COMET

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

ANNUAL REPORT
2021/2022

British Geological Survey

UKRI Natural Environment Research Council

Cumbre Vieja, La Palma, Credit: Ben Esse, University of Manchester.

CONTENTS

INTRODUCTION

The Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) delivers cutting-edge science in Earth Observation (EO), Tectonics and Volcanism. Through the integrated application and development of EO data, ground-based measurements, and geophysical models, COMET studies earthquakes and volcanoes and the hazards they pose. The services, facilities, data and long-term underpinning research in EO science and geohazards that we produce benefit the wider community of environmental scientists while helping the UK and other countries to prepare for, and respond rapidly to, earthquakes and eruptions.

A national-scale community with considerable size and impact, COMET brings together leading scientists across the British Geological Survey (BGS) and 9 UK universities: Bristol, Cambridge, Durham, Leeds, Liverpool, Manchester, Newcastle, Oxford, and University College London (UCL) along with links to a further 10 institutions through our associate scientists. We provide scientific leadership in EO, while also bringing together a vibrant community of postgraduate students and early career researchers.

COMET was founded in 2002, rapidly establishing itself as a leading centre for the integrated exploitation of EO, ground-based data, and geophysical models for research into geohazards. In 2018, COMET was awarded the Royal Astronomical Society's group achievement award in recognition of its unique and long-term contributions.

Since 2014, recognising shared strategic agendas, science drivers, and the benefits of increased collaboration, COMET has been progressively building a strategic partnership with the BGS. We also work closely with the Natural Environment Research Council (NERC), National Centre for Earth Observation (NCEO) and European Space Agency (ESA), as well as many other national and international partners. Our work with business, Government and space agencies helps to ensure that the UK continues to invest in and benefit from satellite missions.

This report gives an overview of COMET's activities during the first year of our new 5-year programme of work. Following a 2-year transition, COMET is now delivered in partnership with BGS and managed as part of the BGS medium-term business cycle. The report highlights major scientific achievements as well as progress against our key objectives covering the period 1st April 2021 – 31st March 2022.

DIRECTOR'S WELCOME

Welcome to COMET's eighth annual report and the first of our new five-year programme of work with BGS. This year, we were able to return to in-person interactions, and a particular highlight was our first "real-world" Annual Science Meeting (ASM) since the pandemic in Castleton, Derbyshire. This meeting provided an opportunity to meet and collaborate with many new colleagues across the entire COMET community, and to focus on our scientific achievements, priorities, and plans. The meeting also marked our first hybrid ASM and an opportunity to meet our new international advisory board members for the first time. In addition to our usual scientific program, we were able to participate in interactive sessions on event response (led by our partners BGS), and on EDI (led by our active EDI working group), and to join a geological tour of the area.

In Year 1 of the 2021-2026 programme, COMET has a new set of scientific objectives that were jointly developed with BGS and are aligned with BGS's strategic priority of "Multihazards and Risk" to deliver national-level science in the observation and modelling of geohazards. Our EO Data and Services work has included the continued growth of the COMET-LiCSAR Sentinel-1 InSAR processing facility, with more than 730,000 interferograms processed, an increase of 70% during the last year alone. We have also developed the LiCSAlert system to automatically detect signs of volcanic unrest in time series of Sentinel-1 interferograms created by the COMET LiCSAR system. COMET and GEM scientists have established a collaboration, funded by NERC, with the aim of improving probabilistic seismic hazard and risk assessment in Central Asia. Under our volcanic hazard theme, volcanic emissions retrieval methods have been tested on case studies of the eruptions of Raikoke (June 2019), La Soufrière St Vincent (April 2021), and Hunga Tonga-Hunga Ha'apai (January 2022) with promising results. COMET scientists were also involved in a NERC-funded urgency project focused on the response to the volcanic eruption at Soufrière, St Vincent in 2020-2021. In addition to our core programme of work, our scientists continue to lead and contribute to a wide range of aligned projects and programmes.

The COMET community continues to grow. This year, we have welcomed two new postdoctoral research fellows. Yannick Caniven joins COMET from the Earthquake Mechanics group at the University of Oxford, focusing on numerical modelling of slow-to-fast earthquakes. Camila Novoa Lizama is a research fellow in deformation modelling working on the DEEPVOLC project at the University of Leeds, using InSAR and numerical modelling to understand the physical processes operating on volcanoes around the world. We also welcome our new COMET Associate Members, Lidong Bie from the University of East Anglia and Craig Magee from the University of Leeds. You can find a list of all our members and associates at the end of this report.

Every year, I am reminded of the scientific excellence represented within COMET through the awards listed in this report, and I would like to congratulate all of our award winners this year on their successes both nationally and internationally. Their achievements are described later in this document. They include a BGS research prize for Ekbal Hussain and outstanding student presentation awards for Alice Turner (AGU), JD Dianala and Rebecca Colquhoun (Seismological Society of America). Tim Craig was named as an EGU Outstanding Early Career Scientist. Tamsin Mather and Marie Edmonds received prestigious honorary titles of Geochemistry Fellows from the Geochemical Society and the European Association of Geochemistry, and Gregory Houseman was honoured with a Fellowship of the Royal Society for his exceptional contribution to science.

Professor Tim Wright
COMET Director

ADVISORY BOARD COMMENTS 2021

COMET Objectives and Scientific Programme

COMET continues to have as its primary goal, delivery of national capability in the observation and modelling of geohazards, including work with the wider scientific community and delivering national public good. In this regard, LiCSAR processing has stabilised and matured with time. The web-based data portals and visualisation tools are excellent. Given this progress, we recommend that COMET think about ways to expand their user base. One example would be to hold regular training sessions on different tools and data types.

The Advisory Board was impressed with the compilation of long-term datasets (SO_2, LiCSAR) that now allow COMET scientists to undertake the next level of analysis and integration, such as maps of crustal strain accumulation and strain rate coming out of GNSS and InSAR data from the Tibetan Plateau and, more broadly, the Alpine-Himalayan Belt. These data place COMET ahead of the curve with regard to wide-scale strain rate mapping and translation to formal hazard estimates. Similarly, the LiCSAlert system for volcanoes is impressive and a similar user-friendly system developed for tectonic applications would be of interest.

Given the rapid advances in data acquisition, we encourage COMET researchers to continue to improve links between EO, development of physics-based models and improvement in overall process-based understanding of volcanic and tectonic systems. COMET is in a particularly good position to integrate different data sets with the goal of addressing specific processes, for example, improved integration of EO with ongoing advances in subsurface volcano science. The Advisory Board also sees exciting opportunities in the development and application of machine learning, applying deep learning methods to the ever-increasing COMET data sets.

Annual Science Meeting

This year's meeting was the second in a row to be conducted remotely. As such, it did a good job of capitalizing on lessons learned from last year's meeting and on the past years' experience with remote platforms and capabilities. An innovation this year was the use of the Gather Town platform. This platform appears to provide an interesting option for helping to maintain the COMET community and to aid transition to sustainable interactions over the long term and may thus serve as a model to other scientific communities worldwide.

As always, the science was presented by a wide range of COMET members, including numerous postdoctoral scientists and postgraduate students, and was both of high quality and nicely delivered via science talks and virtual posters. That said, we encourage COMET to continue to rotate and broaden the oral presentation slots to ensure balance among postdoctoral scientists and more senior scientists. The keynote speakers covered an impressive range of EO and hazard science research. We particularly liked the emphasis on recent events, including hazard response and disaster management, and recommend that online keynote talks remain a feature of future COMET meetings.

Advisory Board Members 2021

Ramon Arrowsmith (Arizona State University)

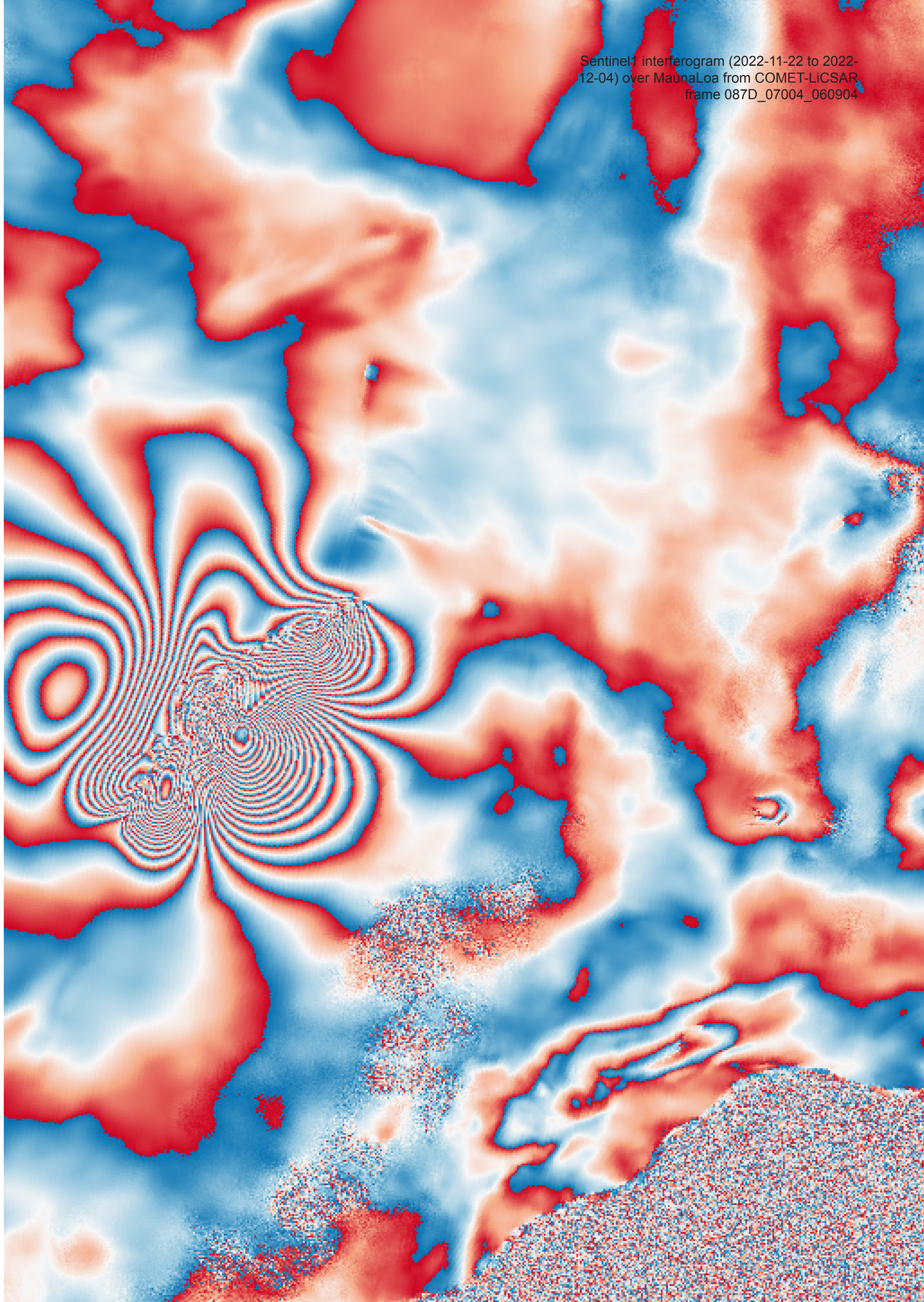
Roland Bürgmann (University of California, Berkeley)

Elisa Carboni (RAL Space-NCEO)

Katharine Cashman (University of Bristol)

Valérie Cayol (University Clermont-Auvergne)

Philippa Mason (Imperial College London)



Sentinel-1 interferogram (2022-11-22 to 2022-12-04) over MaunaLoa from COMET-LiCSAR frame 087D_07004_060904

NEW STARTERS

COMET Postdoctoral Researcher: Yannick Caniven, University of Oxford

Yannick joins COMET through the Earthquake Mechanics group of Jessica Hawthorne at Oxford, focusing on numerical modelling of slow-to-fast earthquakes. After a PhD at the University of Montpellier (France) – earthquake cycle analog modelling, he occupied several post-doctoral positions at CNRS - field investigations and analog/numerical modelling - and at Rice University (Houston, USA) - numerical simulations of dynamic ruptures. His research interests focus on fault mechanics from long-term geological fault growth - damage and structural evolution - to seismic cycle time scales, specifically investigating slip processes from slow to fast earthquakes. Yannick also had an experience in the private sector with Fugro where he conducted seismic hazard assessment studies. Currently, he remains closely involved in several field-based research projects including geomorphological investigation of active tectonics systems and structural quantification of fault damage zones.

COMET Postdoctoral Researcher: Camila Novoa Lizama, Research Fellow in Deformation Modelling, DEEPVOLC project, University of Leeds

After studying some Chilean volcanoes during her PhD in France, Camila now works with InSAR and numerical modelling to understand the physical processes operating on volcanoes around the world. She has worked on how viscoelastic behaviour affects the transient surface displacements observed on volcanoes, as well as how elasto-plastic rheology can be used to infer possible fractures around the reservoir and their propagation to the surface to assess eruption occurrence. In her current work, she also incorporates poro-elastic rheology into models to make a better mechanical assessment of eruptive conditions in volcanoes and to fit InSAR observations.

COMET Associate: Dr Lidong Bie, University of East Anglia

Lidong is a lecturer in Geohazards at the University of East Anglia, in the School of Environmental Sciences. He joined COMET as an affiliated member. His research focuses on lithospheric deformation over various temporal and spatial scales using geodetic and seismological observations. He works with InSAR data to monitor ground deformation due to geohazard events and applies numerical modelling to understand the physical mechanisms underlying observed deformation. He is also interested in seismic tomographic imaging, particularly in subduction zones and continental faulting areas.

COMET Associate: Dr Craig Magee, University of Leeds

Craig is an igneous and structural geologist come geophysicist who specialises in understanding how magma moves and is stored in the crust. He particularly uses seismic reflection data to image ancient volcanoes and magma plumbing systems in 3D. By analysing host rock structures around imaged intrusions, Craig has built an interest in deciphering how magma intrusion translates into host deformation and, eventually, ground movement.

COMET OBJECTIVES

Our science activities have been jointly developed with the BGS and are aligned with BGS priorities in "Multi-hazards and resilience" as set out in their science strategy. We will continue to deliver national capability in the observation and modelling of geohazards, working with the wider scientific community and practitioners to maximise uptake of and impact from the results, as well as delivering national public good.

Our science objectives for 2021-2026 are:

EO data and services

1. Deformation from satellite geodesy

- Improve COMET-LiCSAR Sentinel-1 service
- Improve atmospheric correction services
- Extend the COMET-LiCSAR system to other satellites

2. Topography, deformation, and surface change analysis from high-resolution imagery

- Semi-automation of satellite-derived displacement maps of large ground deformation signals, and of topography and topographic change
- Utilize digital topographic data at global, regional, and local scales to aid the fieldwork activities of COMET members and the mapping of hazards at regional scale
- Derivation and analysis of high-resolution topographic datasets for seismic hazard in and around cities

3. Retrievals of volcanic emissions from satellite spectrometers

- Adapt fast linear retrieval of ash and SO_2 to process data from IASI-NG and IRS
- Extend existing SO_2 and ash time series and investigate retrievals for other volcanic species
- Automation of SO_2 flux time series retrievals

4. Geoinformatics and machine learning

- Improve the sharing of satellite data and time series through the development of an integrated and interactive COMET data portal
- Develop machine learning approaches and tools that can be applied to COMET satellite data sets

Tectonics and volcanism

1. Tectonics and seismic hazard

- Develop and deploy a geodetically-based earthquake hazard model in partnership with the Global Earthquake Model (GEM)
- Produce and deliver maps of active faults, incorporating new results regarding their rates of activity and past earthquakes
- Assess temporal variations in strain across distributed fault networks
- Build dynamic models that can explain lithosphere deformation across timescales

2. Magmatism and volcanic hazard

- Analyse long-term (decadal) patterns of volcanic activity globally
- Assess the contribution of volcanic SO_2 to global climate and aviation
- Develop and test the models needed for interpreting satellite data during volcanic crises

Our annual progress against these objectives is recorded in the 'Science Update' sections of the Annual Report.

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

InSAR-derived horizontal velocities in a global reference frame

Dr Milan Lazecky, COMET Scientific Programmer, University of Leeds
Professor Andy Hooper, COMET Scientist, University of Leeds

With the Copernicus Sentinel-1 Synthetic Aperture Radar (SAR) satellites, the geoscience community acquired a unique tool for making precise measurements of tectonic motion. The COMET LiCSAR system routinely generates Sentinel-1 differential interferograms over tectonic and volcanic areas, and carries out InSAR time series analyses to measure surface deformation in the satellite line-of-sight direction. The InSAR measurements can be used to derive vertical and horizontal motion components, but the line-of-sight sensitivity is very low for the N-S motion component, which is typically estimated using available GNSS data. It is possible to estimate along-track displacements, which are sensitive to N-S motions, by exploiting spectral diversity in the azimuth direction, although the precision is poor. However, the Terrain Observation with Progressive Scan (TOPS) acquisition mode of Sentinel-1, which is the standard mode over land, provides much greater spectral diversity in burst overlap regions, allowing estimation with a precision of around 1 mm within whole overlaps.

In this study, we explore how accurately we can measure the along-track velocities in a global reference frame, as the along-track measurements are with respect to reference satellite positions, localised within the Earth-centered Earth-fixed no-net-rotation framework of the ITRF2014. We estimate the velocities in relatively large blocks containing many burst overlaps, in order to observe large-scale tectonic motion and characterise some of the error sources, such as the solid-earth tides and ionosphere, based on external models.

In addition, we notice, report and correct systematic discrepancies in the azimuth shift values related to known change in orbital ephemerides in mid-2020 for both Sentinel-1 satellites, but we also find offsets between both Sentinel-1A and Sentinel-1B satellites that are still subject to further investigation. We confirm that the major mid-2020 change in precise orbit determination products improved precision of the azimuth shift estimates by 12% (or 4.3 mm in RMSE).

We demonstrate the possibility of recovering precise measurements of large-scale horizontal motion using azimuth shifts estimated from Sentinel-1 data, using average values in 250x250 km cells. The precision significantly improves after incorporating corrections for solid-earth tides and ionospheric propagation, especially at lower latitudes. By combining data from ascending and descending orbits we are able to estimate north and east velocities with average precision of 4 and 20 mm/year (2-sigma), respectively.

