

# COMET

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

ANNUAL REPORT  
**2014/15**





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DIRECTOR'S FOREWORD

It is a great pleasure to introduce this first annual report for the third phase of COMET, and my first as COMET Director. COMET has grown and changed enormously since it was first established in 2002 as a NERC centre of excellence in Earth Observation focused on active tectonics. Under the leadership of Barry Parsons, we became a research theme within the National Centre for Earth Observation (NCEO), incorporating research into active volcanism, and now we enter an exciting new period where, since 1 April 2014, we are funded by NERC through a partnership with the British Geological Survey (BGS).

Despite these changes, our mission has remained largely unchanged. COMET scientists work with satellite Earth Observation (EO) data to understand our dynamic Earth. EO data is at the core of our activities, but our great strength is our breadth, with our expertise spanning from technical aspects of radar interferometry through to field-based tectonic geomorphology and volcanology. We believe that the best way to make major interdisciplinary advances and to have societal impact is to apply our disciplinary expertise collectively to key problems in hazard research.

By pleasant coincidence, just two days after the new phase of COMET began, the European Space Agency (ESA) successfully launched Sentinel-1A, the EU's first satellite in its Copernicus programme. This new radar satellite promises to transform our ability to monitor our dynamic Earth – for the first time, images are being acquired systematically for all of the Earth's tectonic belts and volcanoes, and the data are being provided free of charge.

COMET has been guiding ESA's acquisition strategy to ensure that we obtain the data we need to fully capitalise on this new generation of Synthetic Aperture Radar (SAR) systems, and working with the UK Centre for Environmental Data Archiving (CEDA) to ensure that the UK archive is suitable for the community's needs. Much of the manpower within COMET is currently dedicated to exploiting the opportunities that the Sentinel-1 mission offers, and to ensuring that the benefits of this major EU investment are reaped by the scientific community and wider society.

We are building an automated processing system hosted on the NERC Climate, Environment and Monitoring from Space (CEMS) computing facility at CEDA that will routinely produce deformation measurements for all of the Earth's tectonic belts and volcanoes. The data will be available to the wider community and we will establish a suite of services that add value to these data and help us understand tectonic and volcanic processes.

Early results from Sentinel-1 are very encouraging, with the satellite (and COMET scientists) playing a key role in the international response to the 2014 South Napa (California) and 2015 Gorkha (Nepal) earthquakes, and in the response to the 2014 Pico do Fogo (Cape Verde) and Volcán Calbuco (Chile) eruptions.

COMET has benefited from new member Jean-Philippe Avouac (Cambridge), and associates Jessica Hawthorne, Anja Schmidt (both Leeds), Peter Clarke (Newcastle), Ed Rhodes and Andrew McGonigle (Sheffield). Jean-Philippe's membership, along with our existing work via the Earthquakes without Frontiers project, has meant that COMET scientists have taken an international lead in the ongoing scientific response to the Nepal earthquake, as well as providing detailed advice to the UK Government and responders on the ground. Next year's report will evaluate the considerable scientific and societal impact of this work, but it is already clear that Earth Observation data now play a critical and central role in the response to earthquakes and eruptions, both in terms of understanding what happened, or continues to happen,

and in assisting in the response effort on the ground. Sentinel-1 now guarantees our ability to respond within a few days of any event.

The next year is a critical and exciting period in which we expect to launch prototype services for monitoring deformation from Sentinel-1 and volcanic gas/ash from the Infrared Atmospheric Sounding Interferometer (IASI). We are also engaging with international partners and initiatives to extend the impact of COMET's research.

For example, we are working with the US Geological Survey on routinely incorporating Sentinel-1 deformation data in their earthquake source modelling and "shakemap" predictions, and with the Global Earthquake Model on using Synthetic Aperture Radar Interferometry (InSAR) in the global strain rate model. COMET scientists are playing a leading part in the Committee on Earth Observing Satellites' (CEOS) working group on disasters, in both the volcano and seismic risks pilots, and are working with the Global Volcano Model on building an online global database for volcano deformation.

This report describes the highlights of COMET's research achievements over the year from 1 April 2014, as well as documenting some of our wider impact on society. It has been a strong first year of this new phase, and I look forward to the exciting developments to come.



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## INTRODUCTION

**THE CENTRE FOR OBSERVATION AND MODELLING OF EARTHQUAKES, VOLCANOES AND TECTONICS (COMET) IS A WORLD-LEADING RESEARCH CENTRE PROVIDING NATIONAL CAPABILITY IN THE OBSERVATION AND MODELLING OF TECTONIC AND VOLCANIC HAZARDS.**

COMET brings together scientists from the Universities of Oxford, Cambridge, Leeds, Bristol, Reading, Liverpool and Newcastle and University College London. We use techniques such as InSAR alongside ground-based observations and geophysical models to study earthquakes and volcanoes, and understand the hazards they pose to people and places.

**Providing national capability means that we focus on delivering services, facilities, data and long-term research to deliver world-leading science that can help the UK and others to prepare for and respond rapidly to earthquakes and eruptions, through for example:**

Developing observing systems that provide baseline measurements of volcanic and tectonic processes.

Bringing together nationally- and internationally-recognised scientists to provide leadership in strategic and discipline-based Earth Observation research.

Growing a vibrant and excellent research student community who will form the next generation of Earth Observation scientists.

Providing leadership across the Earth Observation community, working with business, Government and the space agencies to ensure that the UK continues to invest in and benefit from satellite missions.

We work closely with the BGS to deliver cutting-edge research on earthquakes and volcanoes and hazard monitoring services, with our sponsors, NERC, and with ESA and many other national and international partners.

This report gives an overview of COMET's activities during 2014/15, highlighting major scientific advances and achievements. It covers the period 1 January – 31 December 2014 for publications, and 1 April 2014 – 31 March 2015 for all other outputs and activities.

## WELCOME TO:



New COMET member **JEAN-PHILIPPE AVOUAC**, Professor of Geophysics, Geodynamics and Tectonics within the Department of Earth Sciences at the University of Cambridge.

Jean-Philippe's research is aimed at better understanding the relationship between crustal deformation, earthquakes, and landscape evolution. He is particularly interested in developing new approaches from field observations, satellite imagery, and physically based models, especially in the orogenic context, and is currently involved in research programs in the Himalaya, Taiwan, Tien Shan, and Sumatra.

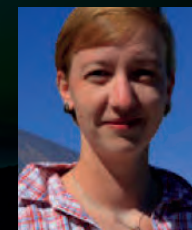
A number of scientists have also joined us as Associates. This new scheme allows researchers working in related areas to participate in our key science meetings and receive our communications, with a view to encouraging collaboration and engagement.



**ANDREW MCGONIGLE** is a Reader in Volcano Remote Sensing at the University of Sheffield. His research is focused on the development and application of remote sensing techniques for environmental and particularly volcanic remote sensing.



**PETER CLARKE** is Professor of Geophysical Geodesy at the University of Newcastle. He works at the interface of geodesy and geophysics, using precise GPS positioning to study the deformation of the Earth due to plate tectonics, tides, and surface mass loading. His interests span the applications of these areas to geohazards such as earthquakes and tsunamis as well as climate change.



**ANJA SCHMIDT** is a Tenure Track Academic Research Fellow at the University of Leeds. She combines expertise in atmospheric science and volcanology to advance current understanding of volcanic impacts and hazards, using a wide range of atmospheric models and volcanological datasets.



**JESSICA HAWTHORNE** is a Tenure Track Academic Research Fellow at the University of Leeds. Her work is aimed at improving understanding of how faults slip by investigating the mechanics of seismic and aseismic slip using frictional modeling, seismology, and borehole strain data.



**ED RHODES** is Professor of Physical Geography at the University of Sheffield and also Professor of Geology at UCLA. His research interests include OSL dating, the Quaternary, geomorphology, neotectonics and thermochronology.

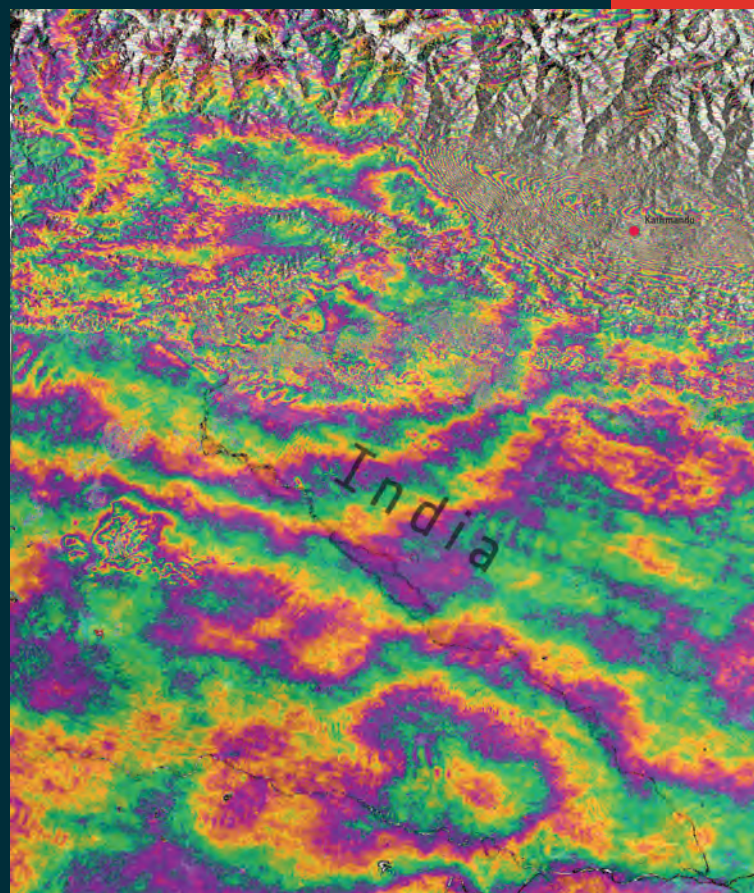


## NERC'S NEW STRATEGY, THE BUSINESS OF THE ENVIRONMENT, STRESSES HOW SEISMIC EVENTS SUCH AS VOLCANOES AND EARTHQUAKES CAN HAVE SERIOUS IMPACTS, AND HOW WE NEED TO USE SCIENCE TO MAKE PEOPLE AND SOCIETY MORE RESILIENT TO ENVIRONMENTAL HAZARDS AND EMERGENCIES.

In response, COMET is aiming to significantly improve the understanding of tectonic and volcanic processes and the hazard they present, and to use this to support risk reduction and hazard management by, for example, influencing policy and informing emergency procedures.

We have three overarching 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 sets with ground-based observations to build new models of these hazardous processes that can be used to mitigate risk.

You can read about our research priorities, which are being worked on by staff across COMET, in more detail on the next pages.



Interferogram showing changes occurring during the 25 April Nepal earthquake.  
Credit: Copernicus data (2015)/ESA/Norut/PPO.labs/COMET-ESA SEOM InSARAP study

## OVERARCHING PRIORITIES

### What is the distribution of tectonic strain and seismic hazard across the continents?

Maps of tectonic strain based on ground measurements are usually too sparse to be used in assessing seismic hazard. To resolve this problem we are developing methods that enable us to use high-resolution InSAR data from ESA's Sentinel-1A satellite to measure tectonic strain.

We will be combining these measurements with ground-based observations to map tectonic strain throughout the Alpine-Himalayan Belt and East African Rift, use the results identify active faults in these areas, and produce new models of seismic hazard.

### How does seismic hazard vary in space and time following major earthquakes?

The earthquakes in New Zealand in 2010 and 2011 were a powerful reminder of how one event can influence another: 182 people died in the Christchurch earthquake less than 6 months after an earthquake 40km west of the city had no fatalities.

Both were on previously unknown faults. But, if we have the right information on the location and magnitude of fault slip and background seismicity rates, we can estimate the continuing seismic hazard. With Sentinel-1, deformation data will be available within a few days of an earthquake. We are using this data to develop a system to quickly estimate the fault location and mechanism for every continental earthquake above magnitude 6.0. Near large population centres, we can use the results, for example, to calculate stress changes on neighbouring faults so we can assess how the seismic hazard is changing.

### What is the structure of the continental lithosphere?

There are lots of things we still don't know about continental deformation:

What controls the sizes and shapes of mountain ranges and sedimentary basins?

What governs the location, magnitude, and style of active deformation?

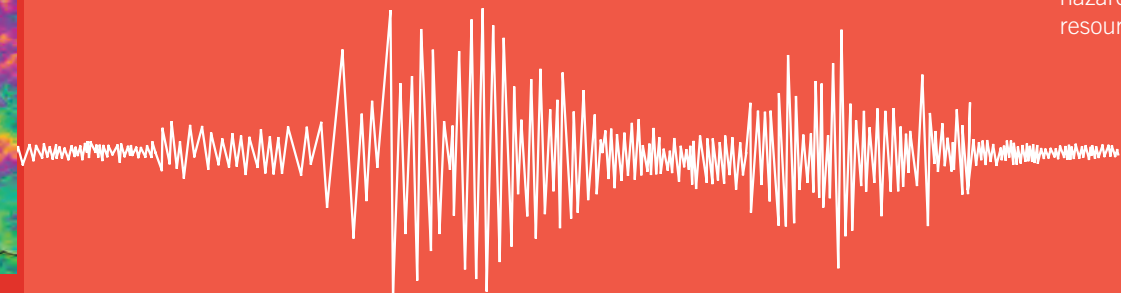
Are long-term stresses supported mainly by the crust or the mantle?

Why do some continental regions deform in a distributed fashion while others appear to behave like rigid blocks?

How can we explain time-varying deformation observed during the earthquake deformation cycle?

The answers depend on the 3D distribution of mechanical strength (rheology) in the continental lithosphere, but this in turn depends on the deformation of the Earth's surface in space and time, which we know little about.

We aim to use the dramatic improvements in our knowledge of the time-dependent surface deformation to make significant progress in understanding the 3D strength distribution in the continents. The results have broad implications, from seismic hazard to the distribution of natural resources.





