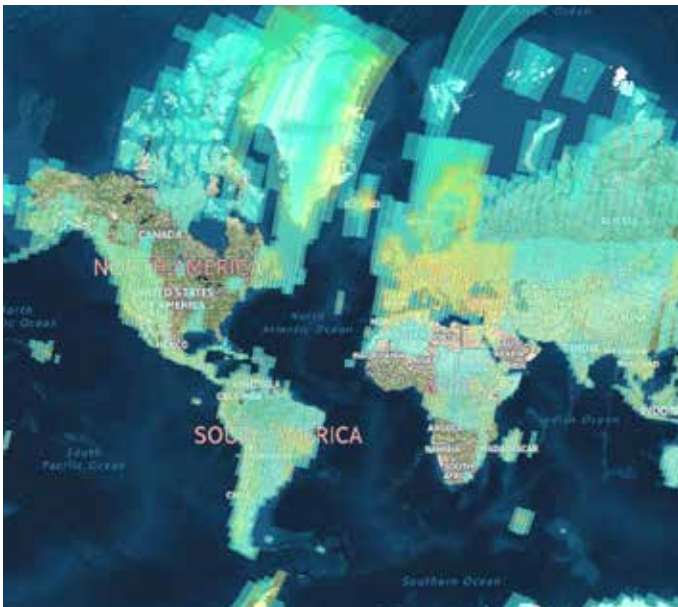
19. The Climate, Environment and Monitoring from Space facility at the UK Satellite Applications Catapult, <https://sa.catapult.org.uk/facilities/cems/>

20. <http://comet.nerc.ac.uk/COMET-LiCS-portal/>

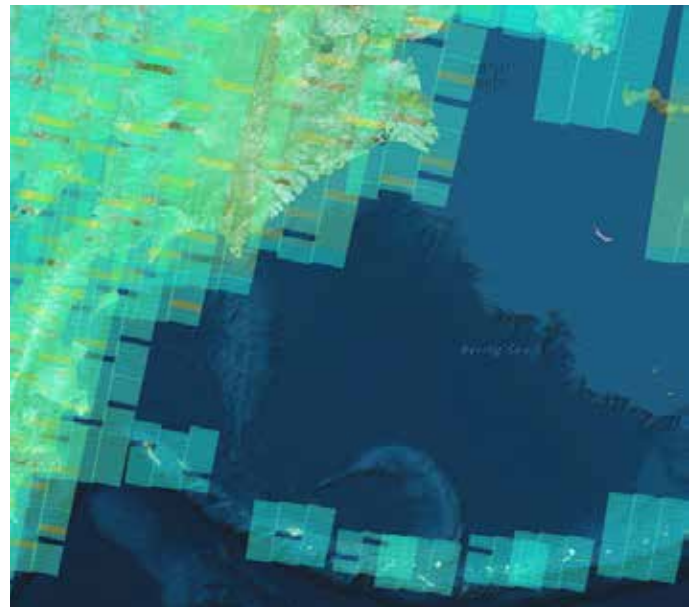
INFLUENCE ESA'S ACQUISITION STRATEGY FOR THE SENTINEL-1 CONSTELLATION BY EXAMINING CURRENT ACQUISITIONS AND CHARACTERISING COHERENCE IN SPACE AND TIME

Emma Hatton, InSAR Facility Manager, Leeds

Working towards the goal of influencing the acquisition strategy for Sentinel-1, a density map of Sentinel-1 acquisitions was prepared prior to the launch of Sentinel-1B. Areas with a higher number of acquisitions are shown in yellow (map shows descending scenes only).



Density map of Sentinel-1 acquisitions



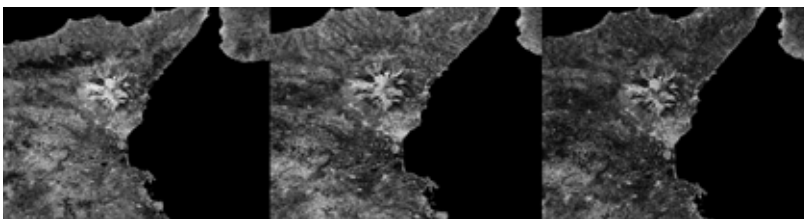
Missing bursts between adjacent scenes

This map also revealed where the ESA processor was affected by a possible rounding error in the slicing strategy which resulted in missing bursts between adjacent scenes.

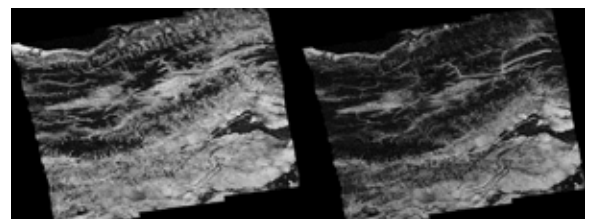
Although this issue was already known, information was passed to the Sentinel-1 Quality Control Team to help identify which areas needed to be corrected.

As larger areas are processed automatically, the coherence of the data can be examined and information fed back to ESA.

Initial results are available over the Alpine-Himalayan Belt. The examples below show Etna at 12, 18 and 24 days, and the edge of the Tien Shan Mountain Range at 24 and 48 days.



Mount Etna eruption (12, 24, 48 days)



Tien Shan (24, 48 days)

ESA's acquisition strategy has now been updated – data will be available for the entire land surface at least every 12 days on a single pass, and in tectonic/volcanic areas. Data will be acquired on ascending and descending passes, at least every 12 days. Ongoing work will refine the acquisition strategy.

EVALUATE METHODS FOR INTEGRATION OF InSAR AND GNSS DATA FOR THE DERIVATION OF HIGH RESOLUTION CRUSTAL VELOCITY AND STRAIN FIELDS

Jonathan Weiss, COMET Researcher, Leeds

The ongoing densification of GNSS networks, combined with rapidly advancing InSAR data and processing techniques, have improved our ability to confidently measure Earth surface motions, identify areas of localized crustal strain, and place constraints on how often earthquakes can occur in a region.

However, most existing strain rate maps still rely solely on sparse, point-based surface velocity measurements (GNSS/GPS) and not the improved spatial resolution provided by InSAR. Combining these complementary data and determining the optimal method to derive velocity and strain rate fields is not straightforward.

To date we have taken two approaches to merging the geodetic datasets including (1) decomposing InSAR line-of-sight velocities into horizontal and vertical components using the smoothed GNSS velocities to constrain the north-south motion and (2) jointly inverting the two types of data for the two- or three-dimensional velocity field.

In parallel, we continue to evaluate methods for deriving continuous velocity and strain rate fields.

Some of the associated results, challenges, and future goals are presented in the Research Highlight “**Combining InSAR and GNSS data to map surface velocities, strain rates, and seismic hazard across the Alpine Himalayan Belt**” on page 48.



PRODUCE COUNTRY-SCALE VELOCITY AND STRAIN MAPS FOR PARTS OF THE ALPINE-HIMALAYAN BELT

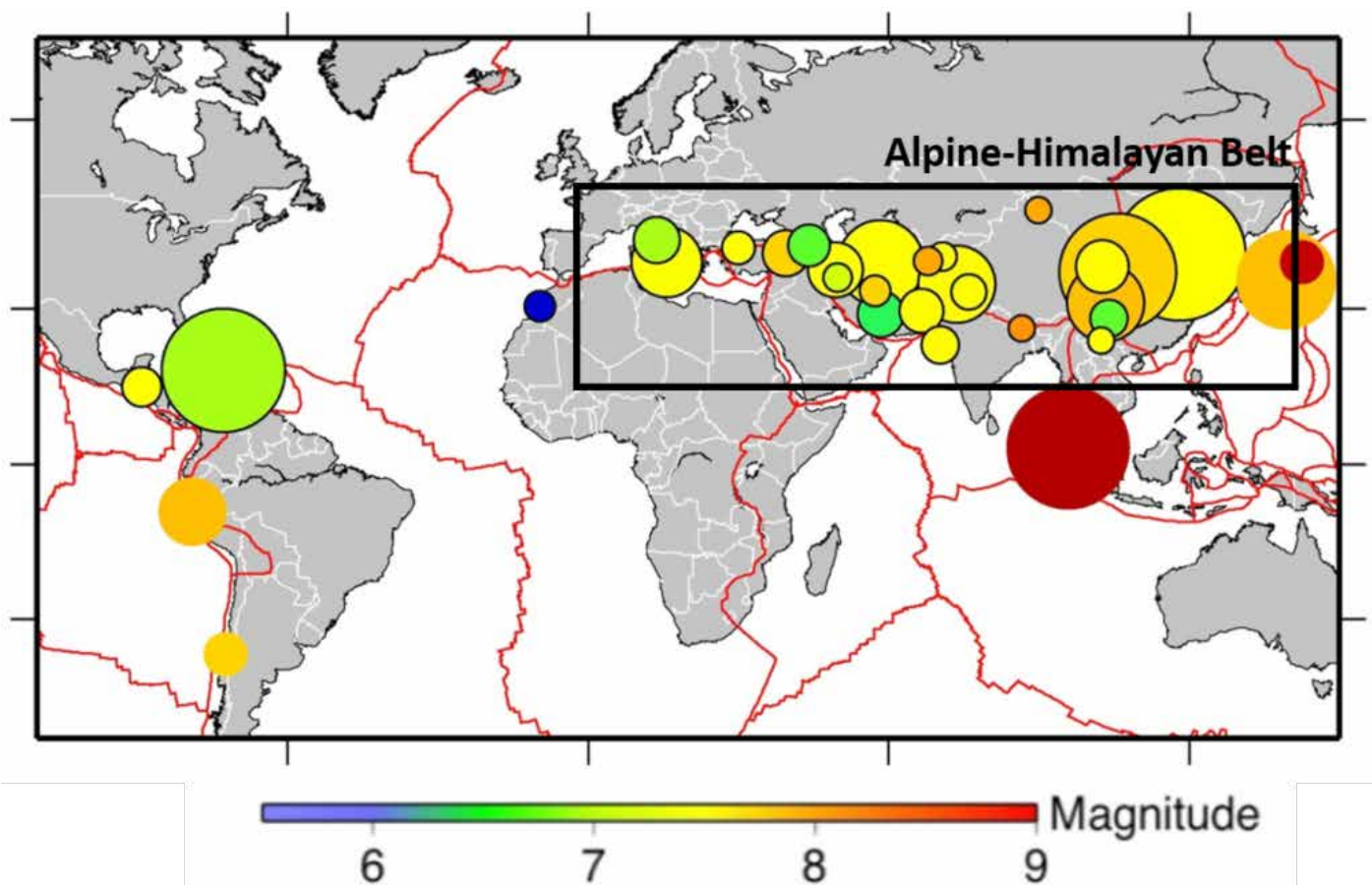
Jonathan Weiss, COMET Researcher, Leeds

We have chosen Anatolia as a test site for evaluating geodetic data integration and velocity/strain mapping methods. Preliminary results, which include country-scale velocity and strain maps, are presented in the Research Highlight “Combining InSAR and GNSS data to map surface velocities, strain rates, and seismic hazard across the Alpine Himalayan Belt” on page 48.

The associated maps were created using a global compilation of GNSS-derived surface velocities (Kreemer *et al.*, 2014) and InSAR observations acquired by Envisat between 2002 and 2010 (Ekbal Hussain, pers. comm.).

We have also used the first 2.5 years of Sentinel-1 mission data to measure crustal velocity for most of Turkey and we are currently incorporating these results into our analysis.

As we systematically generate interferograms and crustal velocities for portions of the Alpine-Himalayan Belt using the COMET/LiCS InSAR processing system (see above) we will quickly expand our strain and earthquake hazard mapping efforts beyond the Anatolian microplate.



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

Austin Elliott, COMET Researcher, Oxford

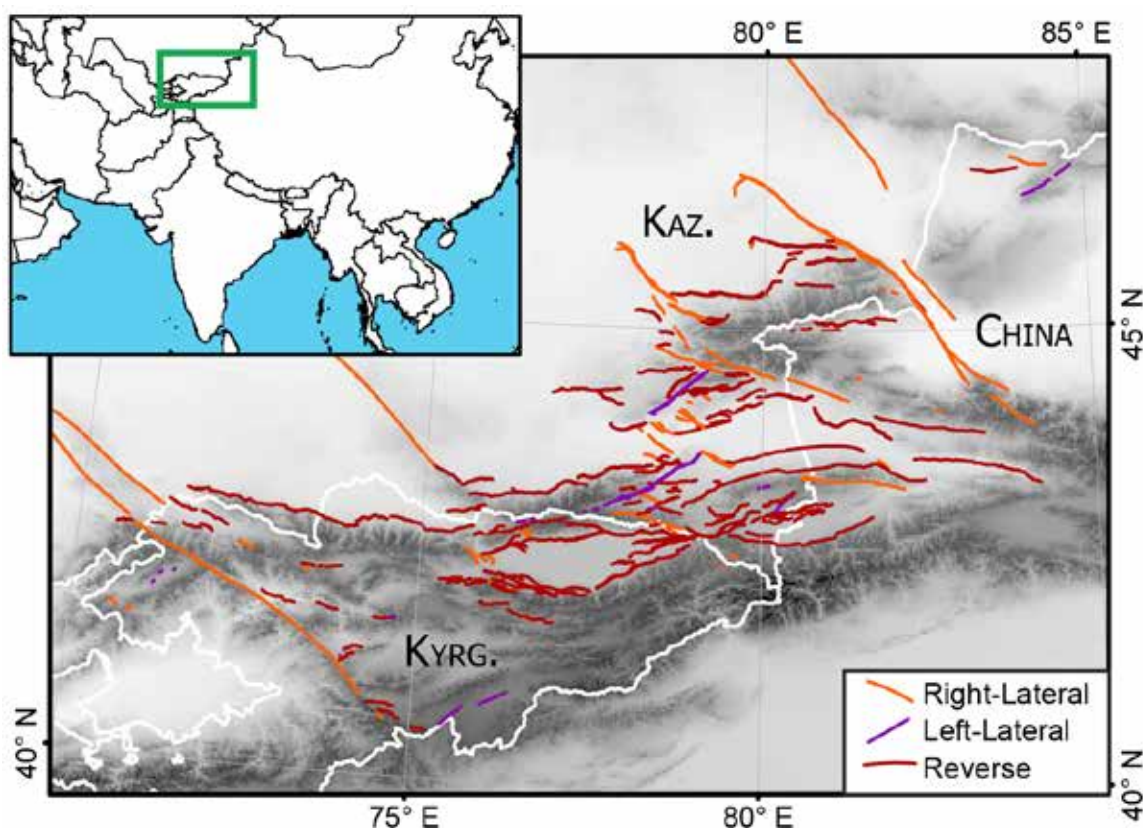
A geographic database of active faults in northern Central Asia has now been assembled, comprising 40 named major faults and over 100 other fault segments. These have been mapped in detail by COMET researchers using a combination of high resolution imagery, topography, and field work.

This database will be used to consolidate and unify the representation of known active faults in the Tien Shan, to disseminate the results of paleoseismic, neotectonic, and structural investigations of these faults undertaken by COMET researchers, and to support a robust regional model of strain accumulation and release in this region of high seismic hazard.

The Tien Shan dataset includes faults mapped in Kyrgyzstan and southern Kyrgyzstan by several members of the COMET team, and has been structured to incorporate scientific details such as rupture age and long-term slip rate on each of the faults where these have been determined.

The dataset is maintained as an ArcGIS geodatabase, and can be easily converted to a variety of alternative formats for dissemination to a range of users and software programs.

By attending and hosting a series of workshops with global colleagues, COMET researchers are also devising strategies for incorporating new or unpublished data into this database to ensure both scientific quality and broad utility for regional seismic hazard applications. In the coming year the fault mapping will be refined based on collective expertise, and the database will be populated with up-to-date scientific results about each studied fault.



Faults mapped by COMET researchers comprising the Tien Shan portion of the COMET Central Asia Fault Database



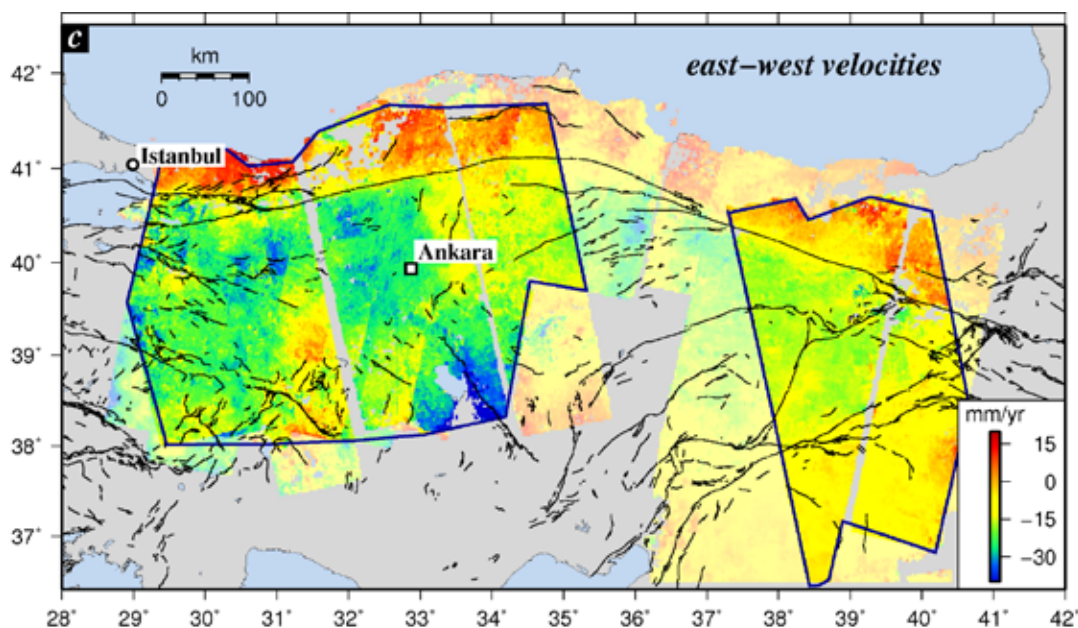
*Tien Shan range of northwestern China
near the border with Kazakhstan and
Kyrgyzstan. Credit: ESA*

USE OBSERVATIONS OF STRAIN, FOR EXAMPLE ALONG THE NORTH ANATOLIAN FAULT, TO CONSTRAIN MODELS OF THE ENTIRE EARTHQUAKE DEFORMATION CYCLE

Ekbal Hussain, COMET PDRA, Leeds

Ekbal Hussain studied the rate of strain accumulation along the entire North Anatolian Fault as the final component of his PhD. He estimated shear strain rates along the fault by combining data from GNSS and InSAR, which enabled him to sample strain rates at times ranging from 1 month to 240 years after the most recent earthquake.

The data were incompatible with simple viscoelastic coupling models of the entire earthquake cycle if the substrate has a uniform Maxwell rheology, and instead require a weak fault zone embedded within a stronger lower crust. The results also support the notion that short-term geodetic observations can directly contribute to long-term seismic hazard assessment. A manuscript has been submitted for review.



East-West velocity of the Anatolia region, showing strain accumulation across the North Anatolian Fault

Istanbul and the Sea of Marmara (centre) and Bosphorus Strait. Turkey's location makes it vulnerable to earthquakes, with the 1000 km-long North Anatolian fault just 15 km south of Istanbul. Credit: ESA



USE THE SPATIAL DISTRIBUTION OF STRAIN AND TOPOGRAPHY TO MAP THE SPATIAL VARIATIONS OF LITHOSPHERE STRENGTH AND BASAL TRACTIONS IN EASTERN TIBET

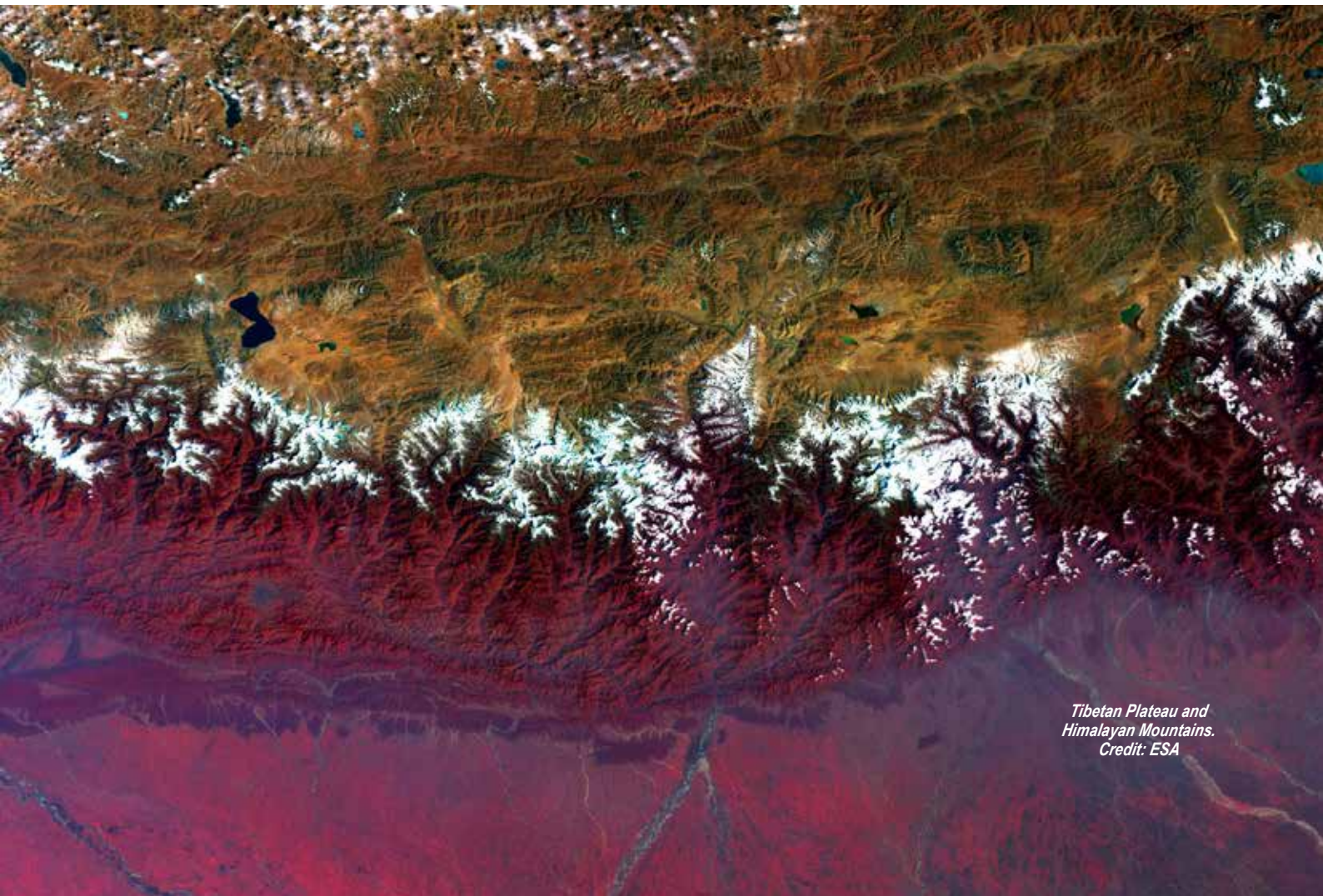
Alex Copley, COMET Scientist, Cambridge

Camilla Penney (PhD student, Cambridge) is leading a modelling project to investigate the effects of lateral variations in lithosphere rheology on the dynamics of continental deformation.

These lateral rheology variations are known to exist from the information provided by earthquake source studies, seismic tomography, and the analysis of gravity anomalies. However, due to simplifying assumptions, or unrealistic geometries or rheology, previous models of continental dynamics have not fully investigated the implications of our observations.

We are using a three-dimensional model that incorporates the rheological information provided by our independent observations. A new method of calculating the time evolution of the topography and strain has been developed.

The models indicate that whether the lowlands bounding a mountain range are formed of anhydrous cratons or volatile-rich young lithosphere controls whether the topography forms steep fronts or gentle slopes, and governs the relative importance of thrust, strike-slip, and normal faulting. The models therefore provide a means to estimate the rheology at depth (e.g. in the lower crust of mountain ranges) based upon the surface topography and surface strain.



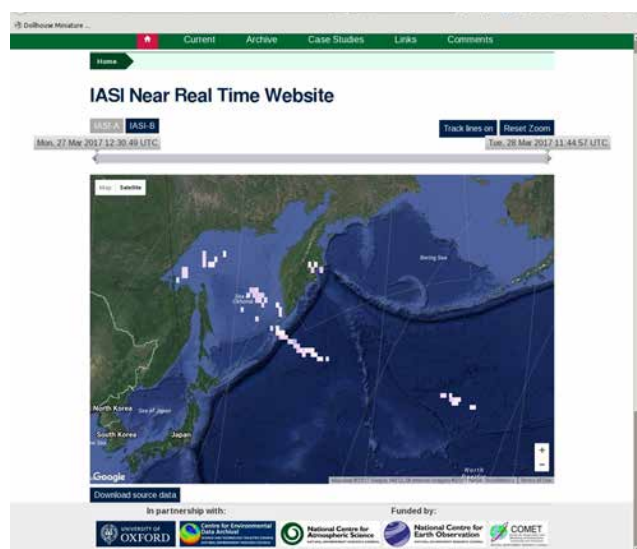
*Tibetan Plateau and
Himalayan Mountains.
Credit: ESA*

DEVELOP AND IMPLEMENT A VOLCANIC ASH FLAGGING ROUTING WITHIN THE COMET IASI NEAR REAL TIME SYSTEM

Elisa Carboni, COMET Researcher, Oxford

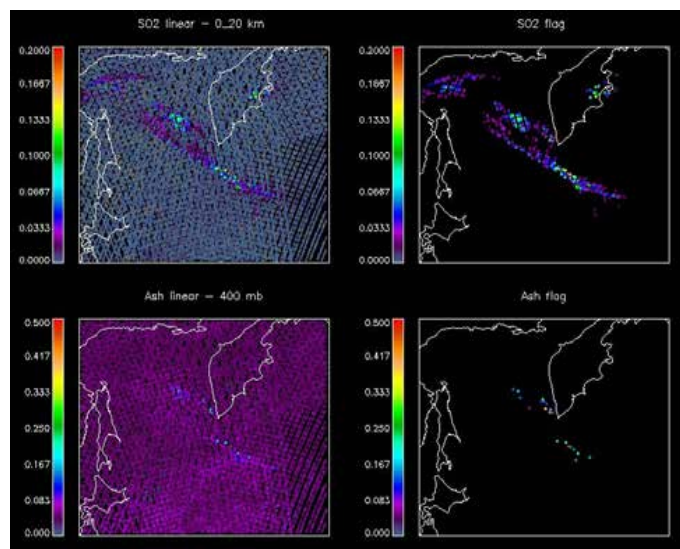
Our *Infrared Atmospheric Sounding Instrument (IASI) Near Real Time website*²¹ displays near real time (NRT) volcanic plume from IASI-A and IASI-B data and is refreshed as soon as a new part of the IASI orbit comes into the CEDA datacentre.

The web page displays volcanic SO₂ plumes and has also now been updated with NRT ash flag computation. IASI data are analysed assuming different altitudes for ash (400, 600 and 800 mb) and vertical distribution for SO₂ (between 0 and 20 km: 1-2 km, 4-5 km, 9-10 km, 14-15 km, 19-20 km). All analysed data are available for download, and the data format is netcdf to allow maximum portability.



The figure above shows the website display image on 28 March 2017, with the plume from the Kambalny eruption in the southern part of the Kamchatka Peninsula, Russia. Note the button 'Download source data' on the bottom left, where it is possible to download the data for SO₂ and ash with different vertical profile assumptions.

This figure shows (left) the SO₂ and ash linear retrieval using all IASI-B data within the previous 24 hours, and (right) the resulting pixels flagged as SO₂ and ash.



21. <http://www.nrt-atmos.cems.rl.ac.uk>

CARRY OUT A GLOBAL ASSESSMENT OF SO₂ VOLCANIC DEGASSING VISIBLE FROM SPACE

Elisa Carboni, COMET Researcher, Oxford

Monitoring SO₂ emissions offers insight into volcanic behaviour and is important for understanding the impacts of volcanism on the environment and climate. Despite this, many volcanoes have little or no ground based monitoring, and so satellite remote sensing is valuable for detecting and quantifying emissions.

Ultraviolet satellite based instruments are most commonly used for this purpose; however, there are advantages to using infrared sensors, such as they can monitor during the night and in some cases can simultaneously retrieve the concentration and altitude of the plume.