However, our corrections only remove a part of the non-deformation component. Our observations show an overall along-track motion trend for descending frames, of a higher velocity than expected by the ITRF2014 plate motion model. While northwards motion estimates provide a relatively good fit to the values predicted by the plate motion model, the eastwards component has a large bias. This is especially true after ionospheric correction, which increases the estimated eastward velocity component over most of the Alpine-Himalayan belt region by median of 13 mm/year.

Such measurements can also be made at much higher resolution, albeit with lower accuracy. These "absolute" measurements can be particularly useful for global velocity and strain rate estimation, where GNSS measurements are sparse.

References:

Preprint (in prep for GRL) available at: https://www.essoar.org/doi/10.1002/essoar.10511058.1

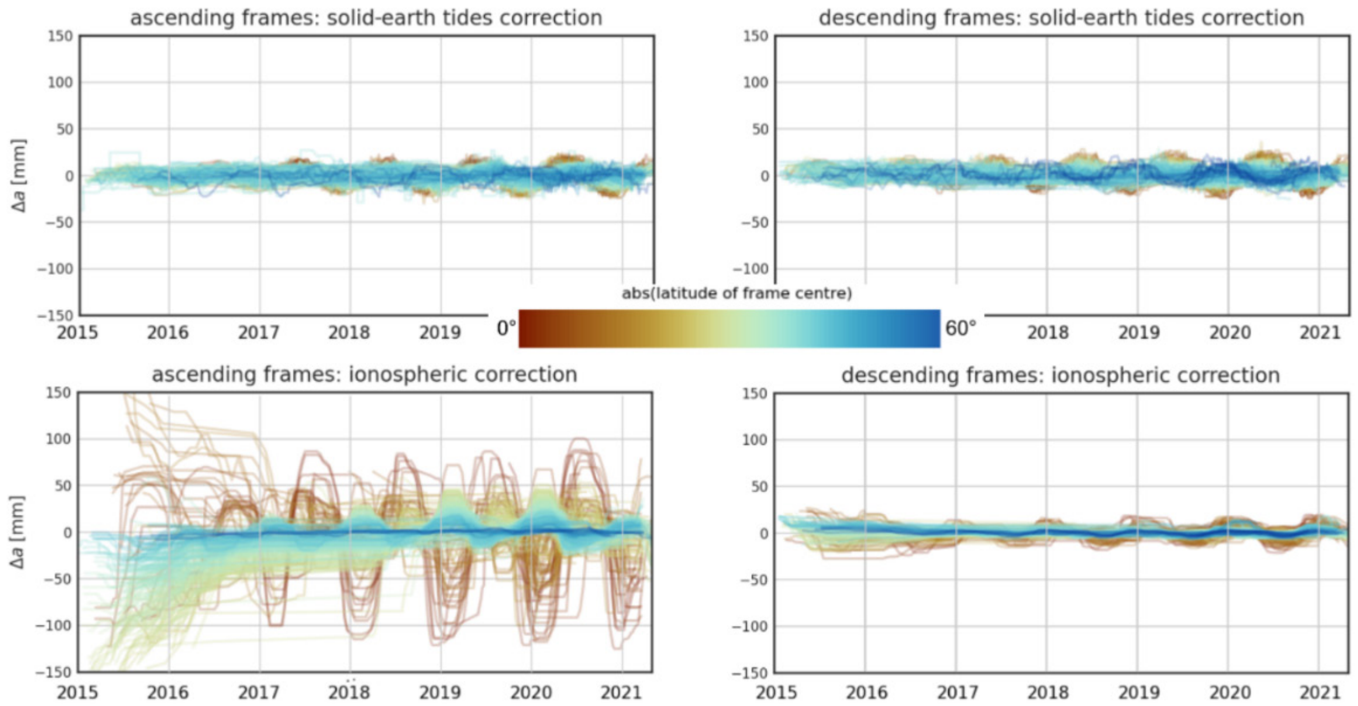


Figure 1. Magnitude of solid-earth tides and ionospheric corrections on time series of Δa values for, left, ascending and, right, descending frames; colour gradient is based on distance from the Equator.

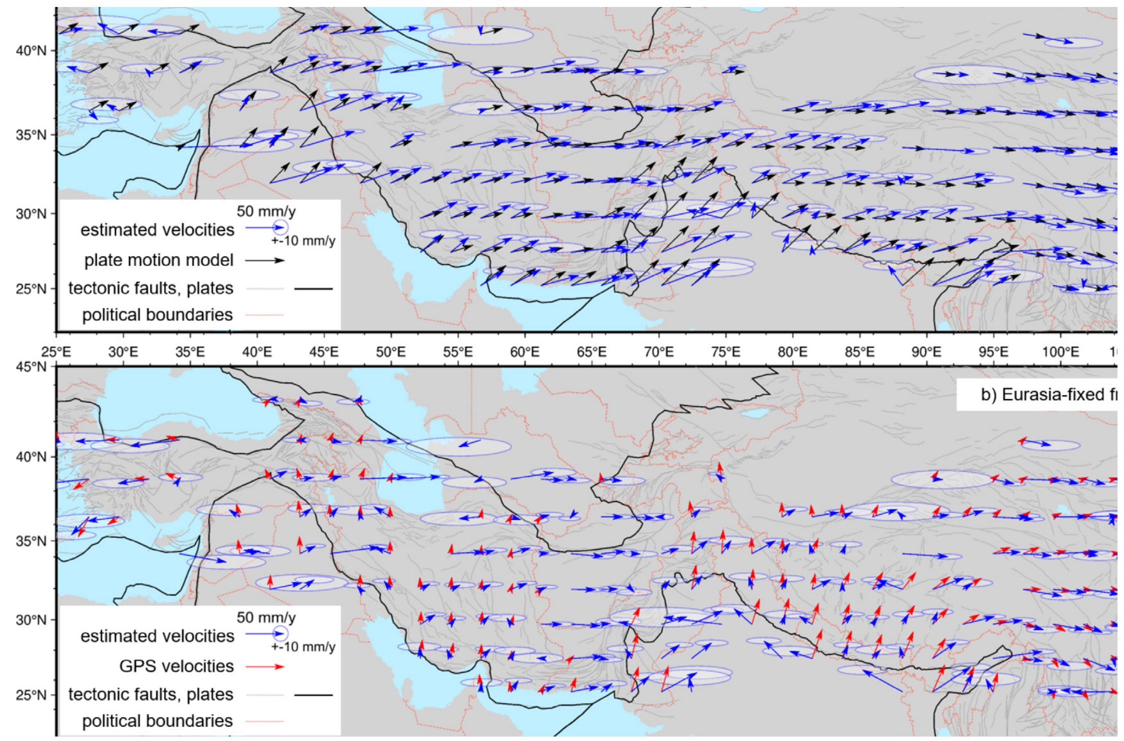


Figure 2. Comparison of our estimated velocity vectors over the Alpine-Himalayan belt subset, corrected for solid-earth tides and ionosphere, to a) the ITRF2014 plate motion model in no-net-rotation condition; and b) GPS velocities in Eurasia-fixed ITRF2014 reference frame. Error ellipses represent 2-σ (RMSE) in respective directions, neglecting their possible correlation. Figure includes global active faults and tectonic plate boundaries.

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

Multi-sensor city mapping for updating building exposure databases

Dr C. Scott Watson, COMET Research Fellow in Earth Observation and Geoinformatics, University of Leeds

The global trend of urbanisation concentrates exposure to disaster risk. One example is the city of Bishkek in Kyrgyzstan, which is exposed to high seismic risk due to its proximity and expansion towards active faults [1]. Horizontal and vertical urban growth can be monitored using a range of EO sensors, which contribute to seismic risk assessments considering a variety of rupture scenarios [2]. The increased availability of high-resolution stereo and tri-stereo satellite imagery allows 2D maps of urban growth to be enhanced with details of building structures and their heights, such that earthquake resistance, economic valuations, and population distribution are better represented in these risk assessments.

We evaluated the capabilities, limitations, and importance of 4D urbanisation assessments using Bishkek as a case study. We used satellite datasets spanning 1979-2021 including KeyHole-9 (Hexagon) (1979), Sentinel-2 (2016–2021), Pleiades (2013), WorldView-2 (2019), and ICESat-2. First, we quantified urban growth and redevelopment, such as the conversion of old residential blocks to new commerical developments, by comparing KeyHole-9 and Sentinel-2 imagery. Second, building footprints were extracted using a region-based convolutional neural network (Mask R-CNN) deep learning workflow applied to sub-metre resolution satellite imagery. Third, we derived high-resolution Digital Elevation Models (DEM) (e.g. Figure 1), which were used to assign building heights and were validated using ICESat-2 altimetry data.

Bishkek expanded approximately 139 km^2 (92%) between1979 and 2021, particularly towards active faults located south of the city, and by approximately 26% (59 km2) of Bishkek's built-up area classified in 1979 was observed to have been redeveloped by 2021. Rates of building growth were in the region of 2,000–10,700 per year and across all time periods our workflow extracted more than 700,000 building polygons. Although deep learning building extraction is more efficient than manual digitisation, issues exist regarding the underestimation of close or adjoining buildings, and the inclusion of unfinished buildings. Refining these methods is required to keep the datasets current in areas lacking national inventories, and where open access datasets such as OpenStreetMap are incomplete or out of date. We found that building heights derived from the tri-stereo Pleiades DEM were most comparable to independent measurements obtained using ICESat-2 altimetry data (normalised absolute median deviation = 0.7 m and mean absolute error = 1.9 m). Therefore, EO data offer a valuable opportunity to maintain city exposure datasets and facilitate dynamic seismic risk assessments.

The work was conducted in collaboration with John Elliott, Ruth Amey, and Kanatbek Abdrakhmatov.

References:

1. Elliott, J.R. Earth Observation for the Assessment of Earthquake Hazard, Risk and Disaster Management. Surveys in Geophysics 2020, 41, 1323-1354, doi:10.1007/s10712-020-09606-4.
2. Amey, R.M.J.; Elliott, J.R.; Hussain, E.; Walker, R.; Pagani, M.; Silva, V.; Abdrakhmatov, K.E.; Watson, C.S. Significant Seismic Risk Potential from Buried Faults Beneath Almaty City, Kazakhstan, revealed from high-resolution satellite DEMs. Earth and Space Science 2021, https://doi.org/10.1029/2021EA001664

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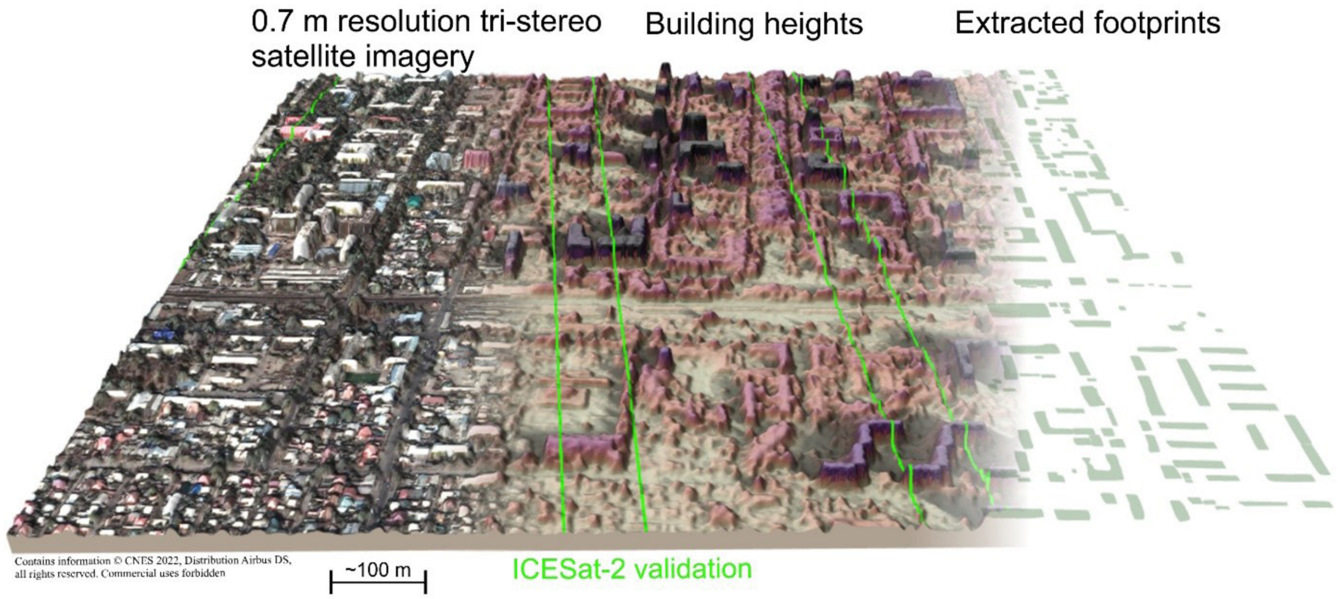


Figure 1. 3D visualisation of the high-resolution satellite imagery used to derive building footprints and heights, which were validated using ICESat-2 data.

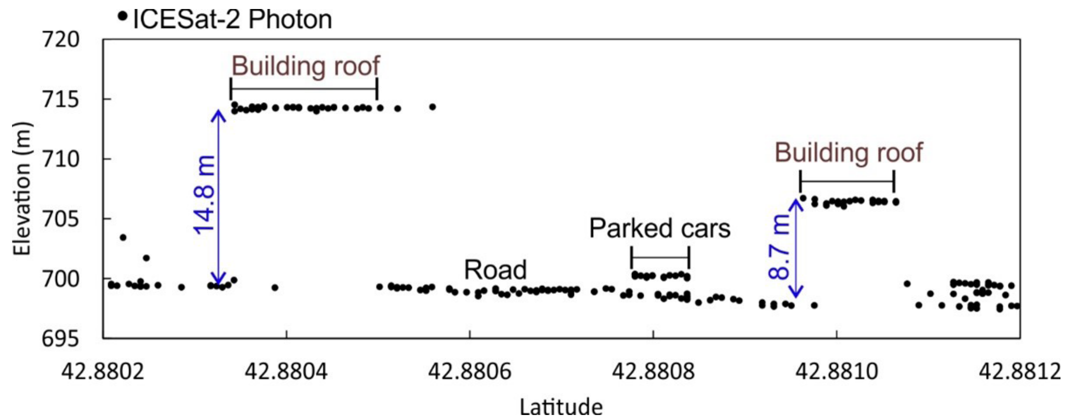


Figure 2. ICESat-2 photon returns from buildings and ground features in Bishkek.

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

Uncrewed Aerial System (UAS) based surveying

Dr Ian Pierce, COMET Postdoctoral Researcher, University of Oxford

As part of our ongoing research with collaborators at the Kyrgyzstan Institute of Seismology (KIS) in Bishkek, we have developed low-cost and easily deployable UAS systems equipped with onboard dGPS systems capable of surveying large areas (e.g. ten's of kilometers length). These systems reduce the need for labour intensive manually-surveyed ground control points (GCPs) during drone-surveys.

A differential GPS (dGPS) system uses two GPS receivers. One is stationary and averages its location over several hours (the 'base'), while the second moves and is used for measurements (the 'rover'). We purchased a pair of Emlid Reach RS2 GPS receivers that work together as a dGPS system. We use the DJI Phantom 4 Pro v2.0 system due to the widely available parts, batteries, and our experience with it. We equip the drone with a Teokit system by Vanvara Digital.

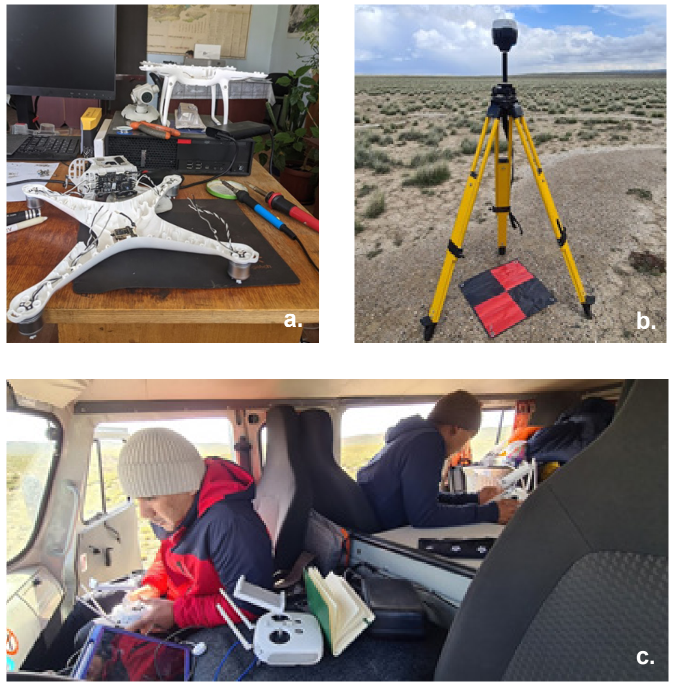


Figure 1. (a). Installing the Teokit chip and antenna into the new Phantom 4 (b) Emlid Reach RS2 setup as a base station over a GCP (c) Flying three Phantoms at once in our UAS mobile command station.

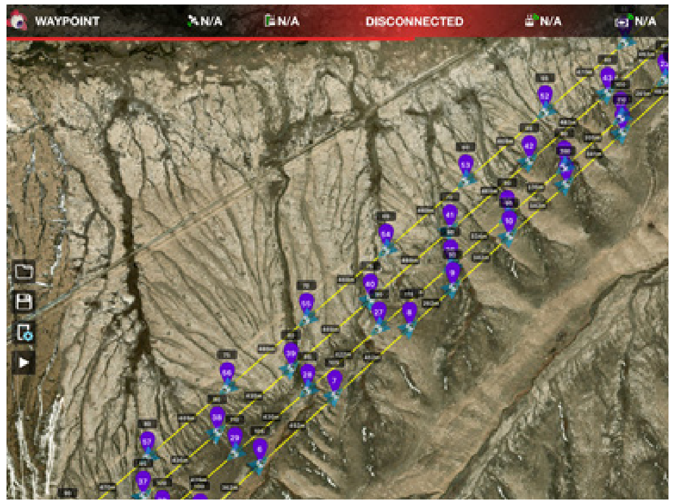


Figure 2. Screengrab from iPad showing the Litchi flight control app and a track planned using Teofly.