**What are the patterns of volcanic deformation and degassing on global and regional scales, and how do these relate to the distribution of global volcanic hazard?**

There are many different types of volcano: from persistently erupting to dormant, and from well-monitored to unexplored. In the 16 least-developed countries with active volcanoes, over 100 million people live within 30km of such a feature, less than 15% of which are monitored. Many are in remote or hostile environments.

Sentinel-1A is helping us to study this activity on a truly global scale. We are using InSAR alongside IASI to observe these volcanoes, and develop better measurements of volcanic deformation and degassing.

We are using this information to establish volcano monitoring services and, ultimately, automated alert systems. We are also studying signs of volcanic unrest and eruption, and combining them with ground measurements to improve models of volcanic activity.

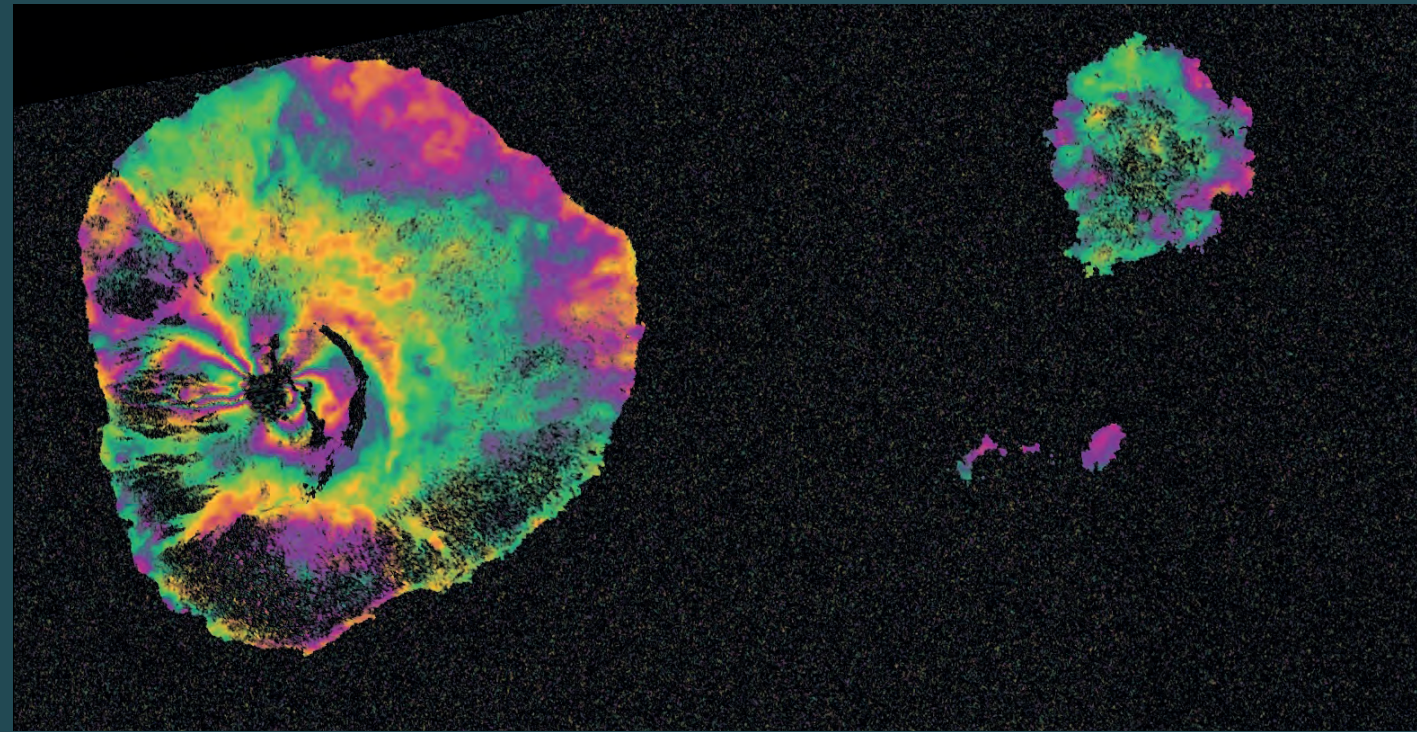
**How does hazard vary in space and time during periods of volcanic activity?**

Active volcanoes can change behaviour with little or no warning. During the 2010 eruption of Merapi in Indonesia, the initial lava was quickly followed by violent explosions and pyroclastic flows, resulting in the worst loss of life in a volcanic eruption for 20 years.

We need to be better at recognising such changes in volcanic activity, and what they might mean.

We are using both satellite and ground-based data to tackle this challenge. Because many volcanic processes are both sudden and short, we will be making particular use of new high-spatial resolution optical and radar imagery and satellites with short revisit-time.

We will be studying active volcanoes in Montserrat, Ecuador, Colombia and Iceland, as well as others that erupt during the project lifetime.



COMET scientists have used data from the Sentinel-1A satellite to map ground movements associated with an ongoing volcanic eruption in the remote island of Fogo, Cape Verde. Credit: Copernicus data (2014)/ESA/Norut-PPO.labs-COMET-SEOM InSARAP study

OUR RESEARCH

**How do we model subsurface processes to better understand variations in volcanic behaviour?**

To model volcanic processes in detail we need information on magma composition, gas emissions, and the “plumbing system” of the volcano. These can help us to both understand both a volcano’s internal state and forecast its future behaviour.

**Before we can develop these models, we need to understand:**

- What drives seismicity, deformation and gas release?
- What causes an eruption to change from effusive to explosive, or to stop?
- What the balance is between intrusive and extrusive magma fluxes in different tectonic settings?
- What governs periodicities and feedbacks in volcanic systems?
- How do the properties of volcanic plumes relate to subsurface processes?

As we collect and understand the data, we are realising that many existing models of volcanic activity are not fit for purpose.

We aim to use data from selected, well-monitored volcanoes to develop a suite of useful models with predictive power that can be applied more widely.





# EARTHQUAKE MONITORING GETS BOOST FROM A NEW SATELLITE –

**DR JOHN ELLIOTT**



John Elliott is a postdoctoral scientist at the University of Oxford. He works on modelling earthquakes using deformation data, and is co-funded by COMET and the Earthquakes without Frontiers consortium.

## Understanding the August 2014 Napa Valley earthquake.

For more than two decades, space-based radar satellites have been measuring how the ground moves with extraordinary precision and spatial resolution. Comparing ground heights from the same places at different times helps scientists to understand the dynamics of a variety of geophysical events including earthquakes.

On 24 August 2014, the San Francisco Bay area was shaken by a  $M_w = 6.0$  earthquake, the region's largest in 25 years. The tremors killed 1 person, injured around 200 and damaged buildings near the quake's epicentre in the southern reaches of California's Napa Valley.

It also set off a scientific scramble to measure the fault's movement, and marked the dawn of a new age of earthquake monitoring thanks to the recent launch of [Sentinel-1A](#).

By combining satellite data with GPS measurements made by our US colleagues on the ground, we were able to show that motion on the fault continued to slip in the weeks following the earthquake in a process called postseismic afterslip.

Using these regularly repeating observations, we found a whole range of different fault slip behaviour on the fault plane: from rapid shallow slip to slower, more prolonged, deeper slip.

Observations such as these are important for constraining types of fault slip behaviour and as a starting point to begin to understand the fault frictional behaviour. This variability should be incorporated into seismic hazard models.

The research received extensive media coverage, including by the BBC: [Sentinel system pictures Napa quake](#), [Sentinel radar satellite tracks continued Napa slip after quake](#)

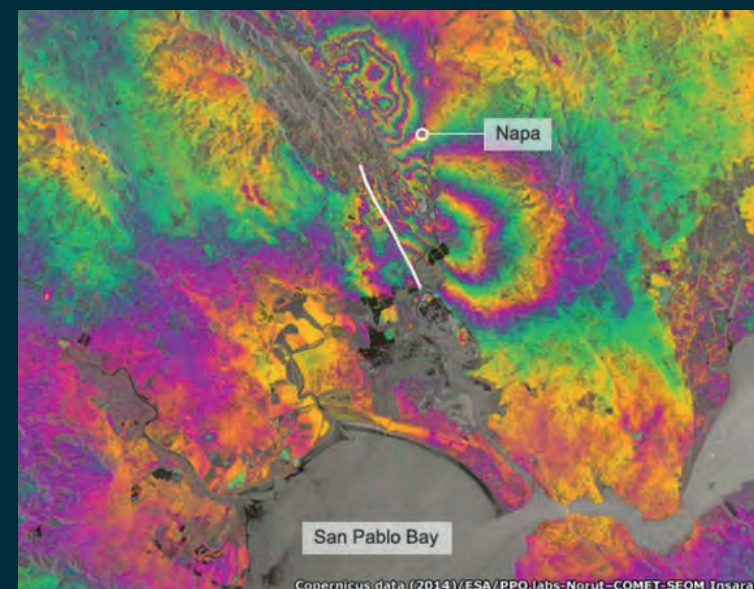


Figure 1: Sentinel-1A interferogram built by comparing scans near California's San Pablo Bay from 7 August 2014 with those from 31 August 2014. The image shows ground displacement contours (changes in colour represent displacement of 2.8 centimetres) of motion toward and away from the satellite due to the 24 August South Napa earthquake. The satellite looks westward and down and therefore measures both horizontal motion along the fault and vertical motions at the ends of the fault.

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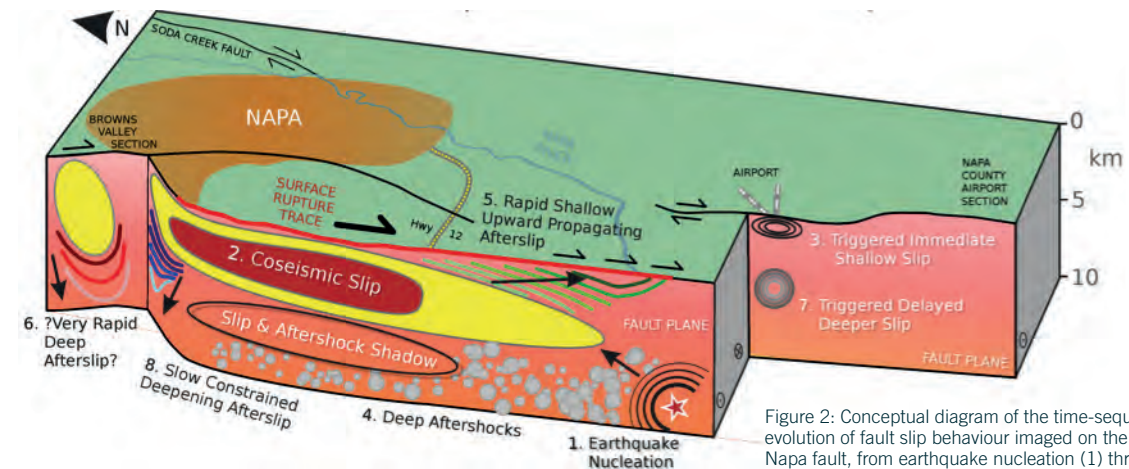


Figure 2: Conceptual diagram of the time-sequence evolution of fault slip behaviour imaged on the Napa fault, from earthquake nucleation (1) through to deep afterslip (8), over the period of two months following the earthquake.

# IRAN FLOWS IN RESPONSE TO ARABIAN PUSH –

**DR RICHARD WALTERS**



Richard Walters is a postdoctoral scientist at the University of Leeds. He works on measuring and modelling regional deformation, and is co-funded by COMET and the Earthquakes without Frontiers consortium.

## Understanding deformation where the Arabian and Eurasian plates converge.

A long-standing problem in continental tectonics has been to understand what controls the distribution of deformation and hence earthquakes.

As Arabia converges with Eurasia by a couple of centimetres each year, the country of Iran is slowly being squashed between two rigid tectonic plates, and recent measurements of deformation from GPS give us the opportunity to test competing ideas. This is an important societal as well as scientific issue – a large and growing population in Iran is exposed to a high degree of seismic hazard.

Modelling the deformation of Iran, we treated the Iranian lithosphere as a thin sheet of viscous fluid that flows under gravity as well as due to the push of the Arabian plate. This model can predict both the GPS velocity field and patterns of earthquake types and locations.

It had been suggested that strength variations within the lithosphere are required to explain the lack of deformation in Central Iran, which has traditionally been thought of as a stronger, rigid region. Instead, we found this feature can be reproduced by taking into account gravity-driven flow of the lithosphere under its own weight.

We also developed a novel method for estimating seismic hazard where GPS velocity measurements are scarce.

We assumed that the motion of the elastic upper crust is driven by the viscous velocity field derived from our model, and calculated slip rates along major fault zones.

The predicted rates agreed well with independent, long-term estimates of slip rate, showing that this is a promising way of estimating seismic hazard from a physically-based model of continental deformation.

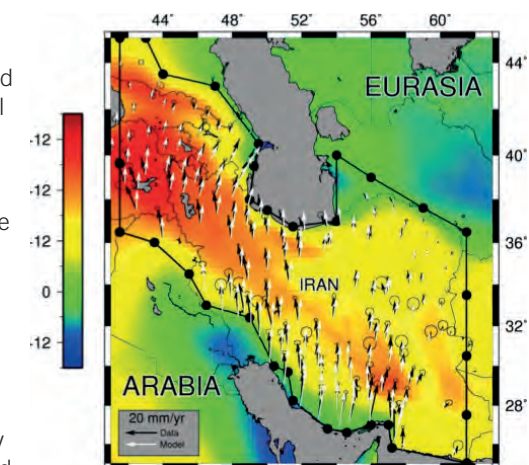


Figure 1: Results from our numerical model of Iranian lithospheric deformation. Model boundaries are shown by the black lines. Deformation is driven by an 'Arabian push' on the southern boundary due to convergence between Arabia and Eurasia, and by variations in gravitational potential energy (GPE) of the lithosphere, shown by the background colour. Crustal velocities relative to a fixed Eurasia and measured by GPS are shown as black vectors, and predicted model velocities are shown by the white vectors.