This study focuses on IASI, for which a number of SO₂ retrieval techniques have been developed, two of which have shown some promise at monitoring low level volcanic emissions.

Here, a 'fast' linear retrieval is applied across the globe to detect sources of SO₂. These results are dominated by emissions from explosive eruptions,

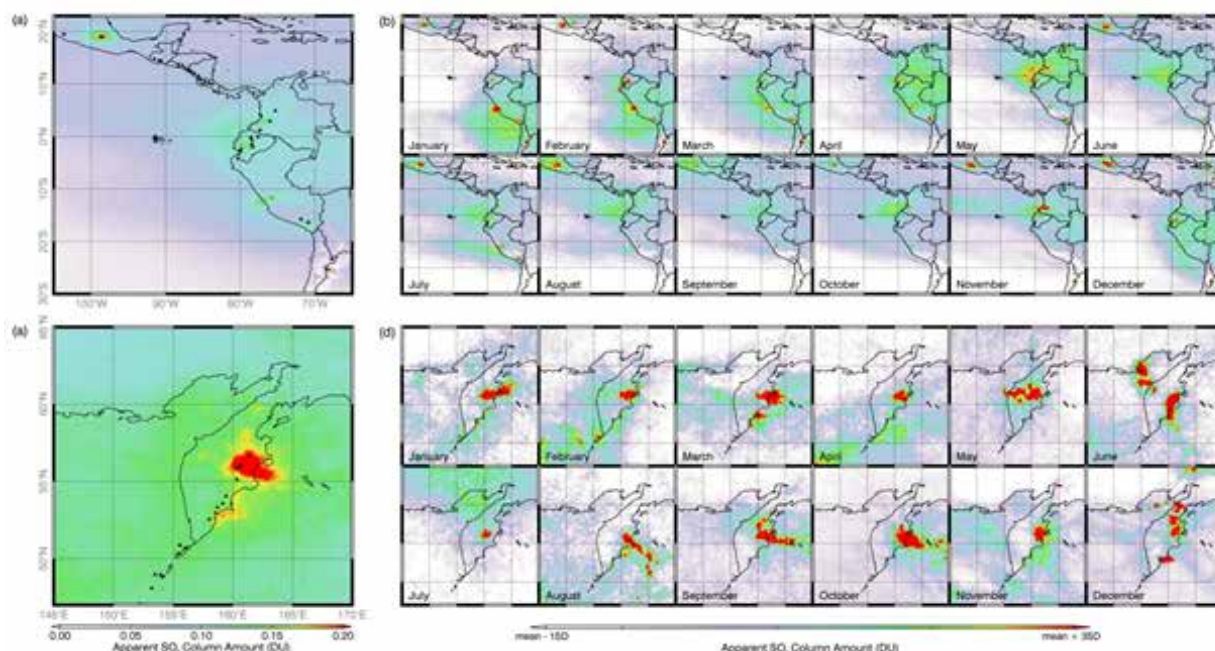
but signals are also evident from smaller eruptions and passive degassing, and from anthropogenic activity.

The figure below shows an example of the elevated levels of SO₂ that were frequently identified at volcanoes in Ecuador and Kamchatka, Russia, and so these areas were selected for further study with a 'full' iterative retrieval which is capable of quantifying the amount of gas emitted.

In both regions, the iterative retrieval captured changing activity which matched reports from the Global Volcanism Program.

At Tungurahua, a comparison between the IASI SO₂ amount and the quantity of SO₂ detected with the Ozone Monitoring Instrument, and ground based flux measurements was possible.

The results were promising with each instrument showing the same trends. These results demonstrate for the first time that IASI can be used to monitor smaller emissions of volcanic SO₂ into the troposphere, which if used alongside other datasets could be a valuable contribution to volcanic monitoring.



Linear retrieval output. (a) Yearly average over Central and South America in 2008. (b) 2008 monthly averages over Ecuador displayed with a colour bar ranging between one standard deviation below the mean to three standard deviations above the mean. (c) Yearly average over Kamchatka in 2010. Note the elevated background signal over the region. This is possibly linked to pollution over China being blown north-east with the prevailing wind. (d) As (b) for Kamchatka in 2010

This update is based on "Exploring the utility of IASI for monitoring volcanic SO₂ emissions", Isabelle A. Taylor, James Preston, Elisa Carboni, Tamsin A. Mather, Roy G. Grainger, Nicolas Theys, Silvana Hidalgo, and Brendan McCormick Kilbride, submitted to the Journal of Geophysical Research.

PRODUCE DOCUMENTATION, INCLUDING A USER MANUAL, FOR THE COMET BAYESIAN DEFORMATION MODELLING SOFTWARE, AND PROVIDE A BETA RELEASE TO SCIENTISTS OUTSIDE COMET

Marco Bagnardi, COMET Researcher, Leeds

The open source COMET Geodetic Bayesian Inversion Software (COMET-GBIS) was officially released to the scientific community on 31 May 2017. The version 1.0 of the software is available from its dedicated webpage²².

The software comes with a detailed user manual describing installation, data preparation, and use of the inversion algorithm. A practical example with three synthetic datasets, two InSAR interferograms and a set of GPS displacements, is also available for testing and to become familiar with the different functions of the software. The software is written in Matlab and each function is documented and fully commented.

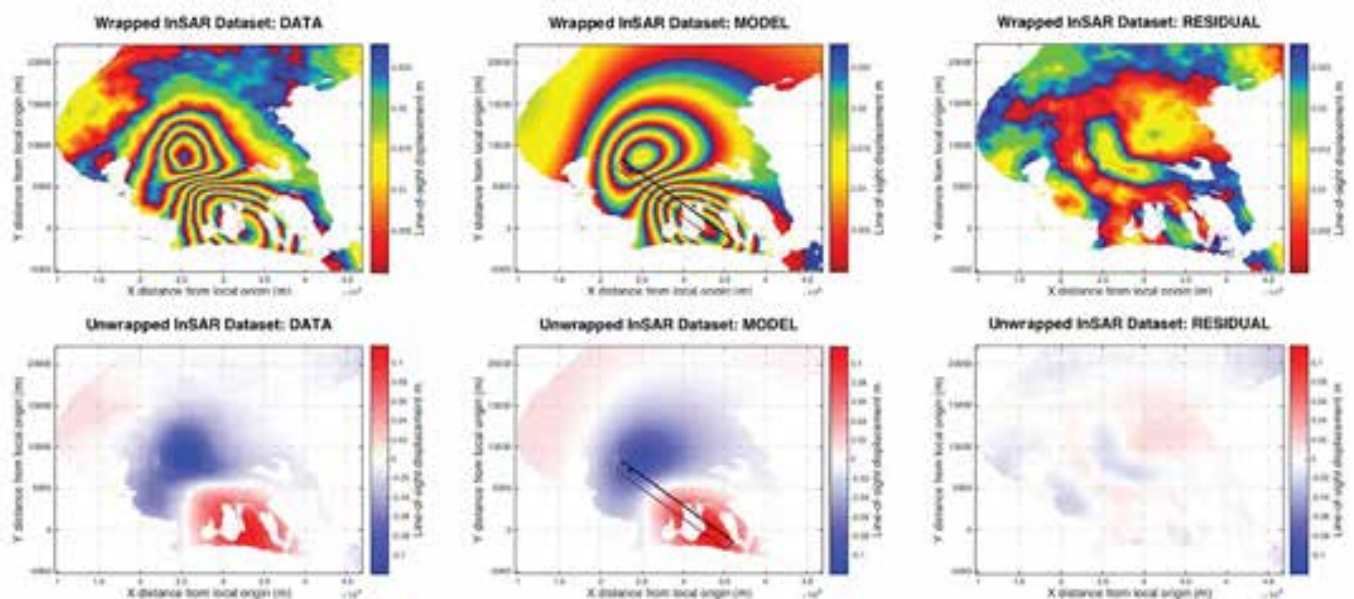
The COMET-GBIS software is designed for the inversion of InSAR and GPS data but can also be easily adapted for the use of other geodetic datasets. A user-friendly tool has been developed to estimate the characteristics of noise in InSAR data. Through an interactive interface, the user can manually select the portion of the image where an experimental variogram is estimated.

After ingesting the different datasets and subsampling spatially dense data (e.g. InSAR), the inversion software retrieves best-fitting source parameters and their full posterior probability density functions (PDFs). PDFs are sampled using a Bayesian approach based on a Markov-chain Monte Carlo algorithm, incorporating the Metropolis algorithm.

Once the inversion is completed, the software can generate a report containing the value of the optimal source parameters, their confidence interval and other statistics (e.g. mean and mode). The report also includes figures showing histograms for each PDF, joint probability plots between pairs of parameters, and comparisons between observations, predicted displacements, and residuals. The report is generated as an html file, ready for printing or web publishing.

The software has been tested by multiple COMET members and for different applications (volcano deformation, earthquakes). Its development will continue in the future to improve the capabilities of the software and to adapt it to new types of geodetic data. We aim to include routines to account for the topographic effect on surface displacements and to add new analytical and numerical forward models.

A scientific publication describing the principles on which the COMET-GBIS software is based is in preparation (Bagnardi and Hooper, in prep.).



Example of software output: comparison between observed InSAR data, modelled displacements, and residuals (difference between observed and modelled displacements)

FOR AT LEAST ONE VOLCANO, DEVELOP A COUPLED MODEL THAT PREDICTS GAS EMISSIONS, PETROLOGY AND GEOPHYSICAL MEASUREMENTS, AND INVERT TO FIND PROBABILITY DISTRIBUTIONS FOR MODEL PARAMETERS

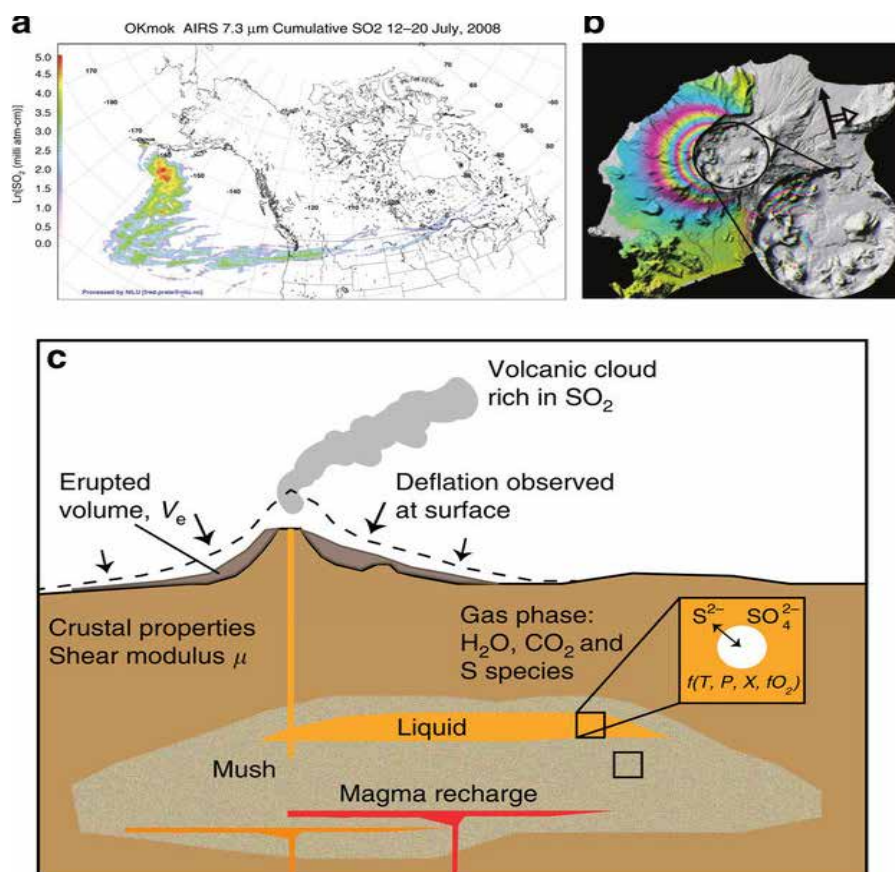
Andy Hooper, COMET Scientist, Leeds/Marie Edmonds, COMET Scientist, Cambridge

A model has been developed which couples thermodynamics with the physics of magma compressibility to understand ground displacements in tandem with gas emissions during discrete explosive eruptions²³.

The model calculates the quantity of exsolved gas (as sulfur gases, water and carbon dioxide) in equilibrium with melt at various pressures, oxidation states and compositions, then calculates the effect of this exsolved gas on the bulk modulus of the magma. The more exsolved gas in the magma, the more muted the ground deformation during eruption, owing to the magma expanding to buffer the volume changes caused by eruption. Using assumptions about the crustal properties (its elasticity), we can use this model to begin to understand the effect of volatiles on the ground displacements observed during eruptions using satellite-based techniques such as InSAR.

This is the first attempt to couple space-borne observations of SO_2 emissions with ground displacements during eruptions. Important results that emerged from the study were that magma compressibility is most sensitive to melt water content and chamber depth, and not carbon and sulfur-rich volatile phases. It is likely that gases accumulate at the roof zones of magma reservoirs in the crust, giving rise to small deformation sources, muted deformation, and high eruptive gas loadings.

Future work will involve applying these models to long-lived, recharging mush-rich magma reservoirs with non-elastic crustal properties (see the figure overleaf and also the Research Highlight **"Gas bubbles in magma strongly affect volcano deformation"** on page 56).



Example observations and a schematic illustration of the model underpinning the study: (A, B) Observations of the 2008 eruption of Okmok Volcano, Alaska, USA. (B) An interferogram generated using a pair of synthetic aperture radar images for the main phase of the explosive eruption between 12 and 13 July 2008 (B) an AIRS image to show the spatial extent and atmospheric concentrations of the SO_2 cloud generated by the explosive phase of the eruption. (C) Schematic diagram to show how sulfur partitions into the gas phase at depth, dependent on melt composition, pressure and oxygen fugacity. The gas phase causes the magma to be compressible, which gives rise to muted ground deformation in response to the evacuation of the magma reservoir during eruption

23. McCormick Kilbride, B., Edmonds, M., Biggs, J. (2016) Observing eruptions of gas-rich compressible magmas from space, Nature Communications <https://www.nature.com/articles/ncomms13744>

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

Juliet Biggs, COMET Scientist, Bristol

The COMET database has entries for over 1000 volcanoes and has already received over 50,000 hits from 13,000 unique visitors.

The website²⁴ provides information about observations of surface deformation at volcanoes around the world, guided by the Global Volcanism Program volcano list. All the volcanoes have a database entry detailing any recorded past deformation events, measured using satellite radar (InSAR) or ground-based methods (e.g., GPS, levelling or tilt). Looking forward to 2017/18, each volcano entry will also be updated with the most recent processed InSAR image using data from Sentinel-1.

CONTINUE THE DEVELOPMENT OF A LOW-COST GNSS SENSOR NETWORK FOR AUTONOMOUS REAL-TIME DEFORMATION MONITORING

Marek Ziebart, COMET Scientist, UCL

COMET UCL is developing low-cost GNSS sensors that are capable of measuring ground displacements with centimetre-level precision. It is envisaged that several of these will be deployed as a network.

Much of the work so far has involved testing different methods of data streaming and power consumption under several different configuration settings, and current trials are assessing the performance of two prototype sensors in terms of precision over different baseline lengths and power consumption. A full update is provided in the Research Highlight *"Developing a low-cost GNSS sensor network for autonomous real-time deformation monitoring"* on page 44.

CONTINUE TO RESPOND TO SIGNIFICANT EVENTS AS THEY OCCUR IN COLLABORATION WITH LOCAL PARTNERS/BGS

COMET Executive and designated event leads

2016 saw major earthquakes in Italy (Amatrice) and New Zealand (Kaikoura), with COMET's response described earlier in this document.

The approach followed the protocol agreed by COMET and BGS in producing information on the location and nature of the faults in the shortest possible timeframe. Further investigations in both locations are now being supported by NERC urgency grants, and we will continue to share datasets and results with the wider community as they become available.

CONTINUE TO STRENGTHEN THE COMET WEBSITE, SPECIFICALLY FOCUSING ON IMPACT, EXPERTISE AND ENGAGEMENT/OUTREACH PAGES

Debbie Rosen, COMET Manager, Leeds

Much of this year's new content has focused on event response, given the scale and extent of the Apennines and New Zealand earthquakes. The LiCSAR portal has also been added to the website, soon to be followed by the deformation modelling software described earlier.

A full review of the website is in progress and, in particular, work is underway to develop new content aimed at PhD students and early career researchers working in EO and modelling, building on the experiences of COMET's own postgraduate community.

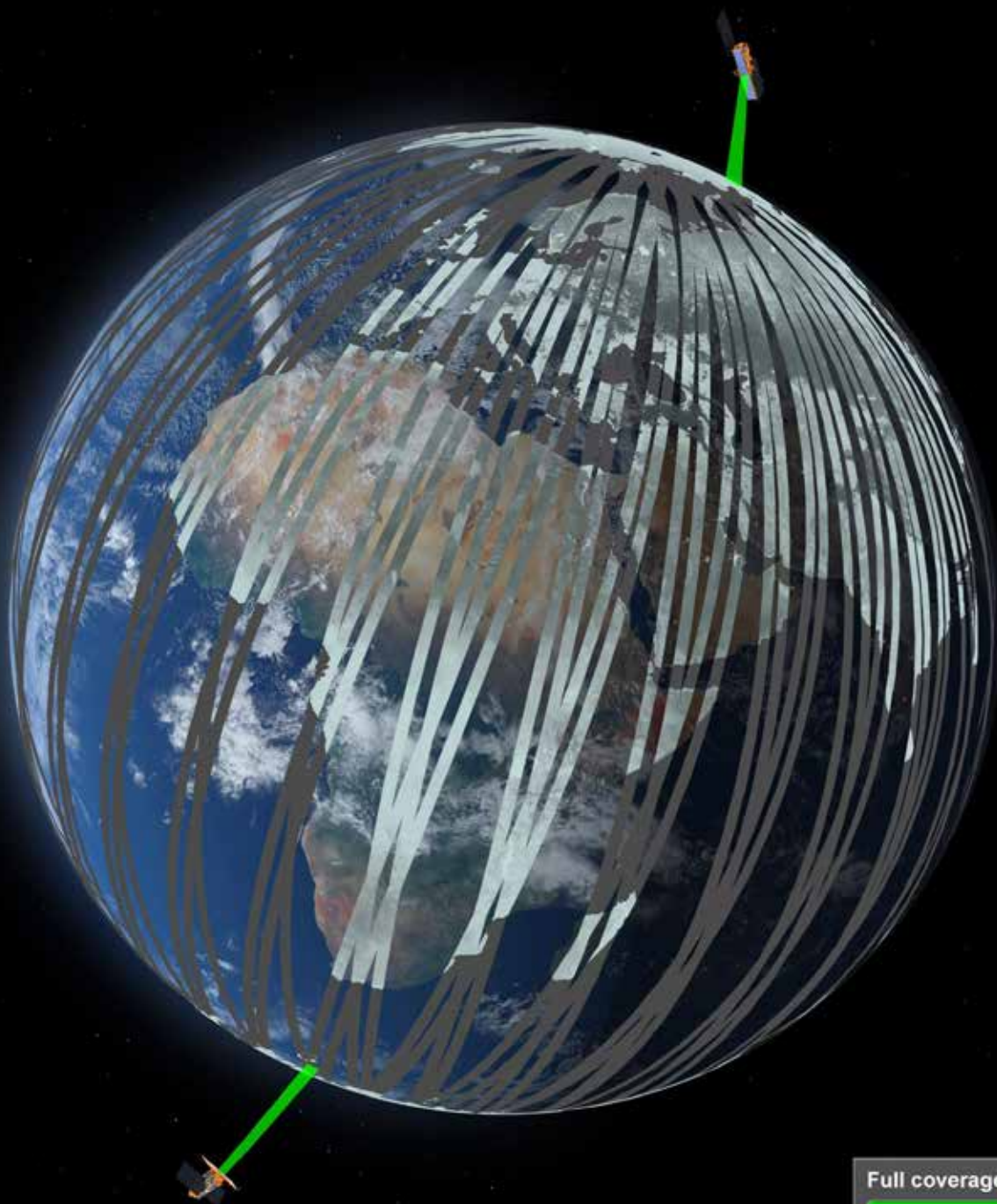
HOLD FOCUSED COMMUNITY MEETINGS, FOR EXAMPLE ON SEISMIC HAZARD IN COLLABORATION WITH THE GLOBAL EARTHQUAKE MODEL

Tim Wright, COMET Scientist, Leeds

A joint COMET-Earthquakes without Frontiers-BGS-Global Earthquake Model (GEM) meeting was held in April 2016.

This included an introduction to each project, an overview of GEM outputs and products, and updates on their seismic catalogues, active faults database, GNSS Strain Rate Model and approach to risk assessment. COMET provided updates from work on the LiCS and EwF projects, including detailed information on work to map active faulting in Central Asia, measuring tectonic strain with InSAR and developing strain rate models using InSAR and GNSS. This was the first step in building a closer relationship with GEM and investigating opportunities for new collaborations. Following the meeting, Ekbal Hussain spent a week at GEM learning how to create damage predictions for realistic earthquake scenarios.

24. <http://volcanodeformation.blogs.illrt.org/>



*Sentinel-1 Constellation.
Credit: ESA*

REVIEW ARTICLE

THE GOLDEN AGE OF TECTONIC REMOTE SENSING

John Elliott (COMET Associate, Leeds), Tim Wright (COMET Scientist, Leeds) and Richard Walters (COMET Scientist, Durham)

Satellite remote sensing techniques have advanced rapidly over the last 20 years, but until now, data quality, quantity and access has often been limited, whilst systematic acquisitions from dedicated satellites have also been lacking. However, as population growth continues in areas of high seismic hazard, there is an increasing need to fully utilise the near-global onshore reach of Earth Observation (EO) techniques to investigate earthquakes and active tectonics.

A new generation of satellite missions, alongside technical advances, is now helping EO to reach its full potential, complementing existing work in seismology, GNSS and field measurements. In particular, Sentinel-1, with its open data policy, is poised to become the main tool for measuring small-scale crustal deformation over large areas for the next two decades, helping us to understand our dynamic planet.

Recent years have seen a step change in the consistency and global coverage of Earth observing systems, along with a shift towards free and open data access. At the same time, there have been significant advances in data processing, a huge increase in the number of radar satellites, with the ability to observe the Earth even in cloudy conditions (particularly important in mountainous regions) and a shift to constellations rather than single satellites, reducing revisit times (to 6 days in the case of Sentinel-1).

These systems are just beginning to be systematically and routinely exploited to respond to both specific earthquakes and longer-term hazard, but together they provide a great opportunity to advance our understanding of active tectonics and earthquakes, and therefore our ability to respond to natural disasters.

Sentinel-1 in particular has made systematic, large scale (100–1,000 km) EO possible following disasters – in fact, the scientific response to major earthquakes now begins with the analysis of satellite imagery: since 1992, Synthetic Aperture Radar Interferometry, or InSAR, has been used to study more than 100 (often continental) earthquakes, providing remote measurements of ground displacement at very high-spatial resolution.

Imagery collected in the aftermath of earthquakes has also been used to map landslides and tsunami inundations, assess building damage, and update seismic earthquake source models to improve estimates of ground shaking.

As InSAR images displacement of the ground surface, it can determine the particular fault that ruptured at depth. This is not always obvious from ground observations, as many major ruptures do not reach the surface. It can also help detangle the complex segmentation pattern of faults that we often observe for many of these major events.

Determining fault slip using InSAR can establish which portions of the fault failed. From this, we can calculate stress transfer onto surrounding faults, identifying the parts of the fault system that have been brought closer to failure. InSAR can also be used to map small displacements, allowing us to detect previously unmapped faults that have been triggered by the earthquake.

Satellite EO can also play a crucial role in understanding large-scale deformation. Past estimates of seismic hazard have often been based on the earthquake record, with historical and instrumental data used to forecast the probability of future earthquakes. However, in most continental active tectonic regions, the time between earthquakes is longer than the historical record. In addition, in areas with long recurrence intervals, the next large earthquake is unlikely to be in the same location as the previous one.

Instead, with InSAR, we can measure interseismic strain in many of these regions, avoiding the reliance on incomplete records of seismicity, and at the same time characterising the physical cause of earthquakes.

InSAR was first used to measure interseismic deformation for the North Anatolian Fault in Eastern Turkey, and has since been used on faults worldwide.

Although there are limitations on InSAR's ability to measure these small ground movements (often due to nuisance signals arising from changes in atmospheric conditions), the development of noise correction and time-series techniques have helped to reduce uncertainties. We can now estimate interseismic strain rate at relatively high-resolution and with a degree of accuracy that offers the potential to investigate a large number of major faults worldwide as well as slower or distributed deforming areas.

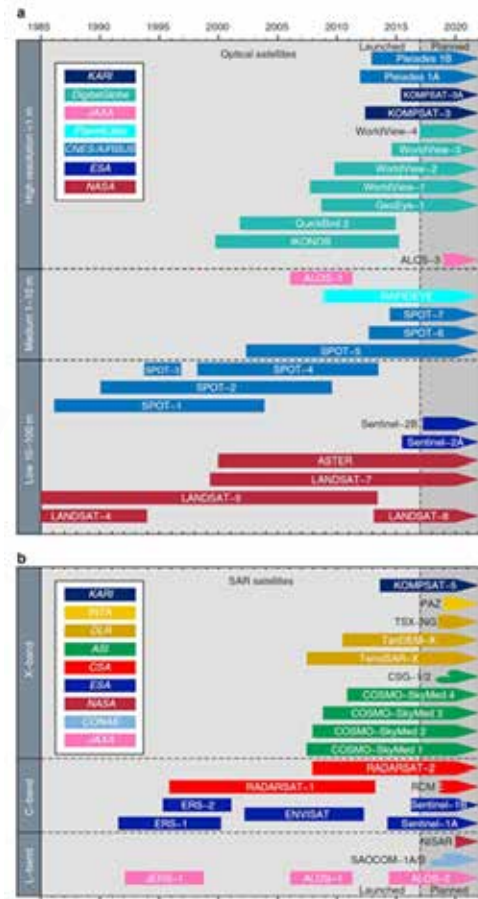
Translating this information into forecasts of seismic hazard is not straightforward, but strain rates based on GNSS have already been used to create a global forecast of seismicity, and InSAR will be used to improve these forecasts in regions where GNSS measurements are sparse.

On longer timescales, EO data can contribute to hazard estimates by informing the development of physics-based models of fault behaviour. The intervals between most earthquakes are much longer than the period for which we have good observations, but we can cleverly combine data to build models that predict how deformation varies throughout the entire earthquake cycle.

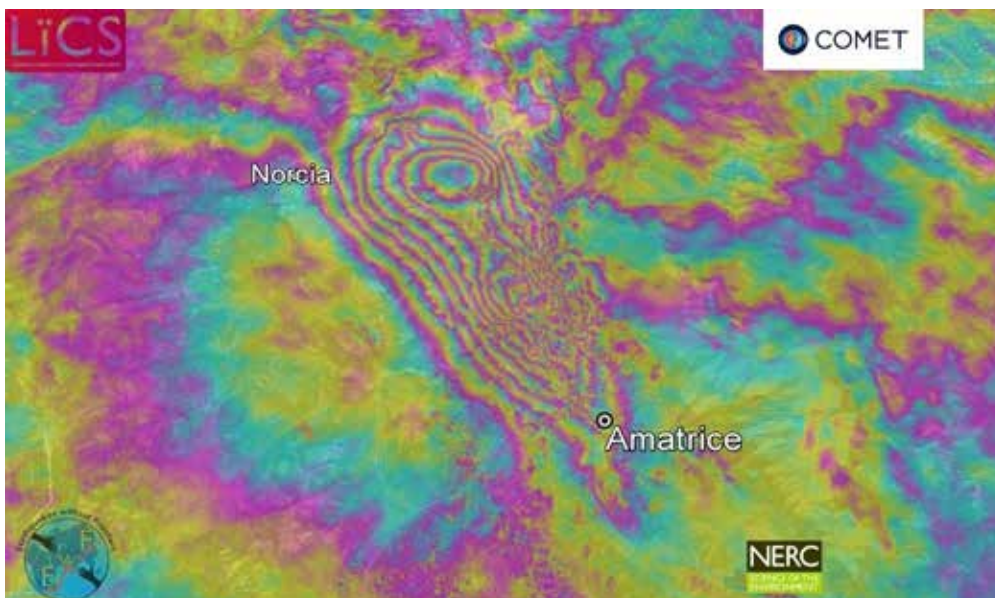
Presuming that all faults behave in a similar way, we can use observations from different faults, at different points in the earthquake cycle, as a proxy for observations through time of a common process. There are a handful of locations across the planet where we have good geodetic observations before and after earthquakes, ranging from Turkey to Alaska, California and Tibet.