The teokit ('teodrone') works by logging the precise time a photo is taken and the full continuous GPS signal that is received by the GPS receiver on the drone. For a 20 minute flight this is about 25 Mb of data, in addition to several hundred photos. The GPS track is corrected in post processing (PPK, post processed kinematic) against the base station that was setup during the survey. The timestamps are used to extract GPS locations at the precise time each photo was taken. Finally this series of timestamped locations is matched to the photos that were taken, to provide highly accurate (<5 cm) photo locations. These corrected photos are then used in a SfM photogrammetry software to reconstruct the earth's surface.

In Kyrgyzstan, UAS flights were typically approximately 150-250 m altitude, at a velocity of approximately 7.5 m/s, collecting photos every two seconds. We used the Litchi iPad app to provide an autopilot for each drone, with flights planned using Teodrone's browser based Teofly flight planner. We used the base station as a single GCP, and did not survey any additional points. We typically flew two drones at a time and were able to collect approximately 5-10 km2 of images per day, depending on weather, road access, and topographic conditions. We used a gasoline generator to charge the drone batteries so we could fly nearly continuously (with 11 batteries).

A typical day's survey results in a SfM point cloud with several hundred million individual points. Finally, the resulting orthoimage resolutions are approximately 5-10 cm/pixel, and DEM resolutions are 10-20 cm. From the two months of work we conducted in summer 2021 we produced by approximately 420 Gb of photos alone, which will roughly double in file size when the SfM processing is finished.

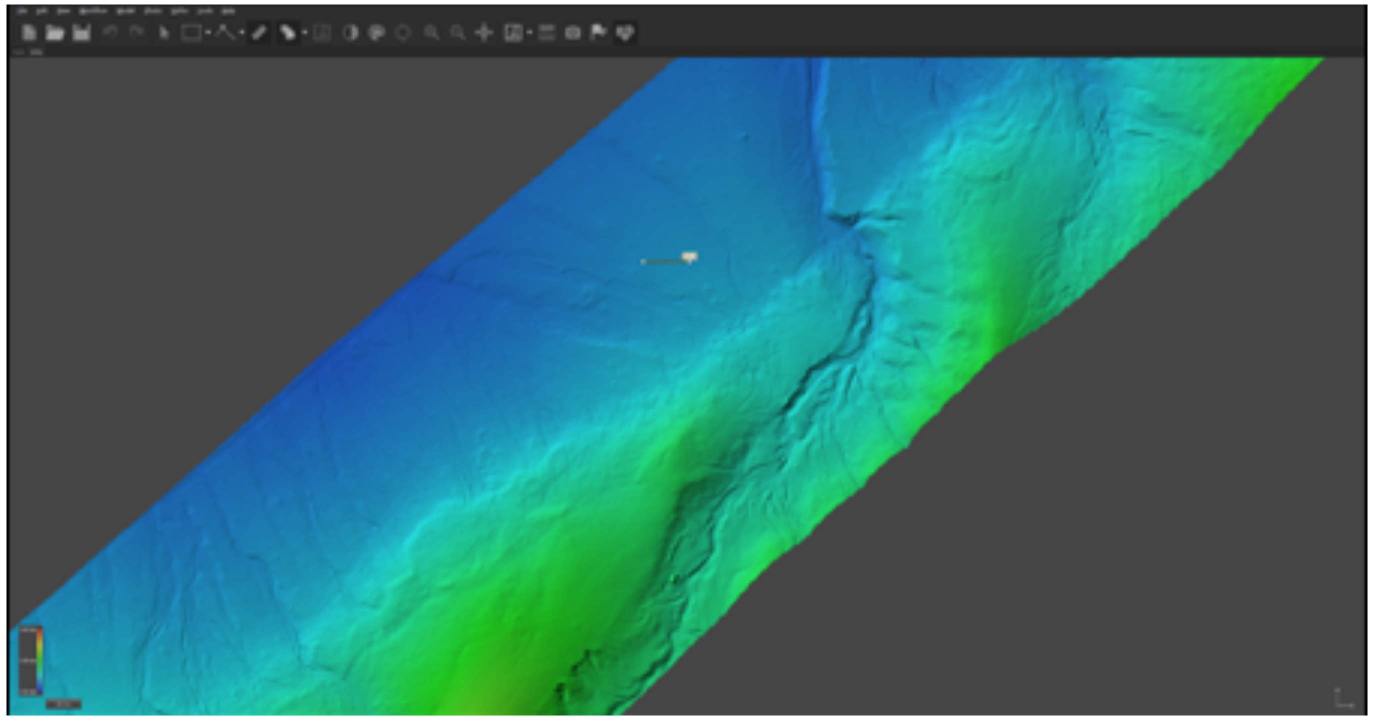


Figure 3. Resulting DEMs show extreme detail in the landscape.

This equipment combined with the workflow outlined above provides a very powerful tool for research in active faults and tectonics. Along with our Kyrgyz partners we are now able to conduct surveys of faults throughout the country with a cost effective, highly portable, and efficient UAS system. The data we collect provide a never-before-seen picture of the effects that earthquakes have on the landscape.

References:

This article first appeared on the "Earthquakes in Central Asia" website

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

How phase bias impacts the InSAR estimated velocities

Dr Yasser Maghsoudi, COMET InSAR Scientific Developer, University of Leeds

With the advent of the European Commission's Copernicus two-satellite Sentinel-1 constellation, operated by ESA, space-borne InSAR has become a key geophysical tool for surface deformation studies. The relatively short revisit time (every 6 days in Europe) is a significant advance because interferograms spanning a short interval maintain better coherence and allow a more accurate estimate of rapid deformation. Despite the clear benefits, using the shorter-interval, multilooked interferograms can introduce a bias in the interferometric phase, which, in turn, biases the estimated velocities. This poses a dilemma – we would like to include all short-interval interferograms and to carry out multilooking because this improves coherence and hugely improves coverage, but the velocities obtained from using these interferograms alone are not reliable. Figure 1 shows that the phase bias is higher in the shorter interferograms and then exponentially decaying in the longer interferograms.

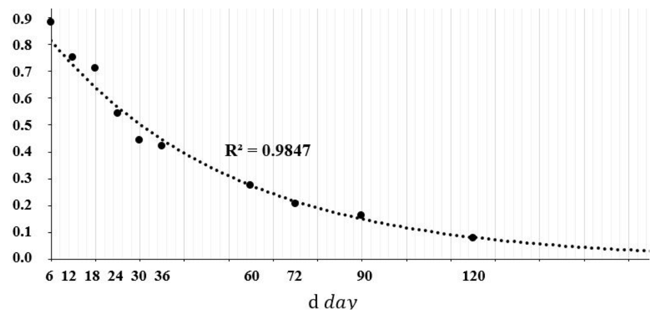


Figure 1. The exponential decay of the phase bias. d is the temporal baseline in days and y axis shows the closure phase calculated by a 1-year interferograms and the shorter interferograms spanning the same time.

We, propose an empirical method for correcting the phase bias, based on the assumption, borne out by our observations, that the bias in an interferogram is linearly related to the sum of the bias in shorter interferograms spanning the same time. We use constant values for a1 and a2, which relate the biases in 6-day interferograms with those in 12-day and 18-day interferograms. This leads to a series of observation equations relating the closure phases Δφ to unknowns bias terms δ.

$$\begin{pmatrix} \Delta\varphi_{i,i+2} \\ \Delta\varphi_{i+1,i+3} \\ \Delta\varphi_{i,i+3} \end{pmatrix} \cong \begin{pmatrix} a_1-1 & a_1-1 & 0 \\ 0 & a_1-1 & a_1-1 \\ a_2-1 & a_2-1 & a_2-1 \end{pmatrix} \begin{pmatrix} \delta_{i,i+1} \\ \delta_{i+1,i+2} \\ \delta_{i+2,i+3} \end{pmatrix}.$$

We have tested the algorithm over a study area in western Turkey by comparing average velocities against results from a phase linking approach, which estimates the single primary phases from all the interferometric pairs, and has been shown to be almost insensitive to the phase bias. Our corrected velocities agree well with those from a phase linking approach (Figure 2).

References:

Maghsoudi, Y., Hooper, A.J, Wright, T.J, Lazecky, M. and Ansari, H. Characterizing and Correcting Phase Biases in Short-Term, Multilooked Interferograms, Remote sensing of Environment, Volume 275, 2022, 113022, ISSN 0034-4257, https://doi.org/10.1016/j.rse.2022.113022.

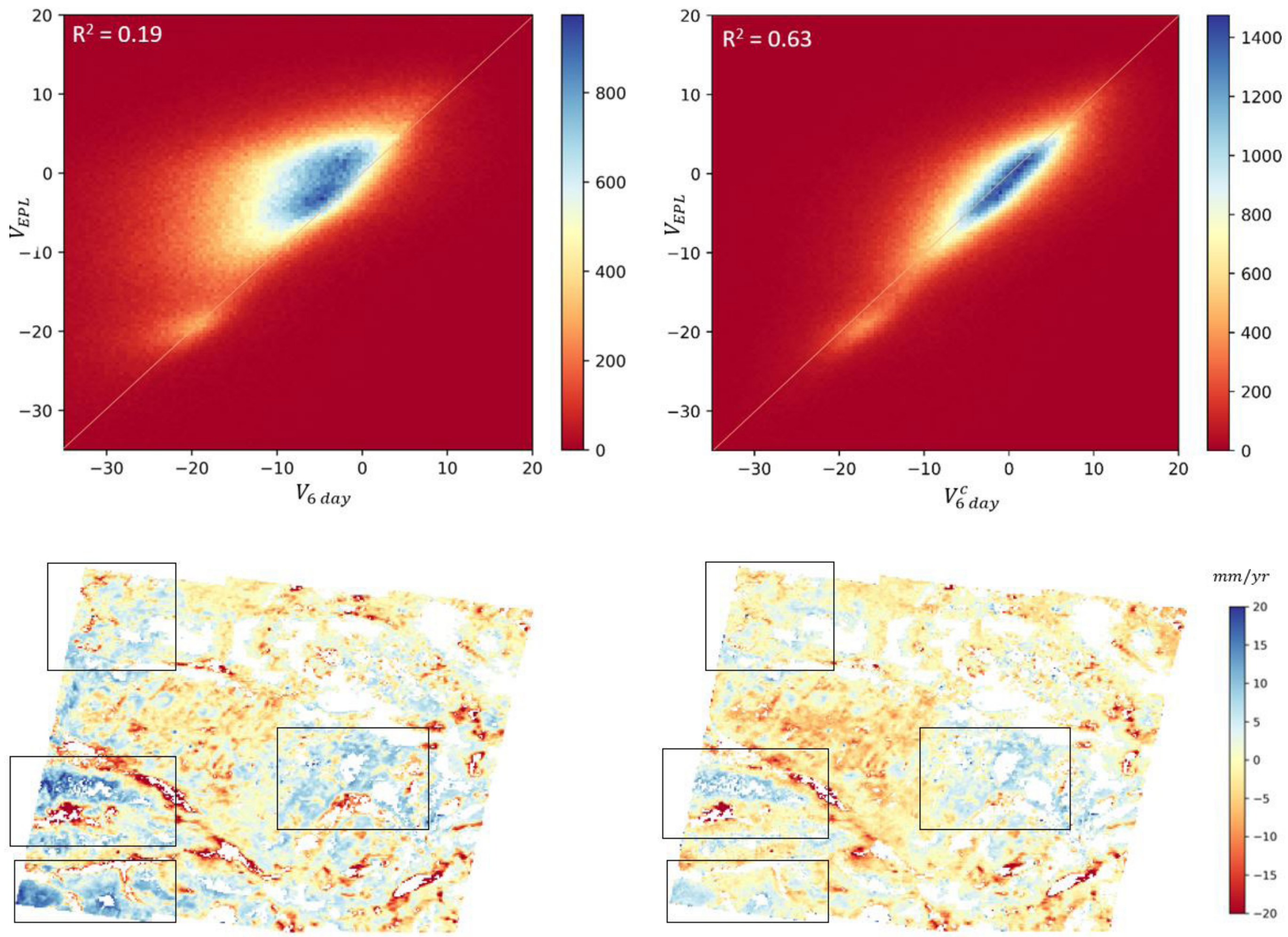


Figure 2: Scatterplot of velocities obtained from Eigen decomposition Phase Linking (VEPL) against velocities obtained from uncorrected 6-day interferograms, $V_{6\,DAY}$ (top left) and 6-day interferograms corrected with our empirical approach $V_{6\,DAY}^{C}$ (top right). The bottom figures show the estimated velocity before (bottom left) and after (bottom right) phase bias correction

Further works are in progress to generalize the approach and provide a routine corrections for the data in the COMET-LiCSAR portal.

SCIENCE UPDATE: EO DATA AND SERVICES

1. Deformation from satellite geodesy

Progress report: improve Comet-LiCSAR Sentinel-1 service.

Dr Yasser Maghsoudi, COMET InSAR Scientific Developer, University of Leeds
Dr Milan Lazecky, COMET Scientific Programmer, University of Leeds

The long-term development of our COMET-LiCSAR Sentinel-1 InSAR processing facility at JASMIN has been continued during this reporting year, optimizing system environment and processing tools (https://comet-licsar.github.io) to further improve quality of interferometric products, including time series. As of March 2022, we have generated approximately 730,000 interferograms, by processing approximately 204,000 sentinel-1 acquisitions in 1865 LiCSAR frames. As can be seen in Table 1, we have processed approximately 300,000 interferograms (67,000 sentinel-1 acquisitions) for this reporting year. Data dissemination through the LiCSAR portal was also improved with the development of an interactive query system, which allows users to filter frames, for example by time series length or days since last processed acquisition.

Figure 1 shows the number of generated interferograms from 2016 to present. The main priority processing zones have been in Alpine-Himalayan Belt (AHB) and the volcanic frames. In AHB, we completed the processing of the frames in Tibet and Iran and moved the frames into the monthly list of updates. For the volcanic frames, we focused on the highest priority "A1" list of volcanoes specified by the Powell report, which drives strategic acquisition for CEOS.

Number of	As of March 2021	As of March 2022
Frames	1773	1865
Processed S-1 acquisitions	136,000	203,000
Generated interferograms	430,000	730,000

Table 1: Status of the system in 2021 and 2022

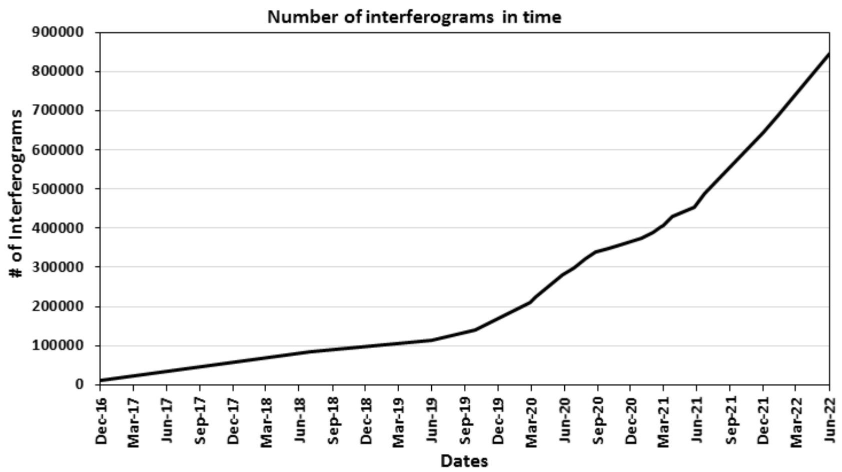


Figure 1: Number of generated interferograms in time.

Progress report: improve atmospheric correction services.

Dr Yasser Maghsoudi, COMET InSAR Scientific Developer, University of Leeds
Dr Milan Lazecky, COMET Scientific Programmer, University of Leeds

The Generic Atmospheric Correction Online Service for InSAR (GACOS) service is now fully ingested in the LiCSAR system. It provides the delay maps per epochs in GeoTIFF format in the same resolution as the other LiCSAR products and in both vertical and LOS directions and allows the user to readily apply the correction to the LiCSAR phase products, using the LiCSBAS package. The two main updates in the GACOS service this year:

- We started to mass produce the GACOS products in the tectonics and volcanic priority zones. Most of the AHB frames and A1 volcanic frames now have their GACOS products already fully generated.
- The LiCSAR GACOS service now provides the corrections for all the "monthly update" frames. Once each epoch is processed in the monthly frame list, the corresponding GACOS data gets generated.

Table 2 shows the number of epochs with GACOS data in the system. Currently, we have generated the GACOS data for 64% of all the processed epochs. This number is 80% and 70% for the AHB and the A1 frames respectively.

Number of	Number of epochs with GACOS (percentage)
All LiCSAR frames	144,000 (64%)
AHB frames	94,000 (80%)
A1 frames	27,000 (70%)

Table 2: The number (and percentage) of he epochs with GACOS data

Progress report: extend the COMET-LiCSAR system to other satellites.

While specific students and postdoctoral scientists have worked adhoc on other satellite systems, the tools for this are yet to be generalised and automated. Work on this objective is scheduled for years 3-5 (starting April 2023).

SCIENCE UPDATE: EO DATA AND SERVICES

2. Topography, deformation, and surface change analysis from high-resolution imagery

Progress report: semi-automation of satellite-derived displacement maps of large ground deformation signals, and of topography and topographic change.

Dr John Elliott, COMET Scientist, University of Leeds

We have developed plans to test the viability of this objective using Sentinel-2, Landsat, and PlanetScope data. We will develop and test methods for producing displacement maps using these satellite products, and compare to recent well-studied earthquakes. Presuming results from these earthquakes can be replicated, Watson will develop methods for semi-automating the process of creating displacement maps through the COMET-LiCS portal. Interpretation of displacement maps is likely to be a manual process, though King will explore options for semi-automating this interpretation. This method is unlikely to be implemented very often, as continental earthquakes large enough to produce displacements detectable by these optical satellites are rare.

Progress report: utilize digital topographic data at global, regional, and local scales to aid the fieldwork activities of comet members and the mapping of hazards at regional scale.

Professor Richard Walker, COMET Scientist, University of Oxford

Topographic datasets underpin much of our field activity and remote sensing analysis. We had success in several applications to the Committee for Earth Observing Satellite (CEOS) Seismic Hazard demonstrator for access to stereo Pleiades data, which has been invaluable in supporting our research. Particular success is demonstrated within Azerbaijan, where the high-resolution DEMs allowed the identification and mapping of a major and previously unknown fault system. Subsequent fieldwork and trenching will develop slip-rates and earthquake histories. We continue to develop efficient workflows and hardware to enable large-scale efficient field survey using drones. The Oxford team have compiled a database of their existing high-resolution topographic data (satellite and drone derived) and plan to disseminate through a short paper, with data access online (subject to data licencing requirements). We are working with high-resolution multibeam bathymetry for projects examining submarine active faulting in Indonesia and the Caspian Sea.