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# PLEIADES DETERMINES CHANGES IN TOPOGRAPHY AT EL MAYOR-CUCAPAH, MEXICO

YU ZHOU

Yu Zhou is a doctoral student at the University of Oxford, working under the supervision of Barry Parsons and Richard Walker.



Very high resolution satellites provide low cost means of measuring ground height changes.

Light detection and ranging (LiDAR) surveys from aircraft have been a valuable tool for determining vertical offsets in earthquakes, but so far their relatively high cost and low availability has limited their applicability.

New generations of very high resolution (VHR) satellites such as Pleiades provide an alternative means of measuring surface topography with precision down to tens of centimetres, at a much lower cost.

To demonstrate how Pleiades stereo imagery can determine height changes of less than a metre, we acquired data for the area around the epicentre of the El Mayor-Cucapah 2010 earthquake (just south of the US-Mexico border) which has also been covered by both pre- and post-earthquake LiDAR surveys.

By establishing differences between the 1m ground resolution Pleiades imagery and the pre-earthquake, 5m ground resolution LiDAR data, we mapped the vertical component of slip in the 2010 earthquake (Figure 1). Our results were comparable to a previous study that used the post-earthquake LiDAR data (Oskin et al., 2012).

The Pleiades stereo imagery also allowed us to resolve a current controversy about the 2013 Mw 7.7 Balochistan earthquake. Previous studies have argued that the fault kinematics switch between strike-slip and dip-slip motion in successive earthquakes (Avouac et al., 2014; Barnhart et al., 2015).

However, by determining the vertical component of motion on the 200+ km long Hoshab fault for the first time, we found that the oblique motion in the 2013 earthquake is typical of this fault.

A constant ratio of vertical to horizontal motion over multiple earthquakes (Figure 2) suggests that the Hoshab fault has experienced the same style of faulting throughout the Late Quaternary.

The Balochistan earthquake provides an example of distributed faulting in a remote and inaccessible area that has been made amenable to detailed near-field investigation by the new generation of very high-resolution satellite stereo imagery.

Figure 1. Elevation difference map showing the vertical component of motion in the 2010 Mw 7.2 El Mayor-Cucapah earthquake. Red dots are measured from serial profiles across the fault trace (positive for south-side-up). PIAZ: Paso Inferior Accommodation Zone. Puerta A.Z.: Puerta Accommodation Zone.

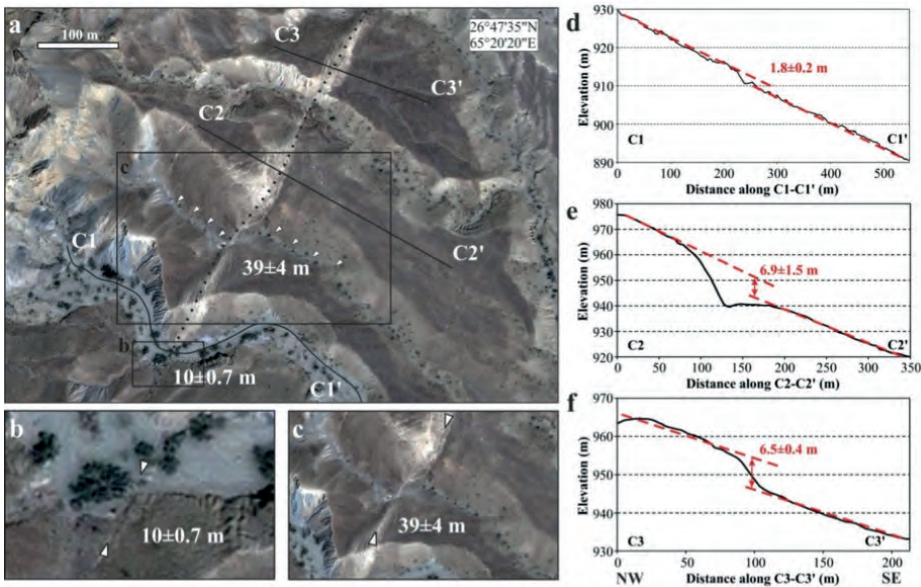
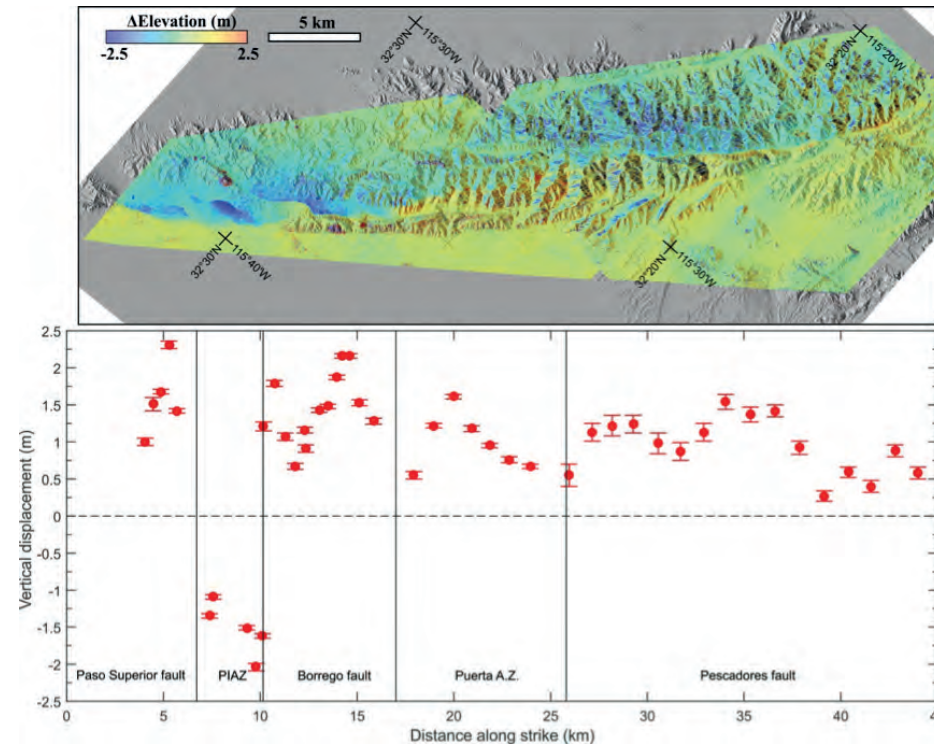


Figure 2. (a) An example of surface displacements along the Hoshab fault. (b) The lateral offset in the 2013 earthquake at this location is 10 m. (c) A gully within an older fan surface is laterally offset by 39 m. (d) Elevation profile C1-C1' from our Pleiades derived 1m topography along the old fan surface shows a vertical displacement of 1.8 m (north-side-up). (e) Elevation profile C2-C2' shows a cumulative vertical displacement of 6.9 m (north-side-up). (f) Elevation profile C3-C3' shows a cumulative vertical displacement of 6.5 m (north-side-up).

Pleiades 1B. Credit: EADS Astrium/Master Image Films 2007

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Pleiades 1B. Credit: EADS Astrium/Master Images Films 2007



# RIFTING EVENT IN ICELAND OBSERVED IN EXQUISITE DETAIL

**PROFESSOR ANDY HOOPER**



Andy Hooper is Professor of Geodesy and Geophysics at the University of Leeds. He has developed new methods for modelling the volcanic and tectonic processes that lead to ground deformation, and led the geodetic monitoring from space and subsequent modelling for the 2010 Icelandic volcanic eruptions whilst also discovering a new link between ice cap retreat and volcanism.

**Research into an Icelandic eruption, published in *Nature*, sheds new light on how the Earth's crust forms.**

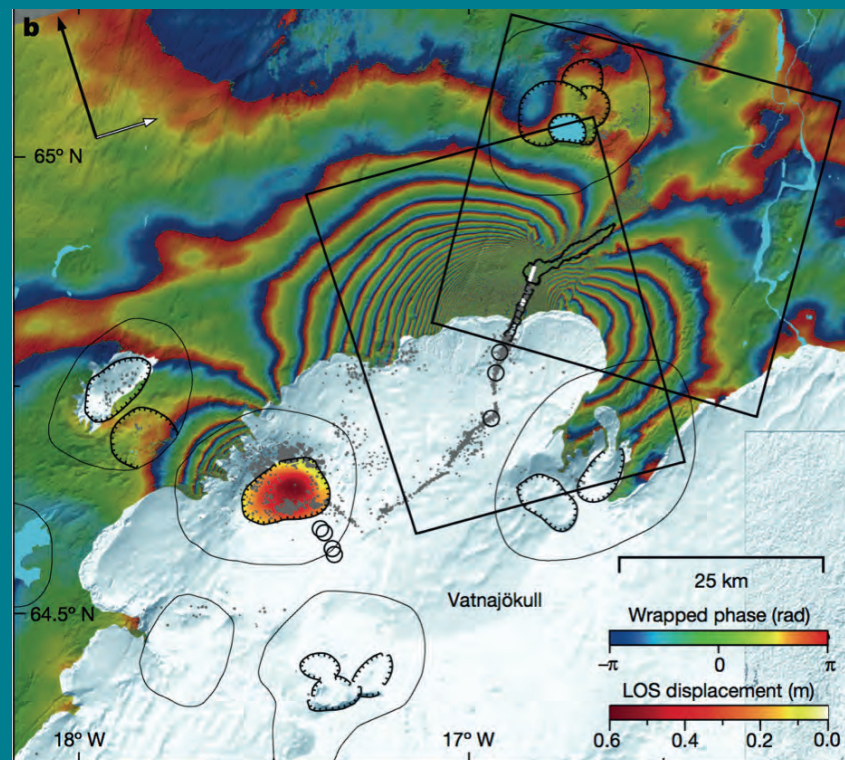


Figure 1. Map from radar interferometry (InSAR) showing the deformation that occurred around Bárðarbunga between 8 August 2013 and 1 September 2014. Each colour cycle represents a further 2.8cm of movement away from the satellite, which reaches more than 2m in total. The yellow-red colours indicate subsidence of the caldera between 27 and 28 August 2014. The grey dots indicate seismicity, which traces the path of the dyke to the eruption sites indicated by white lines.

When Iceland's Bárðarbunga volcano reawakened in August 2014, we had a rare opportunity to monitor how the magma flowed away from the volcano through cracks in the rock.

New crust forms where two tectonic plates are moving away from each other. This mostly happens beneath the oceans, where it is difficult to observe. However, in Iceland this happens beneath dry land, and the events of 2014 were the first time that such a rifting episode had been observed with modern tools like GPS and satellite radar.

Although it has a long history of eruptions, Bárðarbunga has been increasingly restless since 2005. There was a particularly dynamic period in August and September 2014, when more than 22,000 earthquakes were recorded in or around the volcano in just four weeks. These were due to stress being released as magma forced its way through the rock, forming sheet-like features known as dykes.

Using GPS and satellite radar measurements, we were able to track the path of the magma underground for over

45km before it began to erupt at the surface. Lava continued to flow until February 2015.

We were able to show that the dyke propagated at a variable rate, slowing as the magma reached natural barriers, which were then overcome by the build-up of pressure and the initiation of a new segment. The observations explain how the magma rising up underneath volcanoes can be redistributed over larger areas to create new crust where tectonic plates are pulling apart.

Like other liquids, magma flows along the path of least resistance, and we were able to use this simple principle to explain why the dyke at Bárðarbunga changed direction as it progressed. To start with, the magma flow was influenced mostly by the overlying topography, but as it moved away from the steeper slopes, stresses from the extensional

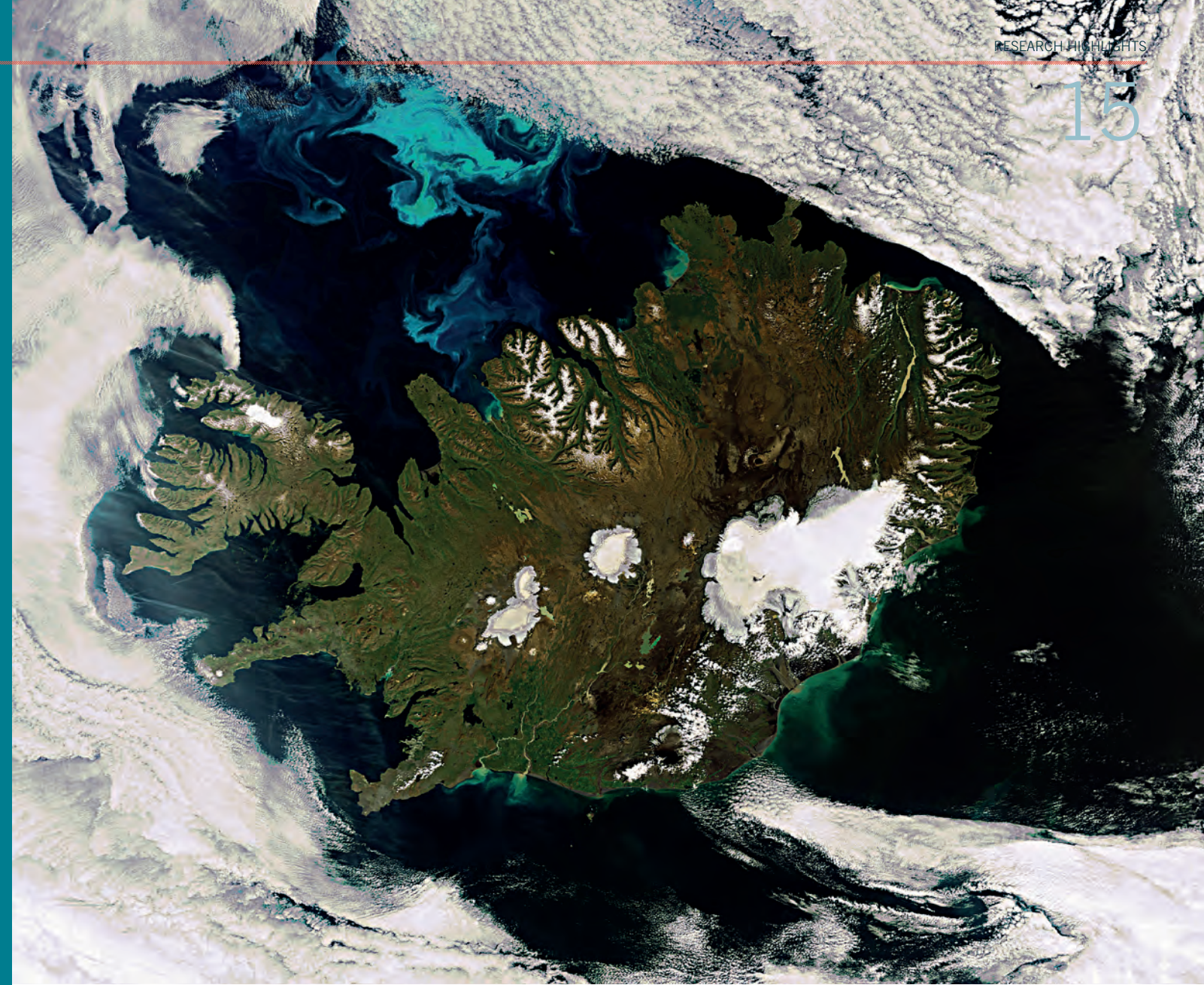
plate movements became more important in controlling the direction of propagation.