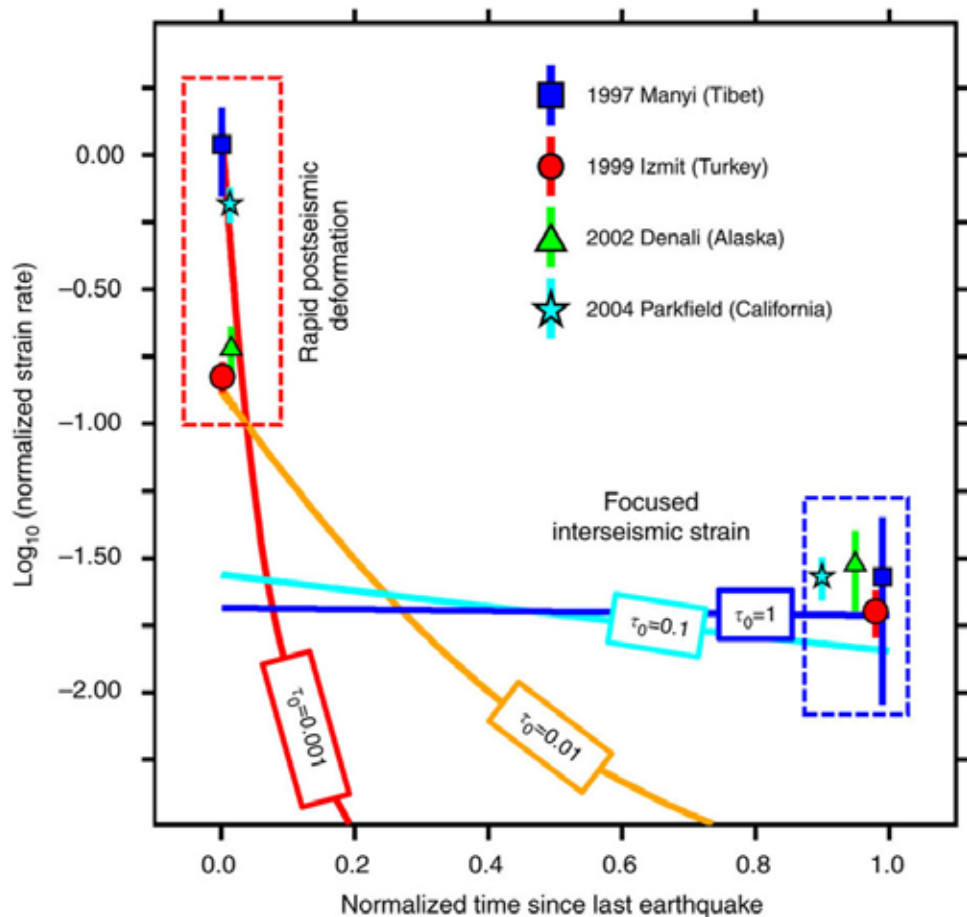
Sentinel-1A, launched in April 2014 and joined in 2016 by the identical 1B. This two satellite constellation offers the chance of 6 day revisit periods, allowing for a greater number of observations and more rapid detection of deformation



Optical and SAR satellite timeline for major Earth Observing satellites with systematic and global coverage used by COMET investigators. Credit: John Elliott



Sentinel-1 interferogram of the ground deformation around Norcia and Amatrice, Italy due to the 24 August 2016 earthquake



Interseismic and postseismic strain rates for 4 strike-slip faults where data are available both before and after a major earthquake

In each case, strain rates immediately after the last earthquake are high (red box), but they do not decay away completely by the end of the cycle- there is a remarkably consistent pattern of interseismic strain late in the earthquake cycle (blue box).

As a result, any successful model of the earthquake deformation cycle must be able to reproduce both interseismic strain and postseismic deformation. This has not always been easy in the past, for example from simple two-layer models of the Earth's lithosphere or from models based on rock mechanics. Employing larger quantities and a better quality of EO data will help us to refine these models for an increasing number of earthquake faults.

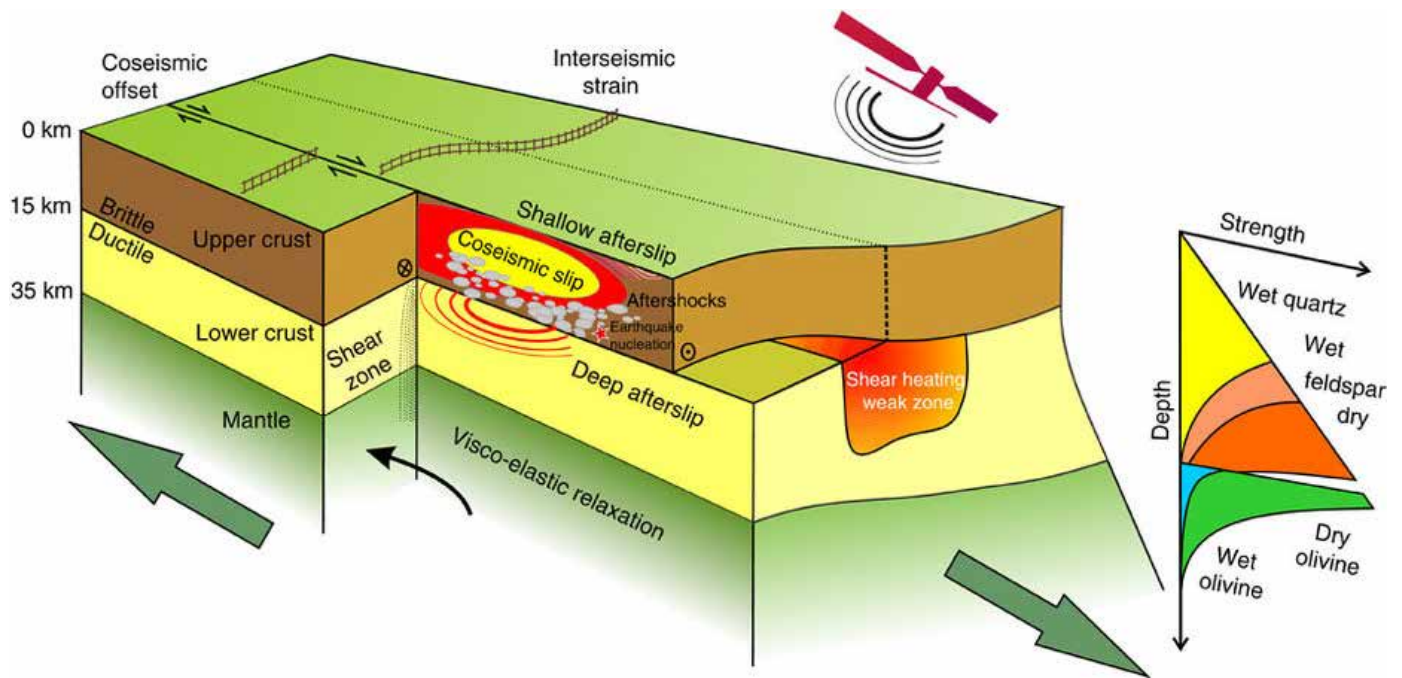
On an even broader scale, satellite data is now allowing us to assess the mechanics of continental deformation. We know that the continents do not deform as large rigid plates like the oceans, but up to now there have been differing views on how this happens.

In one, the continents act like a viscous fluid, with faults reflecting the deformation of a deeper, controlling layer. In the other, the continents are seen as a collection of rigid blocks, each behaving like an independent plate.

Resolving this is important for earthquake hazard assessment - we need to understand the degree to which deformation and earthquakes are focused on major faults, as opposed to being distributed throughout the continents. Long time-series of surface deformation over regional scales from EO will enable us to assess this.

Another question that EO can help to answer is how elastic the deformation in the upper crust actually is in reality. Models tend to assume that the crust behaves elastically between earthquakes, yet geological structures often show plastic, non-reversible deformation.

Combined with field observations, EO can help us to assess to what extent surface deformation reflects elastic strain on faults that will eventually be released in earthquakes, or plastic deformation that builds geological structures.



Satellite geodesy offers the opportunity to measure the complete earthquake cycle: from slip in the upper crust, its relationship with aftershocks and fault segmentation; to postseismic deformation and interseismic strain accumulation across fault zones between earthquakes

Ultimately, satellite missions such as Sentinel-1 are improving our understanding of the entire earthquake cycle, helping us to determine the seismic potential of faults as well as mapping secondary earthquake-triggered hazards such as landsliding and building collapse. In particular, the coming decade will see a dramatic improvement in our ability to observe longer-term and time-varying phenomena such as slow slip events. By combining these satellite observations with measurements from other, more established techniques, we will be able to develop new theories of active tectonics and earthquakes that improve our ability to live safely on this hazardous planet.

RESEARCH HIGHLIGHT

QUANTITATIVE ANALYSIS OF EFFUSIVE ERUPTION USING RADAR AND OPTICAL IMAGERY

Marco Bagnardi (COMET Researcher, Leeds), Pablo González (COMET Scientist, Liverpool) & Andy Hooper (COMET Scientist, Leeds)

A combination of radar and optical imagery has been used to precisely measure the volume of the 2014-2015 lava flow at Fogo and to study its evolution after the emplacement.

Precise, quantitative analyses of topographic changes associated with volcanic and volcano-tectonic activity provide the means to infer key parameters for the assessment of hazards associated with these processes (e.g. magma discharge rate in effusive events, potential for tsunami generation etc.).

To investigate the effusive activity associated with the 2014-2015 eruption at Fogo Volcano, Cape Verde, scientists from the Universities of Leeds and Liverpool used a combination of radar and optical satellite imagery to generate high-resolution Digital Elevation Models (DEM) of the volcanic edifice.

The difference between DEMs, representing the topographic surface at different times (e.g. before and after the eruption), provided the means to estimate the volume of the erupted lava flow.

For the first time in a volcanic environment, very high-resolution tri-stereo optical imagery from the Pleiades-1 satellite constellation was used. This showed a significant increase (by a factor of 6.5) in the number of points for which the height can be retrieved when compared to conventional stereo imagery.

From the Pleiades-1 post-eruption topography, heights were subtracted from a pre-eruptive DEM, obtained using spaceborne synthetic aperture radar (SAR) data from the TanDEM-X mission, and used to constrain the volume of the 2014–2015 lava flow with an unprecedented accuracy for Fogo Volcano.

The volume estimate was then converted into the mean output rate of the 2014–2015 eruption and used to infer a minimum magma supply rate since the last eruption.

Finally, using SAR data acquired by the Sentinel-1 satellite, the team applied SAR interferometry (e.g. InSAR) to measure the lava flow subsidence due to cooling and contraction in the months after its emplacement and compared this to the measured lava flow thickness.

They found a clear spatial correlation, with the maximum subsidence recorded in those areas where lava flow thickness is also maximum. However, other smaller regions showed large cumulative subsidence deviating from the overall linear correlation between thickness and subsidence. The larger subsidence in these areas is most likely related to the highly compactable nature of the substrate onto which the lava flow was emplaced (e.g. ash and talus).

Further work is currently being carried out to integrate topographic data from UAV optical imagery and a terrestrial laser scanner with the Pleiades-1 and TanDEM-X data. This will then be used to estimate the accuracy of each dataset for the generation of an integrated DEM, where data is weighted, pixel by pixel, according to its quality.

This work was funded by COMET, the University of Leeds Climate and Geohazard Services Hub and the Looking inside the Continents from Space (LiCS) project.

Reference: Bagnardi, M. *et al.* (2016) High-resolution digital elevation model from tri-stereo Pleiades-1 satellite imagery for lava flow volume estimates at Fogo Volcano, Geophysical Research Letters, <http://onlinelibrary.wiley.com/doi/10.1002/2016GL069457/abstract>



Top left: Cape Verde Archipelago imaged by Envisat. Credit: ESA. Top right: the destructive effect of the 2014-15 lava flow at Fogo Volcano. In the image, a civil building in the village of Portela, partly buried by the thick and fast-moving lava flow. Credit: M. Bagnardi. Bottom left: Marco at work on Fogo Volcano. Bottom right: Pico do Fogo. Credit: Nicole Richter

RESEARCH HIGHLIGHT

GENERIC InSAR ATMOSPHERIC CORRECTION MODELS (GACOS)

Chen Yu (COMET Research Student, Newcastle), Paola Crippa (COMET Researcher, Newcastle), Zhenhong Li (COMET Scientist, Newcastle) & Nigel T. Penna (Senior Lecturer in Geomatics, Newcastle)

Atmospheric water vapour effects represent one of the major error sources of repeat-pass InSAR, and limit the accuracy of InSAR derived surface displacements. The spatio-temporal variations of atmospheric water vapour make it a challenge to measure small-amplitude surface displacements with InSAR.

In previous studies, several InSAR atmospheric correction models have been successfully demonstrated:

1. Ground based correction models such as those using GNSS observations. Such correction models are limited by the availability (and distribution) of ground observations.
2. Space based correction models including those involving NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and/or ESA's Medium Resolution Imaging Spectrometer (MERIS). These are sensitive to the presence of clouds and there might be a time difference between space based water vapour and radar observations.
3. Numerical Weather Model (NWM) based correction models including those using European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim and/or Weather Research and Forecasting (WRF). Similar to space based correction models, there might be a time difference between NWM and radar observations.

Taking into account the inherited advantages and limitations of GNSS, MODIS and ECMWF water vapour products, the Newcastle COMET team focused on developing generic InSAR atmospheric correction models based on high resolution ECMWF (HRES-ECMWF) output and/or GPS observations.

HRES-ECMWF, run at a resolution of ~16 km and available in near real-time (with a latency of 5-10 hours), was found to have better performance than ERA-Interim in terms of Zenith Total Delays (ZTDs) with RMS differences between HRES-ECMWF and GPS of 8.0–10.3 mm.

A seasonal pattern in its model performance was also identified with higher errors during warmer and wetter months. Tropospheric delays can be routinely retrieved from ground based GNSS stations in all-weather conditions and also in real time (Yu *et al.*, 2017a).

An Iterative Tropospheric Decomposition (ITD) interpolation model has been developed to decouple the total tropospheric delays into (i) a stratified component highly correlated with topography therefore delineates the vertical troposphere profile, and (ii) a turbulent component resulting from disturbance processes (e.g. severe weather) in the troposphere which trigger uncertain patterns in space and time.

The decoupled interpolation model can then be employed to generate dense tropospheric delay maps for correcting water vapour effects on InSAR observations (Yu *et al.*, 2017a, 2017b).

The above findings and models have been integrated to develop a near real time InSAR atmospheric model which is applicable globally and anytime and which relies on both HRES-ECMWF output and GPS observations (Yu *et al.*, 2017c).

To optimally combine these different data sources, a range of factors including GPS network geometry, regional topography and the time differences between ECMWF and InSAR were investigated. Eight regions of the world were chosen, including areas with different topography variations (e.g. both flat and high topographies), different latitudinal ranges (i.e. equatorial and near polar) and different climates (i.e. monsoon and oceanic), and used to evaluate the correction model performance.

The proposed algorithm is able on average to reduce tropospheric errors by at least 50% with a precision of approximately 1 cm for the corrected interferograms.

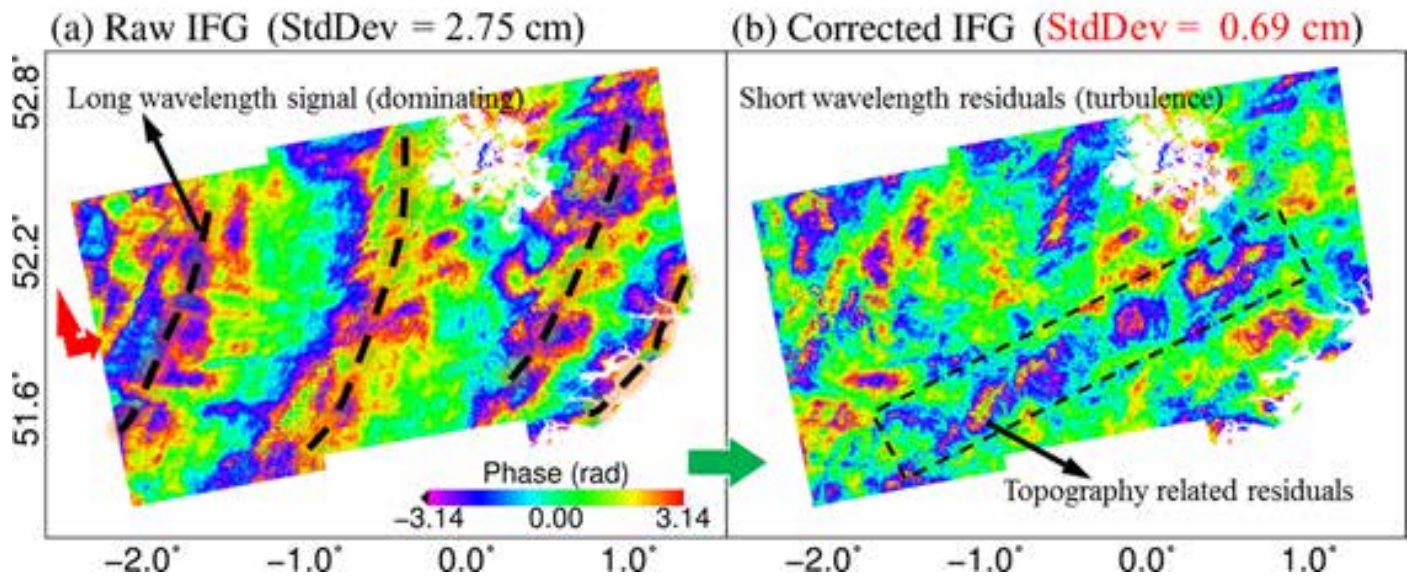
The team has also identified and evaluated multiple quality control indicators (i.e. cross-test RMS, topography variations and time differences) of model performance, which allows users to perform an automatic and flexible correction procedure in near real time mode.

To conclude, the new InSAR atmospheric correction model has the following features: (i) globally available; (ii) operational in a near real time mode; (iii) easy to implement; and (iv) users to be informed how the model performs and whether the correction is recommended.

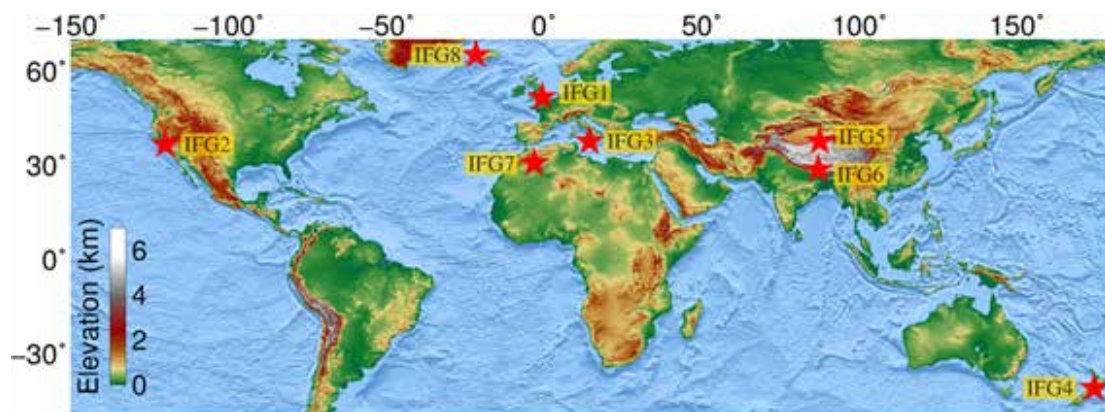
As above, a web-based toolbox ([GACOS: Generic Atmospheric Correction Online Service for InSAR](http://onlinelibrary.wiley.com/doi/10.1002/2016JD025753/full))²⁵ has been developed, in which ITD is employed to generate high-resolution tropospheric delay maps for InSAR correction. GACOS was released online at the 2017 FRINGE workshop in Helsinki, Finland on 6 June 2017.

References:

- Yu, C., Penna, N.T., Li, Z. (2017a) Generation of real-time mode high-resolution water vapor fields from GPS observations, J. Geophys. Res. Atmos. <http://onlinelibrary.wiley.com/doi/10.1002/2016JD025753/full>
- Yu, C., Li, Z., Penna N.T. (2017b) Interferometric synthetic aperture radar atmospheric correction: GPS-based Iterative Tropospheric Decomposition model, Remote Sens. Environ., under review
- Yu, C., Li, Z., Crippa, P., Penna N.T. (2017c) Generic InSAR atmospheric correction models, J. Geophys. Res. – Solid Earth, in prep.
25. <http://ceg-research.ncl.ac.uk/v2/gacos/>



Sentinel-1 interferogram in Southern England: 25th January and 6th February 2017 (12 days apart): (a) Original; (b) Corrected with GPS and HRES-ECMWF. Note that: (i) all the long-wavelength signals are removed; and (ii) most of topography-dependent signals are removed but residuals can be observed in the corrected interferogram (partly due to the location offsets between topography and phase signals)



IFGs	Date1	Date2	Time of day	Interval (days)	GPS network	Location	Improvements
IFG1	20160125	20160206	17:49	12	BIGF	UK	75%
IFG2	20160302	20160326	01:58	24	PBO	US	61%
IFG3	20160313	20160406	05:04	24	RING	Italy	43%
IFG4	20160923	20161017	07:15	24	GeoNet	New Zealand	44%
IFG5	20160112	20160205	12:08	24	-	China	61%
IFG6	20160720	20160813	12:21	24	-	Nepal	39%
IFG7	20161001	20161007	06:11	6	-	Algeria	63%
IFG8	20160609	20160703	18:58	24	-	Iceland	40%

InSAR atmospheric correction validation statistics

RESEARCH HIGHLIGHT

MONTSERRAT CONTINUES TO INFLATE

Professor Jurgen (Locko) Neuberg (COMET Scientist, Leeds)

Despite a lack of eruptive surface activity since 2010, Soufrière Hills volcano continues to show signs of unrest in the form of ongoing outgassing, and inflation of the entire island of Montserrat.

From 1995, Soufrière Hills volcano on Montserrat, West Indies, showed a pattern of inflation and deflation which ended with a partial dome collapse in February 2010. Since then, the eruptive activity has been characterised by constant outgassing and the occasional seismic swarms that are accompanied by short-lived venting of volcanic ash. However, the inflation of the entire island of Montserrat indicates that the eruption is far from over and that fresh magma is accumulating in a reservoir below the island.

Together with Amy Collinson (postdoctoral researcher, Leeds) Locko worked with Karen Pascal at the Montserrat Volcano Observatory (MVO), who is in charge of deformation monitoring on Montserrat, to analyse the deformation data acquired by the local GPS network.

Using numerical modelling, they quantified the accumulation rate of magma below Montserrat, which is in line with the continuing inflation and pressurisation of the island. Other factors that might explain the deformation trend such as tectonic plate movement or crystallisation and pressurisation of an existing (but not growing) magma body were ruled out as major contributors to the deformation trend.

Using this model, they went backwards in time and analysed the eruptive history of Soufrière Hills since 1995, comparing volume changes in the magma reservoir with the amount of erupted material at the surface (Figure 1).

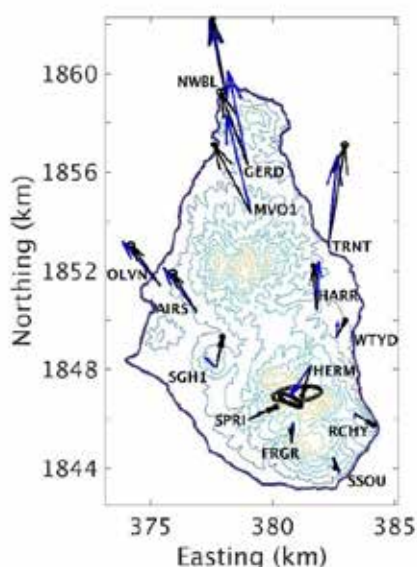


Figure 1: Deformation field on Montserrat depicted by GPS horizontal components in blue. Black arrows show the matching deformation from a numerical model. The data set covers the time period of inflation from 2012 through 2015

Despite the ongoing inflation, the magma volume in the reservoir that existed before the eruption started has not yet been reached. However, in the past, the volcano did not wait until the reservoir was refilled, but started the next eruptive phase sooner (Figure 2). Therefore, the ash venting in the beginning of 2012 might have been a “failed eruption” and the next eruptive phase is overdue.

Further analysis of the change in magma eruption rates and comparison with the amount of actual erupted material will provide insights into the compressibility of magma at depth, and hence, changes of magma properties over time. Research outputs like this feed directly into the discussions of the Scientific Advisory Committee on Montserrat Volcano Activity, and are a crucial contribution by COMET to support decision making by the British and the Montserratian Governments.

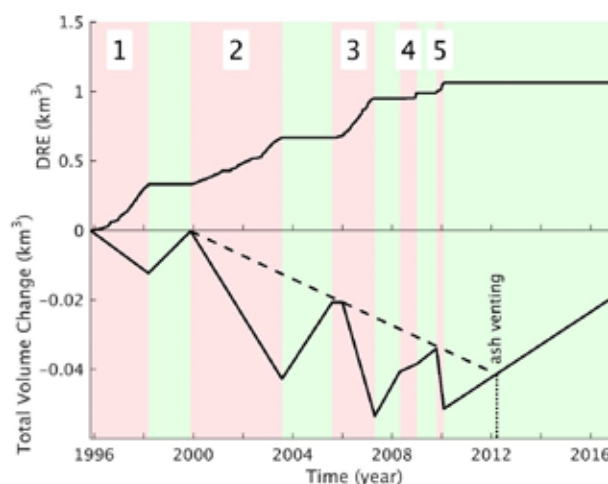


Figure 2: Eruption phases 1 – 5 are indicated in pink, Pauses in green. Top: cumulative erupted volume (adapted from Wadge et al., 2014). Bottom: change in total reservoir volume through time relative to the start of the eruption. Total source volume change assumes the best-fit source with a volume of 1.26 km³. The dashed line indicates the trend of eruption onsets for Phases 2, 3 and 5. The location of the March 2012 ash-venting is indicated



Montserrat ash cloud. Credit: BGS

RESEARCH HIGHLIGHT

DEVELOPING LiCSAR: AUTOMATED PROCESSING OF SENTINEL-1 DATA

Karsten Spaans (PDRA, Leeds) & Emma Hatton (InSAR Facility Manager, Leeds)

InSAR has been widely integrated into Earth surface deformation studies from a geophysical point of view. What makes LiCSAR special is its accessibility, providing the potential to expand the Sentinel-1 user base to include non-expert geophysicists as well as users from new fields such as civil engineering, urban planning and monitoring and the social sciences.

The Sentinel-1 satellite constellation is proving a game changer for monitoring deformation of the Earth's surface. Over the last two years, numerous earthquakes and volcanic eruptions have been imaged with Sentinel-1 interferograms, aiding rapid response and resulting in a greater scientific understanding of these events and their geophysical properties.

However, the main reason that Sentinel-1 is a game changer is the freely available, enormous data volumes that it acquires, allowing unprecedented coverage of areas studied using the technique. Processing this data nonetheless presents a big challenge.

To address this, COMET is developing a system capable of processing all data acquired globally, with the resulting products freely accessible and downloadable through an online portal, to include both wrapped and unwrapped interferograms, coherence estimates, velocity estimates and metadata.

The portal will allow quick access to already processed products, providing a convenient service not just to scientists already familiar with InSAR, but also opening up possibilities for non-expert users.

Several members of COMET have put considerable effort into getting the system operational. In 2015, the Gamma software package was chosen as the basis for the processing system. A batch processing shell was developed around the Gamma software, which has been available for general use within COMET since early 2016 and used by COMET scientists to image several earthquakes, long term tectonic movements and volcanic eruption. These include large events such as the Illapel, Chile earthquake, imaged by Sentinel-1 data in exquisite detail (right).

Processing is mainly supported by the CEMS facility maintained by CEDA. All COMET scientists have access to a high powered processing cluster here, and a full mirror of the Sentinel-1 archive located at the facility means that data does not have to be downloaded before processing, greatly reducing the time necessary to obtain results.