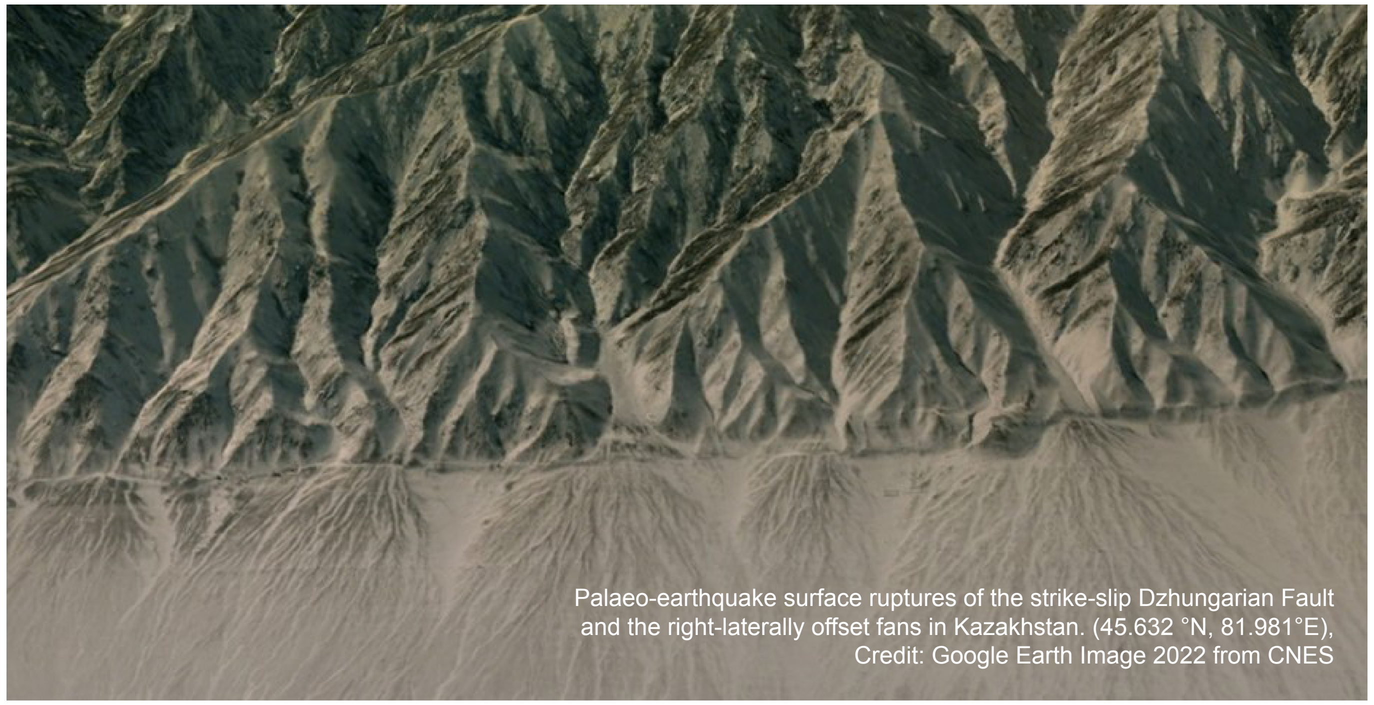
Progress report: derivation and analysis of high-resolution topographic datasets for seismic hazard in and around cities.

Dr John Elliott, COMET Scientist, University of Leeds
Dr C. Scott Watson, COMET Research Fellow in Earth Observation and Geoinformatics, University of Leeds
Professor Richard Walker, COMET Scientist, University of Oxford

We have developed workflows using commercial and open source software to generate DEMs (2 m) from high resolution satellite imagery such as Pleiades and WorldView-2. Through applications to the Committee for Earth Observing Satellites (CEOS) Seismic Hazard demonstrator project, we have acquired and processed stereo Pleiades imagery over several of the major cities of the central Asia region (Ashgabat, Turkmenistan; Dushanbe, Tajikistan; Xian, China) and also for a large region of Azerbaijan in which active faults pose hazard to population centres and to energy infrastructure.

In the absence of ground control, we use ICESat-2 altimetry data for independent validation. Previously generated topographic datasets for the Tomorrow's Cities project are being used to assess multi-hazards affecting urban environments, including earthquakes, floods, and landslides. Deep learning workflows are used to extract building footprints and building heights are assigned using the elevation data to generate exposure datasets relevant to seismic risk calculations. We recently produced a building inventory (over 290,000 in 2021) for the city of Bishkek, Kyrgyzstan, which experiences high seismic risk and is continuing to expand towards active faults.

We are also exploring topography generation capabilities with new datasets such as Pleiades Neo, PlanetScope, and satellite video. The topographic datasets are being used to characterise active fault sources, with expectation of completion of papers over the coming 6 months. We then plan a second phase where we combine the improved geological knowledge with mapping of urban exposure derived from the data to develop earthquake risk models.



Palaeo-earthquake surface ruptures of the strike-slip Dzhungarian Fault and the right-laterally offset fans in Kazakhstan. (45.632 °N, 81.981°E), Credit: Google Earth Image 2022 from CNES

SCIENCE UPDATE: EO DATA AND SERVICES

3. Retrievals of volcanic emissions from satellite spectrometers

Progress report: adapt fast linear retrieval of ash and SO_2 to process data from IASI-NG and IRS

Dr Isabelle Taylor, COMET Postdoctoral Researcher, University of Oxford

IASI-NG and IRS are instruments onboard the Metop-SG and Meteosat third generation platforms respectively. Both of these satellites are currently due to launch in 2024. As there is some time before the launch we have yet to directly work on this objective. However, we are currently advertising a MPhys project (starting in October 2022) which will adapt the linear SO_2 retrieval developed for IASI for the Cross-track Infrared Sounder (CrIS) on board the Suomi NPP and NOAA-20 platforms. This instrument is similar to IASI and adapting our retrievals for CrIS will help to setup our code so that it can be applied to multiple instruments. In addition, it will give us better coverage of global SO_2 emissions.

Progress report: extend existing SO_2 and ash time series and investigate retrievals for other volcanic species

Dr Isabelle Taylor, COMET Postdoctoral Researcher, University of Oxford

We've now applied our SO_2 retrievals to most of the IASI lifetime (mid 2007 – April 2021), with a few gaps which need to be reprocessed. We are currently working on a paper which will accompany this dataset. In addition, we've been working on multiple case studies: Raikoke (June 2019), La Soufrière St Vincent (April 2021) and Hunga Tonga-Hunga Ha'apai (January 2022). Hunga Tonga-Hunga Ha'apai has been an interesting case study with multiple layers of SO_2 and with emissions at heights greater than previously seen with this retrieval scheme. It has therefore been an interesting test of this method with some promising results.

We've also tried using the MIPAS Orbital Retrieval using Sequential Estimation (MORSE) technique developed by Anu Dudhia to get information on SO_2 and other species (including water vapour and sulphate) from the IASI spectra. We've been applying this to Hunga Tonga-Hunga Ha'apai with mixed results and further work is needed.

Progress report: automation of SO_2 flux time series retrievals

Dr Catherine Hayer, COMET Postdoctoral Researcher, University of Manchester

We have developed an automated system that is monitoring several volcanoes every day. The Azores, Etna, La Palma, Taal and Wolf Island are currently being monitored and others are included as required.

4. Geoinformatics and machine learning

Progress report: improve the sharing data and time series through the development of an integrated COMET data portal

Dr Susanna Ebmeier, COMET Scientist, University of Leeds

The COMET LiCSAR portal (https://comet.nerc.ac.uk/comet-lics-portal/) now contains over 800,000 interferograms and is accessed over 1,000 times each month. The Earthquake InSAR Data Provider (EIDP) and COMET Volcanic and Magmatic Deformation Portal both use LiCSAR data to produce more targeted products for applied and observatory scientists. The earthquake data provider contains over 400 activations where the LiCSAR system was triggered following major earthquakes with relevant interferograms are displayed on an interactive event page. Future work will include incorporating published time series velocity datasets on the portal for interactive viewing. The Volcanic and Magmatic portal provides tools for users to analyse LiCSAR results online, including for time series analysis, atmospheric correction, profile generation and detection major displacements from machine learning. The addition of global volcanic emissions retrieved from IASI (SO_2 and ash) to the data portal is underway. Daily TROPOMI SO_2 measurements and back trajectory analyses are also currently available through a separate website for six volcanoes, and we anticipate that this will be expanded to a greater number of volcanoes and integrated into the COMET portal in the future.

Progress report: develop machine learning approaches and tools that can be applied to COMET satellite data sets

Professor Andy Hooper, COMET Scientist, University of Leeds

This work was funded by the COMET co-funding project ERC Consolidator Grant DEEPVOLC and an ESA Living Planet Fellowship awarded to Matthew Gaddes. LiCSAlert is an approach designed by COMET to automatically detect signs of volcanic unrest in time series of Sentinel-1 interferograms created by the COMET LiCSAR system. When new interferograms for a volcano of interest are created, LiCSAlert uses LiCSBAS to create or update the time series for that location, before searching for signs of unrest relative to a baseline stage. The approach is based on identifying signal sources, most of which are expected to be atmospheric, using independent component analysis. This search is directed towards both changes in signals that are already present in the baseline stage (e.g. the acceleration of an existing uplift), and to changes that were not observed in the baseline stage (e.g. the onset of a new deformation source).

Further development of the LiCSAlert algorithm has focused on three topics. Firstly, the algorithm's sensitivity has been improved to successfully isolate more subtle deformation signals in the baseline InSAR time series. This has been tested at Campi Flegrei (Italy), where the spatial and temporal nature of inflation at up to 7 cm/yr was successfully recovered, which is an order of magnitude smaller than the signal recovered at Sierra Negra during the initial development of LiCSAlert. Secondly the ability of LiCSAlert to separate deformation from atmosphere at stratovolcanoes has been enhanced. The original implementation recovered only spatially independent sources but can now also recover sources that are temporally independent. This has been successfully tested at Vesuvius (Italy), where the spatially coincident subsidence and topographically correlated APS could not be fully separated by spatial independent component analysis. Finally, work has been carried out to refine the automation of LiCSAlert on the JASMIN data analysis facility, with particular emphasis being given to the production of time series using LiCSBAS. An initial test set of 12 volcanoes has now been expanded to 32.

The updated algorithm is written in Python3, is open-source, and distributed freely via GitHub.

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

Early stage continental rifting and seismic hazard assessment in East Africa

Dr Luke Wedmore, COMET Postdoctoral Researcher, University of Bristol
Professor Juliet Biggs, COMET Scientist, University of Bristol
Dr Max Werner, COMET Scientist, University of Bristol
Dr Åke Fagereng, COMET Associate, Cardiff University

The East African Rift System is the Earth's largest active continental rift, and provides a natural laboratory for studying continental extension. The rift is home to approximately 120 million people including over 30 million people classed as urban poor by the World Bank. Thus, moderate earthquake hazard here represents a very large seismic risk. Despite this, our knowledge of earthquakes along low strain-rate sections of the East African Rift is limited to incomplete and temporally limited seismicity records. Consequently, seismic hazard in this region is poorly understood and there is low awareness of the seismic risk.

Since 2015, COMET researchers at University of Bristol and Cardiff University alongside colleagues at the Geological Survey Department in Malawi have been investigating the tectonics of the Malawi Rift to provide a new framework for assessing seismic hazard along the East African Rift. To overcome the limitations of the seismic records, we used a combination of field investigations, remote sensing, and geophysical surveys to systematically map the location and properties of active faults in Malawi (Wedmore et al., 2020a; 2020b; Williams et al., 2021a; 2022). The resultant active fault database conforms to the GEM standard, and is freely accessible online (Williams et al., 2021b; 2022).

We discovered evidence for multiple large magnitude (M6+) earthquakes in southern Malawi revealed by the presence of steep, laterally continuous cumulative fault scarps up to 30 m high and approximately 100 km long (Figure 1; Wedmore et al., 2020a). Within individual rift segments, strain is distributed equally between intra-rift and border faults, despite no evidence for magmatism (Figure 1). The faults are segmented but segment boundaries cut across geometrical barriers at the surface suggesting instead that deeper lithospheric weaknesses are affecting the distribution of strain at the surface (Wedmore et al., 2020b). We developed a revised plate model, including a new plate in southern Africa (the San Plate) that provides a better fit to the GPS data (Wedmore et al., 2021). Using this model in conjunction with new GPS data from southern Malawi, we estimate that the extension rate across the Malawi Rift is 0.7-1.2 mm/yr.

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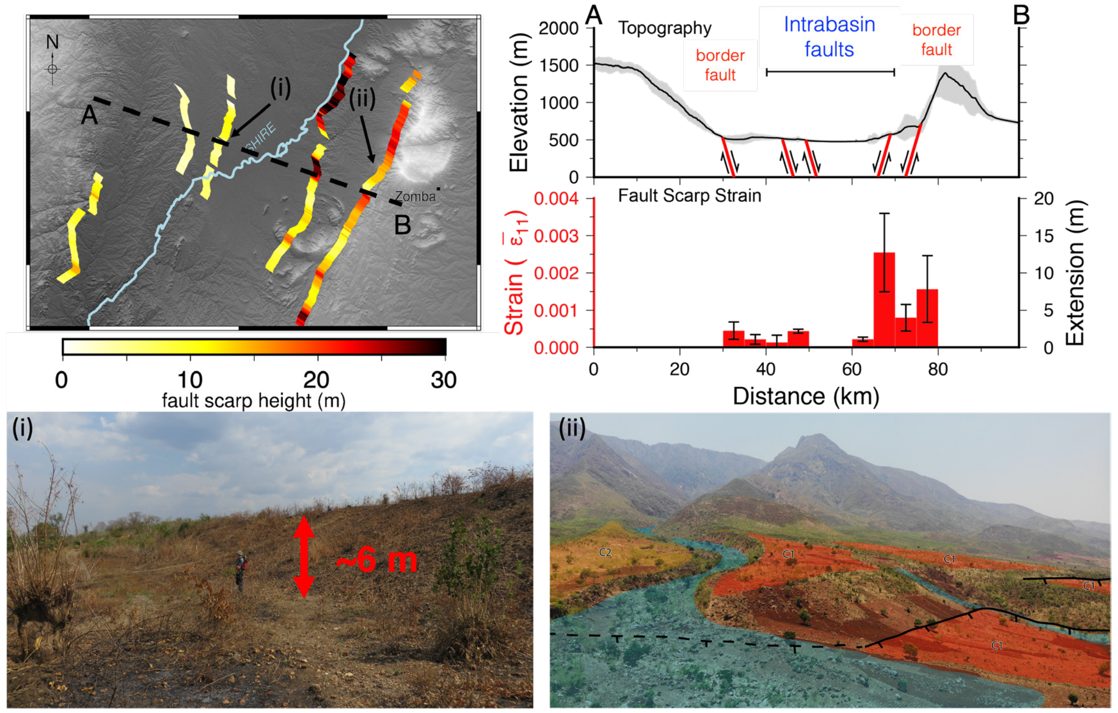

Figure 1

We combined our model of active faults, understanding of strain distribution, fault segmentation and new extension rate estimates using a 'systems based approach' to build a seismic sources model for Malawi where we estimate potential earthquake magnitudes and recurrence intervals for fault segments, individual faults and multi-fault earthquake scenarios (Williams et al., 2021b; in review w. NHESS). This source model will pave the way for a new generation of fault-based probabilistic seismic hazard assessment in Malawi (Figure 2; Williams et al. in review with GJI) and has the potential to be the basis for future seismic hazard assessment in other East African countries.

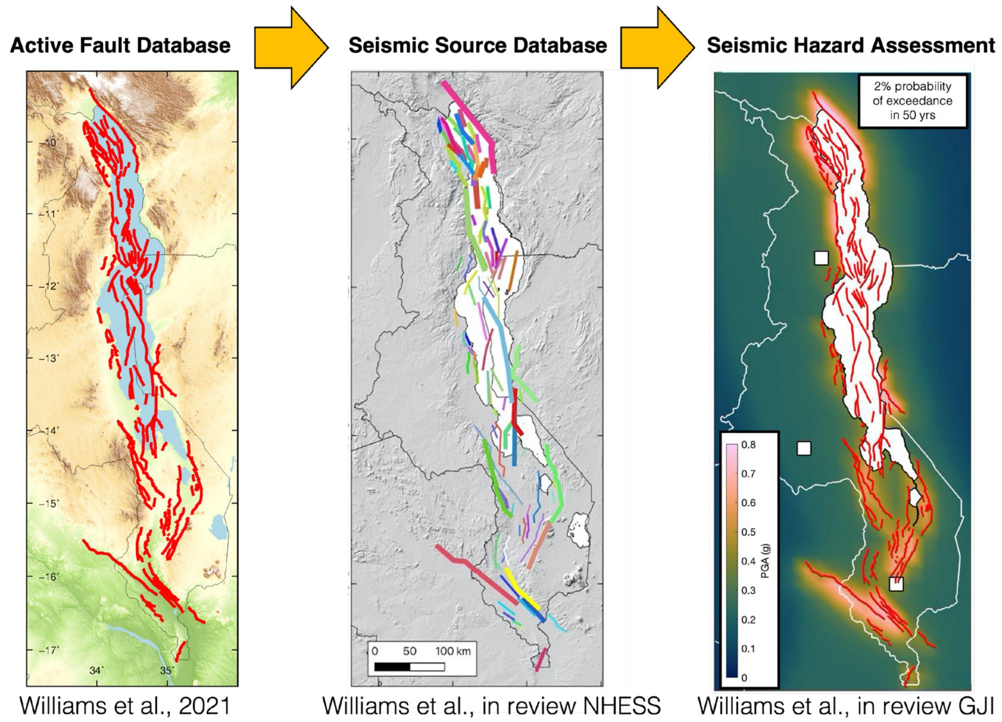

Figure 2

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

The Main Kopetdag fault of Turkmenistan: from palaeoseismology to geodynamics

Dr Richard Walker, COMET Scientist, University of Oxford

The right-lateral strike-slip Main Kopetdag fault (MKDF) of Turkmenistan is a key tectonic feature within the active tectonics of the Arabia-Eurasia continental collision and the geodynamics of the South Caspian basin. The MKDF has a very clear expression in the landscape, yet very little is known of its long-term slip rate or its potential for generating earthquakes. Destructive earthquakes are known within Turkmenistan, including large events in 1895, 1946 and 2000 in the Caspian lowlands, and in 1948 in an earthquake that destroyed Ashgabat, the capital city of Turkmenistan. However there is no record of large events along the intervening fault length of approximately 300 km.