Using radar measurements, we also formed an image of caldera movement over one day. Usually we expect to see just noise in the image, but were amazed to see up to 55cm of subsidence. The ice inside Bárðarbunga's caldera sunk by 16m in total over two weeks as the volcano floor collapsed.

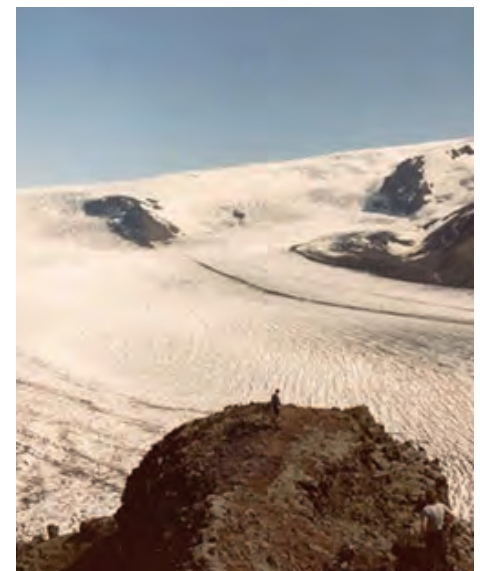
Overall, our observations show that the magma injected into the crust took an incredibly roundabout path and proceeded in fits and starts. Initially we were surprised at this complexity, but the twists and turns can actually be explained by a relatively simple model which considers just the pressure of rock and ice above and the pull exerted by the plates moving apart.

## Reference

Sigmundsson, F., Hooper, A., Hreinsdóttir, S., Vogfjörð, K.S., Ófeigsson, B.G., Heimisson, E.R., Dumont, S., Parks, M., Spaans, K., Gudmundsson, G.B., Drouin, V., Árnadóttir, T., Jónsdóttir, K., Gudmundsson, M.T., Högnadóttir, T., Fridriksdóttir, H.M., Hensch, M., Einarsson, P., Magnússon, E., Samsonov, S., Brandsdóttir, B., White, R.S., Ágústsson, T., Greenfield, T., Green, R.G., Hjartardóttir, Á.R., Pedersen, R., Bennett, R.A., Geirsson, H., la Femina, P.C., Björnsson, H., Pálsson, F., Sturkell, E., Bean, C.J., Möllhoff, M., Braiden, A.K., Eibl, E.P.S. (2014) *Segmented lateral dyke growth in a rifting event at Bardarbunga volcanic system, Iceland*, *Nature* 517, 191-195. doi:10.1038/nature14111



View of Iceland with no cloud from satellite. The white circular patch in the centre of the country is Hofsjökull, the country's third largest glacier and its largest active volcano. The elongated white area west of Hofsjökull is Langjökull, Iceland's second largest glacier. Photo: ESA



Bárðarbunga is partly covered by the Vatnajökull ice cap  
Credit: BGS



# THE 2014-2015 ERUPTION AT FOGO VOLCANO –

**DR MARCO BAGNARDI**

Marco Bagnardi is a postdoctoral scientist at the University of Leeds. He works on measuring and modelling volcanic deformation, and is co-funded by COMET and the EU FUTUREVOLC project.

## Understanding the impacts and highlighting future risks using Sentinel-1A.

Between November 2014 and February 2015, after twenty years of inactivity, Fogo volcano – the most active in the Cape Verde archipelago – erupted for over two months.

Although the eruption received little attention from the international media, it caused the disappearance of two villages under tens of metres of rubbly lava, and the displacement of more than a thousand people.

Since the eruption began, we have been monitoring ground deformation using InSAR techniques. InSAR is one of the best tools for characterising the inner workings of a volcano, particularly in terms of identifying where large volumes of magma are stored and how it moves through the Earth's crust to reach the surface and feed eruptions.

Using data from Sentinel-1A, which had only been operating for a few weeks when the eruption began, meant that our study was the first to use the new satellite to investigate surface deformation associated with volcanic activity.

During the eruption, lava spewed for weeks in vigorous fire fountains which created fast-moving lava flows. The data confirmed that there was no shallow (less than a few kilometres beneath the surface) magma reservoir within the volcano, meaning that magma was instead moving rapidly from depths of more than ten kilometres to feed the eruption at the volcano's summit.

We focused our attention on the magmatic intrusion that was feeding the eruption.

Taking advantage of Sentinel-1A's unique capabilities, particularly its TOPS (Terrain Observation by Progressive Scans) mode, we found that the deformation was probably being caused by the intrusion of a sub-vertical planar body, or dyke, from beneath the volcano to its surface.

We are now analysing the InSAR data to assess the stability of the entire volcanic structure. The intrusion of magma through the volcano could push the volcano's very steep flanks, making them unstable and potentially causing them to crumble, creating enormous landslides.

Importantly, Fogo experienced this kind of event 100,000 years ago and still shows scars on its landscape that evidence a giant landslide into the Atlantic Ocean, potentially causing a large tsunami.



Figure 1: The village of Portela in June 2015. The village is almost entirely covered by a thick lava flow that travelled more than five kilometers from the eruption, leaving only a few roofs that were not entirely engulfed. Credit: M. Bagnardi

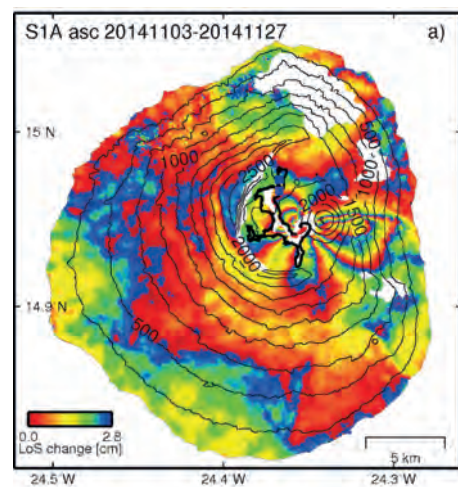


Figure 2: Sentinel-1A TOPS interferogram showing deformation associated with the emplacement of a dike beneath the surface. The ground was displaced for tens of centimetres on both sides of the intrusion. Each colour cycle represents approximately three centimetres of ground motion away from the eruptive fissure.



# VOLCANIC AEROSOLS AFFECT CLOUD PROPERTIES

**DR SUSANNA EBMEIER**

Susi Ebmeier is a postdoctoral scientist at the University of Bristol. She works on observing and modelling volcanic deformation and gas emissions using Earth Observation data, and is co-funded by COMET and the STREVA consortium.

## Satellite data show alteration of cloud droplets downwind of degassing volcanoes in pristine oceanic regions.

Aerosols affect how reflective the Earth is by absorbing and scattering solar radiation directly, or by modifying the properties of clouds. However, we are still uncertain of exactly how aerosols change cloud properties, how they affect global climate, and therefore how they impact on climate change.

It is more difficult to make satellite measurements of the effects of aerosols from passively degassing volcanoes deep in the lower atmosphere than from explosive eruptions that inject gas and aerosol up into the stratosphere. However, the impact of such 'background' volcanic activity is increasingly thought to be important to atmospheric processes.

Prior to our study, measurements of a volcanic impact on cloud properties had been made only during a few episodes of elevated degassing. Using data from three independent satellite sensors (MODIS, AATSR and CERES), we examined differences in cloud and aerosol properties upwind and downwind of isolated volcanic islands. By comparing this information with that from islands without active volcanoes, we could see how volcanic emissions were affecting the clouds.

By analysing a decade of satellite measurements of aerosol and cloud

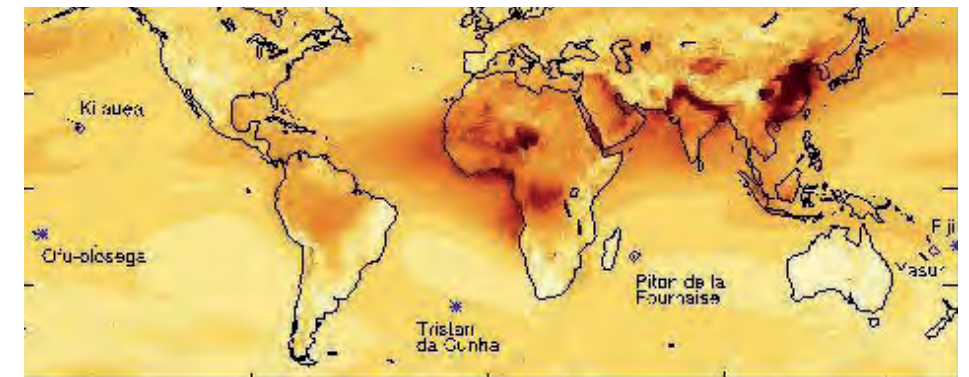


Figure 1: Multiannual mean Aerosol Optical Depth from NASA's MODIS Aqua Collection 6 dataset. Darker red indicates higher aerosol burden. The volcanoes and islands in our study are all in regions of low aerosol optical depth and may therefore be representative of the pre-industrial atmosphere.

properties, we demonstrated that these volcanoes have a long-term net impact on cloud properties. Downwind of the volcanoes, the concentration of aerosol is higher and the cloud droplet size is lower than upwind. Top of atmosphere shortwave radiation flux is also higher downwind of the volcanoes, as smaller droplets tend to be more effective at reflecting solar radiation.

This was the case for a range of eruptive styles including high flux degassing (Kilauea), Strombolian eruptions (Yasur) and minor explosions (Piton de la Fournaise).

Measurements of aerosol effects at isolated volcanic islands may now be the closest analogue to the pre-industrial atmosphere, and offer a rare chance to observe atmospheric processes as they would have been before the industrial revolution.

You can see a short video describing the research on the [NASA Goddard Space Flight Center YouTube channel](#).

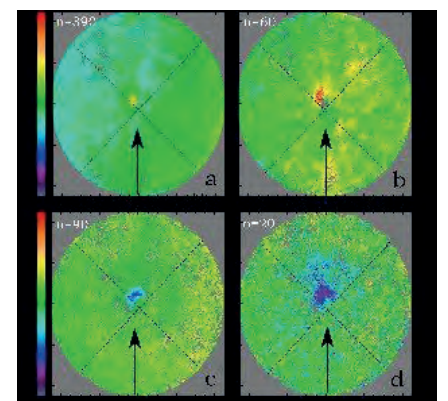


Figure 2: Aerosol optical depth (a & b) and cloud effective droplet radius (c & d) plots for Piton de la Fournaise between 2002 and 2008. Data are rotated according to wind direction at the height of emission, so that for each panel the upper quadrant is downwind of the volcano and the bottom panel is upwind (i.e. the arrow shows wind direction). Panels a & c show aerosol and cloud properties during quiescence, while b & d show elevated aerosol and smaller droplets during minor explosive activity.





# THE VERTICAL DISTRIBUTION OF VOLCANIC SO<sub>2</sub>

**DR ELISA CARBONI**



Elisa Carboni is a postdoctoral scientist at the University of Oxford. She works on developing retrievals of volcanic gas and ash using EO data, and is co-funded by COMET and the SHIVA project.

## Tropical eruptions 'love' the tropopause.

Sulphur dioxide (SO<sub>2</sub>) plays a crucial role in many atmospheric processes. In the troposphere, it leads to the acidification of rainfall, while in the stratosphere it oxidises to form a sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) haze that can affect climate for several years.

Volcanoes contribute around one third of the tropospheric sulphur burden, of which the majority is SO<sub>2</sub>. Satellites play a crucial role in quantifying volcanic SO<sub>2</sub> emissions, but previous measurements have lacked data on the height of these emissions, a key parameter when assessing their effects and lifetime.

The Infrared Atmospheric Sounding Instrument (IASI) on the [Metop satellite](#) can however be used to study volcanic emission of SO<sub>2</sub> using high-spectral resolution measurements from 1000 to 1200cm<sup>-1</sup> and from 1300 to 1410cm<sup>-1</sup> (the 7.3 and 8.7 μm SO<sub>2</sub> bands).

The advantages of the IASI SO<sub>2</sub> measurements are that they are not affected by underlying cloud and are consistent (within the retrieved errors) with other measurements (Brewer ground measurements for the column amount of SO<sub>2</sub> and CALIPSO for plume altitude).

We applied Carboni et al.'s (2012) scheme to measuring volcanic SO<sub>2</sub> amount and altitude for several explosive eruptions between 2008 and 2012 (Carboni et al., in review), showing that the biggest emitter of volcanic SO<sub>2</sub> was Nabro (Eritrea),

followed by Kasatochi (Aleutian Islands) and Grimsvötn (Iceland).

There is a tendency for volcanic SO<sub>2</sub> plumes to reach a point of neutral buoyancy near the tropopause for many of the moderately explosive eruptions observed.

This tendency was independent of the maximum amount of SO<sub>2</sub> (e.g. 0.2 Tg for Dalafilla (Afar, Ethiopia) compared with 1.6 Tg for Nabro) and of the volcanic explosive index (between 3 and 5). All of the eruptions in the tropics (except Nyamuragira, Congo), reached the tropopause. In the mid latitudes, the eruptions of Eyjafjallajökull, Llaima, Copahue and Etna remained confined to the troposphere.