The next challenge involved automating the processing system, allowing it to handle large volumes of data without the need for human interaction. This added a new layer of complexity to the system, requiring the development of a database system for raw data and processed products, and a daemon system that handles the decision making of which products to process, plus performing housekeeping on processing results.

This automated processing system has been developed in-house by the COMET team, and finishing touches are being put on the system at the time of writing. In the meantime, the team has been delivering wrapped interferograms and coherence estimates for data acquired since September 2016 over the Alpine-Himalayan belt via the [COMET/LiCS InSAR portal](http://comet.nerc.ac.uk/COMET-LiCS-portal/)²⁶.

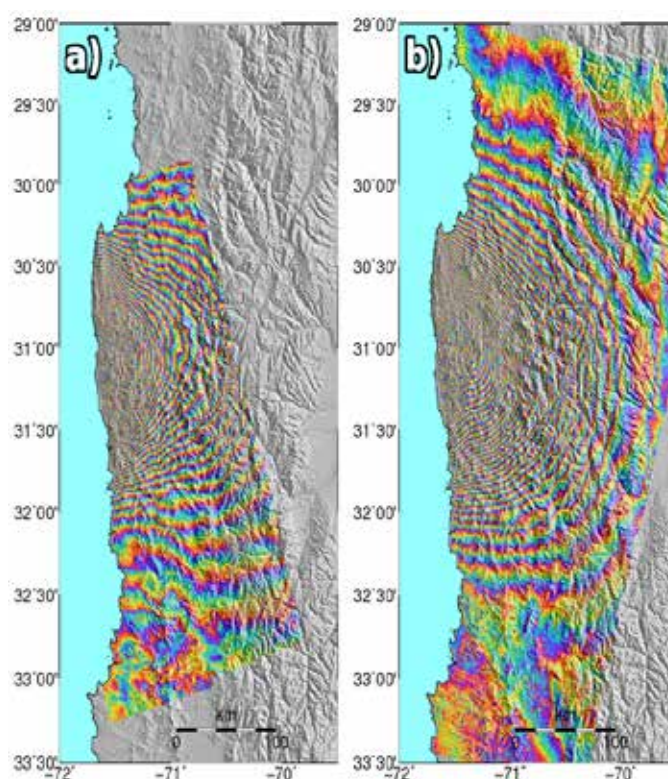
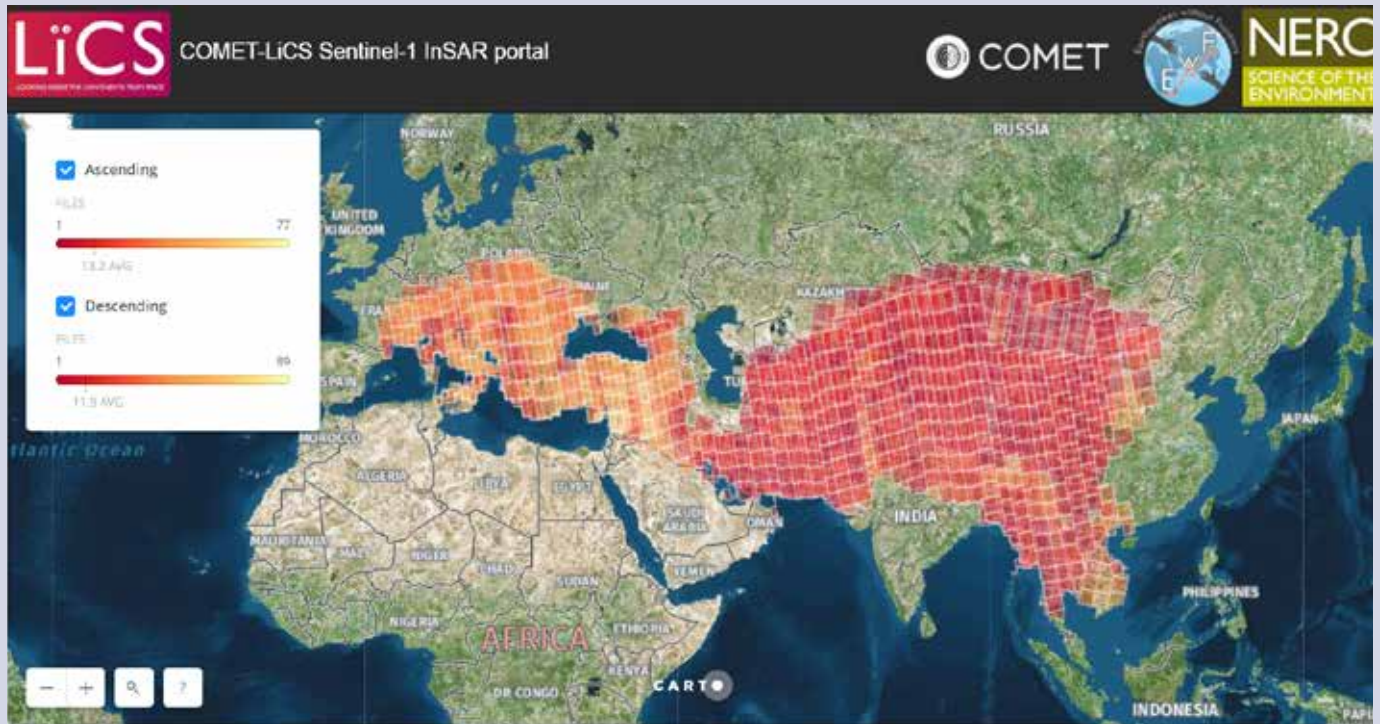


Figure 1: a) ascending and b) descending interferograms covering the Mw=8.3 Illapel, Chile earthquake

The screenshot of the portal (right) provides an idea of the LiCS processing system coverage. The interface provides an overview of data availability, and data downloads are easily accessible through clicking on the scene polygons.

The next steps are to include unwrapped interferograms and linear time series in the data portal, as well as extending the timeseries to include all historically available data. In addition, there are plans to include an automatic fast response system into the processor that prioritises rapid data processing of scenes that contain an earthquake or volcanic eruption.

In the long term, the system will be expanded to process all data worldwide. It will also include nuisance term corrections, like tropospheric and ionospheric corrections, and increase the effectiveness of the time series analysis. All of this will result in a system that provides a consistent, robust and reliable stream of data, useful for both expert and non-expert users.



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

RESEARCH HIGHLIGHT

DEVELOPING A LOW-COST GNSS SENSOR NETWORK FOR AUTONOMOUS REAL-TIME DEFORMATION MONITORING

Chris Atkins (COMET Researcher, UCL) & Marek Ziebart (COMET Scientist, UCL)

At UCL, COMET is developing low-cost GNSS sensors that are capable of measuring displacements with centimetre-level precision. It is envisaged that several of these will be deployed as a network. Much of the work done so far has involved testing different methods of data streaming and power consumption under several different configuration settings.

It has long been possible to use Global Navigation Satellite Systems (GNSS) such as Global Positioning Systems (GPS) to measure displacements with sub-centimetre level precision. Today, precise GNSS techniques are used in a wide variety of applications in engineering and agriculture as well as in the monitoring of geophysical phenomena.

It used to be that measuring displacements with sub-centimetre precision could only be achieved using relatively expensive antennas and receivers, each costing thousands of pounds. However, in recent years low-cost single-frequency 'mass-market' receiver modules and antennas have become available. This work shows that similar levels of performance to geodetic quality equipment can be achieved.

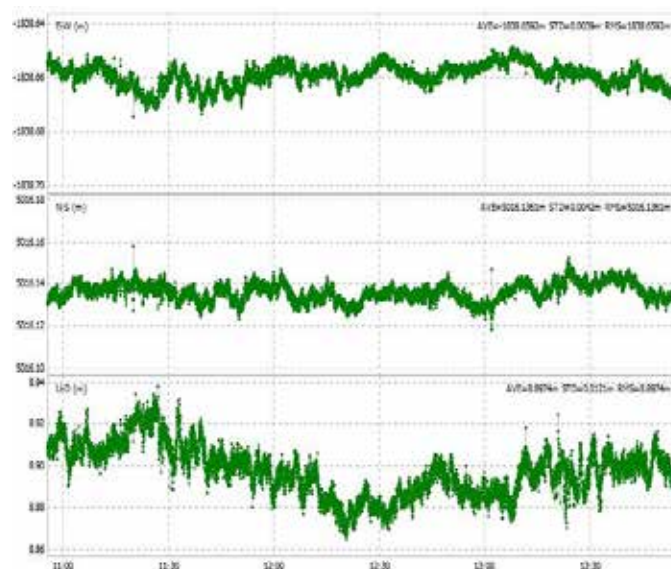
These devices can make highly precise phase measurements of signals from multiple satellite navigation systems such as GPS, GLONASS, Galileo and BeiDou simultaneously, but they are small, lightweight and typically cost only a few tens of pounds each. This makes it feasible to deploy several high-precision sensors without prohibitive costs.

Trials are currently taking place at UCL to assess the performance of two prototype sensors in terms of precision over different baseline lengths and power consumption.

The figure below shows a 1 Hz position time series (easting, northing and height) of a stationary sensor spanning about 3 hours calculated using GPS, GLONASS and Galileo measurements, relative to a second 'base' sensor about 5 km away.



Prototype GNSS sensor on Hampstead Heath



The positions shown are relative to the position of a second sensor placed about 5 km away. Notice that the standard deviation of the position time series is only 4 mm for the horizontal components and 12 mm for the vertical component. This demonstrates that centimetre-level precision is achievable at relatively little expense.

Notice also the oscillating errors present in each of the time series. These are a result of multipath interference and antenna phase centre variation. In the longer term, a new data processing algorithm is to be developed to reduce these effects, thereby further improving the precision.

Power usage is critical if these sensors are to be deployed in remote locations. The sensor can in theory operate continuously for several days using a typical USB power pack, or for a few weeks if a suitable hibernation scheme is applied. There is also a plan to experiment with the use of solar panels.

Currently, the sensors use a Raspberry Pi to log the measurements for later processing. These single-board computers are inexpensive, easy to use, configurable remotely, and they allow functionality to be added relatively easily. The current setup of each prototype sensor (illustrated below) is simple.

In the longer term, the capability for the sensors to transmit raw measurement data will be added and the use of other hardware components will be explored. A network of these sensors will then form part of a real-time deformation monitoring system.

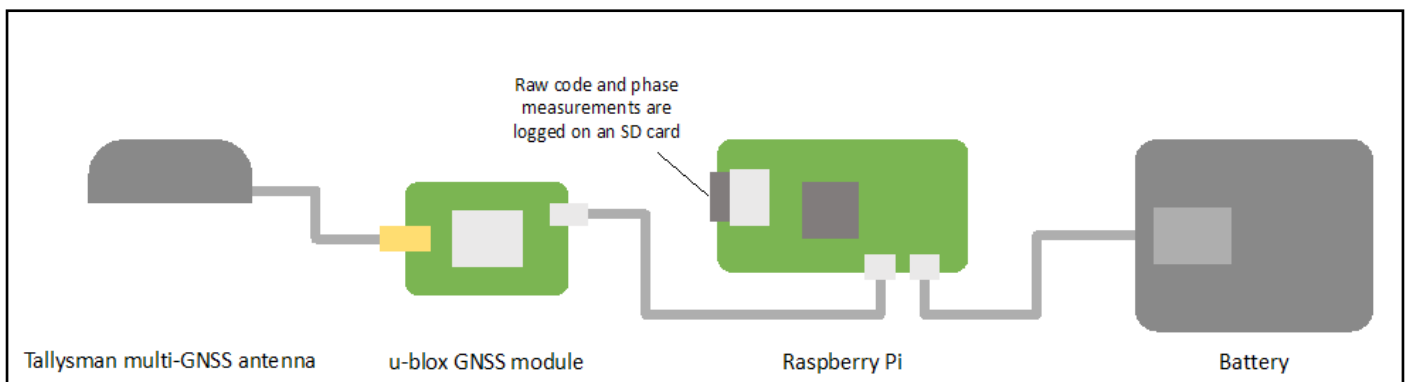
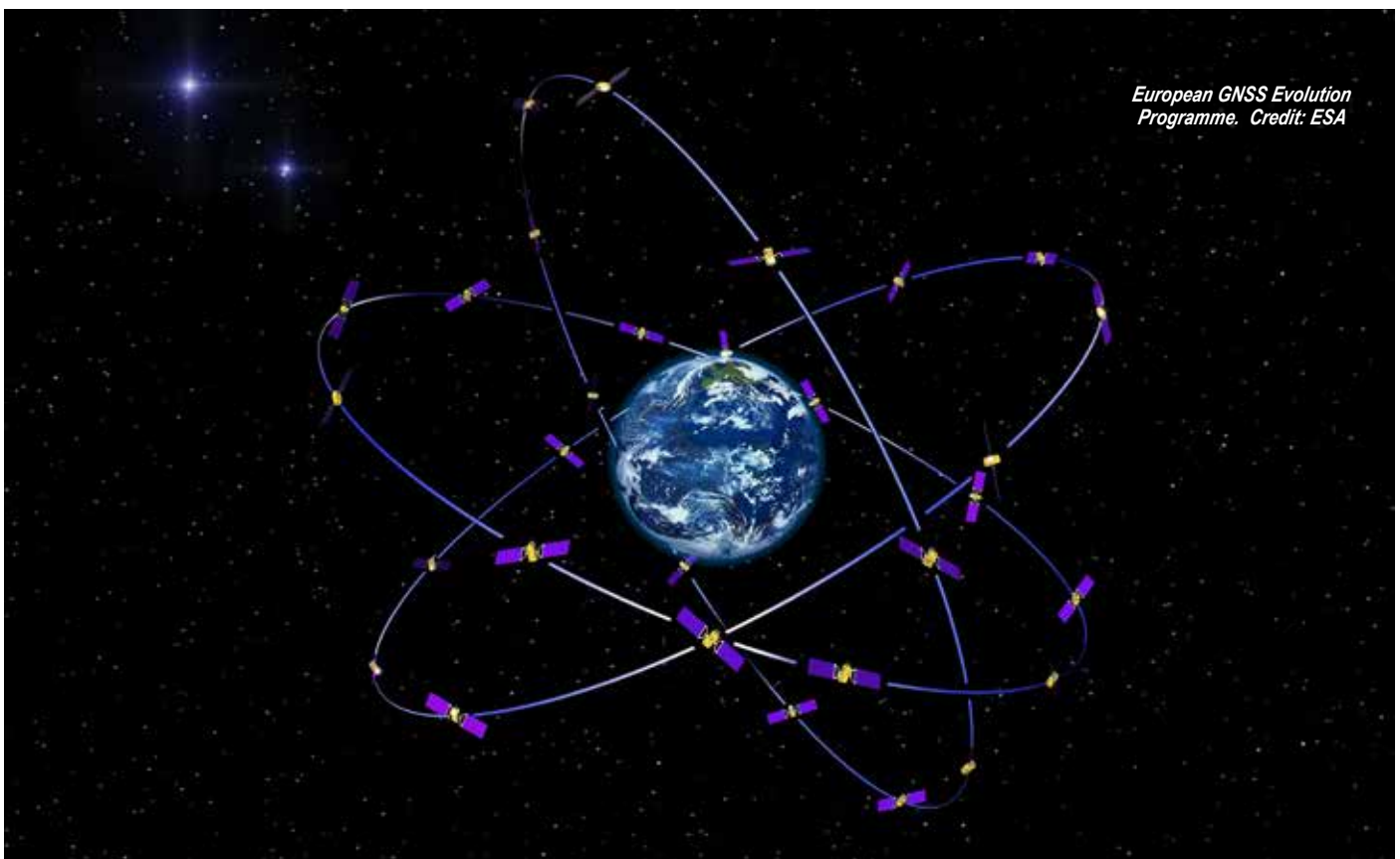


Diagram showing the current system setup of the sensor



RESEARCH HIGHLIGHT

SATELLITE-DERIVED SULFUR DIOXIDE EMISSIONS FROM THE 2014-2015 HOLUHRAUN ERUPTION, ICELAND

Elisa Carboni (COMET Researcher, Oxford), R. Don Grainger & Tamsin Mather (COMET Scientists, Oxford), Anja Schmidt (COMET Associate, Leeds) & Iolanda Ialongo (Research Scientist, Finnish Meteorological Institute)

The 2014-2015 Holuhraun eruption was a major source of sulfur dioxide (SO_2) to the troposphere. Yet the number of ground-based SO_2 measurements was limited, particularly during the Icelandic winter.

This work involved the retrieval of a time series of volcanic SO_2 atmospheric loading and vertical distribution from IASI over the entire eruption period from September 2014 to February 2015.

This study used all the IASI spectral range from 1000 to 1200 cm^{-1} and from 1300 to 1410 cm^{-1} (the 7.3 and 8.7 μm SO_2 absorption bands) to retrieve both the SO_2 amount and the altitude of the plume.

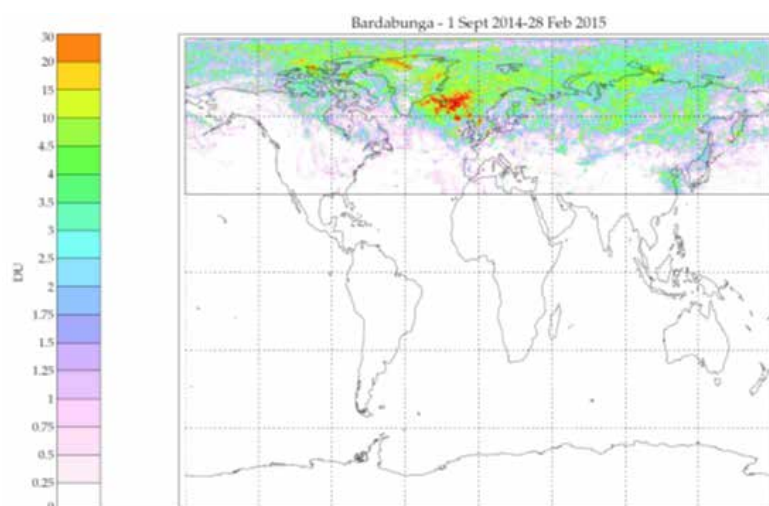
The SO_2 band around 8.7 μm (1000 to 1200 cm^{-1}) is within an atmospheric window range where radiation from the surface can reach the satellite measurements through all the atmospheric layers. This allowed retrieval of the SO_2 amount down to the surface and lower troposphere. A comprehensive error budget for every pixel is included in the retrieval.

To check the validity of the retrieval, the IASI dataset was compared with Brewer ground measurements located at Sodankylä (Finland). This showed that all the SO_2 episodes are consistent between satellite and ground measurements.

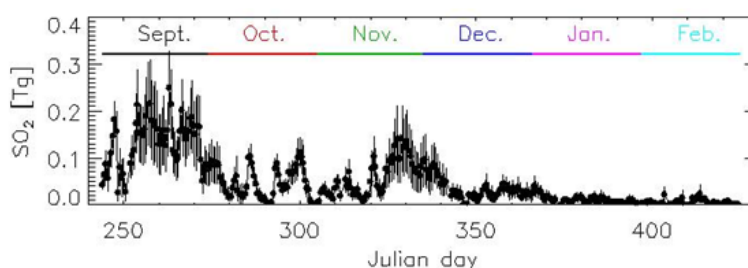
Evolution of the plume (maps of amount and altitude) was studied for the 6-month period where volcanic SO_2 was transported in the lower troposphere all over the north hemisphere from 30 to 90° north.

The figure on the right shows the maximum SO_2 amount retrieved during the 6-month period and illustrates that the Holuhraun plume over-passed a large part of northern hemisphere and nearly all of the Arctic Circle.

A new optimal estimation scheme was developed that uses the atmospheric loadings time series (right) to retrieve emission fluxes together with the average lifetime of SO_2 . Emission fluxes were obtained reaching values up to 200 kt/d and a 'minimum' total mass emitted of SO_2 of $3.7 \pm 0.8 \text{ Tg}$ with an average lifetime of 2.4 ± 0.6 days.



Map showing the maximum of SO_2 column amount (Dobson Unit - DU) retrieved within the considered area from 30 to 90° N (black rectangle) from September 2014 to February 2015



Time series of the total masses and error of SO_2 as function of day from January 2014



*Holuhraun Lava Field. Credit:
ESA/USGS*

RESEARCH HIGHLIGHT

COMBINING InSAR AND GNSS DATA TO MAP SURFACE VELOCITIES, STRAIN RATES, AND SEISMIC HAZARD ACROSS THE ALPINE HIMALAYAN BELT

Jonathan Weiss (COMET Researcher, Leeds)

COMET and EwF scientists are refining methods to combine InSAR and GNSS data to produce large-scale, high-resolution crustal velocity and strain rate fields with the goal of mapping seismic hazard across portions of the Alpine-Himalayan Belt.

Satellite-based geodetic data are becoming an increasingly important component of efforts to assess earthquake hazard across tectonically active regions (see Research Highlight “**Sentinel-1 captures extent of complex multifault rupture in New Zealand earthquake**” on page 54).

In fact, most current earthquake hazard maps rely at least partially on GNSS data. These data provide information on surface velocity, which can be used to map the accumulation of strain around faults by taking the spatial derivative of the velocity field (Figure 1). Since most major strike-slip faults show focused strain at the surface during the interseismic period (Wright, 2016), measuring this signal is crucial.

A major strength of geodetic observations is that they potentially offer relatively uniform global coverage. Over the past few decades the densification of GNSS networks has provided an unprecedented view of the kinematics of deforming regions and a global compilation of GNSS-derived surface velocities has been used to create the Global Strain Rate Model (GSRM; Figure 1; Kreemer *et al.*, 2014).

However, there is a limit to the amount of information we can derive from GNSS data. Large gaps in data coverage typically exist across many deforming regions and particularly in developing countries that cannot afford the installation and maintenance of a network of GNSS receivers. This includes large swaths of the Alpine-Himalayan Belt (AHB) where seismic hazard is arguably drastically underestimated (England and Jackson, 2011; Figure 1).

Further, even in well-instrumented regions like California and Japan, the typical spacing between GNSS observation points of 10-50 km may not be sufficient to distinguish between faults that are locked at the surface and those that are “creeping”. Finally, the scientific community has slowly seen a reduction in the funding of tectonic projects that involve GNSS receiver installation and maintenance since it often takes many years for the studies to bear fruit.

Therefore, these “gaps” in GNSS data coverage are likely to persist and their effect on the corresponding strain rates is obvious: regions of high strain are strongly controlled by the distribution of observations, resulting in strain rate field inaccuracies.

Fortunately, the problems mentioned above are not insurmountable. InSAR can provide observations of surface motions without instruments on the ground, with precision comparable to GNSS, and with a spatial resolution of a few tens of metres (Wright, 2016). A major COMET goal is to integrate InSAR and GNSS data to create country-scale, high-resolution crustal velocity and strain rate fields for parts of the AHB. However, some associated challenges must be overcome.

First, InSAR data provide measurements of surface deformation in the satellite’s line-of-sight (LOS). Due to the near-polar orbit of SAR satellites, the measurements are most sensitive to motion in the east-west and vertical directions and it is often difficult to precisely determine the northern component of the LOS displacement/velocity vector.

In contrast, GNSS receivers directly measure three-dimensional motion although the vertical information is typically much noisier and often not included in published studies. Further, the current Global Strain Rate Model (GSRM) approach explicitly assumes there is no motion in the vertical direction and only solves for the two-dimensional, horizontal strain-rate tensor. In the future, we want to take advantage of the InSAR sensitivity to vertical motions especially in regions that are not solely experiencing strike-slip deformation (e.g. the Himalayas, Iran).

COMET is taking two approaches to deal with the challenge of combining GNSS and InSAR measurements. The first, considered the best way to add InSAR into GSRM-type models, is to decompose InSAR LOS velocities into horizontal and vertical components and then incorporate the horizontal velocities alone. This is achieved by using the smooth, interpolated north component of the GNSS velocities to constrain the north-south motion and solving for the east-west and vertical InSAR displacements (Figure 2; e.g. Hussain *et al.*, 2016).

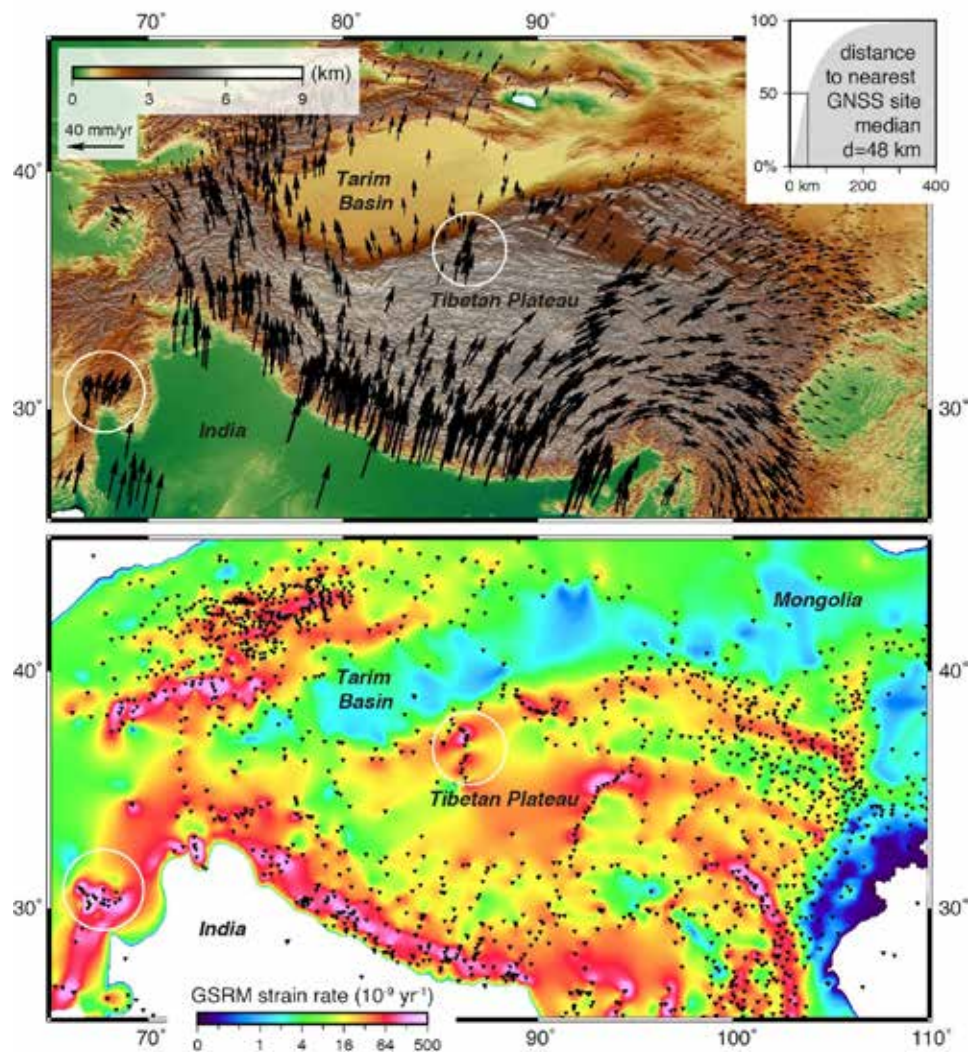


Figure 1: (Top) SRTM topography of the Tibetan Plateau and surrounding regions with GNSS velocities (black vectors) compiled by Kreemer *et al.* (2014) for the GSRM plotted relative to the Eurasian Plate. The vectors reflect the collision of the Indian Plate with Eurasia and the creation of a wide zone of deformation, seismicity, and elevated strain rates that extends from northern India to Mongolia. The inset shows a cumulative histogram of distance to the nearest GPS station for the area. Over 50% of the region lies greater than 50 km from a GNSS site. (Bottom) The second invariant of 2D surface strains from the GSRM, version 2.1, with GNSS sites used to create the strain rate field (black triangles). Rapidly straining regions are preferentially clustered around the GNSS sites indicating that the model is biased towards locations with GNSS data. For example see the two regions outlined with white circles. Areas with few GNSS sites are typically characterized by lower strain rates

The second approach involves directly inverting for the two- or three-dimensional velocity field by dividing the region of interest into a mesh of arbitrary spherical triangles, assuming the velocity varies linearly within each triangle, and relating the GNSS and InSAR measurements within each triangle to the velocities of its vertices by an interpolation function (Wang and Wright, 2012). Finally, under the assumption that strain is constant within each triangle, strain rates are calculated at each vertex. This method, which we refer to as VELMAP (Figure 2), has already been demonstrated in studies of interseismic deformation in eastern Anatolia (Walters *et al.*, 2014) and western Tibet (Wang and Wright, 2012), and plate boundary deformation across the Afar Rift in Ethiopia (Pagli *et al.*, 2014).