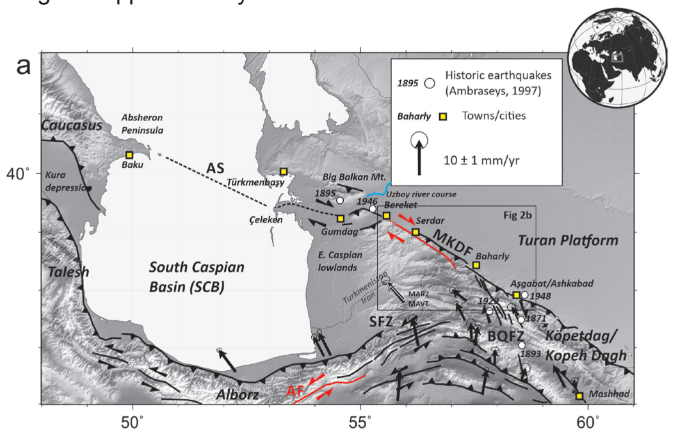

Figure 1. Regional map of active faults around the South Caspian Basin including the Main Kopetdag Fault (MKDF)

A collaborative study between researchers at the Institute of Seismology and Physics of the Atmosphere in Ashgabat, along with colleagues in Iran, Germany, and the UK has aimed to characterise the slip-rate and seismic potential of the MKDF, and to use these results to gain a better understanding of the geodynamics of the South Caspian. In a series of three papers we present geological slip rates and image decadal accumulation of strain across the fault. We found palaeoseismic evidence for large magnitude earthquakes along this major, and yet seismically quiet, fault. Our results suggest relatively rapid slip and a young initiation of the present day tectonics.

Dodd's et al. (2022) measured 9 +/- 2 mm/yr of right-lateral slip and 4 +/- 2 mm/yr of shortening while Walker et al. (2021) determined a geological slip-rate of 9.1 +/- 1.3 mm/yr, but found a much smaller amount of shortening, suggesting much of the shortening imaged by InSAR is not accommodated across a single frontal thrust. We were relieved to find the two sets of measurements were in close agreement, with almost a centimetre of right-lateral slip. Previous attempts to use satellite radar to measure interseismic strain accumulation across the MKDF have suffered from large atmospheric noise, and the only available GNSS measurements have to be extrapolated from across the border in Iran.

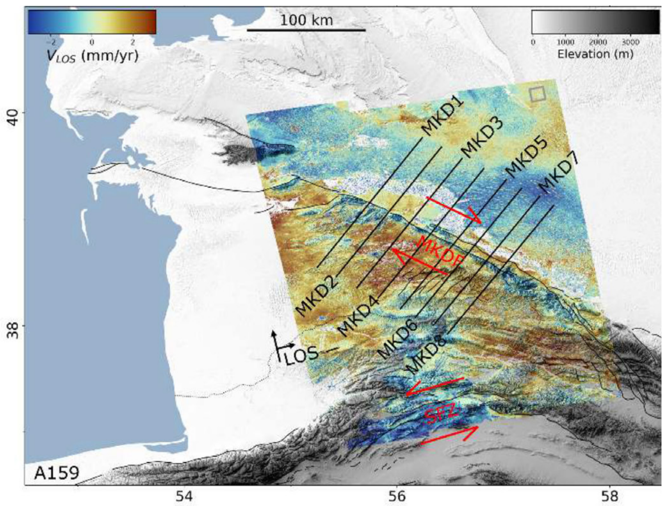

Figure 2a. Line of sight velocity maps for descending Sentinel-1 frames. From Dodds et al., 2022. Geophysical Journal International.

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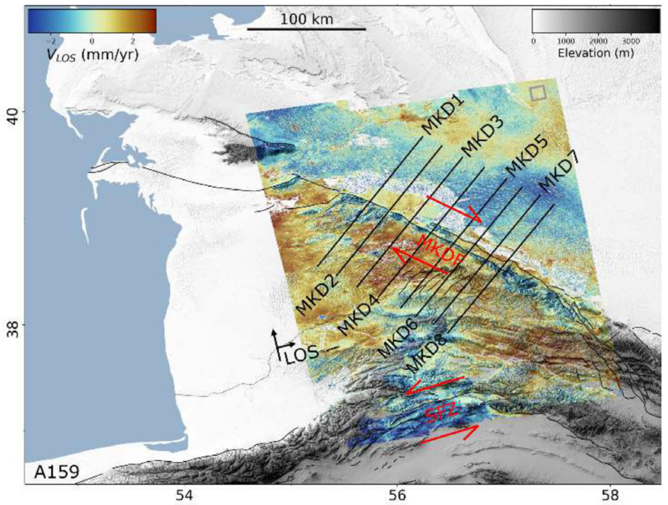

Figure 2b. Line of sight velocity maps for ascending Sentinel-1 frames. From Dodds et al., 2022. Geophysical Journal International.

The rapid slip rates suggest the region has undergone a relatively recent tectonic reorganisation, as the cumulative displacements on the MKDF can be accommodated in only 3-5 Ma. It is surprising that no large earthquakes are recorded, given the rapid slip-rate and the long historical record across large parts of the Arabia-Eurasia collision zone. In the third paper Dodds et al. (2022) mapped ruptures from a previously unknown earthquake that are preserved along much of the length of the fault. The length of the rupture zone, and the distribution of slip, suggest a magnitude of Mw 7.4-7.8. The ruptures are of probably medieval age. They displace surface archaeological remains and are dated through trenching at 600-800 yrs. BP.

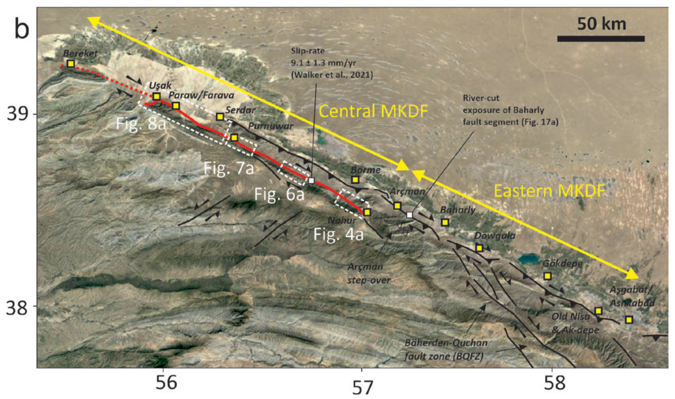

Figure 3. Palaeo-earthquake ruptures along the MKDF

The palaeoseismic study has implications for the hazard posed by the MKDF and provides insight into the completeness of historical earthquake records in the surrounding region. This event presents implications to comparable regions around the world (e.g., Iran, China) that use extended historical earthquake catalogs with assumed levels of completeness to inform seismic hazard assessment. It is likely that additional major earthquakes remain to be discovered through continued remote sensing, paleoseismology, and through the interpretation of archaeological and historical sources.

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This article first appeared on the “Earthquakes in Central Asia” website

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

High-resolution satellite radar reveals pre-eruptive deformation on the crater floor of Mount Agung, Indonesia

Mark Bemelmans, COMET Postgraduate Researcher, University of Bristol

Localised deformation at volcanoes is often related to shallow processes such as magma movement, hydrothermal system pressurisation, or stability of the edifice and recent deposits. The detection of this deformation is critical for eruption and unrest forecasting but requires frequent and dense spatial observations. High-resolution InSAR can achieve <1 m spatial resolution and sub-weekly observations, making it an excellent tool for the detection and monitoring of localised volcano deformation.

In this study, we use high-resolution SAR data acquired by the X-band COSMO-Skymed and C-band Sentinel 1 radar satellites over the summit of Agung (Indonesia) and apply Small-Baseline time series analysis and geodetic modelling to investigate localised pre-eruptive deformation on the summit crater floor. In September 2017, seismic activity increased dramatically at Agung, Indonesia. This triggered the evacuation of 140.000 people living within 9-12 km from the summit. The increased seismicity and surface displacements between Agung and the neighbouring volcano Batur were caused by a dike intrusion at 7-12 km depth. By mid-October 2017 the dike intrusion and related unrest had declined, introducing significant uncertainties in eruption forecasting. However, an eruption began on November 21, 2017, and would continue intermittently until June 2019. Our aim is to understand the shallow processes responsible for the deformation and relate these to the dike intrusion and the timing of magma ascent before eruption.

We show that >15 cm of LOS shortening occurred on the crater floor at the same time as the dike intrusion to the northeast of the volcano. We also observe a second pulse of intra-crater deformation of 3-5 cm within 4-0.5 days prior to the onset of the eruption. We attribute the deformation to a hydrothermal system less than 200 m below the surface that was activated by the injection of magmatic volatiles/fluids. Thus, Agung's shallow magmatic system was active from September 2017, the start of significant unrest. The second pulse of deformation was one of the only precursors to the eruption and is consistent with the interaction between the hydrothermal system and the ascending magma.

High-resolution InSAR was the only tool to detect the localised deformation at Agung, and required tailored processing of satellite data that is not widely-available. This suggests that shallow deformation is occurring undetected at other volcanoes, and could be important for eruption forecasting. The accessibility of high-resolution SAR data needs to be improved to facilitate the integration of high-resolution InSAR in volcano monitoring.

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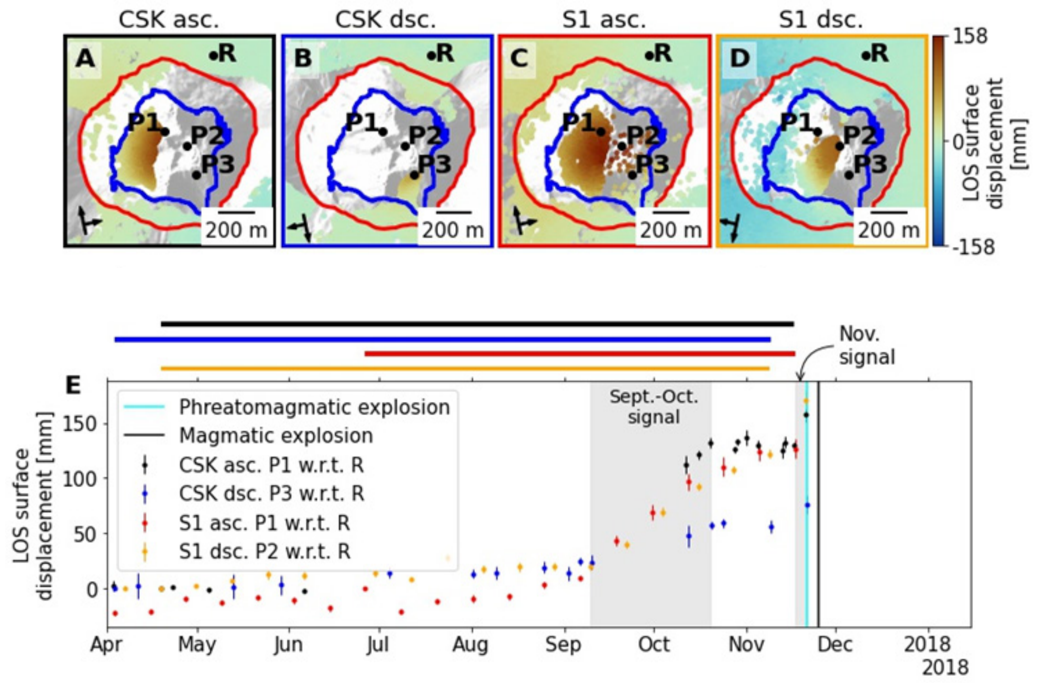

Figure 1: InSAR displacement maps and time series over the summit of Agung. Top: LOS surface displacement from A) CSK ascending April 18, 2017, to November 16, 2017, B) CSK descending April 3, 2017, to November 9, 2017, C) S1 ascending June 26, 2017, to November 17, 2017, D) S1 descending April 18, 2017, to November 8, 2017. Arrows show satellite flight and look direction. E) Time series of LOS surface displacement of point P1 (for CSK and S1 ascending), P2 (for S1 descending), and P3 (for CSK descending) with respect to point R. Error bars indicate 1¼ uncertainty from scatterers within a 25 m radius of P1, P2, P3, and R. Also shown are the phreatomagmatic (cyan) and magmatic (black) explosions on November 21 and 25, 2017, respectively. The time spanned by A-D is showing in with the coloured lines above E. The line colour matches the bounding box colour of A-D.

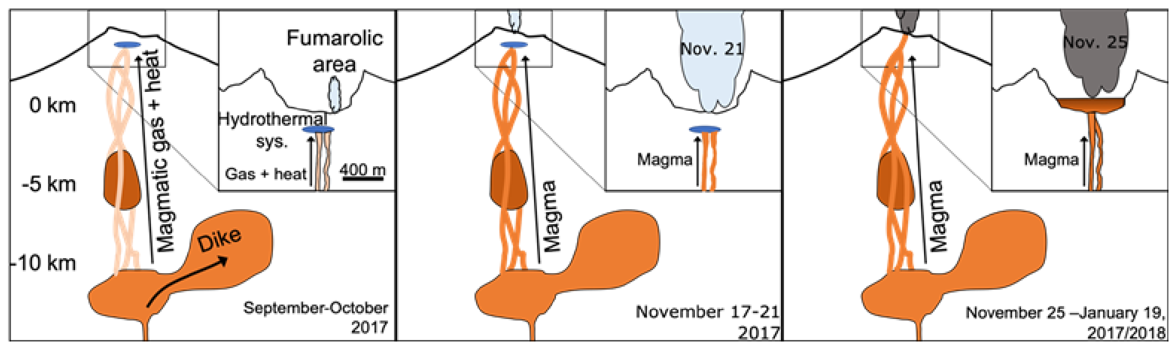

Figure 2: Temporal evolution of events at Agung mapped onto conceptual model of Agung. Panel A shows the first period of intra-crater deformation spanning mid-September to mid-October 2017, where gasses and heat ascended from a dike intrusion between Agung and Batur, pressurising the hydrothermal system at the summit. Panel B shows the second period of intra-crater deformation spanning November 17-21, 2017. Here magma has ascended to shallow depths and is interacting with the hydrothermal system, eventually triggering a phreatomagmatic explosion on November 21, 2017. Panel C shows the period where magma reached the surface to flood the crater floor, starting with a magmatic explosion on November 25, 2017.

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

Fieldwork in La Palma, Canary Islands

Dr. Catherine Hayer, COMET Postdoctoral Researcher, University of Manchester
Ana Pardo Cofrades, COMET Postgraduate Researcher, University of Manchester
Dr. Ben Esse, COMET Postdoctoral Researcher, University of Manchester

Cumbre Vieja, La Palma, is the most active volcano in the Canary Islands, Spain. After 50 years of quiescence, only punctuated by a seismic swarm in 2013, seismicity was detected in early September 2021 below Cumbre Vieja. Over the next week or so, InSAR and GPS detected 20 cm of uplift, and, on 19th September 2021, the volcano erupted. The eruption would continue for almost three months – the longest recorded eruption on La Palma – leading widespread devastation on the island, with damage to infrastructure and buildings.

At the beginning of October, a team from the University of Manchester, including COMET PhD student Ana Pardo Cofrades and COMET scientist Mike Burton, travelled out to the island to assist with the monitoring response. The team, working closely with scientists from INVOLCAN, installed ground-based UV scanners, and started taking FTIR (Fourier Transform InfraRed spectrometer) measurements (Figure 1), adding to the traverse gas measurements being made by INVOLCAN and the satellite analysis being provided by the Manchester group back in the UK (Figure 2).

Ana remained on the island for most of the rest of the eruption, making FTIR measurements and supporting the INVOLCAN response to the eruption. Most of the volcanology research group from Manchester travelled to La Palma (Figure 3) in the middle of November to service and reposition the UV spectrometers and to make tephra measurements.

COMET postdoctoral scientists, Catherine Hayer and Ben Esse, travelled back to La Palma in mid-December 2021 to install additional UV scanners and saw the final explosion of the eruption first hand (Figure 3c).

Results from the group (Figure 1b & Figure 2) were used by INVOLCAN and local government to inform the disaster response. The relationships established throughout this eruption are ongoing and we look forward to working together in the future.

This research was supported by the NERC V-PLUS grant, COMET, BGS, and the Universities of Manchester and Leeds.

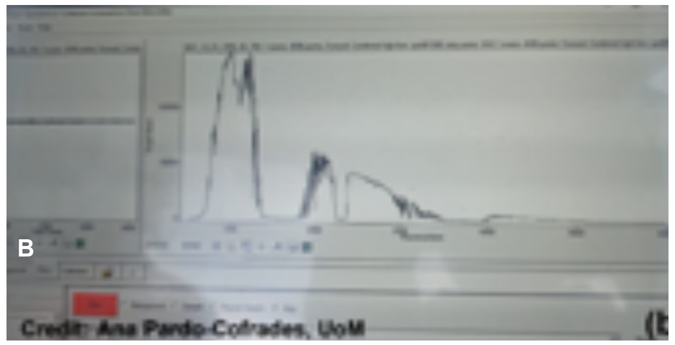

Figure 1. (a) Ana Pardo-Cofrades making FTIR measurements at Cumbre Vieja; (b) FTIR output spectra

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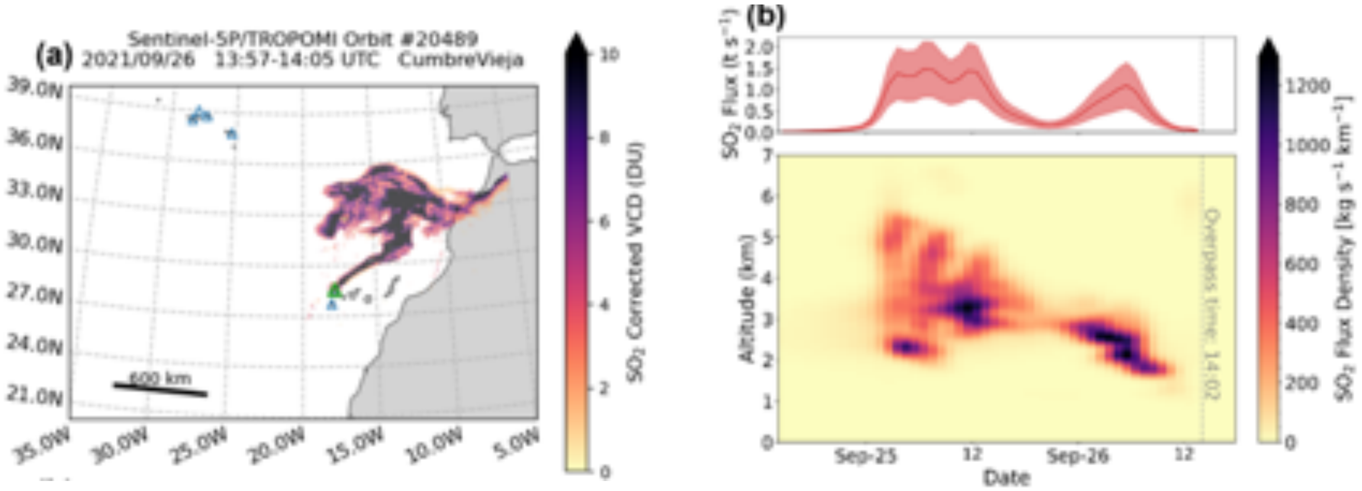

Figure 2. PlumeTraj results from Sentinel-5P/TROPOMI for Cumbre Vieja on 26 Sept 2021. (a) Altitude-corrected SO2 vertical column density concentrations; (b) Flux density plot, showing the height- and time-resolved emission flux from the pixels in (a).