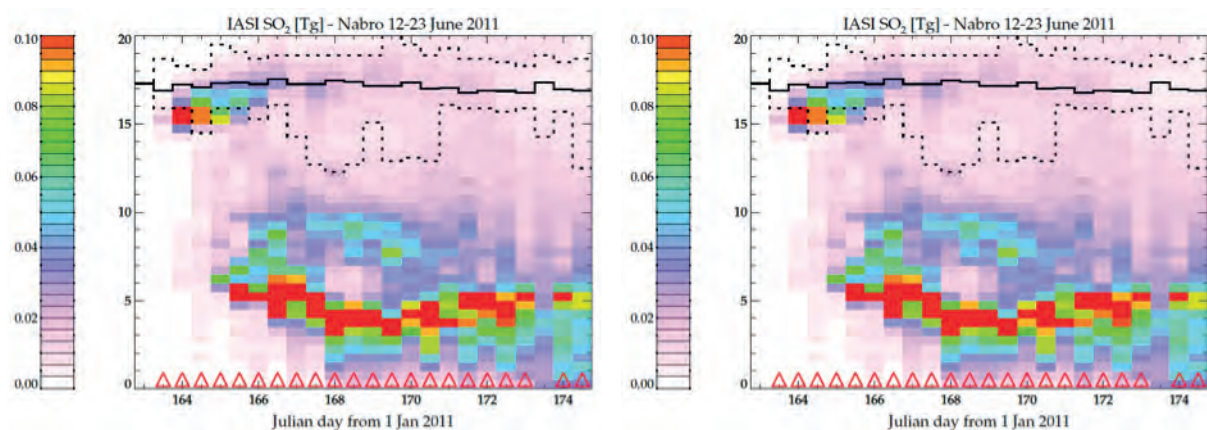


Figure 1. SO<sub>2</sub> vertical distribution for Dalafilla and Nabro volcanic eruption.. The colour represents the total mass of SO<sub>2</sub> in Tg, dark-red represents values higher than the colour-bar. Every column of the plots come from an IASI map (one every 12 hrs). Red triangles in the bottom line indicate the presence of a fresh plume connected with the volcano.

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Carboni, E., Grainger, R.G., Walker, J.C., Dudhia, A., Siddans, R. (2012) *A new scheme for sulphur dioxide retrieval from IASI measurements: application to the Eyjafjallajökull eruption of April and May 2010, Atmospheric Chemistry and Physics*, 12, 11417–11434, 2012. doi:10.5194/acp-12-11417-2012





# COMET RESEARCHERS PUBLISHED A TOTAL OF 42 JOURNAL ARTICLES BETWEEN 1 JANUARY AND 31 DECEMBER 2014 (SEE ANNEX 1). SOME OF THE SELECTED SCIENTIFIC ADVANCES ARE SUMMARISED HERE.

**COPLEY ET AL. (2014)<sup>1</sup>** identified a hazardous active fault in India. The results have major implications for the seismic hazard in the area and our understanding of continental tectonics.

**BIGGS ET AL. (2014)<sup>2</sup>** examined the global link between deformation and volcanic eruption quantified by satellite imagery. This work used statistical methods adopted from medicine to show that deformation is a useful diagnostic tool when forecasting future eruptions.

**YAMASAKI ET AL. (2014)<sup>3</sup>** provided an explanation for the deformation observed during the entire earthquake cycle on the North Anatolian Fault. The results suggest that a weak zone beneath the fault embedded in a stronger background is responsible for the observations of rapid postseismic deformation and focussed interseismic strain.

**WALTERS ET AL. (2014)<sup>4</sup>** used satellite data to map crustal strain in Eastern Turkey. This shows that the areas accumulating seismic strain could be mapped without using any ground based data, and that the results were incompatible with simple block models of the region.

**MCCORMICK ET AL. (2014)<sup>5</sup>** compared satellite- and ground-based measurements of SO<sub>2</sub> emissions from Tungurahua volcano, Ecuador. The authors found 40% difference between the methods investigated, but that satellite observations were a good proxy for ground-based data, and hence for the strength of eruptions.

<sup>1</sup> Copley, A., Mitra, S., Sloan, R.A., Gaonkar, S., Reynolds, K. (2014) *Active faulting in apparently stable peninsular India: Rift inversion and a Holocene-age great earthquake on the Tapi Fault*. *Journal of Geophysical Research*.

<sup>2</sup> Biggs, J., Ebmeier, S.K., Aspinall, W.P., Lu, Z., Pritchard, M.E., Sparks, R.S.J., Mather, T.A. (2014) *Global link between deformation and volcanic eruption quantified by satellite imagery*. *Nature Communications*.

<sup>3</sup> Yamasaki, T., Wright, T.J., Houseman, G.A. (2014) *Weak ductile shear zone beneath a major strike-slip fault: Inferences from earthquake cycle model constrained by geodetic observations of the western North Anatolian Fault Zone*. *Journal of Geophysical Research: Solid Earth*.

<sup>4</sup> 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*.

<sup>5</sup> McCormick, B.T., Herzog, M., Yang, J., Edmonds, M., Mather, T.A., Carn, S.A., Hidalgo, S., Langmann, B. (2014) *A comparison of satellite- and ground-based measurements of SO<sub>2</sub> emissions from Tungurahua volcano, Ecuador*. *Journal of Geophysical Research: Atmospheres*.

## Photos (across):

1/ Southwestern flank of Pico do Fogo volcanic cone on the island of Fogo from the Cha das Caldeiras. Credit: M.Bagnardi

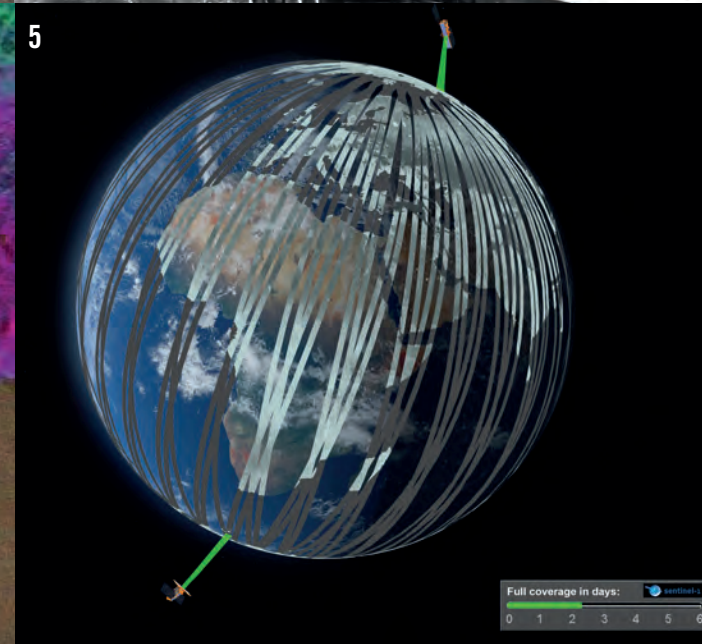
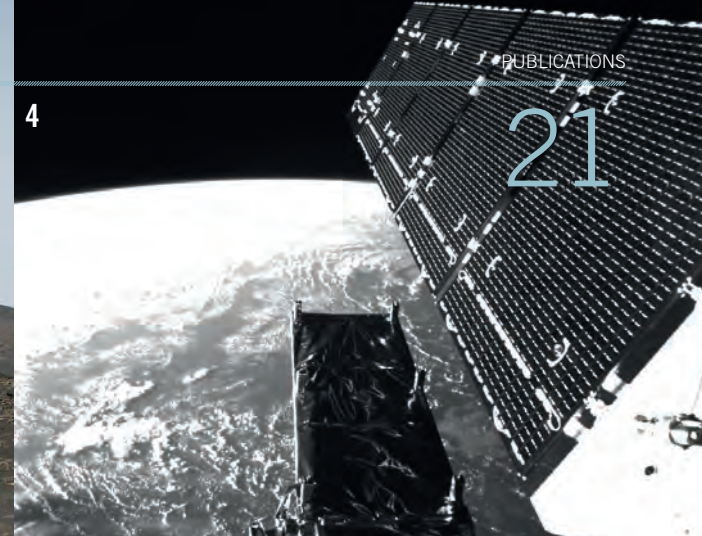
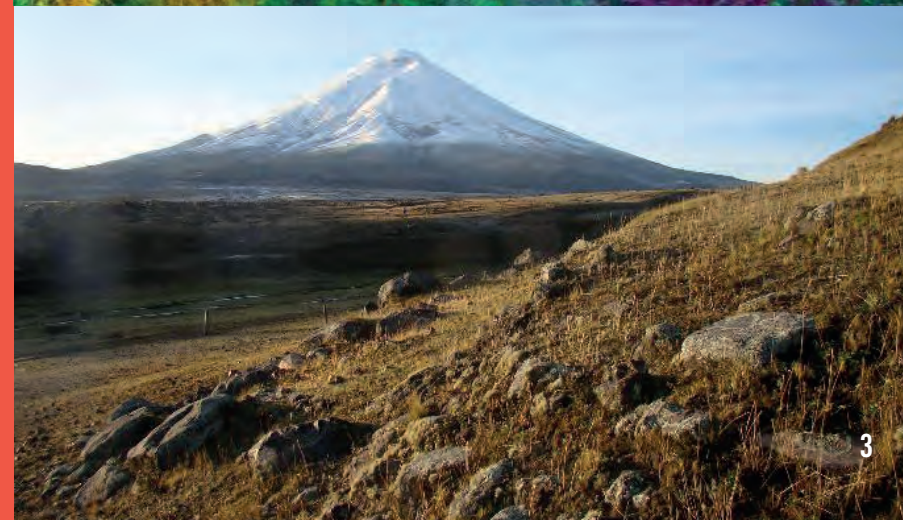
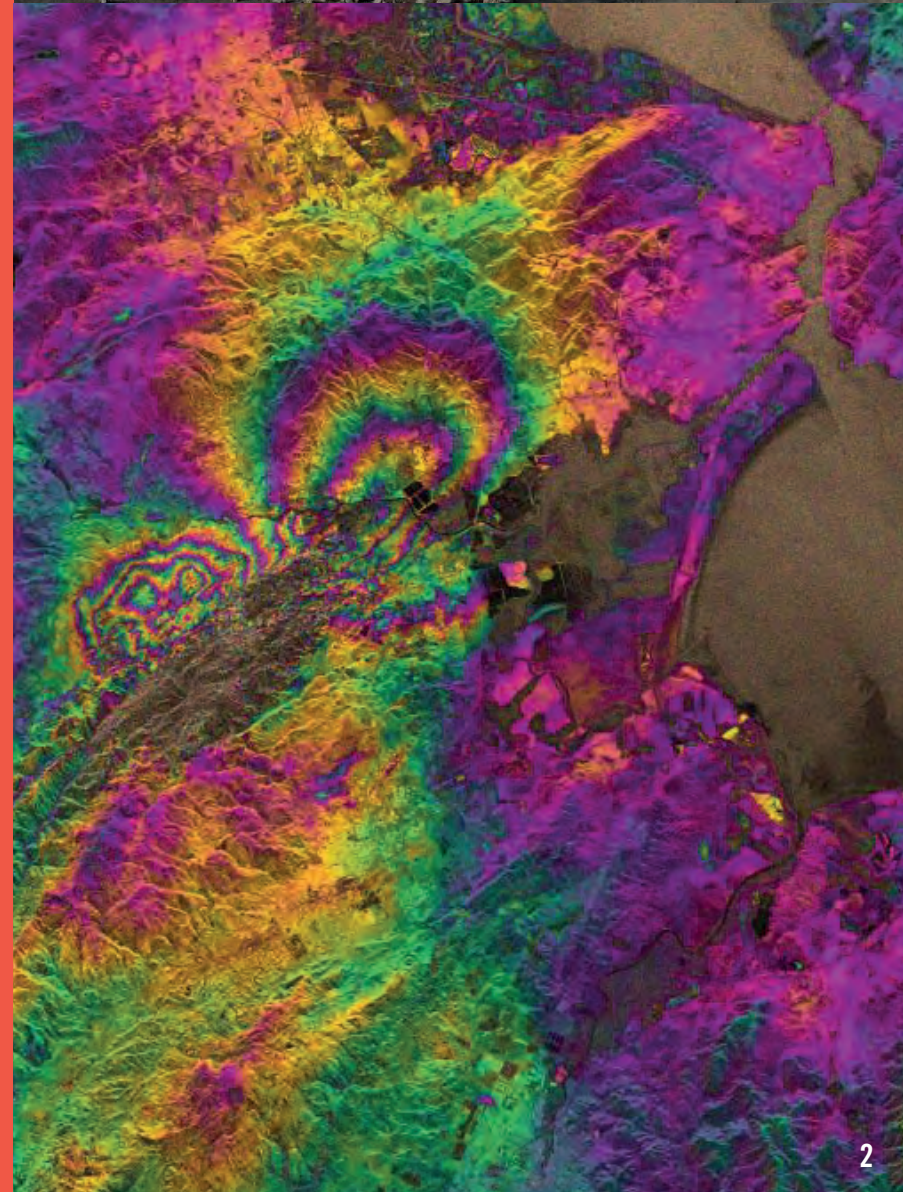
2/ August 2014 Mw 6.0 Napa Valley (California) earthquake. Credit: Copernicus data (2014)/ESA/PPD.labs/Norut/COMET-SEOM Insarap study

3/ Cotopaxi Volcano, Ecuador. Credit: S. Ebmeier

4/ Sentinel-1 solar wing. Copyright ESA

5/ Sentinel-1 constellation. Copyright ESA/ATG medialab

6/ Road in Christchurch, New Zealand destroyed by an earthquake.