So far we have only hinted at an additional challenge related to deriving the continuous or dense representation of the surface velocity field required to calculate strain rates.

To do this, a variety of methods exist that typically involve velocity interpolation or the use of a physical model. The latter imposes a physical description of the system often in the form of elastic, fault-bounded blocks, and requires *a priori* information on fault geometry, etc.

Such an approach is not ideal, primarily because we want to use our strain rate maps to help identify unmapped active faults. Although researchers including those from COMET continue to work towards creating databases of active faults, we may never have a comprehensive global inventory of well-mapped, active faults with associated reliable slip rates (Bird *et al.*, 2015). Therefore, we have chosen to rely on interpolation-based schemes to derive velocity fields.

In addition to VELMAP and GSRM, we continue to test a few alternative velocity/strain field methods. They include a multiscale, spherical wavelets-based approach (TAPE09; Tape *et al.*, 2009), an algorithm that uses spatially dependent weighting to improve the velocity interpolation (Shen *et al.*, 2015), and a new technique called gpsgridded that permits elastic coupling between the two horizontal components of the interpolation (Sandwell and Wessel, 2016). Each of the methods has its own strengths and weaknesses and an ongoing goal is to evaluate and improve upon these approaches.

Figure 2 shows some example velocity and strain rate maps. To date, we have used data from Anatolia for testing because the signal associated with crustal deformation is large, GNSS and InSAR data exist, there is a good record of historical seismicity including recent large earthquakes, and much is known about the regional tectonics.

To a first order our preliminary results generally agree with those from the GSRM. Interpolated velocity fields illuminate the large-scale pattern of crustal motion across the region (as shown in Figure 1).

In particular, an abrupt change in the magnitude of horizontal surface velocity across the Northern Anatolian Fault (NAF) marks the boundary between Eurasia and Anatolia and is a manifestation of the westward motion of Anatolia away from the Arabia-Eurasia collision and towards the Hellenic arc. The change in velocity associated with the East Anatolian Fault (EAF) is not so apparent.

Strain rates are the spatial derivatives of the velocities and provide higher order spatial resolution than the velocities alone (Haines *et al.*, 2015). This higher order information is apparent when examining the strain rate maps for Anatolia (Figure 2), which show several interesting features including a band of relatively high strain (>100 nanostrain/year) straddling the entire NAF and portions of the EAF with isolated regions of very high strain (>200 nanostrain/year). Areas of strain concentration also coincide with east-west trending fault-bounded grabens near the southwestern Anatolian coast.

The strain maps differ in subtle but important ways. For example, as we mentioned previously, the GSRM results are strongly influenced by the distribution of observation points; localized regions of high strain on the NAF and EAF coincide with the GNSS sites.

References:

- Bird, P., Jackson, D.D., Kagan, Y.Y., Kreemer, C., Stein R.S. (2015) GEAR1: A Global Earthquake Activity Rate Model Constructed from Geodetic Strain Rates and Smoothed Seismicity, Bulletin of the Seismological Society of America, <https://pubs.geoscienceworld.org/ssa/bssa/article/105/5/2538/332070/gear1-a-global-earthquake-activity-rate-model>
- Bird, P., Liu, Z. (2007) Seismic Hazard Inferred from Tectonics: California, Seismological Research Letters <https://pubs.geoscienceworld.org/ssa/srl/article/78/1/37/143322/seismic-hazard-inferred-from-tectonics-california>
- England, P., Jackson, J. (2011) Uncharted seismic risk, Nature Geoscience <https://www.nature.com/articles/ngeo1168>
- Haines, A. J., Dimitrova, L. L., Wallace, L. M., Williams, C. A. (2015) Enhanced Surface Imaging of Crustal Deformation: Obtaining Tectonic Force Fields Using GPS Data, New York, Springer Int. Publ. <http://www.springer.com/us/book/9783319215778>
- Hussain, E., Hooper, A., Wright, T. J., Walters, R. J., Bekaert, D. P. S. (2016) Interseismic strain accumulation across the central North Anatolian Fault from iteratively unwrapped InSAR measurements, Journal of Geophysical Research: Solid Earth <http://onlinelibrary.wiley.com/doi/10.1002/2016JB013108/full>
- Kreemer, C., Blewitt, G., Klein, E.C. (2014) A geodetic plate motion and Global Strain Rate Model, Geochemistry, Geophysics, Geosystems <http://onlinelibrary.wiley.com/doi/10.1002/2014GC005407/supinfo>
- Pagli, C., Wang, H., Wright, T.J., Calais, E., Lewi, E. (2014) Current plate boundary deformation of the Afar rift from a 3-D velocity field inversion of InSAR and GPS, Journal of Geophysical Research: Solid Earth <http://onlinelibrary.wiley.com/doi/10.1002/2014JB011391/abstract>
- Walters, R. J., Parsons, B., Wright, T.J. (2014) Constraining crustal velocity fields with InSAR for Eastern Turkey: Limits to the block-like behavior of Eastern Anatolia, Journal of Geophysical Research: Solid Earth <http://onlinelibrary.wiley.com/doi/10.1002/2013JB010909/abstract>
- Wang, H., Wright T.J. (2012) Satellite geodetic imaging reveals internal deformation of western Tibet, Geophysical Research Letters <http://onlinelibrary.wiley.com/doi/10.1029/2012GL051222/full>
- Wright, T. J. (2016) The earthquake deformation cycle, Astronomy & Geophysics <https://academic.oup.com/astrogeo/article/57/4/4.20/1741884>

In contrast, TAPE09 distributes regions of high strain somewhat more uniformly across the faults and both VELMAP and gpsgridded collapse high strain along the surface trace of the NAF. It is noteworthy that VELMAP yields relatively low strain rates along the EAF near its intersection with the NAF compared to the other methods.

Finally, only TAPE09 produces strain rates >50-100 nanostrain/year across portions of the Anatolian interior not clearly associated with the major faults whereas the other methods suggest this region is not straining at all. The distribution of regional seismicity seems to support the TAPE09 results (Figure 2).

To date our comparisons of these complementary velocity/strain mapping methods is purely qualitative stemming from physics-based (dislocation) models into our analysis to quantitatively assess which methods perform best and to test planned enhancements (primarily to VELMAP).

Strain rates alone provide invaluable information on regional seismic hazard but the analysis can be taken one step further. Specifically, based on the notion that strain rates are directly related to the accumulation of stresses around a fault and that earthquakes indicate stress release, strain rate maps in combination with global earthquake catalogues and geologic information (e.g. mapped fault locations and slip rates) help place probabilistic constraints on the magnitudes and frequencies of earthquakes in a region (Bird *et al.*, 2015).

For Turkey, to a first order, shallow (<20 km) earthquake focal mechanisms from the Global Central Moment Tensor (CMT) database (1976-present) tend to occur primarily in regions straining at rates >50 nanostrain/year. In parallel with our InSAR and GNSS but we have begun to incorporate synthetic data data integration and velocity/strain mapping efforts we plan to use relationships described by Bird and Liu (2007) to update the Global Earthquake Activity Rate Model (GEAR1; Bird *et al.*, 2015) and produce shallow seismicity forecasts for the AHB using our improved, high-resolution GNSS/InSAR-derived strain rate maps in combination with the global CMT earthquake catalog and active faults databases.

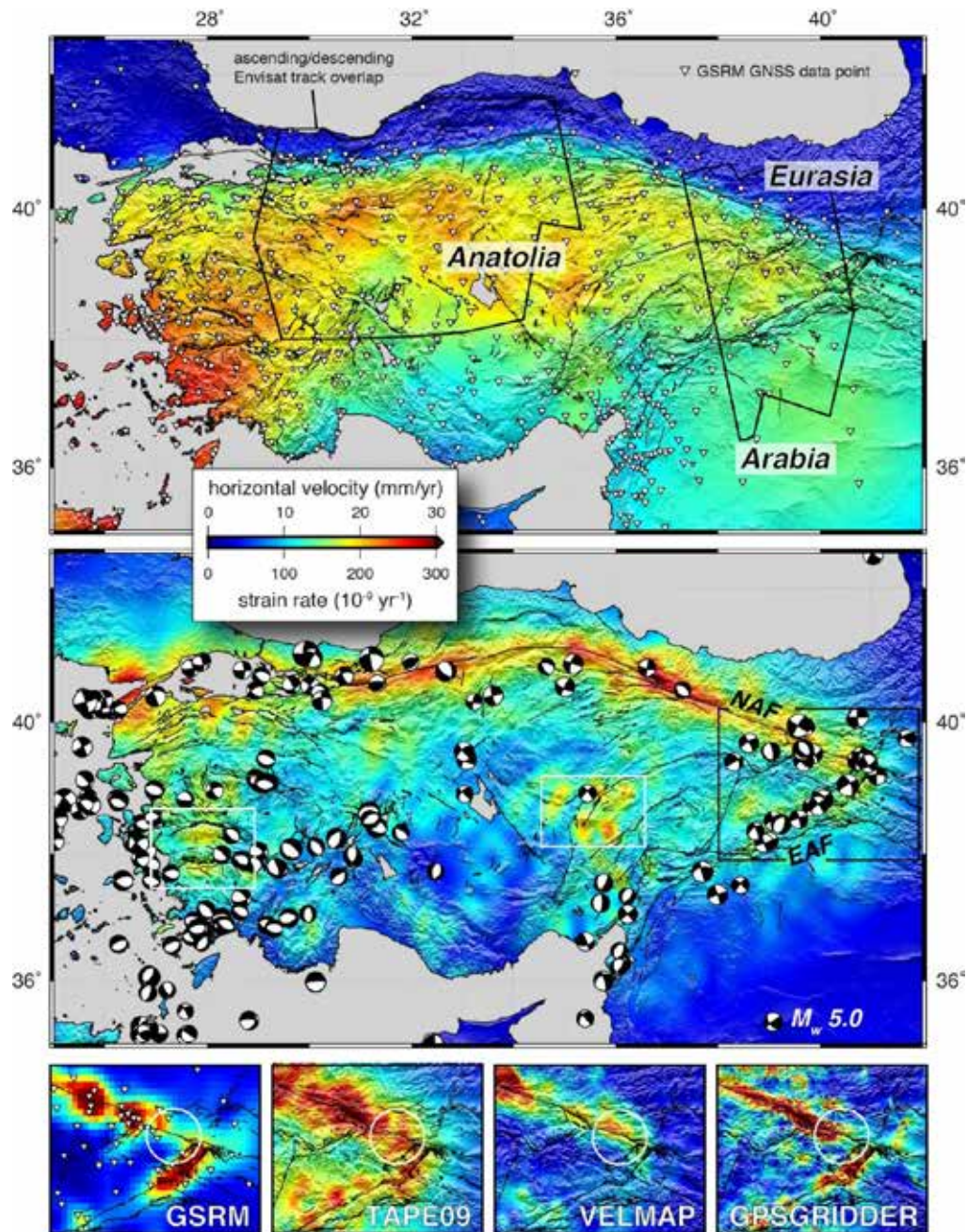


Figure 2: (Top) A velocity field for Anatolia derived from the GSRM GNSS data compilation (white triangles) and InSAR-derived (Envisat) horizontal velocities (Ekbali Hussain, pers. comm.) using the TAPE09 method. Regions with both ascending and descending InSAR data are outlined with black polygons. (Middle) The associated strain rate field derived using TAPE09 with earthquake focal mechanisms from the Global CMT catalog. NAF=Northern Anatolian Fault; EAF=Eastern Anatolian Fault. The white boxed regions indicate the actively straining fault-bounded grabens in the southwest and a region where it's unclear if the spotty high strain rates are real and fault-related or are interpolation artefacts. The black box indicates the region shown in the bottom panels. (Bottom) Strain rate maps for Eastern Turkey derived using the different methods described in the main text. The location of GNSS sites used in the analysis are shown in the GSRM version only. All results other than GSRM use GNSS + InSAR data. The white circles are for method comparison

RESEARCH HIGHLIGHT

SEPARATING VOLCANIC SOURCES IN InSAR DATA USING INDEPENDENT COMPONENT ANALYSIS

Susanna Ebmeier (COMET Associate, Leeds)

One of the challenges of analysing interferograms is distinguishing interesting, geophysical signals, such as earthquake or volcano deformation, from each other, and from atmospheric noise. Robust tests for the independence of geophysical signals are also important for establishing causal links between magmatic, hydrothermal and tectonic processes.

Independent Component analysis (ICA) is a computational signal processing method that decomposes a mixed signal into components that maximise signal independence in either space or time. This relies on the idea that as more and more independent signals are mixed together, their sum gets closer to a Gaussian distribution – so the parts of a mixed signal that are ‘interesting’ will be the least Gaussian.

Finding these components is useful for analysing the relationship between the different deformation processes. Signals caused by the same process can be identified by searching for ‘clusters’ in the identified components. Real geophysical signals are very much more likely to cluster than atmospheric signals, so this is a useful approach both for distinguishing between true deformation and atmospheric noise and for analysing the relationships between geophysical signals.

This approach to analysis was tested on Sentinel-1 data from Paricutin lava flows in Mexico, and on co-eruptive subsidence at Calbuco, Chile. In both cases, deformation had previously been well-characterised, so comparison to ICA decomposition results provides a test of the reliability of the results. At Paricutin, in particular, three distinct patches of subsidence were extracted as a single component – meaning that the deformation mechanism, in this case lava flow contraction, was likely to be the same for all three.

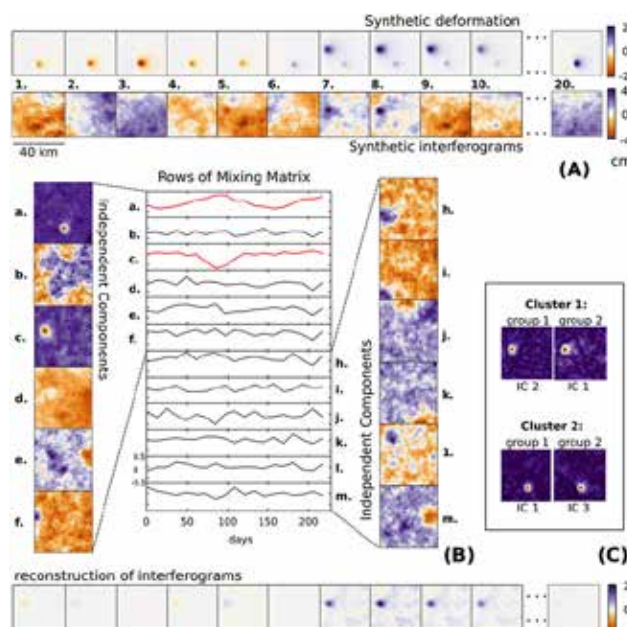


Illustration of independent components of a synthetic set of interferograms capturing two independent deformation sources. (A) Synthetic deformation for two volcanic sources with different temporal signals, and associated synthetic interferograms incorporating various noise sources. (B) Independent spatial components of the set of interferograms, shown with letters to match the corresponding rows of the mixing matrix (C) Clusters of independent components retrieved from (D) Reconstruction of interferograms showing the two independent synthetic deformation sources identified from cluster analysis



Parícutin volcano, Mexico

RESEARCH HIGHLIGHT

SENTINEL-1 CAPTURES EXTENT OF COMPLEX MULTIFAULT RUPTURE IN NEW ZEALAND EARTHQUAKE

John Elliott (COMET Associate, Leeds), Tim Wright (COMET Scientist, Leeds)

Larger earthquakes are known to typically involve rupture on more than a single fault segment, and the distances over which earthquakes can jump between segments is an important topic of research for understanding the dynamics of rupture and also the extent of potential seismic hazard. Analysis of last year's New Zealand earthquake illustrates however the need to rethink how far scenario models go in defining this.

A number of well-studied major earthquakes in the past couple of decades are known to have involved multi-segmented rupture on many fault strands, such as the 1992 Landers event in California and the more recent Darfield earthquake in New Zealand in 2010. However, the major moment magnitude (Mw) 7.8 earthquake that struck the north-eastern edge of the South Island of New Zealand on 14 November 2016 raised the level of complexity observed in multi-rupture earthquakes a step further.

Observations from satellite-derived InSAR coupled with GPS and fieldwork highlighted not only the widespread nature of ground deformation and faulting, but also that the earthquake straddled two distinct seismotectonic domains - rupturing across faults in the North Canterbury fault zone initially, before continuing onto the Marlborough fault system further north and then running offshore, generating a small tsunami.

The need to account for multiple segment ruptures is important for determining seismic hazard assessment and the ultimate size to which an earthquake will grow – in this case from a relatively low magnitude 6 in the initial stages (and preliminary seismological estimates) up to a high magnitude seven by the end - with a dramatic difference in terms of shaking outcomes and major changes to the landscape. The rupture propagated for more than 170 km, and occurred both on previously mapped and unmapped fault segments.

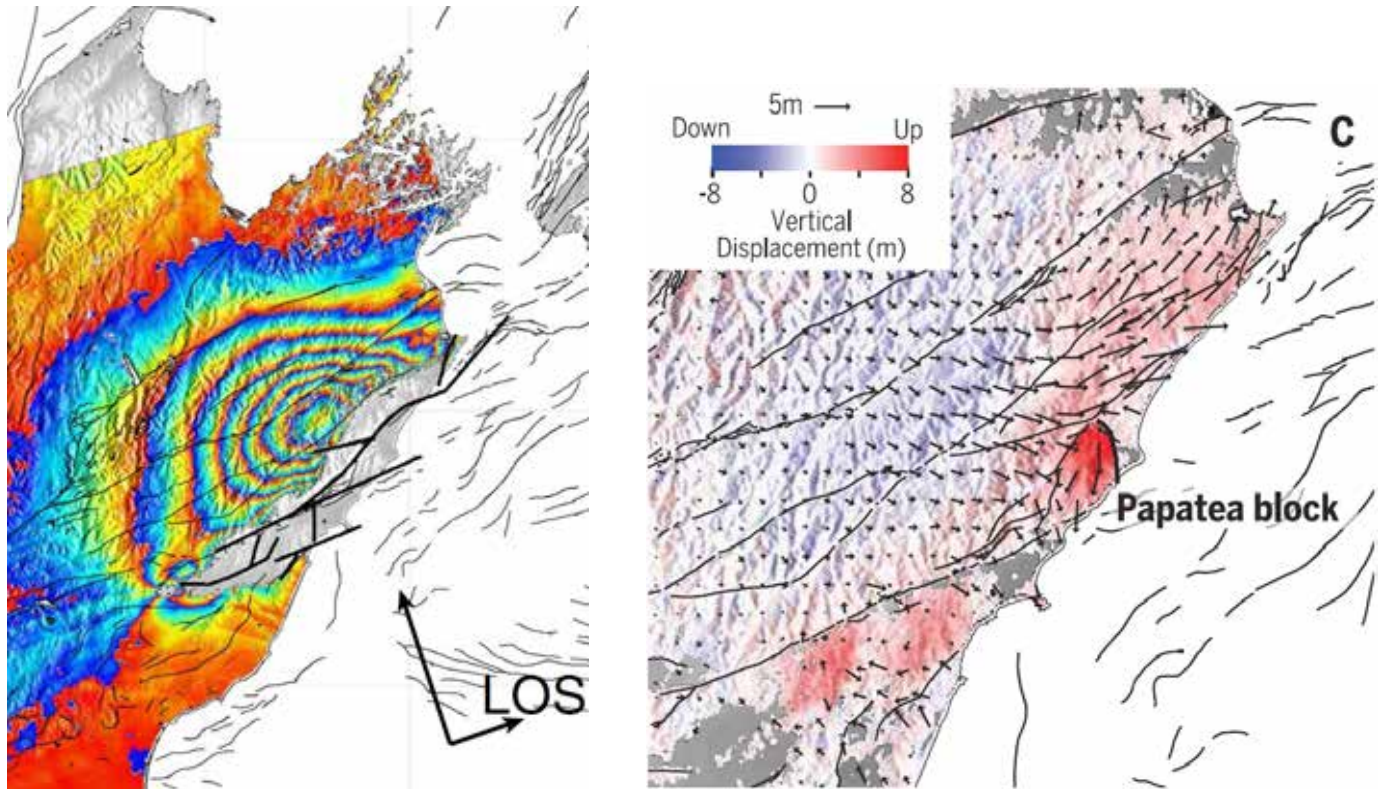
Geodetic measurements from Sentinel-1 SAR offsets as well as field studies indicated that at least 12 major segments were involved, with extensive crustal uplift occurring along the length of the eastern coastline between Cape Campbell and the Kaikoura peninsula.

The combined horizontal and vertical SAR measurements were particularly useful in constraining the surprising behaviour of the Papatea block that popped up by over 8 m, caught between the two main faults of the Kekurengu and Hope faults, and potentially point to a mechanism for the rapid growth of topography in this region.

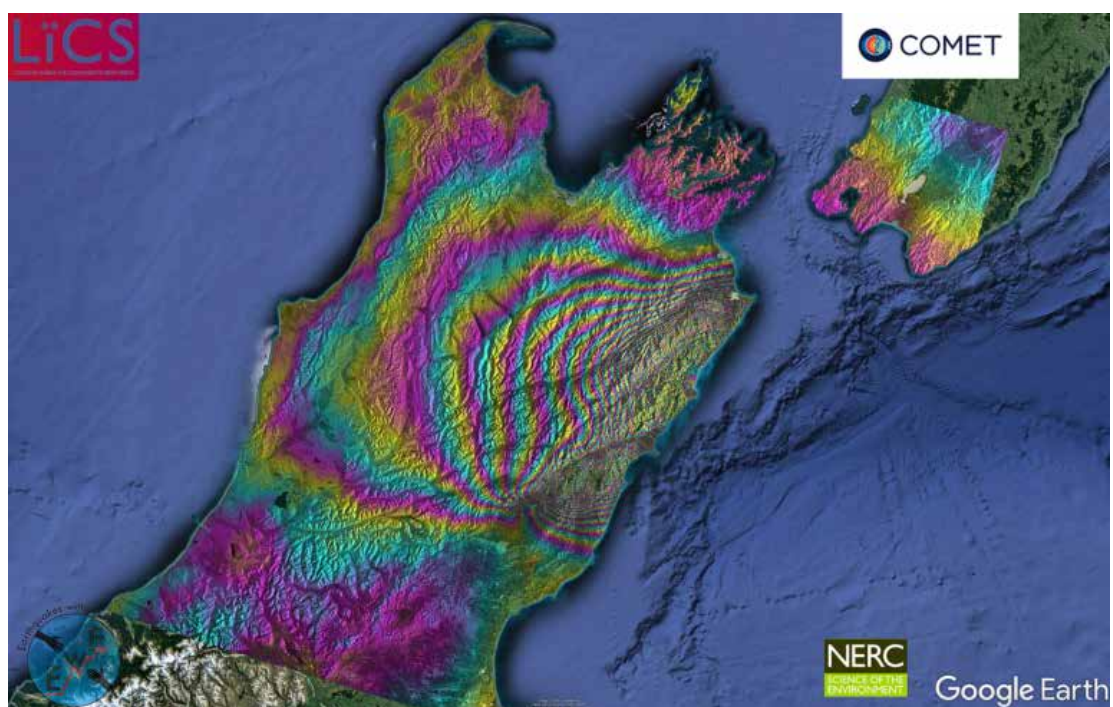
Past field observations of fault ruptures and insights from numerical modelling have suggested rupture is impeded when segmentation occurs over length scales of about 5 km. Additionally, deforming regions are often conceptually broken up into a series of rigid blocks, with a consequence being that the potential seismic hazard scenarios are equally rigid in their suite of outlooks. The complexity and extent of inclusion of multiple fault ruptures in this event provides motivation for re-evaluating how rupture scenarios are defined for seismic hazard models in plate boundary zones worldwide.

This work was undertaken by scientists at GNS New Zealand in collaboration with COMET scientists John Elliott and Tim Wright; lead author Ian Hamling (GNS Wellington) is an ex-COMET PhD student. Ongoing work is being undertaken by COMET to measure the source ruptures in high resolution and examine postseismic deformation in the months after, in further collaboration with scientists in New Zealand and the UK.

Reference: Hamling, I. J. *et al.*, (2017) Complex multifault rupture during the 2016 Mw 7.8 Kaikoura earthquake, New Zealand, Science
<http://science.sciencemag.org/content/356/6334/eaam7194>



Above left: Sentinel 1 interferogram spanning the earthquake showing the ground displacement in 20 cm contours. The black lines indicate the 12 fault segments modelled in this earthquake as actively slipping. Above right: Three-dimensional displacement field associated with the Papatea block captured using radar offsets from Sentinel-1 data combined with ALOS and GPS data. Over 8 metres of uplift is imaged over a length-scale of 10 km as the Papatea block pops up between the Jordan Thrust and the Hope Fault. Below: ALOS-2 interferogram from track 195 showing the coseismic displacement field



RESEARCH HIGHLIGHT

GAS BUBBLES IN MAGMA STRONGLY AFFECT VOLCANO DEFORMATION

Brendan McCormick Kilbride (COMET Researcher, Cambridge)

Satellite observations of co-eruptive gas emissions and ground deformation are reconciled in a new multi-parameter model framework.

Satellite observations of the gas emissions and ground deformation that accompany volcanic eruptions have been made routinely for some decades. Up to now, these observations have been treated independently, but they are fundamentally linked. Establishing an integrated framework for the interpretation of satellite observations is important for fully understanding volcano monitoring data.

When magmas ascend from depth into shallow crustal reservoirs, the drop in pressure favours the partitioning of volatiles from a dissolved to an exsolved state, that is, gas bubbles. These bubbles cause the magma to become more compressible, resulting in muted ground deformation at the surface, and contain the sulfur-rich vapour subsequently injected into the atmosphere.

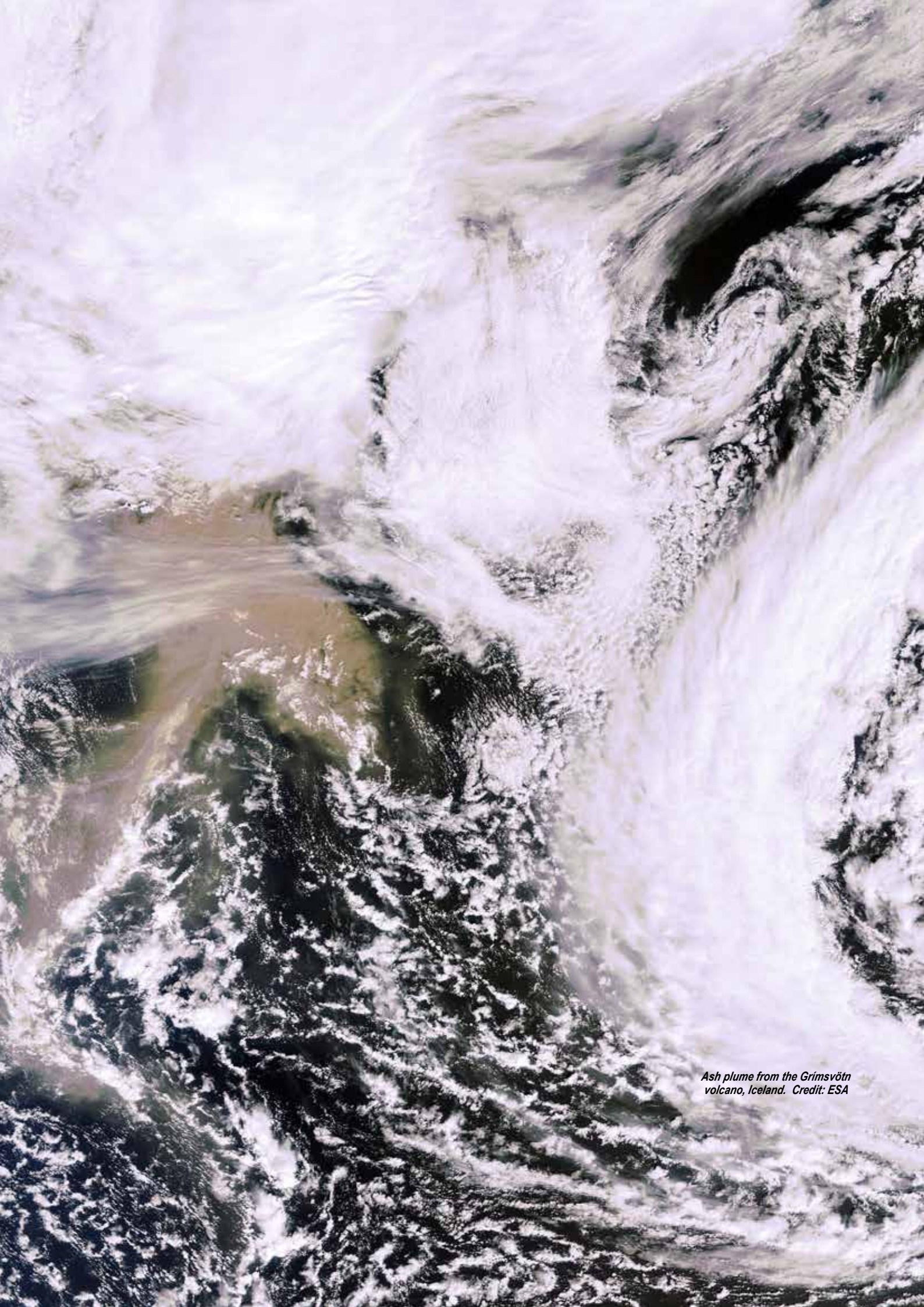
Volatile partitioning varies widely with magma intrinsic properties (composition, pressure, temperature), but is increasingly well-constrained by thermodynamic models. Physics-based models describing the effect of gas bubbles on magma density and compressibility are also well established.