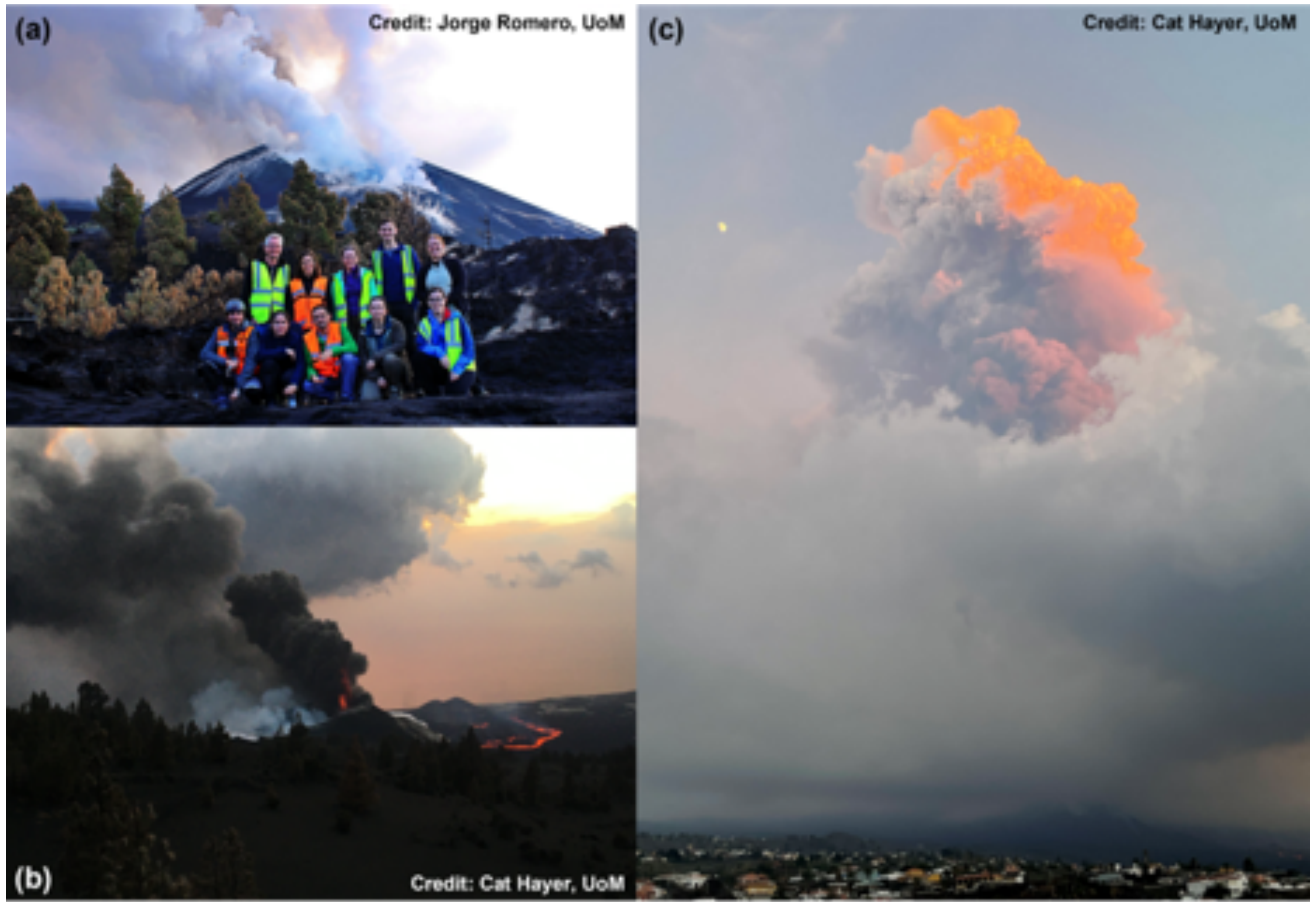

Figure 3. (a) Research team from University of Manchester, along with scientists from INVOLCAN, in front of Cumbre Vieja, 21 Nov 2021; (b) Eruptive plume and lava flow, 17 Nov 2021; (c) Final explosive event on 13 Dec 2021.

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

The eruption on La Palma, a window of opportunity to advance volcano flank collapse research

Dr. Pablo J. González, Honorary Lecturer in Geophysics COMET, University of Liverpool and Tenured Scientist of the Volcanology group of the IPNA-CSIC

Volcanoes collapse, that is an undisputed fact, but we still do not know how and why. The Cumbre Vieja volcano and its latest eruption may help us to unravel this scientific mystery. The scientific community must advance in order to improve the recognition of potential precursor patterns associated with this type of volcanic hazard.

Sixty years have passed since Professor Telesforo Bravo published his study on the subterranean geology of the island of Tenerife. In "El Circo de Las Cañadas y sus dependencias", this pioneer of the discipline in the Canary Islands Archipelago postulated a rather radical theory: the horseshoe-shaped valleys that open up towards the sea and that fill the Canary Islands are the result of massive mass-wasting events due to the collapse of rapidly growing volcanoes. Just two years later, the American James Moore would publish maps of the seafloor around the Hawai'i Islands. These new bathymetric maps were irrefutable and revealing evidence of the existence of colossal submarine deposits due to these collapses.

Since then, science has come a long way, but mechanisms responsible for weakening our volcanoes to the point of collapse remain unknown. Upon reflecting on this problem and field and geophysical evidence, the latest eruption on the island of La Palma may shed light on the resolution of the mystery. Many volcanoes on oceanic islands grow at extraordinarily fast rates, in geological terms. This rapid growth of volcanoes makes them vulnerable to the effect of gravity and eventually they collapse. Fortunately for the inhabitants of the islands, these colossal phenomena only occur very rarely, every several tens to hundreds of thousands of years. However, this remains a real geological hazard. Other collapses, albeit smaller, occur more frequently and can result in fatalities. Even in the distant past, there are significant cases such as the eruption of the Mt. St. Helens volcano in 1980, or in December 2018 at the Anak Krakatau volcano in Indonesia. Therefore, knowing their origin, how they are triggered, and what indicators we could identify as precursors for their forecast are the scientific challenges that need to be addressed.

Cumbre Vieja has long been identified as a candidate for future collapse among the world's volcanoes. Even so, there is no unanimous opinion within the scientific community as to the impact it would generate. A large number of model scenarios have been simulated, ranging from catastrophic futures to very local effects. This disparity of opinion is indicative of the great lack of knowledge with which to refine these forecasts. I point out that this calls for carrying out rigorous, multidisciplinary research.

The recent eruption of Cumbre Vieja is one with the largest eruptive volume in the island's historical record. However, due to the speed of the events, a series of volcano-tectonic events (ground fractures and small eruptive vents) went unnoticed by most people. Magma feeding volcanoes in the Canary Islands, as in many other oceanic islands, typically rises to the surface through dykes. These are relatively vertical, flat and very elongated conduits, i.e. much longer than they are wide. The longest axis is oriented in a direction that usually coincides with a line of weakness of the volcano. This pattern was consistent for most of the course of the 2021 eruption, but broke down during the second half of November. From then on and until the end of the eruption, fractures and eruptive vents broke the ground surface in a different direction (east-west). I stressed the relevance of this remarkable finding and invite specialists in the field to pay more attention to these clues, as they could provide the answer that allows the scientific community to better understand what causes the collapse of volcanoes.
In this way, the eruption on the island of La Palma, which caused so much damage, could also become an opportunity to advance knowledge and help the inhabitants of the islands to live more safely in the shadow of a volcano.

References:

González, P.J. (2022) Volcano-tectonic control of Cumbre Vieja. Science. doi: 10.1126/science.abn5148

Cumbre Vieja, La Palma, Credit: Dr. Pablo J. González

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RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

Mapping the magma plumbing system beneath an active volcano using machine learning methods

Felix Boschetty, COMET Postgraduate Researcher, University of Leeds
Dr David Ferguson, COMET Associate, University of Leeds
Dr Susanna Ebmeier, COMET Scientist, University of Leeds

The majority of Earth's subaerial volcanic activity occurs at volcanic arcs, the chains of volcanoes associated with convergent tectonic plate boundaries (for example, those around the Pacific Ocean). In order to forecast the likely style of future eruptions at arc volcanoes we need to understand how and where magma is stored in the Earth's crust and what changes may occur in these stored bodies of magma that prompt a volcano to erupt. Historically, volcanologists have thought that the magma feeding eruptions was primarily sourced from a single 'magma chamber', a large body of molten rock typically located a few kilometres beneath the volcano's summit. More recently, this simple idea of magma storage has evolved into a more complex model, whereby stored magma exists in numerous smaller bodies distributed at various depths throughout the crust (Cashman et al., 2017). Known as a 'transcrustal magma system', this more nuanced view of magma storage and supply presents new challenges and research opportunities to volcanologists trying to understand what drives volcanoes to erupt.

Villarrica is one of Chile's most active volcanoes and produces frequent eruptions that range in size from effusive lava-flow producing events to large explosive eruptions. The range of eruption styles observed at Villarrica makes it an ideal location to investigate how magma storage may affect eruptive processes. In our recent paper by Boschetty et al (2022) we used machine learning methods to investigate the structure of the magmatic system that feeds this volcano. Our results provide new insights into where magma is located beneath Villarrica and what conditions likely give rise to the most explosive eruptions that have occurred here.

When magma is stored in the crust it cools down and begins to crystallize. In most cases the bodies of melt within a transcrustal magma system contain a large proportion of these crystals as well as molten magma, a composite material known as a 'crystal mush'. The chemical composition of the crystals in a mush layer depends on the type of magma they are forming in, as well as the pressure and temperature conditions. When an eruption occurs, the rising magma can collect crystals from its mush layer, as well as other mush bodies it encounters en route to the surface. Each eruption therefore provides us with a snapshot of the different crystals that exist within a magma plumbing system. By applying machine learning methods to a large multi-element database of crystal compositions from Villarrica we were able to identify distinct clusters of crystal compositions. The presence of these multiple clusters provides evidence for several distinct zones of magma storage and crystallization. By modelling the conditions that each cluster formed in (such as pressure, temperature, and magma type) we were able to map out were magma is stored beneath the volcano. Consistent with the transcrustal magma system conceptual model, we find that the magmas beneath Villarrica are stored in several discrete mush zones, distributed over a range of depths. By examining the different crystal cargoes carried by magmas from different eruptions we infer that Villarrica's most explosive eruptions likely occur due mixing of ascending magmas from deeper storage zones with a shallow, cooler melt body. One of the implications of these results is that it can guide future interpretations of geophysical data in terms of the likely style of an impending eruption.

References

1. Cashman, K.V., Sparks, R.S.J. and Blundy, J.D., 2017. Vertically extensive and unstable magmatic systems: a unified view of igneous processes. Science, 355(6331), p.eaag3055.
2. Boschetty, F.O., Ferguson, D.J., Cortés, J.A., Morgado, E., Ebmeier, S.K., Morgan, D.J., Romero, J.E. and Parejas, C.S., 2022. Insights into magma storage beneath a frequently erupting arc volcano (Villarrica, Chile) from unsupervised machine learning analysis of mineral compositions. Geochemistry, Geophysics, Geosystems, p.e2022GC010333.

Figure 1. Felix Boschetty (University of Leeds) collecting samples near the summit of Villarrica.

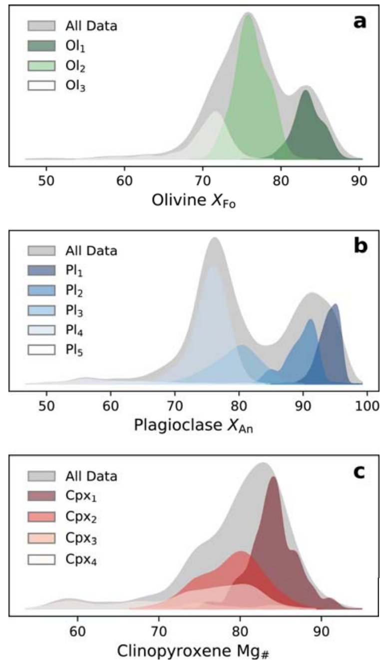


Figure 2. Results of machine learning cluster analysis. For each mineral type the coloured areas show the different clusters identified in multi-elemental compositional data. The grey region shows all the data.

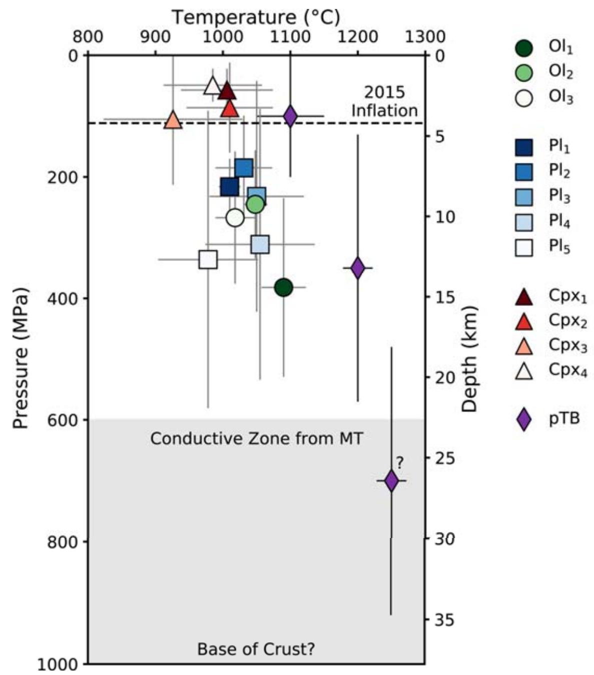


Figure 3. Results of crystallization models showing the pressure (depth) and temperature conditions where each mineral cluster formed. These provide evidence for magma bodies existing down depths of around 20 km beneath the volcano.

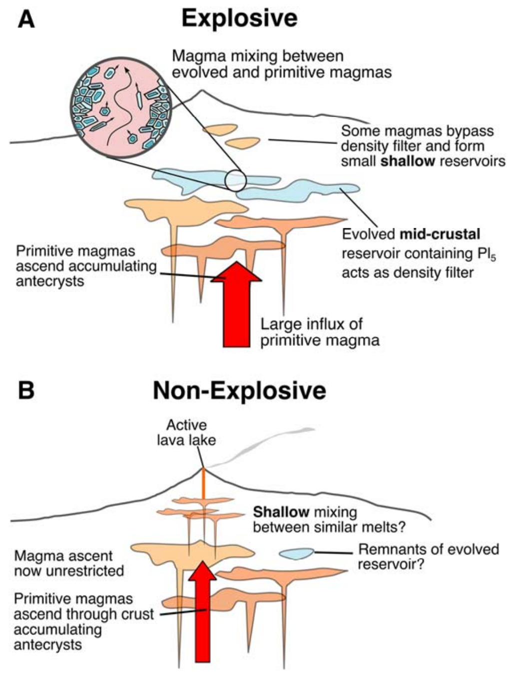


Figure 4. Schematic model showing how magma may migrate though the crustal plumbing network during explosive versus non-explosive eruptions of Villarrica.

SCIENCE UPDATES: TECTONICS AND VOLCANISM

1. Tectonics and Seismic Hazard

Progress report: develop and deploy a geodetically-based earthquake hazard model in partnership with the global earthquake model

Professor Tim Wright, COMET Director, University of Leeds

COMET and GEM Scientists have established a collaboration, funded through NERC, with the aim of improving probabilistic seismic hazard and risk assessment in Central Asia. This project began in 2021 and funding is secured initially for 3 years.

This project has a number of specific targets for each year. In year 1, we have achieved the following:

- The COMET Central Asia Fault Database has been delivered to GEM and ingested in the GEM database.
- We have compiled GNSS data with their uncertainties for Central Asia in a unified reference frame, with bad data weeded.
- We have initiated InSAR processing for Central Asia from Sentinel-1 using the COMET-LiCSAR system.
- We have published earthquake scenario risk calculations for Bishkek & Almaty.
- GEM have set up an initial block model for Central Asia, which will be constrained with the available GPS and fault data sets.
- GEM have established the best available earthquake catalogue for the region.

Collectively, these data sets will be used in 2022 to produce an earthquake hazard model that incorporates geodesy, seismology and geology.

Progress report: produce and deliver maps of active faults, incorporating new results regarding their rates of activity and past earthquakes

Professor Richard Walker, COMET Scientist, University of Oxford

We have completed the compilation of a database of active faulting across the Tien Shan region. We are working to (1) verify results through discussion with a range of regional specialists, and (2) working directly with GEM to fine-tune the fault inputs for the GEM regional hazard model for Asia. We continue to generate pertinent fault slip rate and earthquake data through our NATO SPS project, and will incorporate these into the database.