## SHARING OUR SCIENCE

**DURING 2014/15, ALONGSIDE OUR PLANNED RESEARCH WE WERE BUSY RESPONDING TO SUDDEN EVENTS, SHARING OUR KNOWLEDGE WITH THE SCIENTIFIC COMMUNITY, AND ENGAGING WITH PEOPLE INTERESTED IN VOLCANOES, TECTONICS AND EARTH OBSERVATION MORE BROADLY.**

In September 2014, COMET and the University of Leeds hosted **Wegener 2014: Managing and Modelling our Dynamic Planet**. This was the 17th General Assembly of Wegener on Earth deformation and the study of earthquakes.

The conference focused on recent advances in geodesy, with topics ranging from continental faulting and the earthquake cycle to glacial isostatic adjustment and sea level rise.

It also brought together international experts in InSAR, GPS, gravity measurements, ground observations and numerical modelling to provide a multi-disciplinary perspective on current challenges and opportunities in Earth deformation and dynamics.

COMET and the Looking inside the Continents from Space (LiCS) team have been working closely with ESA to set the acquisition strategy for the new Sentinel-1 satellite constellation. COMET scientists have ensured that data are being acquired for all

tectonic and volcanic areas of the planet, to be used for improved hazard assessment.

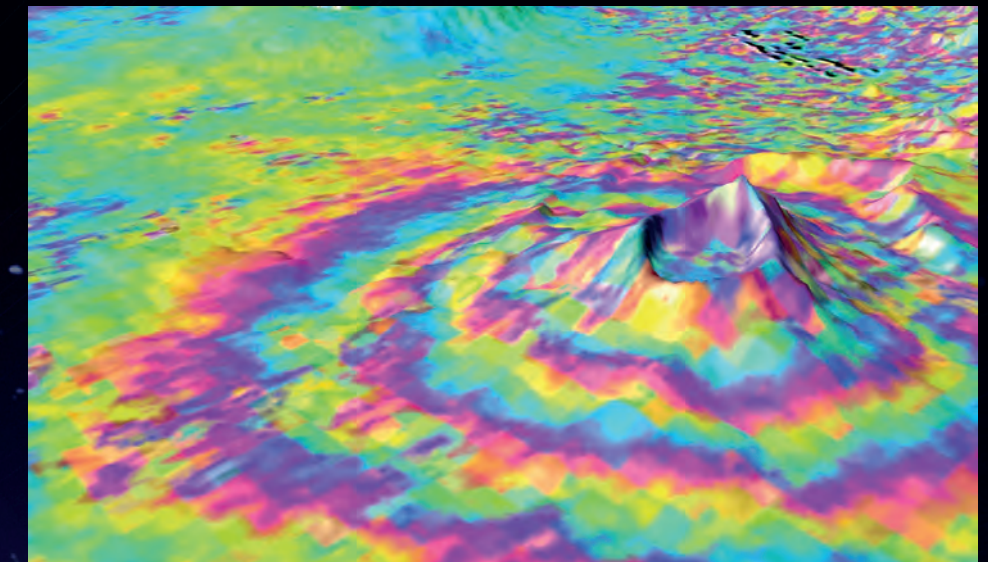
This initiative will ultimately provide processed results to the whole Earth Observation community for all the tectonic and volcanic regions of the planet, providing products including simple interferograms, time series, and regional velocity/strain maps. We will also use these to create products such as earthquake source models, seismic hazard maps, and volcanic deformation alerts.

COMET scientists Barry Parsons and Richard Walker, along with colleagues James Hollingsworth (Arup) and Ed Nissen (Colorado School of Mines), organised the Royal Astronomical Society's Specialist Discussion Meeting *"Tectonics from above: Recent advances in the use of high-resolution topography and imagery"*, held on 13th March 2015.

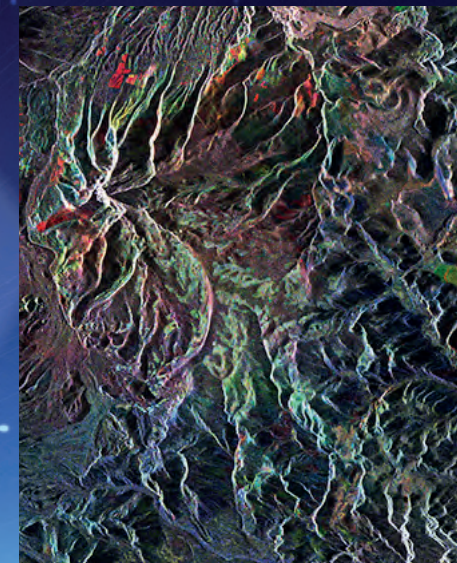
Istanbul, Turkey. Copyright ESA



Volcanic uplift. Copyright ESA



Ecuador's highlands. Copyright ESA



The meeting exposed a wider audience to new data sets (e.g. Tandem-X, LiDAR, Pleiades imagery), and the new methods for generating and analysing these data sets (e.g. photogrammetric DEM extraction, point cloud manipulation) currently available for measuring continental topography and surface displacements. It also provided a forum for the discussion of new tectonic applications of high-resolution topography and imagery.

**COMET researchers gave a total of 17 talks at the 2014 AGU (American Geophysical Union) Fall Meeting – the world's largest Earth and space science conference.**

Our presentations covered topics ranging from volcanic ash emissions through tectonic processes in Turkey, Iran and Pakistan to crustal deformation around an Icelandic volcano.

We also presented 19 posters highlighting our recent research, which attracted interest not only from Earth Observation scientists but also those working in the broader fields of volcanics and tectonics.

We meanwhile gave 10 talks, presented 12 posters and convened 6 sessions at ESA's [2015 Fringe Meeting](#), and contributed to a further 16 presentations and 9 posters. Fringe brings together scientists, Sentinel-1 data users, students, space agencies, and industry to hear about the latest developments in InSAR techniques and their application.

As well as specific research topics, COMET scientists presented strategic issues such as [monitoring tectonic and volcanic deformation using Sentinel-1A](#) with a view to providing processed results for all the tectonic and volcanic regions of the planet (see above), highlighting COMET's leadership in the Earth Observation community.



## COMET RECOGNISES THE IMPORTANCE OF WORKING WITH GOVERNMENTS, NGOS AND OTHER PARTNERS TO ENSURE THAT OUR SCIENCE HAS REAL IMPACT, USING OUR WORK TO SHAPE POLICY DECISIONS AND MANAGE NATURAL HAZARDS.

COMET's Jurgen (Locko) Neuberg and Amy Collinson have carried out significant modelling work for the Scientific Advisory Committee (SAC) of the Foreign Office (FCO), focusing on the Caribbean island of Montserrat where the Soufrière Hills Volcano has been erupting since 1995.

Their numerical models aim to explain volcanic deformation patterns, which can help to assess the nature of the eruption. The results, used as scientific input to support decision making by the FCO and Governor of Montserrat, suggest that the deformation and gas emissions show no sign of slowing down, and so their role is likely to be ongoing.

Locko is also contributing to the work of Ecuador's Institute for Geophysics, focusing on the eruption at Tungurahua, where models are being used to explain tilt signals and seismicity. As at Montserrat, the results will be used to inform decision making processes. At the same time, COMET expertise is being used to train scientists in Quito so they can better understand the eruption for themselves.

The approach also involves participation in simulation exercises to help with emergency

preparedness in Ecuador as well as Dominica. In these exercises, scientists come together to interpret data and report their findings to decision makers, helping to establish working practices and channels of communication for when unrest does actually occur.

COMET is a major partner in the Increasing Resilience to Natural Hazards program, which is co-funded by NERC and the Economic and Social Research Council. We work in both the Earthquakes without Frontiers and Strengthening Resilience in Volcanic Areas consortia, and through this work have built up a network of partners in countries at risk from volcanic and seismic hazard. This network, and the local relationships we have built up, has for example helped us target our response to the 2015 earthquake in Nepal.

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

Internationally, COMET is working with a number of initiatives and organisations to ensure that our work has the highest possible societal impact. We have been leading players in the development and implementation of the CEOS working group on disasters, helping to establish and implement both the Volcano and Seismic Risk pilot projects.

Through these projects, the space agencies have committed to providing data that enable us, and other scientists around the world, to respond to volcanic and seismic disasters, and to prepare for them by assessing the hazard in certain key areas.

We are also working closely with scientists in the Global Earthquake Model, in particular on developing methodologies for incorporating InSAR data in the global strain rate model, which currently only uses global navigation satellite system (GNSS) data.

Furthermore, the response to the Nepal earthquake has opened up a dialogue with the US Geological Survey (USGS) over the use of InSAR in their rapid response source models and "shakemap" predictions of strong ground motions.

Tungurahua. Credit: S. Ebmeier



Soufriere Hills, Montserrat. Credit: BGS



Montserrat. Credit: BGS



Montserrat. Credit: BGS

Tungurahua summit. Credit: S. Ebmeier



Montserrat. Credit: BGS





THE DIRECT, LONG-TERM FUNDING THAT COMET RECEIVES FROM NERC UNDERPINS A MUCH BROADER SPECTRUM OF RESEARCH ACTIVITIES, FUNDED THROUGH OTHER SOURCES. THE MAJOR PROJECTS IN WHICH COMET IS A PARTNER ARE DESCRIBED IN THE NEXT SECTION, BUT IN 2014 COMET SCIENTISTS WERE SUCCESSFUL IN WINNING A NUMBER OF OTHER AWARDS, INCLUDING A STANDARD GRANT, TWO URGENCY AWARDS, AND IMPACT ACCELERATOR FUNDING FROM NERC, AS WELL AS A GRANT FROM ESA TO HELP DEVELOP A GEOSYNCHRONOUS INSAR MISSION.

**Rapid deployment of onshore/offshore seismic stations in the North Chile seismic gap following the April 2014 magnitude 8.2**

**Pisagua earthquake** (Principal Investigator Isabelle Ryder, University of Liverpool, NERC Urgency £52k).

This project was aimed at understanding sub-surface processes in the North Chile seismic gap, as well as helping to identify areas of the subduction zone that have not yet slipped and could therefore rupture in future.

Until March 2014, there had been no major events in the North Chile seismic gap since the 1877 magnitude 8.8 earthquake. In late March 2014, however, there were several small to moderate earthquakes followed by one of magnitude 8.2 (April 2014) along with several aftershocks, including one of magnitude 7.6. There was also the possibility of another large event in the short- to medium term.

Urgency funding was used to install seismometers in the Peruvian coastal region as well as offshore Chile. These extra networks have dramatically improved data coverage around the seismic gap, enabling us to generate detailed models of the subduction zone, which will be of great benefit for future studies of seismic activity in this earthquake-prone area.

Records of ongoing seismic activity will also help to locate aftershocks, identify different types of faulting, and build a detailed picture of how post-earthquake processes relate to earlier events.

Finally, satellite images will show how the surface of the Earth has moved as a result of the recent seismic activity. These will also be used in computer models to estimate the location and magnitude of slip on faults beneath the surface.

**The source and longevity of sulphur in an Icelandic flood basalt eruption plume**

(Principal Investigator Evgenia Ilyinskaia [now at Leeds]; Co-Investigators including Marie Edmonds, Clive Oppenheimer and Tamsin Mather, NERC Urgency £51k).

The ongoing volcanic eruption at Holuhraun, which began in August 2014, presents a rare opportunity to study a flood basalt - a giant volcanic eruption that coats large stretches of land with basalt lava. These are one of the most hazardous volcanic events in Iceland, and have, in the past, had enormous consequences across the northern hemisphere.

The Holuhraun eruption reached flood basalt size around 20 October 2014,

becoming the largest flood basalt in Iceland since the Laki eruption in 1783-84 which killed more than 20% of the Icelandic population, and probably also increased European mortality.

The pollution from Holuhraun also reached “dangerous” level (as defined by the World Health Organisation) on 26 October 2014. Although sulphur dioxide emissions had reached 45 kilotonnes per day in mid-September, the levels of sulphur were much higher than those seen in other recent eruptions in Iceland and perhaps other basaltic eruptions across the globe. This raised questions over where the sulphur was coming from, but the lack of historic data limited confidence in the models used to forecast gas and aerosol concentrations.

Initial studies highlighted that, in some of the erupted materials, sulphur levels were around ten times higher than expected, and that there was a previously overlooked but potentially very large reservoir of sulphur which might help us to understand the extremely high sulphur levels from this eruption.

The team is now carrying out detailed measurements of the lavas and plume chemistry to understand the sulphur budget and to feed into models of plume chemistry and dispersion, which are essential for hazard monitoring.

**Defining models of glacial isostatic adjustment in West Antarctica and Antarctic Peninsula (UKANET): better constraints on Earth**

**structure and uplift** (Co-Investigator Andy Hooper, NERC Standard Grant, £726k)

This project aims to decrease uncertainties in measuring ice mass change in West Antarctica by developing a better understanding of the tectonics of the region. Ice loss from the West Antarctic Ice Sheet (WAIS) currently accounts for around 10% of present-day global sea level rise, and ice loss is accelerating. Accurately predicting changes to the WAIS is however difficult due to uncertainties in measurements of present day ice mass change.

Satellite gravimetry, which determines changes in Earth's gravity field due to surface mass redistribution, and altimetry, which measures changes in the height of the ice surface, can be used to assess how the ice is changing. Crucially, however, both techniques are themselves susceptible to errors introduced by correcting for the uplift of the solid Earth as a result of past ice mass loss, a process known as Glacial Isostatic Adjustment (GIA).

GIA models require information on regional deglaciation history as well as the properties of the solid Earth. Most GIA models only use one-dimensional global averages of Earth structure, but this is a gross oversimplification.

This project is therefore aiming to (i) determine 3D Earth structure in West Antarctica and the Antarctic Peninsula and

(ii) establish present-day uplift rates. It will use 10 broadband seismometers for two years, adjacent to a similar system, to estimate 3D variations in the Earth's structure.

Seismic data have never been collected in the southern Antarctic Peninsula region of West Antarctica before, and so very little is known about the structure of the Earth there. The project will also therefore improve our understanding of the tectonic evolution of the region, whilst long time series of surface deformation measurements will help our understanding of uplift rates due to GIA.

The seismic structure results from this project will be incorporated into a 3D GIA model, with the GIA and deformation results combined to more tightly constrain past and present ice mass change in the southern Antarctic Peninsula and West Antarctica.