This work combines these two types of model in a framework that allows prediction of co-eruptive ground deformation and sulfur dioxide gas yield, predictions which can be tested against a growing global observational dataset.

This approach is the first attempt to reconcile diverse global observations of volcanic eruptions from space, and forms a basis from which to improve and diversify eruption modelling. As observations become better constrained and more precise, integrated modelling of this kind will become commonplace with scope for additional layers of complexity, particularly in reservoir architecture and gas transport mechanisms.

Reference: McCormick Kilbride, B.T., Edmonds, M., Biggs, J. (2016) Observing eruptions of gas-rich compressible magmas from space, Nature Communications <https://www.nature.com/articles/ncomms13744>





Ash plume from the Grímsvötn volcano, Iceland. Credit: ESA

PUBLICATIONS

COMET HAS A STRONG PUBLICATION RECORD: SINCE JANUARY 2014, WE HAVE PUBLISHED 192 ARTICLES IN A BROAD RANGE OF SCIENTIFIC JOURNALS WHICH COVER BOTH THE EARTH AND ATMOSPHERIC SCIENCES.

Of these, 82 were published between 1 January and 31 December 2016 (see Annex 1) - a 28% increase on 2015. Some of the main scientific advances from last year are described below.

Iceland volcano collapse explained

Work by Andy Hooper and Marco Bagnardi (both Leeds) shed new light on how volcanoes collapse during major eruptions.

The Bárðarbunga eruption (August 2014-February 2015) produced 1.5 km³ of basaltic lava. During the eruption, the top of the volcano caldera sagged downwards, leaving a bowl shaped depression over 13 km long and up to 65 m deep.



Eruption column and lava flow from the air on 22 September 2014. Credit: Thórdís Högnadóttir

The COMET researchers used satellite data to measure ground deformation at the caldera. As the topography changed, the data revealed movement of faults that reached to within a kilometre or so of the surface. Combined with other techniques, this created a detailed picture and timeline of how the caldera was collapsing and why.

They concluded that from 16 August 2014 – before the eruption began – magma had been migrating out of a chamber 12 km below the ground, forming a fracture in the Earth's crust. Continued monitoring showed that the magma was moving sideways from the volcano before finally erupting at Holuhraun, 47 km to the northeast, two weeks later.



The eruption in Holuhraun on its fourth day (3 September 2014). Credit: Thórdís Högnadóttir

Further analysis showed that a few days after the initial migration, the outflow of magma activated faults around the edge of the caldera leading to a series of earthquakes, which marked the beginning of the caldera collapse. The collapsing roof then acted like a piston forcing even more magma out of the chamber below, which in turn led to further collapse.

Airborne volcanic ash detection using infrared spectral imagery

This study, co-authored by Tamsin Mather (Oxford) demonstrated for the first time that airborne remote detection of volcanic ash is possible. Airborne volcanic ash is a known hazard to aviation, but there are no current means to detect ash in-flight as the particles are too fine for on-board radar detection and, even in good visibility, ash clouds are difficult or impossible to detect by eye.

The research involved designing and building a bi-spectral, fast-sampling, uncooled infrared camera device (AVOID) to examine its ability to detect volcanic ash more than 50 km ahead of aircraft. Experiments conducted over the Atlantic Ocean, off the coast of France, involved an artificial ash cloud being created using ash from the 2010 Eyjafjallajökull eruption in Iceland. The measurements made by AVOID, along with additional sampling, confirmed its ability to detect and quantify ash in an artificial ash cloud. This is the first example of airborne remote detection of volcanic ash from a long-range flight test aircraft.

Experiments conducted over the Atlantic Ocean, off the coast of France, involved an artificial ash cloud being created using ash from the 2010 Eyjafjallajökull eruption in Iceland.

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Thick ash pouring from Iceland's Eyjafjallajökull volcano on April 17 2010. Credit: NASA

Massive quake shifts perceptions of earthquake hazard models

Satellite images of the 2016 Kaikoura earthquake on New Zealand's South Island enabled scientists to analyse the quake in an unprecedented level of detail.

Using data from the Sentinel-1 and ALOS-2 satellites, COMET researchers John Elliott and Tim Wright (both Leeds) could see how ruptures were taking place across many separate faults.

Pre- and post-earthquake satellite images measured the extent of land movement, showing that Kaikoura's earthquake caused sections of earth to move up to 25 metres and created surface ruptures measuring 12 metres. This caused large scale landslides and triggered a tsunami.

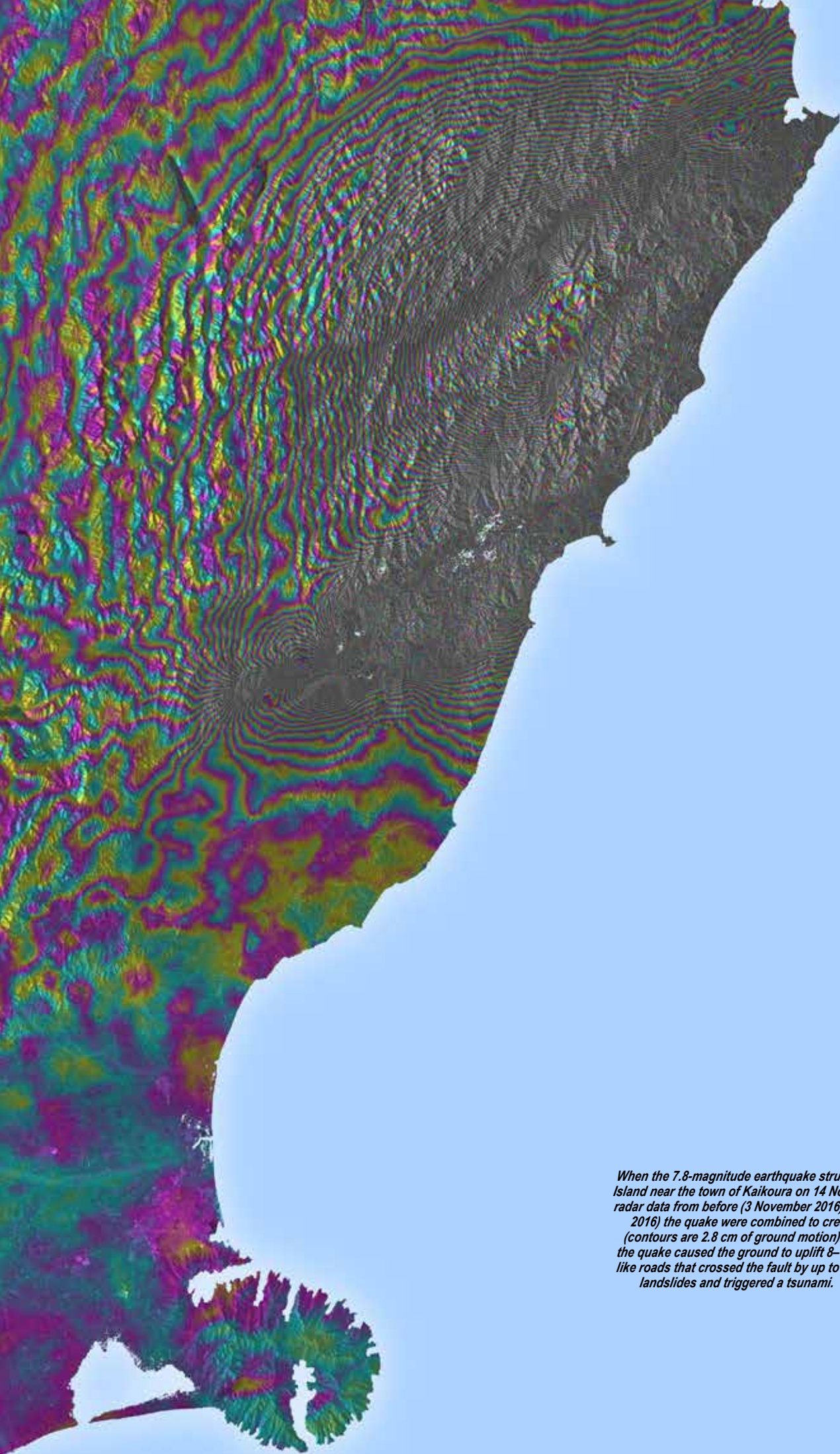
The full range of data analysed from Kaikoura's earthquake included satellite imagery, field observation, GPS data and coastal uplift data. The research will prompt reassessment of how many different faults can be involved in a single earthquake and could potentially feed into revaluations of seismic hazard models.



Science cover from 14th April 2017 issue showing earthquake uplift across the coastal platform at Waipapa Bay, off New Zealand's South Island.



Reference: Hamling *et al.* (2016) Complex multi-fault rupture during the 2016 M7.8 Kaikoura earthquake, New Zealand, Science First Release
<http://science.sciencemag.org/content/356/6334/eaam7194>



When the 7.8-magnitude earthquake struck New Zealand's South Island near the town of Kaikoura on 14 November 2016, Sentinel-1 radar data from before (3 November 2016) and after (15 November 2016) the quake were combined to create this interferogram (contours are 2.8 cm of ground motion). The results show that the quake caused the ground to uplift 8–10 m and offset features like roads that crossed the fault by up to 12 m. This caused large landslides and triggered a tsunami. Credit: ESA/J.Elliott

FUNDING SUCCESS

The long-term funding that COMET receives from NERC via BGS underpins a much broader spectrum of research activities. Major collaborations are described in the next section, but in 2016/17 COMET scientists and associates were successful in winning a number of other awards.

Rapid investigation of co- and post-seismic deformation resulting from the 24th August 2016 Amatrice earthquake (M6.2)

Laura Gregory (COMET Associate, Leeds)/Richard Walters (COMET Scientist, Durham)

Funder: NERC (Urgency Grant)

Value: £52k

Duration: 2016 – 2017

This work is aiming to fully characterise the nature of the Amatrice earthquake in terms of what happened during and what is continuing to occur after the seismic event. It is using a variety of techniques including satellite radar measurements and modelling of co- and post-seismic deformation, GNSS measurements of ground deformation, photogrammetry and laser scanning to make high resolution measurements of the surface rupture, detailed field work in the region of the earthquake, and modelling techniques to determine how this earthquake affected stress on the surrounding faults.



COMET PhD student Huw Goodall contemplates the surface rupture that resulted from the 30th Oct M6.6 event. The rupture strikes across the side of Mt Vettore in the distance

Seismic Cities

John Elliot/Laura Gregory (COMET Associates, Leeds)/Tim Wright (COMET Scientist, Leeds)

Funder: NERC (Global Challenges Research Fund – Resilience)

Value: £175k

Duration: 2017

This initiative will develop a blueprint for the concept of “Seismic Cities”, a powerful approach for raising awareness of the devastating potential of earthquakes in cities and for making them more resilient to such shocks. It will bring together a range of stakeholders to target communities vulnerable to seismic hazard, and to develop cities that can better cope with future environmental shocks from earthquakes.



City of Santiago, Chile, home to over 6 million people. A recently recognised active fault (San Ramon, red lines) lies on the eastern edge of the city

Initially targeting Santiago (Chile), satellite imagery will be used to construct a 3D model of the built environment and highlight active fault structures within the city. This will be integrated with community resources to better communicate the findings derived from the scientific data. The long-term aim is to raise resilience to earthquake hazard across the whole world to the standards of the US, New Zealand and Japan.

Rapid recovery of high resolution topographic and kinematic data from the Kaikoura quake, New Zealand

Ed Rhodes (COMET Associate, Sheffield)/John Elliott (COMET Associate, Leeds)/Barry Parsons (COMET Scientist, Oxford)/David Mackenzie (COMET Researcher, Oxford)

Funder: NERC (Urgency Grant)

Value: £64K

Duration: 2017

The magnitude 7.8 earthquake on the South Island of New Zealand ruptured on a complex pattern along a series of twelve separate faults, with dramatic surface ruptures (with up to ~10m of horizontal slip) and large-scale landsliding between Kaikoura and Blenheim. This project will i) record key selected examples of these temporary landscape features before they are destroyed by surface processes, to help tell the difference between initial fault slip during the earthquake from post-seismic movement; and ii) emplace a number of semi-permanent GPS recorders to capture the rate and timing of post-seismic movement over a period of around 3 months.

Harnessing 'citizen science' to reinforce resilience to environmental disasters: creating an evidence base and community of practice

Tamsin Mather/David Pyle (COMET Scientists, Oxford)

Funder: NERC (Global Challenges Research Fund – Resilience)

Value: £159k

Duration: 2017

This project will a) improve understanding of how we should use citizen science to address challenges around and build resilience to environmental hazards; and b) create and nurture an international transdisciplinary community of practice to contribute to future projects. It will learn lessons and synthesise knowledge from previous citizen science programs and existing initiatives; and understand what the barriers to success are with these types of project and try to break them down. Citizens are at the heart of the project and so it will involve conversations with communities in three contrasting study sites (Ecuador, the English-speaking Caribbean and Nepal) to inform the synthesis and critical analysis of the challenges encountered in country.

Unseen but not unfelt: resilience to persistent volcanic emissions (UNRESP)

Evgenia Ilyinskaya (COMET Associate, Leeds)/Clive Oppenheimer (COMET Scientist, Cambridge)/Tamsin Mather (COMET Scientist, Oxford)

Funder: NERC (Global Challenges Research Fund – Resilience)

Value: £150k

Duration: 2016-2017

UNRESP seeks to reduce the impact of Nicaraguan volcano Masaya's persistent volcanic emissions (PVE) on the local populations by introducing

early warning and mitigation procedures for episodes when volcanic air pollution reaches hazardous levels.

While Masaya will be used as a pilot location, the results will be applicable to other areas in Nicaragua impacted by PVE, and translatable to other countries.

Rapid deployment of a seismic array in Ecuador following the April 16th 2016 M7.8 Pedernales earthquake

Pablo González (COMET Scientist, Liverpool)

Funder: NERC

Value: £52k

Duration: 2016-2017

This project will rapidly deploy a seismological network at the southern end of the April 16th 2016 M7.8 Pedernales earthquake in Ecuador. Alongside other partners, this seismological network will record earthquake activity continuously for a period of 10 months, with a service after 5 months.

The dataset obtained will provide unprecedented resolution on imaging aftershock activity on the subduction interface, and be used to detect earthquakes which will be located while jointly determining high-resolution 3D velocity structure in this tectonically complex subduction zone.

Ice landform characterization and permafrost dynamics around the Pingo National Landmark, Tuktoyaktuk, Northwest Territories, Canada

Pablo González (COMET Scientist, Liverpool)

Funder: NERC (UK Arctic Office)

Value: £20k

Duration: 2017

This UK-Canada bursary project aims to apply novel satellite and UAV methodologies to obtain unprecedented high-resolution topographic information of ice landforms in the coastal plains of the Western Canadian Arctic.

The project will carry out a systematic survey to identify and quantitatively characterize the morphology of pingos (permafrost generated ice-cored hills); and test whether pingos are currently undergoing systematic growth, stability or decline due to environmental changes in the Western Canadian Arctic. Working in collaboration with Canadian scientists, the goal is to enhance capability to monitor permafrost and ice-landforms dynamics with EO data as a key element in understanding the impact of environmental changes in Arctic regions.

Understanding volcanic risk in Turkey

Juliet Biggs (COMET Scientist, Bristol)

Funder: RCUK Newton TUBITAK

Value: £200k

Duration: 2016-2019

Geological and historical records of the ten active volcanoes in Turkey indicate potential in several of them for major explosive eruptions. Over 4 million people live within 30 km of an active volcano and over 15 million live within 100 km.

The last major volcanic disaster in Turkey occurred in 1840 from Mount Ararat, when an estimated 1900 people lost their lives. However, there is a 70% chance of a major eruption in this century based on global statistics and preliminary analysis of Turkish eruption records. In particular, access in Eastern Turkey is limited due to the security situation, requiring an innovative solution for monitoring remote or inaccessible volcanoes. This project, led by Bristol's Stephen Sparks, will involve remote sensing using various tools such as satellite and aerial imagery and InSAR and identifying analogue systems.

PREPARE: Enhancing Preparedness for East African Communities through Seismic Resilience Engineering

Juliet Biggs (COMET Scientist, Bristol), Ake Fagereng (COMET Associate, Cardiff), Mike Kendall (COMET Associate, Bristol)

Funder: EPSRC (Global Challenges Research Fund).

Value: £1.41m

Duration: 2017-2020

PREPARE develops a holistic seismic risk management framework for East Africa and co-produces practical tools and guidelines for enhanced disaster preparedness in close partnerships with local governmental and academic institutions.

It is aimed at overcoming existing barriers to designing seismically resilient infrastructure in least developed countries using advanced risk assessments and suitable low-cost engineering solutions.

COMET's involvement lies in tectonic investigations of strain accumulation and release in the Malawi Rift system and other East African countries, providing more accurate information on the potential earthquake rupture characteristics of fault systems (i.e. location, length and recurrence interval of large earthquakes).

Improving seismic hazard assessment in the continents with satellite geodesy

Tim Wright (COMET Scientist, Leeds)

Funder: Royal Society Challenge Grant

Value: £100k

Duration: 2016 – 2017

This project will work with collaborators at Addis Ababa University to produce a new high-resolution map of dynamic surface motions throughout Ethiopia, using satellite measurements from GPS and InSAR. This fundamental new data set will be used to address pressing challenges in understanding the hazards in Ethiopia associated with volcanism, earthquakes, and landslides.

The Rise of Mountains

John Elliott (COMET Associate, Leeds)

Funder: Royal Society (University Research Fellowship)

Value: £510k

Duration: 2016-2021

This work will address how a mountain chain grows; whether this is primarily along its edges, or is more pervasive. To discriminate between models of the distribution of strain within the crust, it will exploit new satellite datasets to measure the rate of change in surface height across a mountain chain, the Tien Shan in Central Asia, hundreds of kilometres in extent.

It will also use independent atmospheric models to correct for atmospheric noise, and assess the varying contributions to uplift, from tectonics to erosion and ice unloading. The resulting mapping of deformation will enable better assessments of earthquake hazard in the future.

Dragon-4: Earth observations for geohazard monitoring and risk assessment

Zhenhong Li (COMET Scientist, Newcastle)

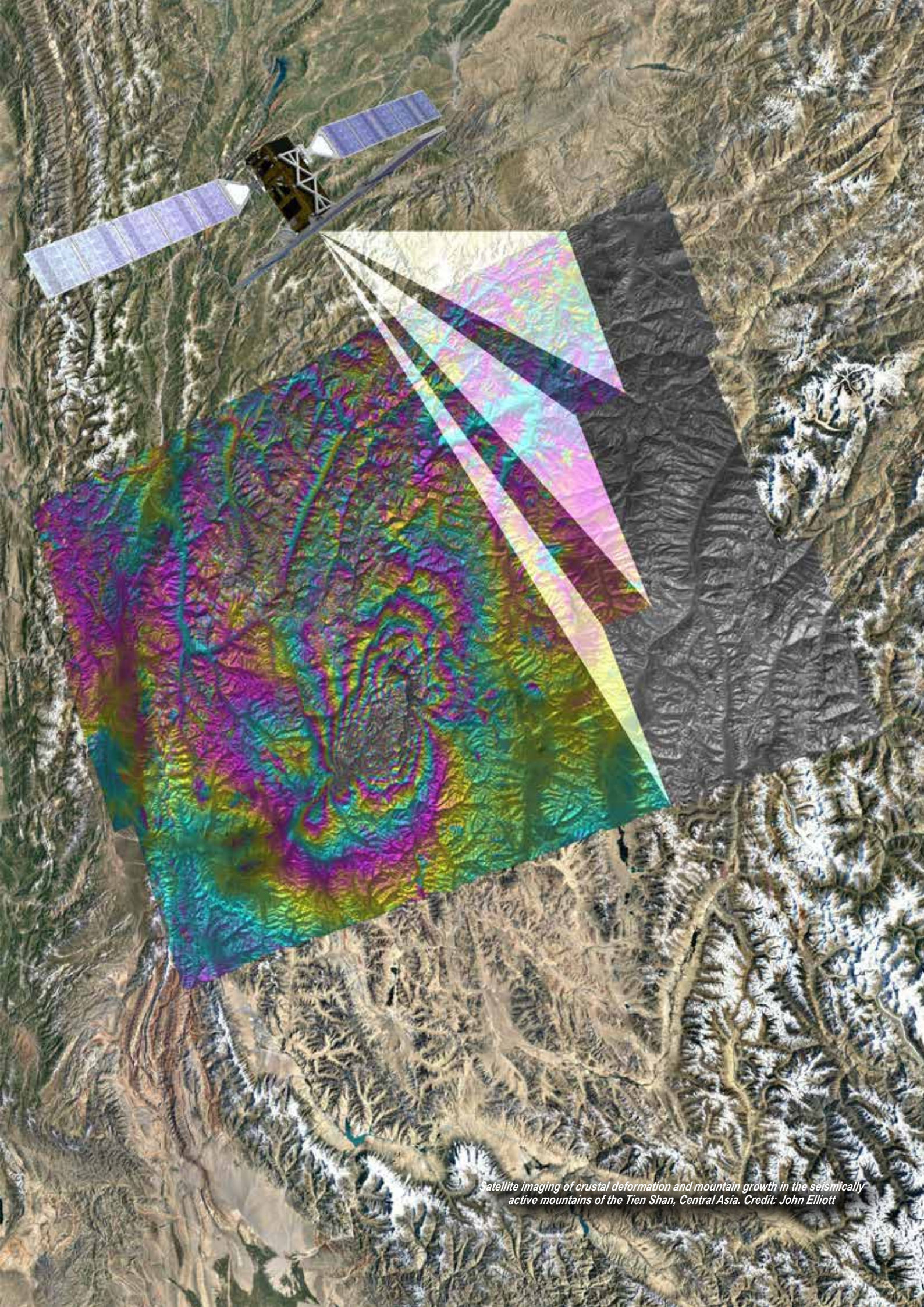
Funder: ESA

Value: €70k

Duration: 2016 – 2020

This project aims to employ Earth observations to rapidly respond to large earthquakes and induced landslides, make detailed active fault maps, determine present-day deformation and assess seismic and landslide risks in the study regions.

It focuses on active faults and seismic risk assessment in China; landslide hazards in the Three Gorges region and landslides induced by large earthquakes; and earthquake precursors from space.



Satellite imaging of crustal deformation and mountain growth in the seismically active mountains of the Tien Shan, Central Asia. Credit: John Elliott

COLLABORATIONS & PARTNERSHIPS

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



Earthquakes without Frontiers²⁷

(EwF), led by James Jackson (Cambridge), 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.

Over the past year, the EwF team has undertaken extensive field campaigns to investigate faults and earthquakes in Kyrgyzstan, Kazakhstan and Turkmenistan. These have included the Dzhungarian Fault in the Tien Sian, using drones to map the effects of the 1992 M7.2 earthquake; the Chilik-Chon Kemin Fault which, in 1889, caused one of the largest continental earthquakes ever recorded (M8.3); and the Ashgabat Fault, one of the most spectacular faults in Central Asia.



Looking inside the Continents from Space²⁸

(LiCS), led by Barry Parsons (Oxford) and Tim Wright (Leeds), is a NERC large grant 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. It 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.

In December 2016 the LiCSAR service was launched, providing links to EU Copernicus Sentinel-1 InSAR products available for download. Interferograms and coherence maps are produced automatically using the LiCSAR processor, which builds on the Gamma SAR and Interferometry software. New interferograms should be available within two weeks of data acquisition. The initial focus is on the Alpine-Himalayan tectonic belt, but we are working on processing the complete archive for tectonic and volcanic areas globally.



FutureVolc²⁸, led by the University of Iceland and Icelandic Meteorological Office, has been a long-term monitoring experiment looking at geologically active regions of Europe that are prone to natural hazards.

It developed the "supersite" concept, integrating space- and ground-based observations to improve monitoring and evaluation of volcanoes.

FutureVolc as an EC sponsored project ended in March 2016, although the collaboration between COMET and the FutureVolc partners continues. Recent outputs include work described earlier in this report on gradual caldera collapse at Bárðarbunga Volcano, Iceland.



RiftVolc²⁹, 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 project is currently carrying out ground-based geophysics using networks of GPS receivers, gravimeters, seismometers and magnetotelluric equipment complemented by satellite observations using InSAR to detect surface deformation and ASTER to measure fumarole behaviour.



Strengthening Resilience in Volcanic Areas³⁰

(STREVA), led by the University of East Anglia, 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.

Work is focusing on volcanoes in Ecuador, Colombia and Montserrat, including Tungurahua, Reventador and Soufriere Hills, where we are strengthening links between geodesy, seismology and modelling on different timescales. STREVA has run capacity building workshops on the use of InSAR in volcano observatories in Colombia (2016, 2011), Ecuador (2013) and Costa Rica (2013).

Spectrally High resolution Infrared measurements for the characterisation of Volcanic Ash³¹

(SHIVA), which ended in March 2017, aimed to study the properties of volcanic ash using information contained in infrared spectra and the change in composition during an eruption, in order to better understand the volcanic processes that control eruptive activity. As well as publications, outputs from the project include:

- A new optimal estimation retrieval scheme for ash/aerosol using IASI measurements in both clean and cloudy conditions. Results have been validated with other satellite and aircraft measurements;
- Laboratory measurements of the spectral mass extinction coefficient, at 0.33 through to 19 microns, and size distribution of a range of volcanic ash samples, showing considerable variation in their optical properties particularly associated with their infrared absorption features. These measurements can be directly applied to improve the accuracy of satellite retrievals of ash columnar concentration.