Progress Report: Assess Temporal Variations In Strain Across Distributed Fault Networks

Dr Laura Gregory, COMET Scientist, University of Leeds
Professor Richard Walker, COMET Scientist, University of Oxford

In a series of three papers published over recent months we focus on the Main Kopetdag fault of Turkmenistan. We have assessed the long-term slip, short-term strain accumulation, and the style and magnitude of earthquakes from palaeoseismology. Wilkinson (DPhil, Oxford) has completed a combined InSAR, seismology, and geological study of the Ilyak fault in Tajikistan, which shows large changes in slip behaviour along strike, and potentially through time. Over the coming six months we aim to complete a paper comparing geological and geodetic rates of faulting across Iran. We continue to work towards our goal of assessing temporal variation in earthquake occurrence across the Tien Shan through widespread palaeoseismic trenching and slip-rate determination within our NATO SPS project.

We have ongoing work in the Mediterranean investigating fault slip rates and fault interaction on millennial timescales. Goodall (PhD, Leeds) completed a PhD using cosmogenic isotopes at multiple localities on the same fault to investigate how earthquake recurrence varies through time and along strike. His first publication (Goodall et al., 2021) demonstrates that pulses of rapid slip rate are temporally correlated along strike, and that slip rates are reduced on one fault where fault strands overlap. Several papers are in preparation comparing fault slip rates across the entire central Apennine fault network, and Gregory is PI of an ongoing project assessing temporal variations of strain and fault interaction in western Turkey.

Progress report: build dynamic models that can explain lithosphere deformation across timescales

Professor Alex Copley, COMET Scientist, University of Cambridge

Over the past year, research on this objective has progressed through: (1) studies examining the interplay between present-day geological structure, large-scale lithosphere geometry, and the slip in earthquakes (Craig et al 2022; Wang et al 2022); (2) new insights into the relationship between the spatial distribution of earthquakes and the long-term evolution of mountain ranges with laterally-variable foreland strength (Knight et al 2022); (3) the development of a new method for establishing the history of mountain-building events using the pressure and temperature conditions recorded by suites of metamorphic rocks (Copley and Weller 2022); and (4) a synthesis of the thermal and tectonic characteristics of the Earth's largest known mountain-building events through geological history, and an investigation of the underlying dynamic controls (Weller et al 2022). A new PhD student in Leeds has recently begun working on this objective, focussing on extensional settings.

SCIENCE UPDATES: TECTONICS AND VOLCANISM

2. Magmatism and Volcanic Hazard

Progress report: analyse long-term (decadal) patterns of volcanic activity globally

Dr Susanna Ebmeier, COMET Scientist, University of Leeds

In last year, COMET scientists have been developing and analysing decadal time series of volcano displacements and SO_2 emission. This has included using the Sentinel-1 archive (up to seven years) to establish the best strategies for automatic processing (e.g., in East Africa), volcano monitoring (Turkey and Ecuador) and for testing the performance of machine learning based detection of deformation (various volcanoes globally). Current PhD projects and related research have also involved analysis of multi-sensor radar imagery over decades including research into volcanism in the Galapagos, Indonesia and Iceland. Global SO_2 retrievals from IASI have also been extended to mi-2021, and now span 14 years.

Progress report: assess the contribution of volcanic SO_2 to global climate and aviation

Dr Isabelle Taylor, COMET Postdoctoral Researcher, University of Oxford

We've now produced a large SO_2 dataset for most of the IASI lifetime (2007-2021). We are preparing to archive this dataset at the Centre for Environmental Data Analysis (CEDA) and producing a paper to accompany this. The dataset will contain information on the amount and height of SO_2 and incorporates a number of eruptions of different sizes and types, and more frequent emissions (including from more persistent volcanic degassing and anthropogenic sources). Combined with the results from other satellite instruments this can be used to begin exploring the possible impacts of these plumes on aviation and climate.

Progress report: develop and test the models needed for interpreting satellite data during volcanic crises

Professor Juliet Biggs, COMET Scientist, University of Bristol

Two of the most widely observed co-eruptive volcanic phenomena - ground deformation and volcanic outgassing - are fundamentally linked via the mechanism of magma degassing and the development of compressibility. We developed thermodynamic models – constrained by petrological data - to reconstruct volatile exsolution and the consequent changes in magma properties. We find that magmatic H_2O content has the most impact on both co-eruptive SO_2 flux and surface deformation. Our findings have general implications for typical basaltic systems: the higher water content of arc magmas makes them more compressible than ocean island magmas and leads to muted or non-existent deformation being observed during arc eruptions, consistent with observations (Yip et al, in press).

In 2016, White and McCausland propose a direct (power-law) relationship between seismic moment and magma volume, which could be used for eruption forecasting (White and McCausland, 2016). We reassessed the relationship using data from 17 InSAR studies and a Bayesian approach to consider uncertainties. We find that the empirical relationship derived from anthropogenic injection sites systematically underpredicts volume changes observed during VT swarms near volcanoes. A new relationship derived specifically from VT swarms provides a better fit, but large uncertainties mean that estimates of intruded volume range by three orders of magnitude (95% confidence) for a given cumulative seismic moment release. We conclude that the currently available dataset is too sparse and the uncertainties too large to use for reliably forecasting eruption magnitude (Meyer & Biggs, 2021).

References:

Meyer, K., Biggs, J., & Aspinall, W. (2021). A Bayesian reassessment of the relationship between seismic moment and magmatic intrusion volume during volcanic unrest. Journal of Volcanology and Geothermal Research, 419, 107375.

White, R., & McCausland, W. (2016). Volcano-tectonic earthquakes: A new tool for estimating intrusive volumes and forecasting eruptions. Journal of Volcanology and Geothermal Research, 309, 139-155.

Eruption of Mount Agung, Bali


Kyrgyzstan. Credit: Roberta Wilkinson, University of Oxford

IMPACT, INNOVATION AND INFLUENCE

COMET works closely with governments, Non-Governmental Organisations (NGOs) and other partners to deliver real-world impact, shape policy decisions and improve how we manage natural hazards.

Through our partnership with BGS, we provide emergency advice for the Scientific Advisory Group in Emergencies (SAGE) and Cabinet Office Briefing Room (COBR) and further scientific expertise on volcanic hazards and impacts as requested to UK government departments and the European Emergency Response and Coordination Centre.

We have also developed close links with the GEM and Global Volcano Model (GVM) as well as the US Geological Survey (USGS) and their Powell Centre Working Group. We sit on the Committee on Earth Observation Satellites (CEOS) Working Group on Disasters (leading the Pilot and Demonstrator projects) and Deep Carbon Observatory, and make our data available via the European Plate Observing System (EPOS). Finally, we work with the space agencies, advising ESA on Sentinel-1's acquisition strategy and helping to develop new EO missions, with COMET scientists sitting on the Mission Advisory Groups for Earth Explorer 10 mission Harmony, and Sentinel-1-NG.

COMET members contribute to research in response to significant global events. This year COMET scientists were involved in a NERC funded urgency project focused on the response to volcanic eruption at the Soufriere, St Vincent in 2020-2021. The work involved coordinated petrological, geochemical and volcanological work involving Universities of Oxford, Plymouth, UEA, Montserrat Volcano Observatory, Seismic Research Centre, University of the West Indies, and the Smithsonian Institution

COMET actively contributes to co-designed and innovative research seeking to increase the use and benefits of data and develop tools and applications:

The EUROVOLC **citizen science web platform** for observations of volcanic events provides a platform for collating observations from people witnessing volcanic phenomena at European and other volcanoes.

The NERC Innovation Project **Making Volcano Deformation Data Accessible** is developing web-based products and services to allow volcano observatories to use automatically processed satellite data; building capacity in ODA countries to access and interpret satellite data; and implementing and refining algorithms to flag volcanic unrest and allow the development of an alert system.

The NERC Innovation Project on analysis of seismic hazard and risk for improved welfare in Bishkek, Kyrgyzstan was delivered in collaboration with the Institute of Seismology, Bishkek and with GEM Foundation.

SAFER PREPARED - Earth scientists and engineers from Bristol and Malawi collaborate on the GCRF SAFER PREPARED project whose primary purpose was to contextualise the schools inspection app developed in the SAFER project for use in inspection of schools in Malawi.

COMET members engage in activities of national and international importance in an advisory capacity:

Samantha Engwell (COMET Scientist, BGS) was selected to join the WMO/ICAO Volcanic Science for Aviation Advisory Group to provide advice on the current state of knowledge with regards to volcanic emissions and their transport, and their impact on aviation.

Andy Hooper (COMET Scientist, University of Leeds) was chosen to serve on the Mission Advisory Group for the Sentinel-1 NG mission, the follow on from the current Sentinel-1 satellite constellation.

Juliet Biggs (COMET Scientist, University of Bristol) and **Andy Hooper** (COMET Scientist, University of Leeds) both serve on the Harmony Mission Advisory Group for Earth Explorer 10.

Luke Bateson (COMET Scientist, BGS) and **Alessandro Novellino** (COMET Scientist, BGS) served as members of the Advisory Board for the European Ground Motion Service (EGMS). EGMS provides consistent and reliable information regarding natural and anthropogenic ground motion over the Copernicus Participating States and across national borders, with millimetre accuracy. The EGMS represents a baseline for ground motion applications at continental, national and local level. For the first time this service provides free and consistent information on ground motion for all of Europe. This quantitative information is wide reaching and enables the public and government to be better informed on the hazards in their area.

Jurgen Neuberg (COMET Scientist, University of Leeds) Chairs the Montserrat Scientific Advisory Committee.

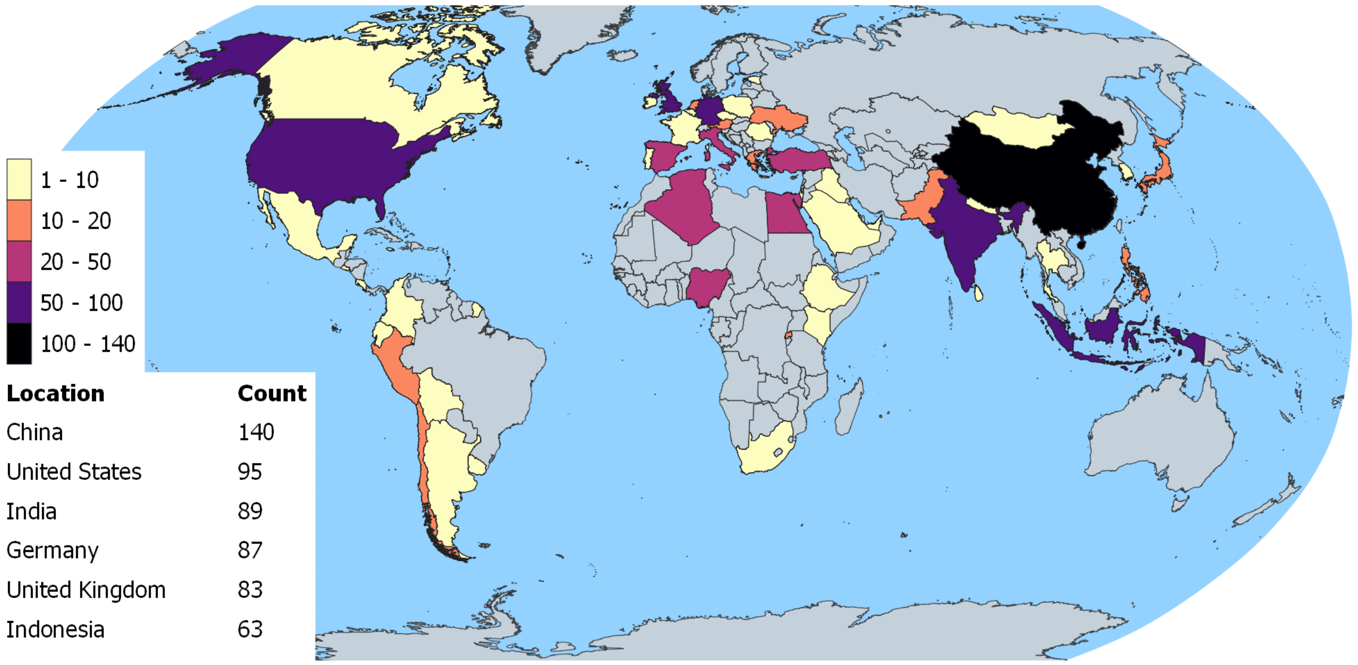
TRAINING AND EDUCATION

Our flagship training event is our annual InSAR course, held in Leeds over three days each autumn. The course aims to improve InSAR processing and analysis skills for students and early career researchers as well as those working in industry and the public sector, focusing on topics such as accessing and processing data, time series analysis and data modelling. Due to Covid-19 restrictions, the 2021 workshop was again held online with 348 participants joining virtually from around the world at different stages in their careers. All teaching materials and processing was completed in new online Jupyter notebooks, which facilitated remote participation.

Our membership of the Copernicus Academy means that we are connected to European research institutions and other organisations to jointly develop lectures, training courses, internships and educational material. The aim is to empower the next generation with suitable skill sets to use Copernicus data and information services to their full potential.

We also contribute to a wide range of external training courses, nationally and internationally.

COMET InSAR Training Workshop 2021 - Participants per country



Location	Count
China	140
United States	95
India	89
Germany	87
United Kingdom	83
Indonesia	63


Drone image from Mongolia fieldwork, Credit: Ben Johnson, University of Oxford

COMMUNICATION, OUTREACH AND ENGAGEMENT

Communication and public engagement are important aspects of COMET's mission as we aim for the science we produce to be understood by a wide variety of people across the world.

Webinars

COMET webinars promote research from COMET scientists in 1 hr seminars (40 – 50 minutes + questions), which are advertised to our wider COMET community, and uploaded to our YouTube channel, social media, and website.

Our COMET webinars[1] have covered a number of topics, including: monitoring volcano deformation with InSAR & machine learning; deformation above inflating igneous sills in sedimentary basins; measurements of volcanic plumes with the Infrared Atmospheric Sounding Interferometer (IASI); and using satellites to inform seismic hazard and risk estimates in Central Asia. 3 COMET+ webinars included presentations on: Present-day crustal deformation of Java, Indonesia using GPS data, geohazard assessment of Mexico City's metro system from SAR interferometry observations and impacts of climate change on the stratospheric volcanic sulfate aerosol lifecycle. In total we have offered 12 webinars, presented from 8 different institutions, including 2 from speakers outside of the UK.

Over the last year, we have attracted over 100 registrations per webinar. Our webinars uploaded to YouTube in this reporting period have reached a large audience, with over 2100 views.

Website

The COMET website has received 58,100 views and 25,235 visitors in the last year. The website highlights our research and latest news but also enables access to our webinars, datasets and services, including the volcano deformation database.[2] We are currently updating the look and content of the website to ensure that it is user-friendly and up-to-date.

We have gained over 300 Twitter followers over the last year – we now have 2,986 followers.[3] Our Instagram followers have also risen to 100.[4]

Media

Our work is widely accessible online and in print and COMET experts are contacted by the media to provide expert information about a range of topics. COMET members have commented on a wide range of topics and shared their research in the media over the last year including on: the air pollution impacts of the Geldingadalur eruption, the aviation impacts of the La Palma eruption, the influence of sea-level rise and fall on the eruptive activity of the Santorini Volcano, the amount of energy released by volcanic eruptions deep in our oceans, and the Tonga eruption.

Public engagement and outreach

COMET contributed EO analysis, images, and animations of Quito city to two museum exhibits (Museo Interactivo de Ciencia and Museo de la Ciudad, Quito) coordinated by the Tomorrow's Cities project. Members actively engage in local public events and seminars.

COMET members have given 5 talks to Schools groups and COMET Scientist Tamsin Mather (University of Oxford) was interviewed by the GeogPod – The Geographical Association's podcast. COMET Postgraduate Researcher, Ana Pardo Cofrades took part in the 'Cosmic Cast' series, whilst still in the field, to discuss her ongoing fieldwork of collecting rock samples and monitoring gas emissions at the La Palma eruption. COMET Postgraduate Researcher Alice Turner was also interviewed for the same series.

1 comet.nerc.ac.uk/comet-webinar-series/
2 comet.nerc.ac.uk/volcanoes/
3 @nerc_comet
4 www.instagram.com/comet_nerc/

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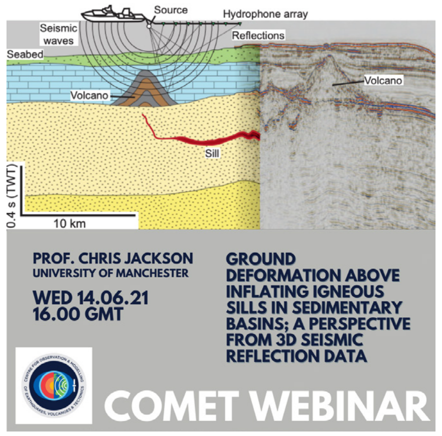

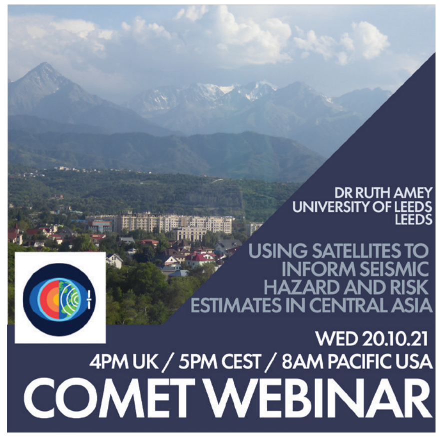

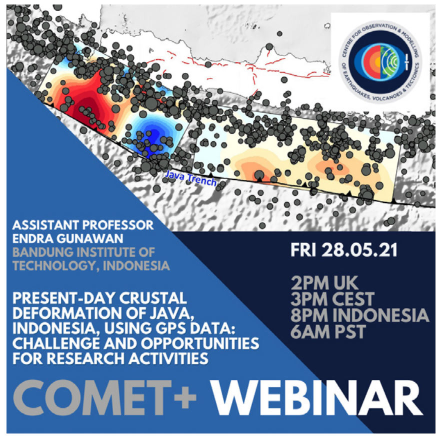

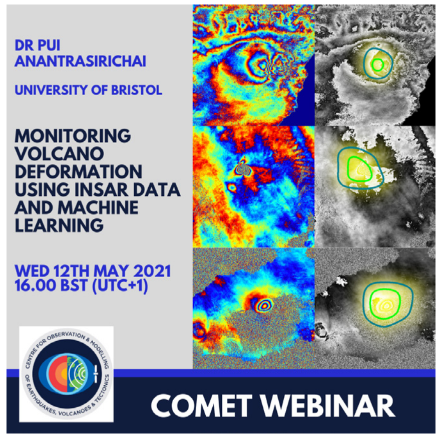

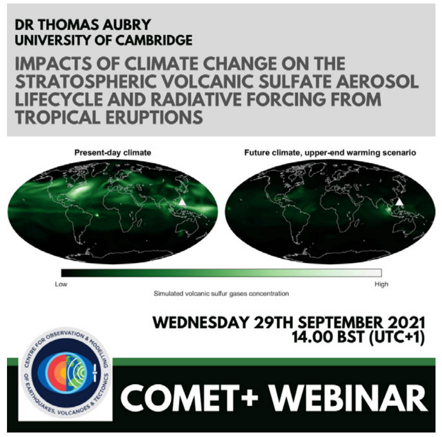

COLLABORATIONS AND PARTNERSHIPS

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

DEEPVOLC is an ERC funded programme let by Andy Hooper at the University of Leeds that aims to forecast volcanic activity by applying artificial intelligence to new data. DEEPVOLC will apply deep learning algorithms to satellite data to combine knowledge from all volcanoes that have been active in the satellite-monitoring era. This will enable us to use knowledge of how volcanoes behave globally to identify deformation at volcanoes locally, and forecast how it will evolve. The aim is to create tools that can aid in forecasting of volcanic activity.