**Other funding secured by COMET includes an ESA-funded project “Utilisation of future telecom satellites for Earth Observation” was completed in December 2014 (Principal Investigator Geoff Wadge, £21k). This involved a technical study of the capability of a geostationary radar mission, preparatory to the ESA Earth Explorer 9 programme entitled GeoSTARe (Geosynchronous SAR for Terrain and Atmosphere observation with high Revisit).**

**COMET scientist Alex Copley (University of Cambridge) is meanwhile Co-Investigator on a NERC impact acceleration award “Seismic evaluation in NW India” (£23k).**



## COLLABORATIONS AND PARTNERSHIPS

COMET continues to strengthen its scientific collaborations and links within the UK and overseas, with our staff working on a range of projects with national and international partners. These projects enhance our science programme not only through the additional funding but also data, ideas and, most importantly, people.

### EARTHQUAKES WITHOUT FRONTIERS (EWF)

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



### FUTUREVOLC

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



### STRENGTHENING RESILIENCE IN VOLCANIC AREAS (STREVA)

STREVA is an innovative interdisciplinary project aiming to develop and apply a practical and adaptable volcanic risk assessment framework. The results will be used to develop plans to reduce the negative consequences of volcanic activity on people and assets.

Led by the University of East Anglia, the project brings together researchers from universities and research institutes from across the UK with those from areas affected directly by volcanic activity.

### RIFTVOLC

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

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

### SPECTRALLY HIGH RESOLUTION INFRARED MEASUREMENTS FOR THE CHARACTERISATION OF VOLCANIC ASH (SHIVA)

SHIVA is studying the properties of volcanic ash using ground- and space-based high resolution infrared spectrometer measurements.

The project will look at changes in ash composition during an eruption in order to better understand volcanic processes, particularly shedding light on processes of magma ascent and fragmentation in volcanic eruptions.

### LOOKING INSIDE THE CONTINENTS FROM SPACE (LICS)

LiCS is using data from the Sentinel-1 constellation to revolutionize our knowledge of how continents deform, how strain accumulates during the earthquake cycle, and how seismic hazard is distributed.

The team is combining satellite data with ground-based observations to map tectonic strain at high spatial resolution throughout the Alpine-Himalayan Belt and East African Rift, and using the results to inform new models of seismic hazard.

The project has potential to deliver widespread benefits in many sectors, from geospatial services and government policy to the insurance/re-insurance industry and meteorological offices.



Sentinel-1 in orbit. Copyright ESA

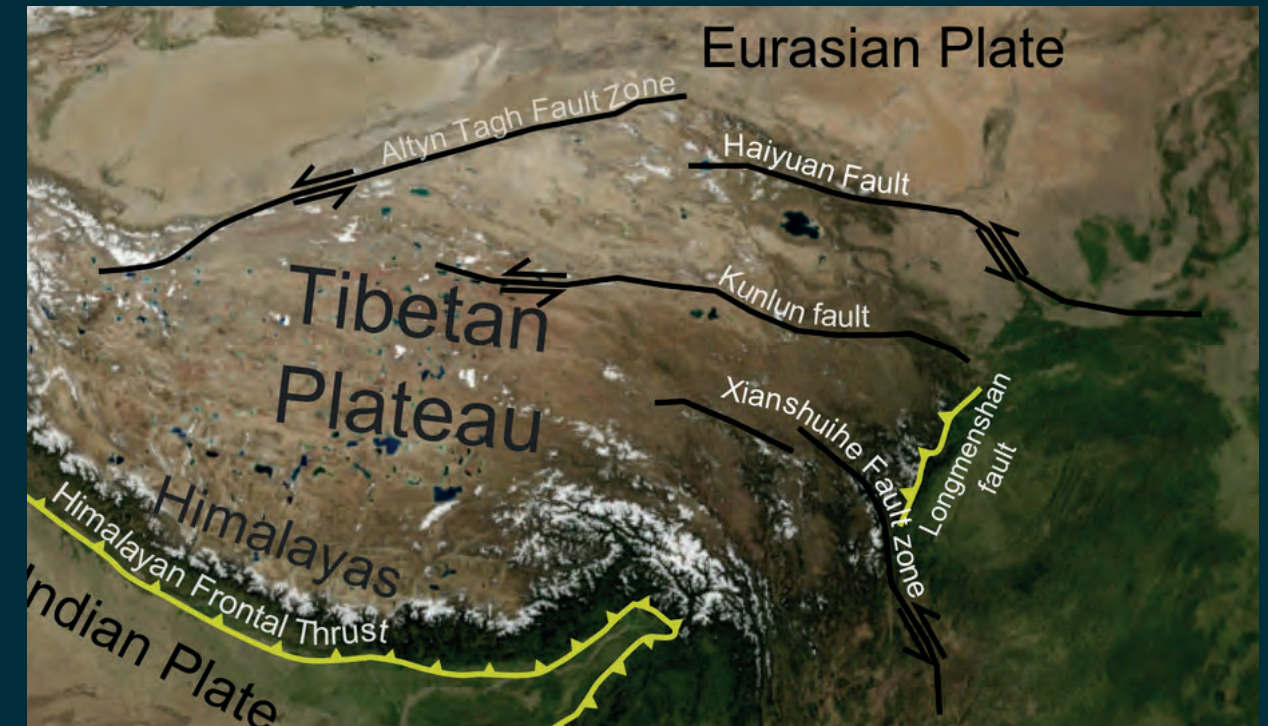


## POSTGRADUATE COMMUNITY

COMET SUPPORTS A VIBRANT COMMUNITY OF AROUND 50 RESEARCH STUDENTS, ALL OF WHOM ARE INTEGRAL TO OUR ACTIVITIES. AS WELL AS DEVELOPING THE NEXT GENERATION OF EARTH AND ENVIRONMENTAL SCIENTISTS, WE AIM TO EQUIP THEM WITH THE SKILLS THEY NEED TO DEVELOP SCIENTIFIC AND POLICY SOLUTIONS FOR TACKLING GLOBAL ENVIRONMENTAL CHALLENGES.



Izmit earthquake in northern Turkey



Altyn Tagh Fault Zone

The 2015 COMET student meeting was held in Oxford Earth Sciences in January, and was attended by around 50 COMET members. We heard excellent talks from 24 students on research ranging from technical aspects of InSAR through to terrain mapping of volcanoes using crowd sourced imagery.

**Ekbal Hussain and Austin Elliott** both received Outstanding Student Paper Awards for their poster contributions to the American Geophysical Union Fall 2014 Meeting.

Ekbal's poster explored *"The relationship between aseismic slip and postseismic creep"*. The focus of the work was to measure the post-earthquake ground movements following the 1999 Izmit earthquake in northern Turkey.

To do this, he analysed satellite radar data to produce maps showing the ground deformation rate over the region of the earthquake. This showed that between 2003 and 2010 a portion of the Izmit rupture has been undergoing steady sliding, known as fault creep, at an average rate of about 6mm/yr.

This steady sliding was found to be limited to the upper few kilometres (<5 km) of the crust. However, in the earthquake itself, the maximum fault movements were calculated to have occurred at a depth of 6-12 km. The results suggest that the shallow fault creep is releasing some of the strain (stored energy) in the shallow portions of the fault, but is not sufficient to release the total accumulated stress.

Austin's poster was meanwhile titled *"Slip rate gradients along parallel strands of the eastern Altyn Tagh fault confirm modeled rupture behavior at a transpressional bend"*.

It explained that through Aksay bend, the Altyn Tagh fault zone slip rate is uniformly  $6-7 \pm 2$  mm/yr, with nearly 9 out of 10 earthquake ruptures halted by the restraining bend itself. Conversely, one in 10 overcomes the barrier and continues to grow in magnitude.

Austin also found that ground observations closely matched his model results, validating model physics and supporting the use of joint modelling-observational studies to constrain the proportion of earthquake ruptures that successfully navigate a geometric barrier.

Cambridge students **Andy Howell**, **Camilla Penney** and **Kirsty Reynolds** attended an [International Centre for Theoretical Physics \(ICTP\)](#) workshop on earthquake hazard in Iran, where they not only heard about the latest developments but also had the opportunity to share their own knowledge and experience to benefit others.

The [International Conference and School on Structure, Tectonics and Earthquakes in the Alborz-Zagros-Makran Region](#) was specifically designed to benefit scientists in countries that are vulnerable to earthquake hazards, but who currently lack the infrastructure, expertise, national capability or critical mass to be effective.

The students, along with more senior members of COMET, contributed to training activities under the general framework of international cooperation in areas such as continental tectonics, monitoring and observing earthquake hazards, understanding tsunamis and landslides, and modelling continental deformation and the earthquake cycle.



## AWARDS AND RECOGNITION

### COMET'S ACHIEVEMENTS WERE RECOGNISED IN SEVERAL WAYS DURING 2014/15:

**JULIET BIGGS** and co-authors won the 2014 Lloyds Science of Risk Prize for their paper Global link between deformation and volcanic eruption quantified by satellite imagery, which appeared in Nature Communications. The paper demonstrates the statistical link between volcanic eruptions and satellite measurements of deformation, shows how InSAR can be used for volcano monitoring, and highlights its potential for hazard assessment in inaccessible areas.

COMET Director **TIM WRIGHT** received the American Geophysical Union's 2014 Geodesy Section Award, presented annually to an early or mid-career scientist in recognition of major advances in geodesy.

**RICHARD WALTERS** was awarded the Royal Astronomical Society's Keith Runcorn Prize (best thesis in geophysics and planetary science) for his thesis 'Geodetic observation and modelling of continental deformation in Iran and Turkey'.

**EKBAL HUSSAIN** and **AUSTIN ELLIOTT** received Outstanding Student Paper Awards for their contributions to the American Geophysical Union Fall 2014 Meeting.

The Geological Society awarded the Murchison Medal to **GEOFF WADGE** for his significant contribution to the science by means of a substantial body of research and for contributions to 'hard rock' studies.

**JAMES JACKSON** received the Wollaston medal – the highest award given by the Geological Society, for geologists who have had a significant influence by means of a substantial body of excellent research in pure or applied aspects of the science.



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

We work closely with the national and international media to get our messages across. Highlights include John Elliott's news story on the Napa Valley earthquake on the BBC website (September 2014); Clive Oppenheimer and Marie Edmonds' article And now, the volcano forecast for Phys.Org (October 2014), describing how the ability to monitor volcanoes has dramatically improved in recent years; Tamsin Mather and David Pyle were interviewed for BBC Radio 4's Costing the Earth episode Lava: A dangerous game (March 2014).

In July 2014, COMET, along with the STREVA project, contributed to UK Universities Week by bringing a 3m tall working replica of Soufrière St. Vincent volcano, the [London Volcano](http://londonvolcano.com/), to the Natural History Museum. The exhibit and activities showed schoolchildren and other visitors how volcanoes work, why we care about them, and what we can do to prepare for the hazard.

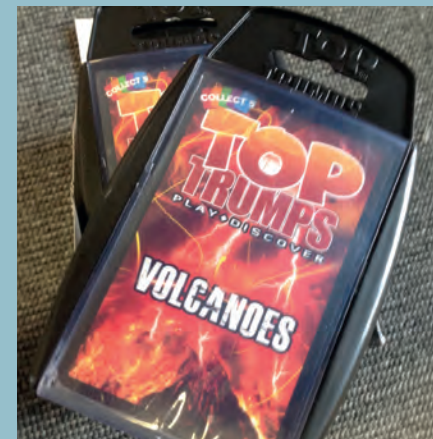


London Volcano <http://londonvolcano.com/>

## COMMUNICATION AND ENGAGEMENT

Over 2000 school children visited the exhibit, which had more than 15,000 visitors in total. There were also 8000 page views on the website.

Accompanying the London Volcano was a game of [Volcano Top Trumps](#), aimed at educating children about the devastating trail of destruction created by past eruptions and the potential havoc that might be caused by future ones. More than a thousand packs have been sold to date.



COMET scientist and deputy director Tamsin Mather was also featured in the book [Volcanologist – Ignite: The Coolest Jobs on the Planet](#) (Hugh Tuffen and Melanie Waldron, Raintree, 2014). The book aims to help schoolchildren to find out what's involved in becoming a volcanologist, what inspired today's scientists to follow their career paths, the equipment and skills used and the challenges of conducting research and experiments in the shadow of erupting volcanoes.

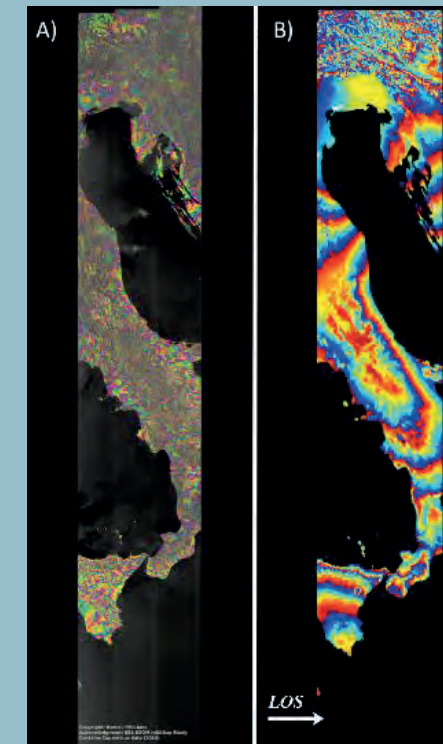
Blog posts are a great way of making our science accessible. COMET student David Bekaert blogged about his [tropospheric correction for Sentinel-1a](#), providing technical detail on how weather models can be used to estimate the scale of atmospheric delays in Sentinel-1a satellite radar data.

Alex Copley meanwhile contributed to the UN Office for Disaster Risk Reduction's blog with his post on [understanding earthquakes and mitigating risks](#), which focused on understanding the hazard posed by the active fault-lines within the Earth's crust that produce earthquakes when they rupture.