27. <http://ewf.nerc.ac.uk/>

28. <http://futurevolc.hi.is/>

29. <https://riftvolc.wordpress.com/>

30. <http://streva.ac.uk/>

31. <https://volcano.atm.ox.ac.uk/index.php/SHIVA>



POSTGRADUATE COMMUNITY

COMET supports a vibrant community of around 80 research students. The 2017 COMET student meeting, held at Newcastle University in January, was attended by 60 COMET members and collaborators. We heard excellent talks from our postgraduates on topics ranging from monitoring volcanic ash to modelling earthquake sequences. Many of these outlined the work described in the 14 student first-author COMET papers published in 2016:

Arnold, D. W. D., Biggs, J., Wadge, G., Ebmeier, S. K., Odber, H. M., & Poland, M. P. (2016) Dome growth, collapse, and valley fill at Soufrière Hills Volcano, Montserrat, from 1995 to 2013: Contributions from satellite radar measurements of topographic change, *Geosphere* doi: 10.1130/GES01291.1

Hayer, C.S., Wadge, G., Edmonds, M., Christopher, T. (2016) Sensitivity of OMI SO₂ measurements to variable eruptive behaviour at Soufrière Hills Volcano, Montserrat, *Journal of Volcanology and Geothermal Research* doi:10.1016/j.jvolgeores.2016.01.014

Hussain E., Hooper A., Wright T.J., Walters R.J., Bekaert D.P.S. (2016) Interseismic strain accumulation across the central North Anatolian Fault from iteratively unwrapped InSAR measurements, *Journal of Geophysical Research: Solid Earth* doi:10.1002/2016JB013108

Hussain, E., Wright, T.J., Walters, R.J., Bekaert, D., Hooper, A., Houseman, G.A. (2016) Geodetic observations of postseismic creep in the decade after the 1999 Izmit earthquake, Turkey: Implications for a shallow slip deficit, *Journal of Geophysical Research B: Solid Earth* doi:10.1002/2015JB012737

Hutchison, W., Biggs, J., Mather, T.A., Pyle, D.M., Lewi, E., Yirgu, G., Caliro, S., Chiodini, G., Clor, L.E., Fischer, T.P. (2016) Causes of unrest at silicic calderas in the East African Rift: New constraints from InSAR and soil-gas chemistry at Aluto volcano, Ethiopia, *Geochemistry, Geophysics, Geosystems* doi:10.1002/2016GC006395

Hutchison, W., Pyle D.M., Mather, T.A., Yirgu, G., Biggs, J., Cohen, B.E., Barfod, D.N., Lewi E. (2016) The eruptive history and magmatic evolution of Aluto volcano: new insights into silicic peralkaline volcanism in the Ethiopian Rift, *Journal of Volcanology and Geothermal Research* doi:10.1016/j.jvolgeores.2016.09.010

Hutchison, W., Fusillo, R., Pyle, D.M., Mather, T.A., Blundy, J., Biggs, J., Yirgu, G., Cohen, B.E., Brooker, R., Barfod, D.N., Calvert, A.T. (2016) A pulse of mid-Pleistocene rift volcanism in Ethiopia at the dawn of modern humans, *Nature Communications* doi:10.1038/ncomms13192

Mackenzie, D., Elliott, J.R., Altunel, E., Walker, R.T., Kurban, Y.C., Schwenninger, J.L., Parsons, B. (2016) Seismotectonics and rupture process of the Mw 7.1 2011 Van reverse faulting earthquake, Eastern Turkey, and implications for hazard in regions of distributed shortening, *Geophysical Journal International* doi:10.1093/gji/ggw158

Middleton, T. A., Walker, R.T., Rood, D.H., Rhodes, E.J., Parsons, B., Lei, Q., Elliott, J.R., Ren, Z., Zhou, Y. (2016) The tectonics of the western Ordos Plateau, Ningxia, China: slip rates on the Luoshan and East Helanshan Faults, *Tectonics* doi:10.1002/2016TC004230

Parker, A.L., Biggs, J., Lu, Z. (2016) Time-scale and mechanism of subsidence at Lassen Volcanic Center, CA, from InSAR, *Journal of Volcanology and Geothermal Research* doi:10.1016/j.jvolgeores.2016.04.013

Pering, T.D., McGonigle, A.J.S., James, M.R., Tamburello, G., Aiuppa, A., Delle Donne, D., Ripepe, M. (2016) Conduit dynamics and post-explosion degassing on Stromboli: a combined UV camera and numerical modelling treatment, *Geophysical Research Letters* doi:10.1002/2016GL069001

Robertson, E.A.M., Biggs, J., Cashman, K.V., Floyd, M.A. and Vye-Brown, C. (2016) Influence of regional tectonics and pre-existing structures on the formation of elliptical calderas in the Kenyan Rift, *Geological Society, London, Special Publications* doi:10.1144/SP420.12

Robertson, E.A.M., Biggs, J., Edmonds, M., Clor, L., Fischer, T. P., Vye-Brown, C., Kandie, R. (2016) Diffuse degassing at Longonot volcano, Kenya: Implications for CO₂ flux in continental rifts, *Journal of Volcanology and Geothermal Research* doi:10.1016/j.jvolgeores.2016.06.016

Zhou, Y., Walker, R.T., Elliott, J.R., Parsons, B. (2016) Mapping 3D fault geometry in earthquakes using high-resolution topography: Examples from the 2010 El Mayor-Cuicapah (Mexico) and 2013 Balochistan (Pakistan) earthquakes, *Geophysical Research Letters* doi:10.1002/2016GL067899.

The research highlights which follow describe in detail some of the outstanding science being delivered by our students.

MEASURING DECAYING ERUPTION RATE AT EL REVENTADOR, ECUADOR USING HIGH-RESOLUTION SATELLITE RADAR

David Arnold is a postgraduate at the University of Bristol working in the areas of volcanology, geohazards and risk, with a focus on agile InSAR for volcano monitoring.

Following a large explosive volcanic explosion in 2002, El Reventador, Ecuador has experienced several periods of eruption, the most recent of which is still ongoing. Satellite remote sensing is being used to monitor the eruption.

El Reventador is located in a remote part of the Ecuadorian rainforest, but can still have a significant impact on human population - ash fall from the 2002 eruption caused power outages and cancelled flights in the Ecuadorian capital, Quito, and pyroclastic flows and lahars damaged a nearby road and oil pipeline.

El Reventador's remoteness makes it difficult to monitor with ground based techniques, since maintaining instruments either requires good enough weather conditions for a helicopter to land technicians near the volcano, or a long trek through dense jungle.

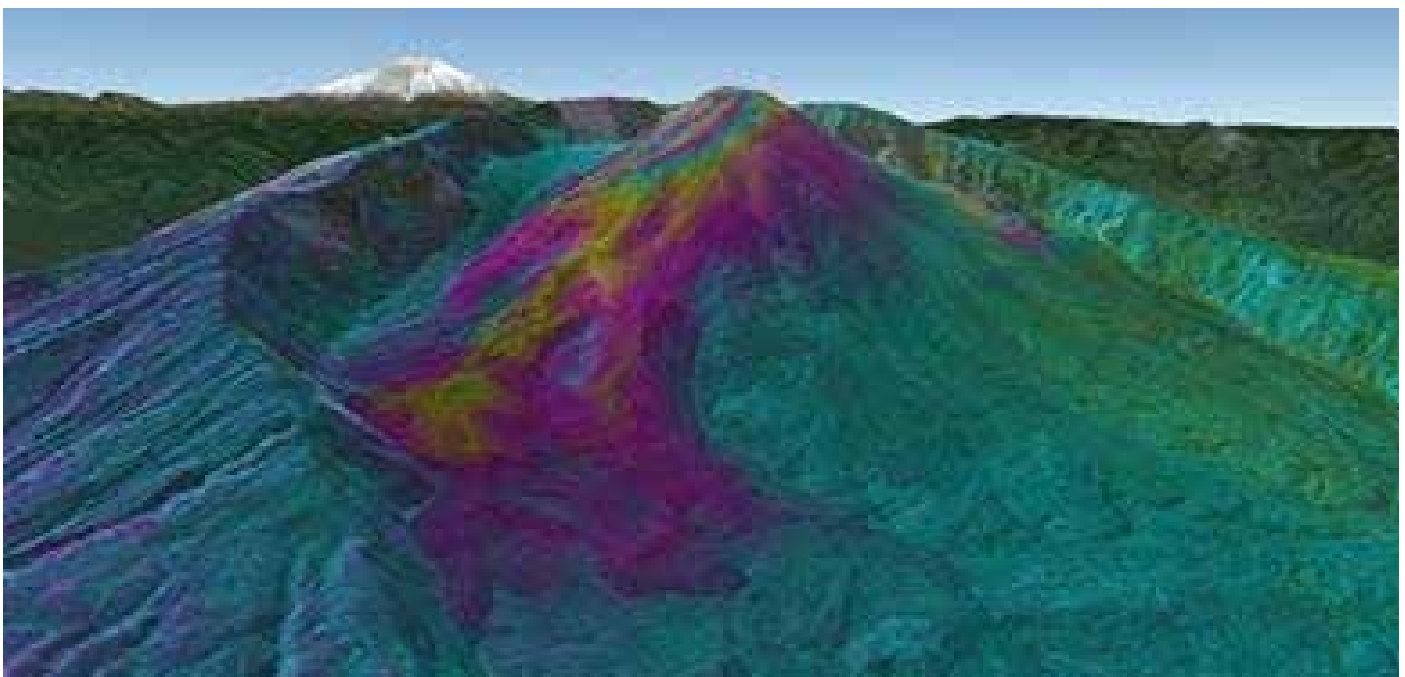
Satellite based remote sensing therefore provides an ideal technique for monitoring the ongoing eruption, especially SAR due to its ability to make observations through clouds and at night.

Working with colleagues in Ecuador, data from Radarsat 2 and TanDEM-X has been used to map the emplacement of lava flows throughout the most recent phase of the eruption at El Reventador, which began in 2012. Using the high-resolution data provided by these satellites allows precise estimations of the thickness of lava flow deposits, which reach up to 75 m in places.

Looking at variations in the erupted lava volume through time allows the rate of eruption to be estimated and how this is changing as the eruption progresses to be modelled.

The findings show that the eruption rate has decayed with an approximately exponential trend over the past 5 years. The decrease in eruption rate can be explained with a model for the magmatic system which suggests there is a single reservoir beneath El Reventador that is depressurising as the eruption progresses, and is resupplied with magma from below at a low, but constant, rate.

Radarsat 2 interferograms have also been used to monitor ground deformation at El Reventador, which is mostly associated with subsidence of cooling lava flows. Measurement of one magmatic deformation episode has been attributed to a volumetrically small opening of the conduit shortly after the start of activity in 2012, but there is no evidence for magmatic deformation after this. Deformation signals associated with magma intrusion would indicate an increase in magma supply to the volcano, which could mean an increase in the hazard posed by the volcano to nearby infrastructure.



Topographic fringes from a TanDEM-X image pair, showing the thickness of recent lava flows at Volcán El Reventador, Ecuador, as viewed from the southeast. One complete colour cycle corresponds to 25 m of new lava. Images like these supplement limited ground-based measurements, and make it possible to see how the rate of eruption is changing over time

INFRARED IMAGERY OF VOLCÁN DE FUEGO: MULTI-SPECTRAL INFRARED CAMERA ARRAY PROVIDES INSIGHT INTO PAROXYSMS

Ailsa Naismith is a postgraduate student in her first year of study at the University of Bristol. Her work focusses on observing processes and understanding hazards associated with the active Volcán de Fuego in Guatemala.

Fuego is an active stratovolcano in southern Guatemala, located within the Central American Volcanic Arc. Recent ground-based observations of Fuego have revealed a distinctive recurring pattern of behaviour. As part of a fieldwork campaign conducted in early 2017, researchers deployed an array of multi-spectral infrared cameras around Fuego. These cameras captured the growth of an ephemeral summit cone, and built on prior knowledge of the volcano's activity obtained from infrared data captured in 2016.

A primary goal of studying Fuego is to understand the mechanisms that trigger a paroxysmal event³². Acquisition of thermal data and subsequent analyses of time-series will inform understanding of what provokes paroxysm, and lead to improved hazard forecasting. Combining observations from infrared cameras with satellite and visual imagery may provide future advances in understanding.

New observations of Fuego have provided further insight into its changing summit conditions. In 2016, Fuego generated 16 paroxysmal eruptions, set within a recurring cycle of activity: against a background of near-continuous Strombolian activity, the volcano first generates lava flows, before building a transient cone in its summit crater that is eventually destroyed in a paroxysmal eruption which produces pyroclastic flows. The cycle recurred approximately every three weeks.

Analyses of images obtained throughout 2016 have detected well-defined periods of increasing thermal emissions related to lava flow extrusion and paroxysmal summit activity. In February 2017, a research campaign that was directed by Guatemala's national monitoring institute, INSIVUMEH, and led by a team of volcanologists and engineers from the University of Bristol, deployed an array of multispectral infrared cameras at various locations to measure activity at Fuego's summit.

Images obtained from the cameras between 19th and 23rd February show an increase in convexity at the summit, presumably representing the growth of a transient cone fed by rising magma. The cone continued to grow during the days preceding a paroxysm that occurred on 25th February. Destruction of an ephemeral cone by a paroxysmal eruption may contribute to ensuing pyroclastic flows.

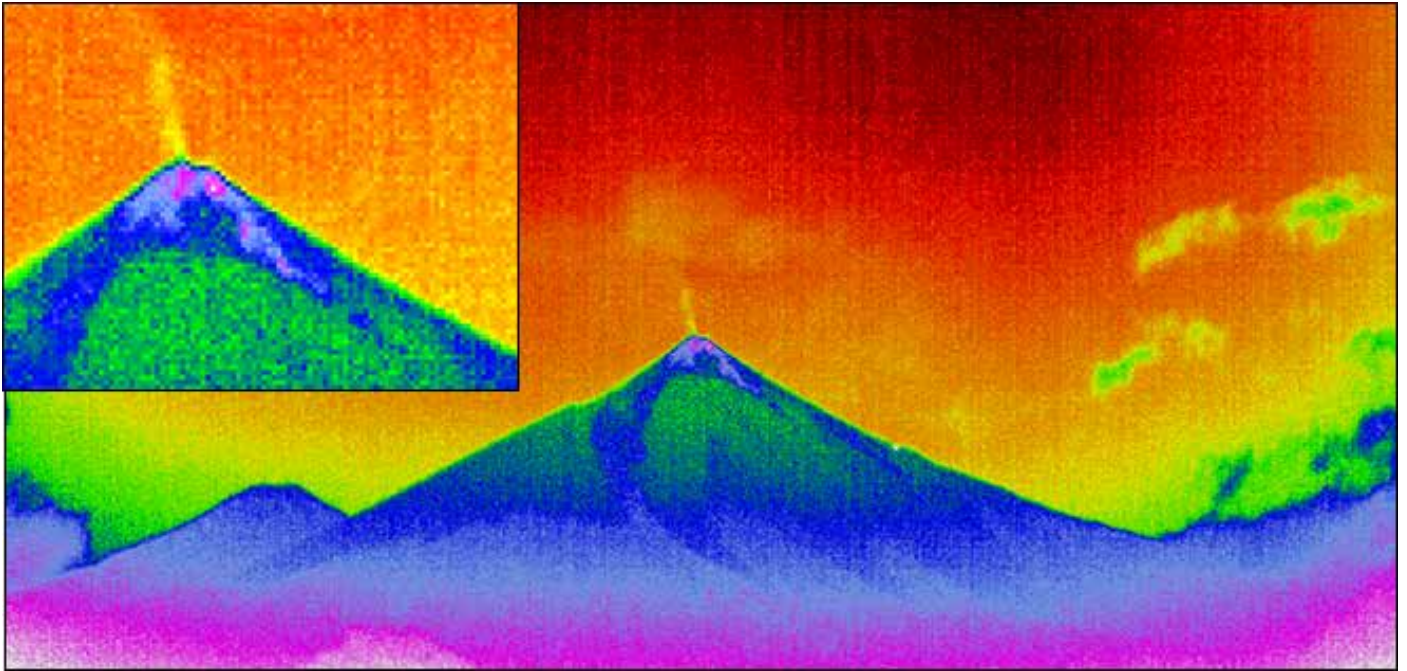
This work is the beginning of what promises to be an interesting avenue of research. The cameras' high spatial resolution allows detailed information of the summit to be captured, giving opportunity to better understand regions where there are significant changes prior to eruption.

Capture of a full eruptive cycle – including SO₂ and ash emission rates, as well as thermal anomalies and morphology changes at the summit – would greatly inform our understanding of Fuego's eruptive cycle, and of primary controls on triggering of paroxysm and pyroclastic flow.

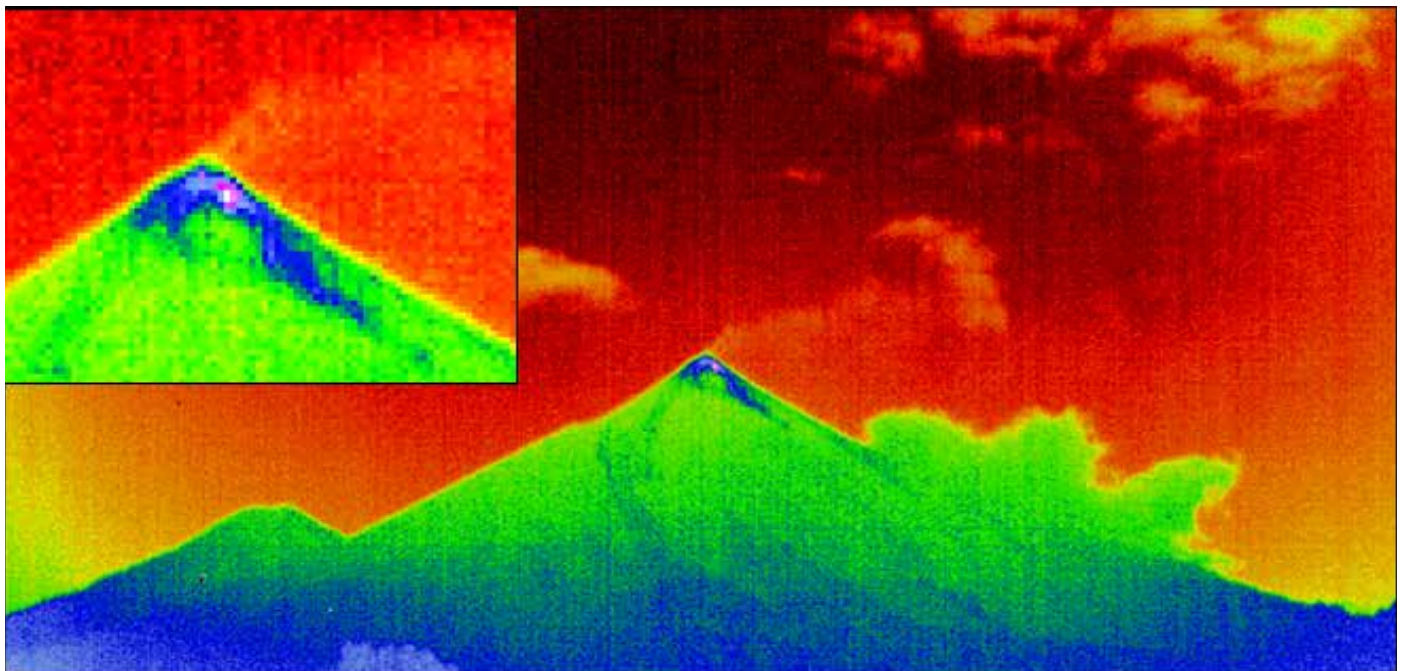


Infrared cameras set up at Fuego Observatory with view of Fuego's summit

32. "Paroxysm" is defined as the short-lived climax of a paroxysmal event, distinguished by the heightened intensity of eruptive activity that may produce fire fountaining, eruptive column, and lava flows. See: <http://www.ct.ingv.it/it/component/content/article/11-notizie/news/433-what-is-a-paroxysm.html>



Infrared image of Fuego at 06:53 local time (UTC-6) on 21/02/17, with zoom of summit inset



Infrared image of Fuego at 07:45 local time (UTC-6) on 23/02/17, with zoom of summit inset. An increase in convexity in summit morphology can clearly be seen between the first and the second inset

MONITORING THE MAKRAN

Camilla Penney is a postgraduate student at the University of Cambridge studying continental tectonics. She uses information from earthquakes, satellite imagery and GPS to study how continents move and change shape over time.

Combining datasets has helped COMET scientists to understand one of the world's most enigmatic subduction zones.

The Makran subduction zone, which runs for 1000 km parallel to the southern coasts of Iran and Pakistan, is a difficult place to access. As a result, there are many outstanding questions about the deformation of the region, particularly the onshore part of the overriding plate.

By working with Iranian and Pakistani colleagues, and combining data from GPS, seismology and satellite imagery, we have been able to study the kinematics of the Makran, and to understand how deformation in the region varies in both space and time.

The key question in terms of hazard is whether the Makran megathrust is accumulating elastic strain, which could be released in a large, probably tsunamigenic earthquake. An M8 earthquake in 1945 demonstrated that the eastern (now Pakistani) part of the megathrust can produce large earthquakes. However, there is no record of historical earthquakes in the western (Iranian) Makran, although this may be because of the region's sparse population.

Using new GPS data collected by colleagues in Iran, it was found that shortening observed in the Iranian Makran is consistent with elastic strain accumulation above a locked megathrust. This result suggests that the western Makran may move in large earthquakes, posing a risk to the rapidly growing megacity of Karachi, as well as the Omani capital, Muscat, and industrialising ports in Iran and Pakistan.

This elastic strain accumulation might also provide the solution to another long-standing tectonic question. The Sistan Suture Zone, to the north of the Makran, accommodates right-lateral motion between central Iran and Afghanistan on a series of north-south striking faults. These faults don't continue through the Makran, raising the question of how right-lateral motion is accommodated at the southern end of the Sistan Suture Zone.

It may be that this motion is transferred across the Jaz Murian depression onto right-lateral faults at the western end of the Makran. This requires the Jaz Murian depression to be bounded by normal faults. By looking at the geomorphology, it can be inferred that the depression is bounded by active dip-slip faults, with no evidence of thrust faulting. However, no shallow normal-faulting earthquakes have been observed around the Jaz Murian. This leads to the suggestion that the faults bounding the Jaz Murian are held in compression in the megathrust interseismic period and may then move in normal-faulting earthquakes after a megathrust earthquake in the western Makran.

As the world's largest exposed accretionary prism, the Makran also provides an interesting insight into how strain in accretionary prisms varies in space and time. The majority of onshore shallow earthquakes in the Makran are strike-slip and several, including the 2013 Minab and Balochistan earthquakes, show evidence of thrust faults being reactivated in a new strain regime. This suggests that the Makran accretionary prism has reached the maximum elevation which can be supported by the underlying megathrust, allowing us to make inferences about the frictional properties of the megathrust.

Undoubtedly, the Makran has many more insights to offer into the kinematics of subduction zones and accretionary prisms. Continued international collaboration, along with combining a wide range of techniques, should further understanding both of this region and of subduction tectonics globally.



Map of the Makran region. Red lines are mapped strike-slip faults in SE Iran (Walker and Jackson, 2004; Regard et al., 2005). SSZ is the Sistan Suture Zone and MZP is the Minab-Zendan-Palami fault zone. The red line outlined in white is the trace of the surface ruptures of the 2013 Balochistan (Pakistan) earthquake on the Hoshab fault (Avouac et al., 2014), and the red dot shows the location of the 2013 Minab earthquake. The red outlined region shows the approximate rupture area of the 1945 Mw 8.1 earthquake from Byrne et al. (1992). JM = Jaz Murian depression

AWARDS AND RECOGNITION



Andy Hooper (Leeds)

Andy received the 2016 American Geophysical Union (AGU) James B. Macelwane Medal in recognition of his contributions to the geophysical sciences. He was also conferred as an AGU Fellow.



Zhenhong Li (Newcastle)

Zhenhong was awarded the 2016 ESA and National Remote Sensing Centre of China Award of Excellence for the DRAGON-3 project, which explores crustal deformation and infrastructure.



Richard Walters (Durham)

Richard was awarded the 2017 Geological Society William Smith Fund for excellence in contributions to applied and economic aspects of geoscience.



Barry Parsons (Oxford)

Barry received the 2017 European Geophysical Union (EGU) Augustus Love Medal for his contributions to research in marine geophysics, mantle convection and continental tectonics.



Juliet Biggs (Bristol)

Juliet was awarded the 2017 British Geophysical Association's (BGA) Bullerwell Lecture for her outstanding contribution to geophysics.



Tim Wright (Leeds)

Tim was named as the 2017 Royal Astronomical Society's Harold Jeffreys Lecturer in recognition of his work on using InSAR to measure tectonic and volcanic deformation.

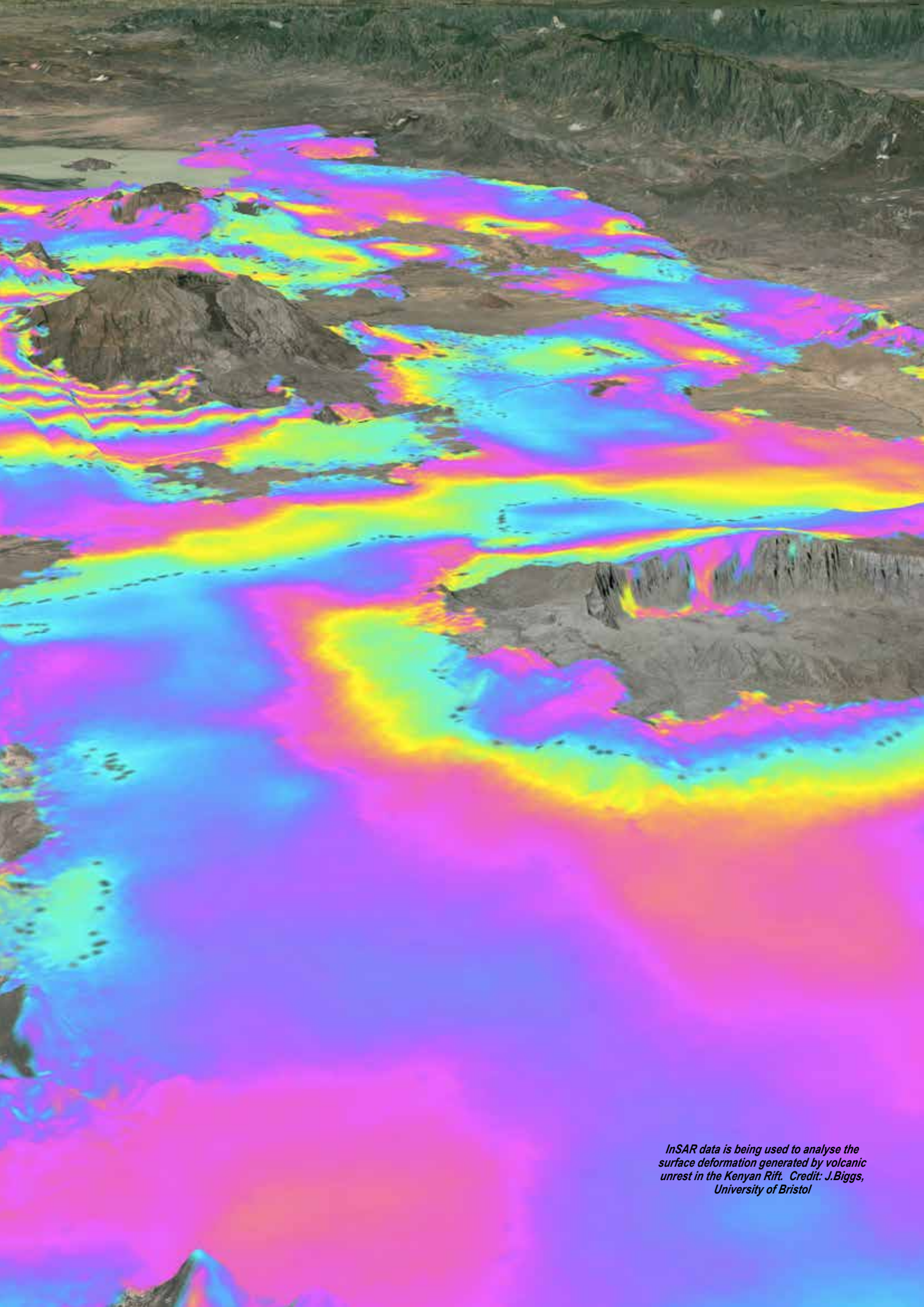


Taken from the Monte Vettore fault scarp, in central Italy, following the 30th October 2016 magnitude 6.6. earthquake. Credit: Laura Gregory & Huw Goodall

FUTURE PLANS

COMET is continuing to deliver high-impact national capability science. In 2017/18, our specific objectives are to:

1. Continue the development of the COMET/LiCS InSAR processing system to include unwrapped interferograms and linear time series, and average LoS velocities. Share results via the ESA G-TOP and EPOS portal.
2. Establish an automatic fast response system within LiCSAR that prioritises rapid data processing of earthquakes and eruptions.
3. Make time series and velocity fields available for the Alpine Himalayan Belt and East African Rift. Share results via the ESA GTEP and EPOS portal.
4. Produce the first strain map for the Alpine Himalayan Belt from GNSS and InSAR, and deliver a country-scale deformation map for Ethiopia. Continue to evaluate methods for deriving continuous velocity and strain rate fields.
5. Refine and further populate the database of active faults in Central Asia using collective expertise and up-to-date scientific results about each studied fault, and make it publically available.
6. Develop and implement tools to populate the volcano deformation database with the most recent processed InSAR image using data from Sentinel-1.
7. Further refine IASI SO₂ and ash retrieval techniques for monitoring low level volcanic emissions as well as specific eruptions.
8. Continue the development of the COMET Bayesian deformation modelling software, including routines to account for the topographic effect on surface displacements and new analytical and numerical forward models.
9. Further develop a low-cost GNSS sensor network for autonomous real-time deformation monitoring, focusing on assessing the performance of two prototype sensors in terms of precision over different baseline lengths and power consumption.
10. Formally sign the COMET-BGS Memorandum of Understanding, promoting the strategic and working relationship between the two organisations accordingly, including regarding event response.
11. Strengthen links between COMET and relevant national and international research organisations such as GEM and VMSG, facilitating collaboration and discussion.
12. Develop and deliver a COMET webinar series aimed at sharing COMET research both within COMET and across the wider Earth Observation community.
13. Consult the wider COMET community on the future direction of COMET, identifying strategic goals and new opportunities for 2019 onwards.