EUROVOLC[1] is a European Commission Horizon2020 Infrastructure project established to support interconnection and collaboration within the European volcanological community and enable access to the community's research infrastructure and data. The project builds upon experiences of FUTUREVOLC, with partners from 9 European countries representing volcano research and monitoring institutions, civil protection agencies, a Volcanic Ash Advisory Centre (VAAC) and companies from R&D, IT and geothermal industries.

The European Plate Observing System (EPOS)[2] is a long-term plan to facilitate integrated use of data, data products, and facilities from distributed research infrastructures for solid Earth science in Europe. EPOS brings together Earth scientists, IT experts, decision makers, and public to develop new concepts and tools that will help us to better manage geohazards.

Global Earthquake Model (GEM)[3] - COMET has extended collaboration with GEM through a project aimed at improving probabilistic seismic hazard and risk assessment in Central Asia.

The NERC-funded **Looking inside the Continents from Space** (LiCS) project is using Sentinel-1 data to revolutionise our knowledge of how continents deform, how strain accumulates during the earthquake cycle, and how seismic hazard is distributed. LiCS is combining satellite data with ground-based observations to map tectonic strain throughout the Alpine-Himalayan Belt and East African Rift, using the results to inform new models of seismic hazard. The LiCSAR service provides Sentinel-1 InSAR products for download, with interferograms and coherence maps produced automatically using the LiCSAR processor and new interferograms available within two weeks of data acquisition. The initial focus on the Alpine-Himalayan tectonic belt is also being expanded with the aim of producing a complete archive for tectonic and volcanic areas globally, as well as development of a rapid event response facility.

R4Ash (Radar-supported next-generation forecasting of volcanic ash hazard), a NERC-funded project, is developing new approaches to forecasting the extent and evolution of ash-rich volcanic plumes, alongside techniques for understanding uncertainty and state-of-the-art satellite observations of volcanic plumes. This will provide critical insights into how plumes evolve as they are dispersed, and obtain real-time data that will be transformational for volcanic plume forecasting and hazard assessment.

1. eurovolc.eu
2. www.epos-eu.org/
3 www.globalquakemodel.org/gem

RISE (Real-Time Earthquake Risk Reduction for a Resilient Europe) - Earthquakes are the deadliest natural hazard. The aim of RISE is to develop tools and measures to reduce future human and economic losses. RISE is a three-year project financed by the Horizon 2020 programme of the European Commission and led by ETH Zurich.

RiftVolc[4], led by the Universities of Edinburgh and Bristol, focuses on volcanoes and volcanic plumbing systems in the East African Rift Valley. It is investigating what drives eruptions over geological timescales; what controls the active magmatic system and volcanic unrest; and what the potential threats from future volcanic activity are. RiftVolc has led to a step change in our understanding of many Ethiopian volcanoes, with recently published research addressing topics such as post-caldera volcanism along the Main Ethiopian Rift, and seasonal patterns of seismicity and deformation at the Alutu geothermal reservoir.

The **UKRI GCRF Urban Disaster Risk Hub** is a £20 million international collaboration aiming to provide new understanding of multi-hazard for four target cities (Istanbul, Kathmandu, Nairobi and Quito), and inform policy development on risk reduction as a result. The project includes using EO techniques, primarily satellite data, to produce data sets and information on hazard that can be used by Hub partners in achieving the wider project aims.[5]

The NERC **V-Plus** (Volcanic plume understanding and forecasting: Integrating remote-sensing, in-situ observations and models) project is seeking to transform our understanding of volcanic plumes and deliver methods and tools that enhance monitoring and forecasting capabilities in the UK and beyond. It will exploit data from the new TROPOMI satellite mission to characterise and track volcanic plumes, and combine this with other observations and atmospheric modelling to study plumes with unprecedented fidelity, and translate the tools for direct use by VAACs and volcano observatories.

4. riftvolc.wordpress.com/
5. www.tomorrowscities.org/

AWARDS AND RECOGNITION

Gregory Houseman (Emeritus COMET Scientist, University of Leeds) was honoured with Fellowship of the Royal Society. This prestigious title is awarded to scientists who have made an exceptional contribution to science.

Tamsin Mather (COMET Scientist, University of Oxford) received the honorary title of Geochemistry Fellow from the Geochemical Society and the European Association of Geochemistry, in recognition of a broad spectrum of scientific achievements that have advanced geochemistry. In addition Tamsin became the Chair of the Volcanic and Magmatic Studies Group and was elected member of the Academia Europaea.

Marie Edmonds (COMET Scientist, University of Cambridge) has received the honorary title of Geochemistry Fellow from the Geochemical Society and the European Association of Geochemistry, in recognition of a broad spectrum of scientific achievements that have advanced geochemistry. Marie was also presented with the Geological Society's Bigsby Medal.

Ekbal Hussain (COMET Scientist, BGS) was awarded a national BGS research prize in recognition of efforts to drive forwards the InSAR capability at the BGS.

Alice Turner (COMET Postgraduate Researcher, University of Oxford) was awarded an AGU Outstanding Student Presentation Award.

John Dianala and **Rebecca Colquhoun** (COMET Postgraduate Researcher, University of Oxford) were both awarded the Seismological Society of America 2021 Student Presentation Award, which honours excellent poster or oral presentations at the Annual Meeting, which was held virtually in April.

David Ferguson (COMET Associate, University of Leeds) achieved a Fellowship of the Higher Education Academy in the August review panel of the PRiSE scheme.

Tim Craig (COMET Scientist, University of Leeds) was named as a recipient of the 2022 EGU Outstanding Early Career Scientist Awards. Geodynamics (GD) Division. Tim was also named as the 2022 Bullerwell Lecturer by the British Geophysical Association, as an Outstanding Early-Career Scientist.

Anja Schmidt (COMET Associate, University of Cambridge) was a finalist in Physical Sciences and Engineering at the 2022 Blavatnik Awards for young scientists in the UK.

COMET ANNUAL REPORT 2022

EQUALITY, DIVERSITY AND INCLUSION

COMET is committed to delivering practical changes that help increase equality, diversity, and inclusion within our community.

COMET has an EDI working group. During 2021-2022 the group has:

- Requested the optional collection of EDI data with the aim of identifying and addressing any inequalities, and allowing us to make specific adjustments or interventions to attendance at and participation in COMET events. 126 COMET members participated in an EDI survey in advance of the COMET Annual Meeting 2021.
- Coordinated a series of COMET+ webinars. The COMET+ webinar series aims to promote research being undertaken by collaborators of COMET scientists. Particularly in-country collaborators, early career researchers, and scientists from minority backgrounds.
- Developed a set of fieldwork guidelines.
- Led a dedicated EDI session at the COMET Annual Meeting.
- Provided important recommendations for the development of the summer internship programme and the ways in which this is advertised.
- Produced a code of conduct and complaints policy for COMET.

OUR MEMBERS, APRIL 2021 - MARCH 2022

COMET Directorate

Tim Wright (Leeds)
COMET Director

Juliet Biggs (Bristol)
Deputy Director (Volcanoes)

Susanna Ebmeier (Leeds)
Deputy Director (Volcanoes)
covering **Juliet Biggs** maternity leave

Marek Ziebart (UCL)
Deputy Director (Earth Observation)

Alex Copley (Cambridge)
Deputy Director (Earthquakes and Tectonics)

Colm Jordan (BGS)
BGS Representative

Luke Bateson (BGS)
BGS Representative

Susan Loughlin (BGS)
BGS Representative

Suzanne Banks (Leeds)
COMET Finance Administrator

Naomi Nathan-Thomas (Leeds)
COMET Finance Administrator

Ruth Lawford-Rolfe
COMET Manager
covering **Charlotte Royle** maternity leave

Charlotte Royle (Leeds)
COMET Manager

Lucy Sharpson (Leeds)
COMET Research Administrator

COMET Scientists

As well as contributing to our objectives and partnerships through co-funded projects, COMET Scientists play a key role in internal review and forward planning for the COMET science programme.

Brian Baptie (BGS)

Mike Burton (Manchester)

Timothy Craig (Leeds)

Melanie Jane Duncan (BGS)

Marie Edmonds (Cambridge)

John Elliott (Leeds)

Samantha Engwell (BGS)

Pablo Gonzalez (Liverpool)

Don Grainger (Oxford)

Laura Gregory (Leeds)

Jessica Hawthorne (Oxford)

Andy Hooper (Leeds)

Ekbal Hussain (BGS)

James Jackson (Cambridge)

David Kerridge (BGS)

Tamsin Mather (Oxford)

Ilaria Mosca (BGS)

Jurgen (Locko) Neuberg (Leeds)

Alessandro Novellino (BGS)

David Pyle (Oxford)

Susanne Sargeant (BGS)

Richard Walker (Oxford)

Joanna Walsh (BGS)

Richard Walters (Durham)

Matthew Watson (Bristol)

Max Werner (Bristol)

COMET Emeritus

Philip England (Oxford)

Gregory Houseman (Leeds)

Barry Parsons (Oxford)

Geoff Wadge (Reading)

COMET Research Staff

COMET Research Staff are all directly funded by core COMET National Capability funding.

Fabien Albino (Bristol)

Pui Anantrasirichai (Bristol)

Matthew Gaddes (Leeds)

Tamarah King (Oxford)

Milan Lazecky (Leeds)

Yasser Maghsoudi (Leeds)

Chris Rollins (Leeds)

Isabelle Taylor (Oxford)

C. Scott Watson (Leeds)

COMET Postdoctoral Researchers

COMET Postdoctoral Researchers usually work directly with or are supervised by a COMET Scientist.

Ruth Amey (Leeds)

Yannick Caniven (Oxford)

Simon Daout (Oxford)

Ben Esse (Manchester)

Catherine Hayer (Manchester)

Hui Huang (Oxford)

Krisztina Kelevitz (Leeds)

Camila Novoa Lizama (Leeds)

Simone Mancini (BGS)

Qi Ou (Oxford)

Ian Pierce (Oxford)

Julien Renou (Oxford)

Zahra Sadeghi (Leeds)

Lin Shen (Leeds)

Iris van Zelst (Leeds)

Luke Wedmore (Bristol)

Chen Yu (Newcastle)

OUR MEMBERS, APRIL 2021 - MARCH 2022

COMET Associates

COMET Associate Scientists are collaborators who are engaged with our science programme; this includes postdoctoral researchers with independent research fellowships who are based in COMET research teams. Associates are not funded by COMET, but are invited to annual science meetings (and other meetings as appropriate), included in internal communications, and encouraged to collaborate and engage with other COMET members for mutual benefit.

Philip Benson (Portsmouth)
Lidong Bie (UEA)
Sarah Boulton (Plymouth)
Peter Clarke (Newcastle)
John Douglas (Strathclyde)
Ake Fagereng (Cardiff)
David Ferguson (Leeds)
Matt Fox (UCL)
James Hickey (Exeter)
Anna Hicks (BGS)
Evgenia Ilyinskaya (Leeds)
Chris Jackson (Manchester)
Mike Kendall (Oxford)
Zhenhong Li (Newcastle)
Brendan McCormick Kilbride (Manchester)
Craig Magee (Leeds)
Andrew McGonigle (Sheffield)
Zoe Mildon (Plymouth)
Andy Nowacki (Leeds)
Camilla Penney (Cambridge)
Tom Pering (Sheffield)
Margherita Polacci (Manchester)
Ed Rhodes (Sheffield)
Dylan Rood (Imperial)
Anja Schmidt (Cambridge)
Margarita Segou (BGS)
Charlotte Vye-Brown (BGS)
Tom Wilkes (Sheffield)
Sam Wimpenny (Cambridge)
Annie Winson (BGS)

Cumbre Vieja, La Palma,
Credit: Ana Pardo Cofrades, University of Manchester

Flat alluvial fan and the uplifted northern range front of the western Zailisky Alatau, Kazakhstan, Credit: CH Wendy Tsai, University of Oxford

OUR MEMBERS

COMET Students

All COMET students receive supervision from COMET Scientists or COMET Postdoctoral Researchers. While a few studentships are funded directly by COMET, most of the students within the COMET community are externally funded.

Josefa Sepulveda Araya (Leeds)
Nick Barber (Cambridge)
Pedro Espin Bedon (Leeds)
Mark Bemelmans (Bristol)
Rachel Bilsland (Leeds)
Alice Blackwell (Leeds)
Reza Bordbari (Leeds)
Felix Boschetty (Leeds)
Elizabeth Callander (Durham)
Manon Carpenter (Leeds)
Jennifer Castelino (Leeds)
Robbie Churchill (Bristol)
Ana Pardo Cofrades (Manchester)
Rebecca Colquhoun (Oxford)
Jacob Connolly (Leeds)
James Dalziel (Bristol)
Juliette Delbrel (Manchester)
John Dianala (Oxford)
Manuel-Lukas Diercks (Plymouth)
Nicholas Dodds (Oxford)
Edna Dualeh (Leeds)
Bob Elliott (Durham)
Jin Fang (Leeds)
Natalie Forrest (Leeds)
Dan Gittins (Oxford)
Olivia Hogg (Cambridge)
Alex Jenkins (Bristol)
Yu Jiang (Liverpool)
Benedict Johnson (Oxford)
Russell Khan (Bristol)
Lizzie Knight (Cambridge)
Fei Liu (Leeds)
Ahmed Mahmoud (Nottingham)
Grace Manley (Oxford)
Neill Marshall (Oxford)
Emily Mason (Cambridge)
Jack McGrath (Leeds)
Gauhar Meldebekova (Newcastle)
Sophie Miocevich (Cambridge)
Christopher Moore (Leeds)
Elish O'Grady (Leeds)
Aisling O'Kane (Cambridge)
Alice Paine (Oxford)
Jessica Payne (Leeds)
Pawan Piromthong (Leeds)
Victoria Purcell (Leeds)
Maddie Reader (Bristol)
Eoin Reddin (Leeds)
Marine Roger (Newcastle)
Michelle Rygus (Pavia, BGS)
Daniel Sefton (Leeds)
Anza Shakeel (Durham)
Dinko Sindija (Leeds)
Chuang Song (Newcastle)
Richard Strange (Oxford)
Chia-Hsin (Wendy) Tsai (Oxford)
Alice Turner (Oxford)
Megan Udy (Leeds)
Dehua Wang (Leeds)
Andrew Watson (Leeds)
Rachel Whitty (Leeds)
Andrew Whyte (Cambridge)
Roberta Wilkinson (Oxford)
Cindy Lim Shin Yee (Bristol)
Stanley Yip (Bristol)
Eva Zand (Leeds)

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Fagradaisfjall, Iceland,
Credit Evgenia Ilyinskaya,
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Artist's impression of Sentinel-1B, Credit: ESA-P Carril

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GLOSSARY

AHB	Alpine-Himalaya Belt
ASM	Annual Science Meeting
BGS	British Geological Survey
CEDA	Centre for Environmental Data Analysis
CEOS	Committee on Earth Observation Satellites
CNRS	Centre National de la Recherche Scientifique
COBR	Cabinet Office Briefing Room
COMET	Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics
CrIS	Cross-track Infrared Sounder
DEEPVOLC	Forecasting Volcanic Activity Using Deep Learning (ERC-funded Project)
DEM	Digital Elevation Model
EIDP	Earthquake InSAR Data Provider
EDI	Equality, Diversity and Inclusion
EGMS	European Ground Motion Service
EGU	European Geophysical Union
EO	Earth Observation
EPOS	European Plate Observing System
ESA	European Space Agency
GACOS	Generic Atmospheric Correction Online Service for InSAR
GCP	Ground Control Point
GCRF	Global Challenges Research Fund
GEM	Global Earthquake Model
GeoTIFF	Tag Image File Format with embedded georeferencing
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GVM	Global Volcano Model
IASI	Infrared Atmospheric Sounding Interferometer
ICAO	International Civil Aviation Organisation
InSAR	Synthetic Aperture Radar Interferometry
INVOLCAN	Instituto Volcanológico de Canarias
IPNA-CSIC	Instituto de Productos Naturales y Agrobiología, Consejo Superior de Investigaciones Científicas
IRS	Infrared Sounder
ITRF	International Terrestrial Reference System
JASMIN	The UK's data analysis facility for environmental science
KIS	Kyrgyzstan Institute of Seismology
LiCS	Looking inside the Continents from Space
LOS	Line of Sight
MKDF	Main Kopetdag Fault
MORSE	MIPAS Orbital Retrieval using Sequential Estimation
NATO-SPS	North Atlantic Treaty Organisation – Science for Peace and Security
NCEO	National Centre for Earth Observation
NERC	Natural Environment Research Council
NGO	Non-Governmental Organisation
NOAA	US National Oceanic and Atmospheric Administration
RISE	Real-Time Earthquake Risk Reduction for a Resilient Europe (Horizon 2020 project)
RMSE	Root Mean Square Error
SAGE	Scientific Advisory Group for Emergencies
SAR	Synthetic Aperture Radar
TOPS	Terrain Observation with Progressive Scan
TROPOMI	Tropospheric Monitoring Instrument
UAS	Uncrewed Aerial System
UCL	University College London
USGS	US Geological Survey
VAAC	Volcanic Ash Advisory Centre
WMO	World Meteorological Organisation

Drone image in Kyrgyzstan, Credit: Roberta Wilkinson, University of Oxford

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