And Tamsin Mather wrote a guest post for the [London Volcano blog on volcanic lightning during the 1902 eruption of St. Vincent](#), highlighting the importance of the electrification of volcanic plumes in alerting scientists to eruptions at remote volcanoes. In February 2015, Tim Wright gave an open lecture, When Continents Collide: Active Deformation and Seismic Hazard, at the Geological Society. The talk described how we can use the latest satellites to make extraordinarily accurate measurements of continental deformation, how we can use this information to understand where damaging earthquakes are likely to occur, and how the results can be used to reduce the devastating impacts of earthquakes. The talk, aimed at a general audience, was streamed live and is [available to view online](#).

COMET researchers have spoken at Royal Astronomical Society Open Meetings, where members of the public can listen to leading scientists talk about their work. The November 2014 meeting included a presentation by Richard Walters (recipient of the Keith Runcorn Thesis Prize) on continental deformation and seismic hazard across the Middle East from a satellite perspective.

We also reach a wide audience through our [new website](#), via twitter (@NERC\_COMET) and by issuing press releases on topics such as the [Napa Valley earthquake](#) and [Bárðarbunga eruption](#). **Annex 2 contains a list of media highlights. (see page 43).**



Sentinel 1a Interferogram over Italy. Credit NORUT and PPO.labs as part of ESA InSARAP using Copernicus data. B) Estimated tropospheric correction using the 75 km ERA-1 weather model product, courtesy of D. Bekaert.



**THE NEXT YEAR IS CRITICAL FOR COMET'S PLANS TO DELIVER HIGH-IMPACT NATIONAL CAPABILITY SCIENCE. COMET STAFF AND SCIENTISTS ARE GEARING UP TO HANDLE THE VAST VOLUMES OF RADAR DATA FROM SENTINEL-1A, AND PLAN TO LAUNCH A PROTO-TYPE SYSTEM FOR AUTOMATIC INTERFEROGRAM GENERATION BY APRIL 2016.**

A proto-type service for monitoring volcanic SO<sub>2</sub> using IASI data has already gone live (9 June 2015), and further work is underway improving this system, including adding volcanic ash retrievals. We also aim to build on our international partnerships and collaborations to maximise the impact of COMET activities. And we will continue to provide expertise and advice in response to events, such as the Nepal Earthquake, as they occur.

## **SPECIFIC GOALS FOR THE NEXT YEAR (APRIL 2015 – MARCH 2016) INCLUDE:**

- Launch an automated InSAR system for tectonic and volcanic regions using data from Sentinel-1.
- Launch a volcanic SO<sub>2</sub> monitoring system using data from IASI. Upgrade the system in response to user feedback and add a volcanic ash retrieval.
- Build and launch an online global volcano deformation database. The aim is to provide a summary of past deformation and, ultimately, quick look Sentinel-1 images for scientists and decision makers in volcano observatories.
- Complete the development of volcano deformation inversion software, including a module for the generation of pressure/volume change time series, and release a trial version to the community.
- Continue respond to events as they occur, in collaboration with local partners, and develop a response protocol in collaboration with BGS.
- Evaluate COMET's response to the Gorkha (Nepal) Earthquake, 25 April 2015.
- Continue to work with ESA to evolve the acquisition schedule for Sentinel-1, particularly in response to the launch of 1B in early 2016.
- Develop collaboration with the Global Earthquake Model on the incorporation of InSAR derived velocities in the global strain rate model.
- Begin to build a formal COMET database of active faulting in the Alpine-Himalayan belt, beginning with Central Asia.
- Work with the USGS on incorporating COMET geodetic results from Sentinel-1 in their rapid source modelling and 'shakemap' estimates of strong motion.
- Employ a PDRA at UCL to continue work on joint GNSS-Seismic instrumentation.
- Continue to develop the content and style of the COMET website.



BGS	British Geological Survey
CEDA	Centre for Environmental Data Archival
CEMS	Climate, Environment and Monitoring from Space
CEOS	Committee on Earth Observation Satellites
COMET	Centre for the Observation and Modelling of Earth quakes, Volcanoes and Tectonics
EO	Earth Observation
ESA	European Space Agency
EwF	Earthquakes without Frontiers
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IASI	Infrared Atmospheric Sounding Interferometer
InSAR	Synthetic Aperture Radar Interferometry
LiCS	Looking inside the Continents from Space
Mw	Moment magnitude
NCEO	National Centre for Earth Observation
NERC	Natural Environment Research Council
NGO	Non-Governmental Organisations
SAR	Synthetic Aperture Radar
SHIVA	Spectrally High resolution Infrared measurements for the characterisation of Volcanic Ash
STREVA	Strengthening Resilience in Volcanic Areas
USGS	US Geological Survey

# ANNEX 1 – COMET PUBLICATIONS JANUARY – DECEMBER 2014

**Biggs, J., Ebmeier, S.K.,** Aspinall, W.H., Lu, Z., Pritchard, M.E., Sparks, R.S.J., **Mather, T.A.** (2014) *Global link between deformation and volcanic eruption quantified by satellite imager*, Nature Communications. doi:10.1038/ncomms4471

Caricchi L., **Biggs J.**, Annen C., **Ebmeier S.K.** (2014) *The influence of cooling, crystallisation and re-melting on the interpretation of geodetic signals in volcanic systems*, Earth and Planetary Science Letters. doi:10.1016/j.epsl.2013.12.002

Cashman, K., **Biggs, J.** (2014) *Common processes at unique volcanoes—a volcanological conundrum*, Frontiers in Earth Science. doi:10.3389/feart.2014.00028

Champenois, J., Pinel, V., Baize, S., Audin, L., Jomard, H., **Hooper, A.**, Alvarado, A., Yepes, H. (2014) *Large-scale inflation of Tungurahua volcano (Ecuador) revealed by Persistent Scatterers SAR interferometry*, Geophysical Research Letters. doi/10.1002/2014GL060956/epdf

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**Copley, A.**, Faridi, M., Ghorashi, M., Hollingsworth, J., **Jackson, J.**, Nazari, H., Oveisi, B., Talebian, M. (2014) *The 2012 August 11 Ahar earthquakes: consequences for tectonics and earthquake hazard in the Turkish-Iranian Plateau*, Geophysical Journal International. doi:10.1093/gji/ggt379

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**Craig, T.J., Copley, A., Jackson, J.** (2014) *A reassessment of outer-rise seismicity and its implications for the mechanics of oceanic lithosphere*, Geophysical Journal International. doi: 10.1093/gji/gguo13

**Craig, T.J., Copley, A., Middleton, T.A.** (2014) *Constraining fault friction in oceanic lithosphere using the dip angles of newly-formed faults at outer rises*. Earth and Planetary Science Letters. doi:10.1016/j.epsl.2014.02.024





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**Ebmeier, S. K., Biggs, J.**, Muller, C., & Avarð, G. (2014) *Thin-skinned mass-wasting responsible for widespread deformation at Arenal volcano*, *Frontiers in Earth Science*. doi:10.3389/feart.2014.00035

**Ebmeier, S.K.**, Sayer, A.M., **Grainger, R.G., Mather, T.A., Carboni, E.** (2014) *Systematic satellite observations of the impact of aerosols from passive volcanic degassing on local cloud properties*, *Atmospheric Chemistry and Physics*. doi:10.5194/acp-14-10601-2014

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**McCormick, B.**, Herzog, M., Yang, J., **Edmonds, M., Mather, T.A.**, Carn, S., Hidalgo, S., Langmann, B. (2014) *A comparison of satellite- and ground-based measurements of SO<sub>2</sub> emissions from Tungurahua volcano, Ecuador*, *Journal of Geophysical Research: Atmospheres*. doi:10.1002/2013JD019771

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Wang, H., **Elliott, J.R., Craig, T.J., Wright, T.J.**, Liu-Zeng, J., **Hooper, A.** (2014) *Normal faulting sequence in the Pumqu-Xainza Rift constrained by InSAR and teleseismic body-wave seismology*, *Geochemistry, Geophysics, Geosystems*. doi: 10.1002/2014GC005369

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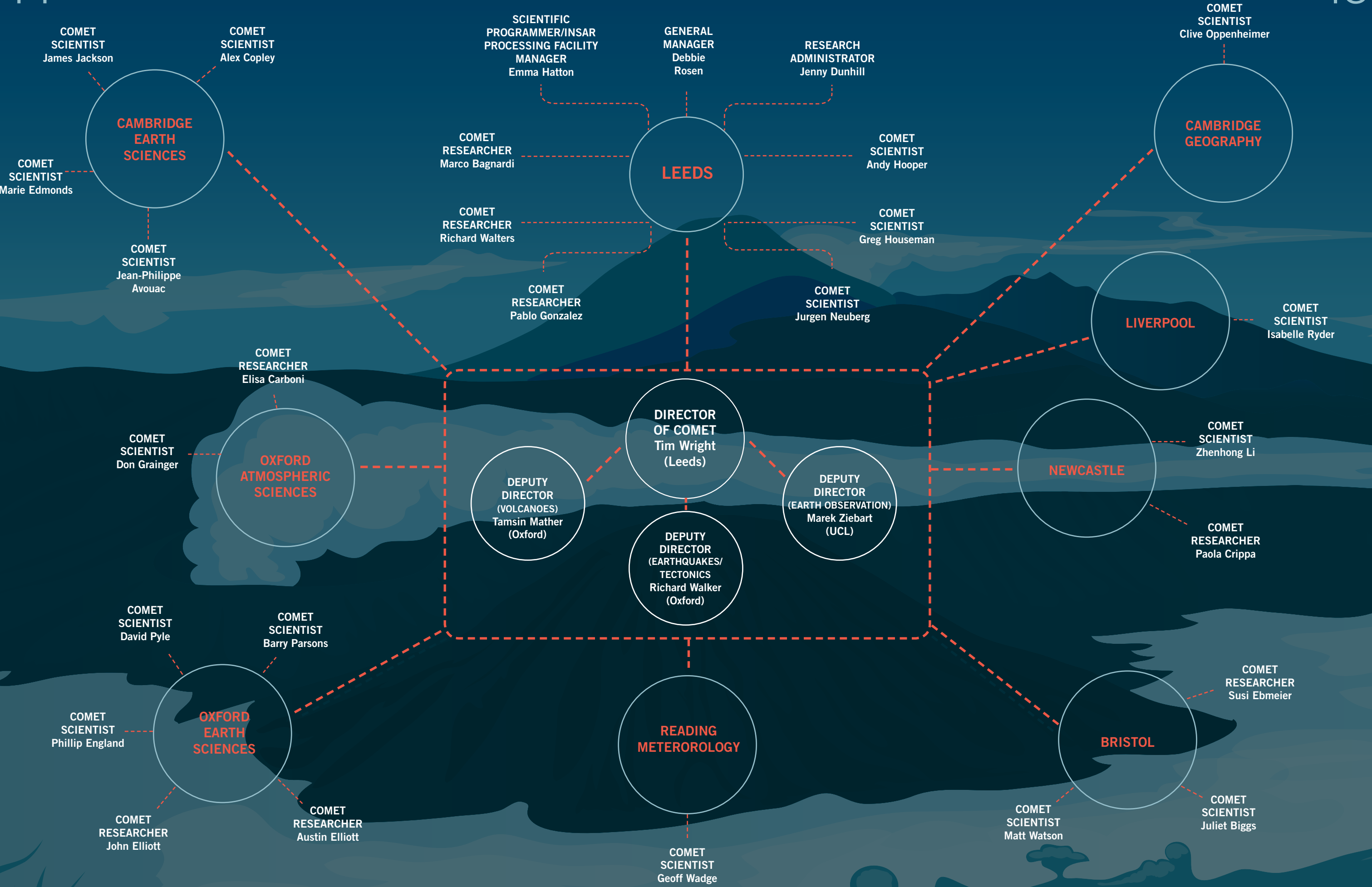
# ANNEX 2 – SELECTED COMET MEDIA ENGAGEMENT AND COVERAGE

## APRIL 2014 – MARCH 2015

Story	When	Who	Appears In
<a href="#">The psychedelic image from space that reveals just how big the Napa earthquake really was</a>	September 2014	Tim Wright	Daily Mail online
<a href="#">Sentinel system pictures Napa quake</a>	September 2014	John Elliott	BBC Science Focus Magazine
<a href="#">ESA's new satellite can map earthquakes from space</a>	September 2014	Andy Hooper	Irish Examiner
<a href="#">Sentinel system pictures Napa quake</a>	September 2014	John Elliott	Australian Times
<a href="#">Fascinating radar images of an earthquake</a>	September 2014	Tim Wright	Videnskab DK
<a href="#">And now, the volcano forecast</a>	October 2014	Marie Edmonds/ Clive Oppenheimer	Phys. Org. website
<a href="#">Silent earthquakes point the way to earthquake prediction</a>	November 2014	Pablo Jose Gonzalez Mendez/ TJW/AH	El Pais
<a href="#">Europe's mission to Earth</a>	November 2014	Tim Wright	American Aerospace Magazine
<a href="#">Why Icelandic volcano threat remains</a>	November 2014	Tim Wright	CNN online
<a href="#">Fogo volcano on Sentinel's radar</a>	December 2014	Tim Wright	ESA website
<a href="#">Motion capture</a>	December 2014	Tim Wright	Room Space Journal online
<a href="#">Sentinel radar satellite tracks continued Napa slip after quake</a>	December 2014	Tim Wright	BBC website
<a href="#">Earth grew new layer under Iceland volcano</a>	December 2014	Andy Hooper/Karsten Spaans	Times of India
<a href="#">Earth grew layer under Iceland volcano</a>	December 2014	Andy Hooper/Karsten Spaans	Yahoo India
<a href="#">How a satellite is transforming earthquake monitoring</a>	February 2015	John Elliott/Austin Elliott/Tim Wright/Andy Hooper	io9
<a href="#">Lava: A dangerous game</a>	March 2015	Tamsin Mather/David Pyle	BBC Radio 4's Costing the Earth









# COMET

## ANNUAL REPORT

# 2014/15

If you need further information or have a more general enquiry please email [comet@leeds.ac.uk](mailto:comet@leeds.ac.uk), or tweet us at @NERC\_COMET.