InSAR data is being used to analyse the surface deformation generated by volcanic unrest in the Kenyan Rift. Credit: J.Biggs, University of Bristol

GLOSSARY

AHB	Alpine Himalayan Belt	ITD	Iterative Tropospheric Decomposition
BGA	British Geophysical Association	LiCS	Looking inside the Continents from Space
BGS	British Geological Survey	LOS	Line of Sight
CEDA	Centre for Environmental Data Analysis	NAF	North Anatolian fault
CEMS	Climate, Environment and Monitoring from Space	NASA	US Space Agency (National Aeronautics and Space Administration)
CEOS	Committee on Earth Observation Satellites	NCEO	National Centre for Earth Observation
COMET	Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics	NERC	Natural Environment Research Council
CMT	Central Moment Tensor	NGO	Non-Governmental Organisation
CNRS	French National Centre for Scientific Research	NRT	Near Real Time
DBI	Deformation Bayesian Inversion	PDF	Posterior Probability Density Functions
DEM	Digital Elevation Model	PVE	Persistent Volcanic Emissions
EAF	East Anatolian Fault	SAC	Science Advisory Committee
EO	Earth Observation	SAR	Synthetic Aperture Radar
EPOS	European Plate Observing System	SHIVA	Spectrally High resolution Infrared measurements for the characterisation of Volcanic Ash
ESA	European Space Agency	STREVA	Strengthening Resilience in Volcanic Areas
EwF	Earthquakes without Frontiers	TLS	Terrestrial Laser Scanning
GCRF	Global Challenges Research fund		
GEM	Global Earthquake Model		
GNSS	Global Navigation Satellite System		
GPS	Global Positioning System		
G-TEP	Geohazards Thematic Exploitation Platform		
GSRM	Global Strain Rate Model		
GVM	Global Volcano Model		
IASI	Infrared Atmospheric Sounding Interferometer		
INGV	Istituto Nazionale Geofisica e Vulcanologia		
InSAR	Synthetic Aperture Radar Interferometry		

ANNEX 1 2016 PUBLICATIONS

- Abdrakhmatov K.E., Walker R.T., Campbell G.E., Carr A.S., Elliott A., Hillemann C., Hollingsworth J., Landgraf A., Mackenzie D., Mukambayev A., Rizza M., Sloan R.A. Multisegment rupture in the 11 July 1889 Chilik earthquake (Mw 8.0–8.3), Kazakh Tien Shan, interpreted from remote sensing, field survey, and paleoseismic trenching, *Journal of Geophysical Research: Solid Earth* doi:10.1002/2015JB012763
- Arnold, D. W. D., Biggs, J., Wadge, G., Ebmeier, S. K., Odber, H. M., & Poland, M. P. Dome growth, collapse, and valley fill at Soufrière Hills Volcano, Montserrat, from 1995 to 2013: Contributions from satellite radar measurements of topographic change, *Geosphere* GES01291-1
- Atkins, C., Ziebart, M. Effectiveness of observation-domain sidereal filtering for GPS precise point positioning, *GPS Solutions* doi:10.1007/s10291-015-0473-1
- Bagnardi, M., González, P.J., Hooper, A. High-resolution digital elevation model from tri-stereo Pleiades-1 satellite imagery for lava flow volume estimates at Fogo Volcano, *Geophysical Research Letters* doi:10.1002/2016GL069457
- Balis, D., Koukoulis, M.-E., Siomos, N., Dimopoulos, S., Mona, L., Pappalardo, G., Marengo, F., Clarisse, L., J Ventress, L., Carboni, E., G Grainger, R., Wang, P., Tilstra, G., Van Der A, R., Theys, N., Zehner, C. Validation of ash optical depth and layer height retrieved from passive satellite sensors using EARLINET and airborne lidar data: the case of the Eyjafjallajökull eruption, *Atmospheric Chemistry and Physics* doi:10.5194/acp-16-5705-2016
- Barnie T.D., Keir D., Hamling I., Hofmann B., Belachew M., Carn S., Eastwell D., Hammond J.O.S., Ayele A., Oppenheimer C., Wright T. A multidisciplinary study of the final episode of the Manda Hararo dyke sequence, Ethiopia, and implications for trends in volcanism during the rifting cycle, *Geological Society Special Publication* doi:10.1144/SP420.6
- Bekaert, D.P.S., Segall, P., Wright, T.J., Hooper, A.J. A Network Inversion Filter combining GNSS and InSAR for tectonic slip modeling, *Journal of Geophysical Research B: Solid Earth* doi:10.1002/2015JB012638
- Biggs, J., Robertson, E., Cashman, K.V. The lateral extent of volcanic interactions during unrest and eruption, *Nature Geoscience* doi:10.1038/ngeo2658
- Bonforte A., González P.J., Fernández J. Joint terrestrial and aerial measurements to study ground deformation: Application to the Sciara del Fuoco at the stromboli volcano (Sicily), *Remote Sensing* doi:10.3390/rs8060463
- Carboni, E., Grainger, R.G., Mather, T.A., Pyle, D.M., Thomas, G.E., Siddans, R., Smith, A.J.A., Dudhia, A., Koukoulis, M.E., Balis, D. The vertical distribution of volcanic SO₂ plumes measured by IASI, *Atmospheric Chemistry and Physics* doi:10.5194/acp-16-4343-2016
- Catlos, E. J., A. M. Friedrich, T. Lay, J. R. Elliott, S. Carena, B. Upreti, P. Decelles, B. Tucker & R. Bendick Nepal at Risk: Interdisciplinary Lessons Learned from the April 2015 Nepal (Gorkha) Earthquake and Future Concerns, *GSA Today* doi:10.1130/GSATG278GW.1
- Chen, M., Tomas, R., Li, Z., Motagh, M., Li, T., Gong, H., Li, X., Yu, J., Gong, X. Imaging Land Subsidence Induced by Groundwater Extraction in Beijing (China) Using Satellite Radar Interferometry, *Remote Sensing* doi:10.3390/rs8060468
- Copley A., Woodcock N. Estimates of fault strength from the Variscan foreland of the northern UK, *Earth and Planetary Science Letters* doi:10.1016/j.epsl.2016.07.024
- Copley, A., Jolivet, R. Fault rheology in an aseismic fold-thrust belt (Shahdad, eastern Iran), *Journal of Geophysical Research B: Solid Earth* doi:10.1002/2015JB012431
- Corradini, S., Montopoli, M., Guerrieri, L., Ricci, M., Scollo, S., Merucci, L., Marzano, F.S., Pugnaghi, S., Prestifilippo, M., Ventress, L.J., Grainger, R.G., Carboni, E., Vulpiani, G., Coltelli, M. A multi-sensor approach for volcanic ash cloud retrieval and eruption characterization: The 23 November 2013 Etna lava fountain, *Remote Sensing* doi:10.3390/rs8010058
- Crippa, P., Sullivan, R.C., Thota, A., Pryor, S.C. Evaluating the skill of high-resolution WRF-Chem simulations in describing drivers of aerosol direct climate forcing on the regional scale, *Atmospheric Chemistry and Physics* doi:10.5194/acp-16-397-2016
- Crippa P., Castruccio S., Archer-Nicholls S., Lebron G.B., Kuwata M., Thota A., Sumin S., Butt E., Wiedinmyer C., Spracklen D.V. Population exposure to hazardous air quality due to the 2015 fires in Equatorial Asia, *Scientific Reports* doi:10.1038/srep37074
- Dai, K., Li, Z., Tomás, R., Liu, G., Yu, B., Wang, X., Cheng, H., Chen, J. & Stockamp, J. Monitoring activity at the Daguangbao mega-landslide (China) using Sentinel-1 TOPS time series interferometry, *Remote Sensing of Environment* doi:10.1016/j.rse.2016.09.009
- Daout, S., Jolivet, R., Lasserre, C., Doin, M.-P., Barbot, S., Tapponnier, P., Peltzer, G., Socquet, A., Sun, J. Along-strike variations of the partitioning of convergence across the Haiyuan fault system detected by InSAR, *Geophysical Journal International* doi:10.1093/gji/ggw028
- Ebmeier, S. K., Elliott, J.R., Nocquet, J.M., Biggs, J., Mothes, P., Jarrin, P., Yépez M., Aguaiza, S., Lundgren, P., Samsonov, S. Shallow earthquake inhibits unrest at Chiles-Cerro Negro volcanoes, Ecuador-Colombian border, *Earth and Planetary Science Letters* doi:10.1016/j.rse.2016.09.009
- Ebmeier, S. K. Application of independent component analysis to multitemporal InSAR data with volcanic case studies, *J. Geophys. Res. Solid Earth* doi:10.1002/2016JB013765
- Elliott, J.R., Jolivet, R., Gonzalez, P., Avouac, J.-P., Hollingsworth, J., Searle, M., Stevens, V., Himalayan Megathrust Geometry and Relation to Topography Revealed by the Gorkha Earthquake, *Nature Geoscience* doi:10.1038/NGEO2623
- Elliott, J.R., Walters, R.J., Wright, T.J. The role of space-based observation in understanding and responding to active tectonics and earthquakes, *Nature Communications* doi:10.1038/ncomms13844
- Feng, W., Lindsey, E., Barbot, S., Samsonov, S., Dai, K., Li, P., Li, Z., Almeida, R., Chen, J., Xu, X. Source characteristics of the 2015 MW 7.8 Gorkha (Nepal) earthquake and its MW 7.2 aftershock from space geodesy, *Tectonophysics* doi:10.1016/j.tecto.2016.02.029
- Floyd, M. A., Walters, R.J., Elliott, J.R., Funning, G.J., Svarc, J.L., Murray, J.H., Hooper, A.J., Larsen, Y., Marinkovic, P., Burgmann, R., Johanson, I.A., Wright, T.J. Spatial variations in fault friction related to lithology from rupture and afterslip of the 2014 South Napa, California, earthquake, *Geophysical Research Letters* doi:10.1002/2016GL069428
- Fuchs M.J., Hooper, A., Broerse, T., Bouman, J. Distributed fault slip model for the 2011 Tohoku-Oki earthquake from GNSS and GRACE/GOCE satellite gravimetry, *Journal of Geophysical Research: Solid Earth* doi: 10.1002/2015JB012165
- Gong, W., Thiele, A., Hinz, S., Meyer, F.J., Hooper, A., Agram, P.S. Comparison of small baseline interferometric SAR processors for estimating ground deformation, *Remote Sensing* doi:10.3390/rs8040330
- Grützner, C., Fischer, P., Reicherter, K. Holocene surface ruptures of the Rurrand Fault, Germany—insights from palaeoseismology, remote sensing and shallow geophysics, *Geophysical Journal International* doi:10.1093/gji/ggv558
- Grützner, C., Schneiderwind, S., Papanikolaou, I., Deligiannakis, G., Pallikarakis, A., & Reicherter, K. New constraints on extensional tectonics and seismic hazard in northern Attica, Greece - the case of the Milesi Fault, *Geophysical Journal International* doi:10.1093/gji/ggv443
- Gudmundsson, M.T., Jónsdóttir, K., Hooper, A., Holohan, E.P., Halldórsson, S.A., Ófeigsson, B.G., Cesca, S., Vogfjörð, K.S., Sigmundsson, F., Högnadóttir, T., Einarsson, P., Sigmarrsson, O., Jarosch, A.H., Jónasson, K., Magnússon, E., Hreinsdóttir, S., Bagnardi, M., Parks, M.M., Hjörleifsdóttir, V., Pálsson, F., Walter, T.R., Schöpfer, M.P.J., Heimann, S., Reynolds, H.I., Dumont, S., Bali, E., Gudfinnsson, G.H., Dahm, T.,

- Hayer, C.S., Wadge, G., Edmonds, M., Christopher, T. Sensitivity of OMI SO₂ measurements to variable eruptive behaviour at Soufrière Hills Volcano, Montserrat, *Journal of Volcanology and Geothermal Research* doi:10.1016/j.jvolgeores.2016.01.014
- Hickey, J., Gottsmann, J., Nakamichi, H., Iguchi, M. Thermomechanical controls on magma supply and volcanic deformation: Application to Aira caldera, Japan, *Nature Scientific Reports* doi:10.1038/srep32691
- Hussain E., Hooper A., Wright T.J., Walters R.J., Bekaert D.P.S. Interseismic strain accumulation across the central North Anatolian Fault from iteratively unwrapped InSAR measurements, *Journal of Geophysical Research: Solid Earth* doi:10.1002/2016JB013108
- Hussain, E., Wright, T.J., Walters, R.J., Bekaert, D., Hooper, A., Houseman, G.A. Geodetic observations of postseismic creep in the decade after the 1999 Izmit earthquake, Turkey: Implications for a shallow slip deficit, *Journal of Geophysical Research B: Solid Earth* doi:10.1002/2015JB012737
- Hutchison, W., Biggs, J., Mather, T.A., Pyle, D.M., Lewi, E., Yirgu, G., Caliro, S., Chiodini, G., Clor, L.E., Fischer, T.P. Causes of unrest at silicic calderas in the East African Rift: New constraints from InSAR and soil-gas chemistry at Aluto volcano, Ethiopia, *Gcubed* doi:10.1002/2016GC006395
- Hutchison, W., D.M. Pyle, T.A. Mather, G. Yirgu, J. Biggs, B.E. Cohen, D.N. Barfod and E. Lewi The eruptive history and magmatic evolution of Aluto volcano: new insights into silicic peralkaline volcanism in the Ethiopian rift, *Journal of Volcanology and Geothermal Research*, doi:10.1016/j.jvolgeores.2016.09.010
- Hutchison, W., R. Fusillo, D.M. Pyle, T.A. Mather, J. Blundy, J. Biggs, G. Yirgu, B.E. Cohen, R. Brooker, D.N. Barfod and A.T. Calvert A pulse of mid-Pleistocene rift volcanism in Ethiopia at the dawn of modern humans, *Nature Communications* doi:10.1038/ncomms13192
- Kettermann, M., Von Hagke, C., Van Gent, H.W., Grützner, C., Urai, J.L. Dilatant normal faulting in jointed cohesive rocks: A physical model study, *Solid Earth* doi:10.5194/se-7-843-2016
- Karasözen E., Nissen E., Bergman E.A., Johnson K.L., Walters R.J. Normal faulting in the Simav graben of western Turkey reassessed with calibrated earthquake relocations, *Journal of Geophysical Research: Solid Earth* doi:10.1002/2016JB012828
- Kilbride B.M., Edmonds M., Biggs J. Observing eruptions of gas-rich compressible magmas from space, *Nature Communications* doi:10.1038/ncomms13744
- Lewi E., Keir D., Birhanu Y., Blundy J., Stuart G., Wright T., Calais E. Use of a high-precision gravity survey to understand the formation of oceanic crust and the role of melt at the southern Red Sea rift in Afar, Ethiopia, *Geological Society Special Publication* doi:10.1144/SP420.13
- Li, P., Li, Z., Muller, J.-P., Shi, C., Liu, J. A new quality validation of global digital elevation models freely available in China, *Survey Review* doi:10.1179/1752270615Y.0000000039
- Li, Y.-S., Shen, W.-H., Wen, Y.-M., Zhang, J.-F., Li, Z.-H., Jiang, W.-L., Luo, Y. Source parameters for the 2015 Nepal Earthquake revealed by InSAR observations and strong ground motion simulation, *Chinese Journal of Geophysics (Acta Geophysica Sinica)* doi:10.6038/cjg20160417
- Li, Z., Wright, T., Hooper, A., Crippa, P., Gonzalez, P., Walters, R., Elliott, J., Ebmeier, S., Hutton, E., Parsons, B. Towards InSAR everywhere, all the time, with Sentinel-1, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* doi:10.5194/isprsarchives-XLI-B4-763-2016
- Liu, P., Li, Q., Li, Z., Hoey, T., Liu, G., Wang, C., Hu, Z., Zhou, Z., Singleton, A. Anatomy of subsidence in Tianjin from time series InSAR, *Remote Sensing* doi:10.3390/rs8030266
- Liu, Y., Xu, C., Li, Z., Wen, Y., Chen, J., Li, Z. Time-Dependent afterslip of the 2009 Mw 6.3 Dachaidan Earthquake (China) and viscosity beneath the Qaidam Basin inferred from postseismic deformation observations, *Remote Sensing* doi:10.3390/rs8080649
- Livio F., Michetti A.M., Vittori E., Gregory L., Wedmore L., Piccardi L., Tondi E., Roberts G., Central Italy Earthquake Working Group, Blumetti A.M., Bonadeo L., Brunamonte F., Commerci V., Di Manna P., Ferrario M.F., Faure Walker J., Frigerio C., Fumanti F., Guerrieri L., Iezzi F., Leoni G., McCaffrey K., Mildon Z., Phillips R., Rhodes E., Walters R.J., Wilkinson M. Surface faulting during the August 24, 2016, central Italy earthquake (Mw 6.0): Preliminary results, *Annals of Geophysics* doi:10.4401/ag-7197
- Lu, C., Li, X., Li, Z., Heinkelmann, R., Nilsson, T., Dick, G., Ge, M., Schuh, H. GNSS tropospheric gradients with high temporal resolution and their effect on precise positioning, *Geophysical Journal International* doi:10.1002/2015JD024255
- Mackenzie, D., Elliott, J.R., Altunel, E., Walker, R.T., Kurban, Y.C., Schwenninger, J.L., Parsons, B. Seismotectonics and rupture process of the Mw 7.1 2011 Van reverse faulting earthquake, Eastern Turkey, and implications for hazard in regions of distributed shortening, *Geophysical Journal International* doi:10.1093/gji/ggw158
- Mather, T.A. Volcanoes and the environment: lessons for understanding Earth's past and future from studies of present-day volcanic emissions, *Journal of Volcanology and Geothermal Research* doi:10.1016/j.jvolgeores.2015.08.016
- Merucci, L., Zakšek, K., Carboni, E., Corradini, S. Stereoscopic estimation of volcanic ash cloud-top height from two geostationary satellites, *Remote Sensing* doi:10.3390/rs8030206
- Middleton, T.A., Walker, R.T., Rood, D.H., Rhodes, E.J., Parsons, B., Lei, Q., Elliott, J.R., Ren, Z., Zhou, Y. The tectonics of the western Ordos Plateau, Ningxia, China: Slip rates on the Luoshan and East Helanshan Faults, *Tectonics* doi:10.1002/2016TC004230
- Middleton, T.A., Walker, R.T., Parsons, B., Lei, Q., Zhou, Y., Ren, Z. A major, intraplate, normal-faulting earthquake: The 1739 Yinchuan event in northern China, *Journal of Geophysical Research B: Solid Earth* doi:10.1002/2015JB012355
- Najman, Y., Bracciali, L., Parrish, R.P., Chisty, E., Copley, A. Evolving strain partitioning in the Eastern Himalaya: The growth of the Shillong Plateau, *Earth and Planetary Science Letters* doi:10.1016/j.epsl.2015.10.017
- Naranjo, M. F., Ebmeier, S. K., Vallejo, S., Ramón, P., Mothes, P., Biggs, J., Herrera, F. Mapping and measuring lava volumes from 2002 to 2009 at El Reventador Volcano, Ecuador, from field measurements and satellite remote sensing, *Journal of Applied Volcanology* doi:10.1186/s13617-016-0048-z
- Nissen, E., Elliott, J.R., Sloan, R.A., Craig, T.J., Funning, J.G., Hutko, A., Parsons, B.E., Wright T.J. Limitations of rupture forecasting exposed by instantaneously triggered earthquake doublet, *Nature Geoscience* doi:10.1038/ngeo2653
- Nomikou, P., Druitt, T.H., Hübscher, C., Mather, T.A., Paulatto, M., Kalnins, L.M., Kelfoun, K., Papanikolaou, D., Bejelou, K., Lampridou, D., Pyle, D.M., Carey, S., Watts, A.B., Weiß, A.B., Parks, M.M. Post-eruptive flooding of Santorini caldera and implications for tsunami generation, *Nature Communications* doi:10.1038/ncomms13332
- Parker, A.L., Biggs, J., Lu, Z. Time-scale and mechanism of subsidence at Lassen Volcanic Center, CA, from InSAR, *Journal of Volcanology and Geothermal Research* doi:10.1016/j.jvolgeores.2016.04.013
- Pering, T.D., McGonigle, A.J.S., James, M.R., Tamburello, G., Aiuppa, A., Delle Donne, D., Ripepe, M. Conduit dynamics and post-explosion degassing on Stromboli: a combined UV camera and numerical modelling treatment, *Geophysical Research Letters* doi:10.1002/2016GL069001
- Prata, A.J., Dezitter, F., Davies, I., Weber, K., Birnfeld, M., Moriano, D., Bernardo, C., Vogel, A., Prata, G.S., Mather, T.A., Thomas, H.E., Commas, J., Weber, M. Artificial cloud test confirms volcanic ash detection using infrared spectral imaging, *Scientific Reports* doi:10.1038/srep25620

Reed, B.E., Grainger, R.G., Peters, D.M., Smith, A.J.A. Retrieving the real refractive index of mono- and polydisperse colloids from reflectance near the critical angle, *Optics Express* doi:10.1364/OE.24.001953

Roberts, M.J., Hensch, M., Belart, J.M.C., Spaans, K., Jakobsson, S., Gudmundsson, G.B., Fridriksdóttir, H.M., Drouin, V., Dürig, T., Adalgeirsdóttir, G., Riishuus, M.S., Pedersen, G.B.M., Van Boeckel, T., Oddsson, B., Pfeffer, M.A., Barsotti, S., Bergsson, B., Donovan, A., Burton, M.R., Aiuppa, A. Gradual caldera collapse at Bárðarbunga volcano, Iceland, regulated by lateral magma outflow, *Science* doi:10.1126/science.aaf8988

Robertson, E., Biggs, J., Edmonds, M., Clor, L., Fischer, T. P., Vye-Brown, C., Kandie, R. Diffuse degassing at Longonot volcano, Kenya: Implications for CO₂ flux in continental rifts, *Journal of Volcanology and Geothermal Research* doi:10.1016/j.jvolgeores.2016.06.016

Robertson, E. A. M., Biggs, J., Cashman, K. V., Floyd, M. A., & Vye-Brown, C. Influence of regional tectonics and pre-existing structures on the formation of elliptical calderas in the Kenyan Rift, Geological Society, London, Special Publications doi:10.1144/SP420.12

Ruiz-Constán, A., Ruiz-Armenteros, A.M., Lamas-Fernandez, F., Martos-Rosillo, S., Manuel Delado, J., Bekaert, D.P.S., João Sousa, J., Gil, A.J., Caro Cuenca, M., Hanssen, R.F., Galindo-Zalvidar, J., Sanz de Galdeano, C. Multi-temporal InSAR evidence of ground subsidence induced by groundwater withdrawal: the Montellano aquifer (SW Spain), *Environmental Earth Sciences* doi:10.1007/s12665-015-5051-x

Searle, M. P., N. M. W. Roberts, S-L. Chung, YH. Lee, K. L. Cook, J. R. Elliott, O. M. Weller, M. R. St-Onge, X-W. Xu, X-B. Tan & K. Li Age and Anatomy of the Gongga Shan batholith, eastern Tibetan Plateau, and its relationship to the active Xianshui-he fault, *Geosphere* doi:10.1130/GES01244.1

Shirzaei, M., Ellsworth, W.L., Tiampo, K., González, P.J., Manga, M. Surface uplift and time-dependent seismic hazard due to fluid injection in eastern Texas, *Science* doi:10.1126/science.aag0262

Spaans K, Hooper A. InSAR processing for volcano monitoring and other near-real time applications, *Journal of Geophysical Research B: Solid Earth* doi:10.1002/2015JB012752

Stockamp J., Bishop P., Li Z., Petrie E.J., Hansom J., Rennie A. State-of-the-art in studies of glacial isostatic adjustment for the British Isles: A literature review, *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* doi:10.1017/S1755691016000074

Sullivan R.C., Crippa P., Hallar A.G., Clarisse L., Whitburn S., Van Damme M., Leaitch W.R., Walker J.T., Khlystov A., Pryor S.C. Using satellite-based measurements to explore spatiotemporal scales and variability of drivers of new particle formation, *Journal of Geophysical Research: Atmospheres* doi:10.1002/2016JD025568

Talebian M., Copley A.C., Fattahi M., Ghorashi M., Jackson J.A., Nazari H., Sloan R.A., Walker R.T. Active faulting within a megacity: The geometry and slip rate of the Pardisan thrust in central Tehran, Iran, *Geophysical Journal International* doi:10.1093/gji/ggw347

Tomás R., Li Z., Lopez-Sanchez J.M., Liu P., Singleton A. Using wavelet tools to analyse seasonal variations from InSAR time-series data: a case study of the Huangtupo landslide, *Landslides* doi:10.1007/s10346-015-0589-y

Twigg M.M., Ilyinskaya, E., Beccaceci, S., Green, D.C., Jones, M.R., Langford, B., Leeson, S.R., Lingard, J.J.N., Pereira, G.M., Carter, H. Holuhraun eruption on the UK atmosphere, *Atmospheric Chemistry and Physics* doi:10.5194/acp-16-11415-2016

Ventress, L.J., McGarragh, G., Carboni, E., Smith A.J., Grainger R.G. Retrieval of ash properties from IASI measurements, *Atmospheric Measurement Techniques* doi:10.5194/amt-9-5407-2016

Vignelles, D., Roberts T.J., Carboni, E., Ilyinskaya, E., Pfeffer, M., Dagsson Waldhauserova, P., Schmidt, A., Berthet, G., Jegou, F., Renard, J.B. Balloon-borne measurement of the aerosol size distribution from an Icelandic flood basalt eruption, *Earth and Planetary Science Letters* doi:10.1016/j.epsl.2016.08.027

Vye-Brown C., Sparks R.S.J., Lewi E., Mewa G., Asrat A., Loughlin S.C., Mee K., Wright T.J. Ethiopian volcanic hazards: A changing research landscape, *Geological Society Special Publication* doi:10.1144/SP420.16

Wadge G., Biggs J., Lloyd R., Kendall J.-M. Historical volcanism and the state of stress in the east African rift system, *Frontiers in Earth Science* doi:10.3389/feart.2016.00086

Walker R.T., Telfer M., Kahle R.L., Dee M.W., Kahle B., Schwenninger J.-L., Sloan R.A., Watts A.B. Rapid mantle-driven uplift along the Angolan margin in the late Quaternary, *Nature Geoscience* doi:10.1038/ngeo2835

Wright T.J. The earthquake deformation cycle, *Astronomy and Geophysics* doi:10.1093/astrophys/atw148

Wright T.J., Ayele A., Ferguson D., Kidane T., Vye-Brown C. Magmatic rifting and active volcanism: Introduction, *Geological Society Special Publication* doi:10.1144/SP420.18

Weiss, J.R., Brooks, B.A., Foster, J.H., Bevis, M., Echalar, A., Caccamise, D., Heck, J., Kendrick, E., Ahlgren, K., Raleigh, D., Smalley, R., and Vergani, G. Isolating active orogenic wedge deformation in the southern Subandes of Bolivia, *Journal of Geophysical Research* doi:10.1002/2016JB013145

Zhou, Y., Walker, R.T., Elliott, J.R., Parsons, B. Mapping 3D fault geometry in earthquakes using high-resolution topography: Examples from the 2010 El Mayor-Cucapah (Mexico) and 2013 Balochistan (Pakistan) earthquakes *Geophysical Research Letters* doi:10.1002/2016GL067899

Zhou Y., Walker R.T., Hollingsworth J., Talebian M., Song X., Parsons B. Coseismic and postseismic displacements from the 1978 Mw 7.3 Tabas-e-Golshan earthquake in eastern Iran, *Earth and Planetary Science Letters* doi:10.1016/j.epsl.2016.07.038







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