COMET

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

ANNUAL REPORT
2020 / 2021

British Geological Survey

UKRI Natural Environment Research Council

Cover image: Quito, Ecuador. C. Scott Watson

Sentinel-5P Liftoff, Credit: ESA-Stephane Corvaja, 2017

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INTRODUCTION

The Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) delivers world-leading 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 world-leading scientists across the British Geological Survey (BGS) and 10 UK universities: Bristol, Cambridge, Durham, Leeds, Liverpool, Manchester, Newcastle, Oxford, Reading and University College London (UCL). 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 world-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 partnership, 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 2020-21, the second year of our transition phase to a closer partnership with BGS, highlighting major scientific achievements as well as progress against our key objectives. It covers the period 1st April 2020 – 31st March 2021.

COMET ANNUAL REPORT 2021

DIRECTOR'S WELCOME

When we started this programme year in April 2020, we didn't imagine that COMET's seventh annual report would be prepared amidst an ongoing pandemic. While we have adapted to new ways of working from home offices, we are looking forward to returning to more in-person interactions (hopefully!) in the near future. After our successful first virtual annual meeting in June 2020, we held an engaging second virtual COMET Annual Meeting via Gather in June 2021. While we are planning for a face-to-face meeting in 2022, we hope to retain some features of online meetings permanently to facilitate wider, more convenient and more environmentally friendly access to our assemblies.

We have now completed our two-year "transition period" during which we have developed and solidified our working relationship with BGS. You can read about progress towards our goals in this report. One major achievement this year has been the approval of our proposed work plan for the 5-year period from April 2021 and the subsequent finalised 2021-2026 contract with BGS for the next five years of COMET National Capability funding. We are pleased to report that we have also finalised a collaboration agreement with all COMET partner institutions until March 2026, so we are looking forward to continuing working collaboratively across our partner universities and with BGS over the next few years.

COMET has seen several new arrivals in the last year. Two new staff scientists have joined COMET over the last year: Dr Matthew Gaddes, based at the University of Leeds and co-funded by an ESA Living Planet Fellowship, and Dr Tamarah King working on faulting and geomorphology, at Oxford Earth Science. We have also welcomed Dr Lin Shen as a COMET Postdoctoral Researcher at Leeds, researching volcanic deformation using InSAR techniques, and Professor Chris Jackson, Chair in Sustainable Geoscience at the University of Manchester, as a COMET Associate. See the 'New Starters' section of this report to find out more about our new members. We would also thank the staff members who have left during the past year for everything they have done for COMET and wish them the best in their new roles.

As usual, I'd like to offer my congratulations to numerous award winners (listed later in the document) in the year to April 2021, at all levels within COMET: Edna Dualeh (Leeds) was awarded Geological Remote Sensing Group (GRSG) student award, Marie Edmonds (Cambridge) was presented with the prestigious AGU Joanne Simpson Medal, John Elliott (Leeds) was awarded the international AGU John Wahr Early Career Award, Ekbal Hussain (BGS) received the BGS Instant Recognition Award, Tamsin Mather (Oxford) was elected a member of the Academia Europaea, Ailsa Naismith (Bristol) was selected to receive the Willy Aspinall award at the national Volcanic and Magmatic Studies Group (VMSG) awards, and Aisling O'Kane (Cambridge) was awarded the AGU Outstanding Student Presentation Award.
And of course congratulations to everyone for surviving an extremely challenging year.

Professor Tim Wright,
COMET Director (April 2021)

COMET COPING WITH COVID-19

Over the past year, COMET members have kept connected with each other from their home offices in various ways. From an increased reliance on Zoom and shared documents/files on Microsoft Teams to communicating through virtual avatars in Gather, we have kept the COMET science programme and social interactions running online. In some cases, the "new way of working" has even facilitated collaborations and closer working relationships across institutional boundaries!

The early weekly COMET coffee mornings included activities such as quizzes, origami (lots of origami!) and group painting. As people became more fatigued by online gatherings, we reduced the meetings to once per month and focused them around a discussion topic, such as equality, diversity and inclusion (EDI) initiatives, effective public engagement, and introductions to new research students. We will keep reviewing these monthly meetings to ensure there is a continued desire for them and that they remain useful.

COMET ANNUAL REPORT 2021

ADVISORY BOARD COMMENTS 2020

Annual Meeting

The 2020 COMET Annual Meeting faced the unusual challenge of running remotely because of the coronavirus pandemic. Interestingly, however, it also offered opportunities to re-imagine meeting strategies aimed specifically at reducing COMET's carbon footprint, a challenge presented by last year's Advisory Board report. Overall, the transition to videoconferencing worked well, in large part because of the efforts of COMET General Manager Charlotte Royle and Staff Member Chris Rollins, who set up and rapidly updated the Slack channel and quickly posted videos of the presentations.

The science presented by a wide range of COMET members, including numerous postdocs and PhD students, was not only of high quality but also nicely delivered via virtual posters with follow-up discussions on the Slack channel. The report by the students during the final closing session suggested that the format worked well. We were also impressed with the choice of keynote speakers, who joined from around the world and gave stimulating talks that covered not only different aspects of Earth observation science but also bridged to questions of science policy and risk assessment.

COMET clearly contributes substantially to the human capital of EO sciences in the UK. COMET has always attracted a diverse group of students and postdocs with regard to country of origin. The Earth science and Physics communities, in general, suffer from an extreme deficit of Black scientists. For this reason, we applaud the organization of breakout groups that focused on diversity issues; we also urge the leadership to act on some of the more tractable ideas that arose.
The only downside to the remotely run meeting was the inevitable loss of the casual contacts, discussions, and team building activities that are an important component of COMET annual meetings.

COMET Objectives

The long-term objective for COMET of providing broad and timely access to EO data is rapidly being realised. We are particularly impressed by the automated processing efforts, as highlighted by LICSAR, the extent to which COMET products are being used outside COMET, and that access is increasing rapidly. From the perspective of the end user, an important component of usability is the intercomparison that is now being done between different sensors and processing techniques. This is valuable, particularly for users who are not familiar with the details of data acquisition and processing. Also important is development of usage metrics in addition to open data and open codes.

COMET is also making important advances in the development of physics-based models and their integration with the observational data. The high standard of fundamental research is evidenced by not only the excellent science updates, which were both comprehensive and clearly presented, but also the impressive list of publications by, and awards to, COMET scientists. We also anticipate that COMET scientists in BGS and HEIs will benefit from the opportunities that arise from stronger collaboration.

2020 Board members in attendance:

Ramon Arrowsmith (Arizona State University)

Roland Bürgmann (University of California, Berkeley)

Kathy Cashman (University of Bristol)

Philippa Mason (Imperial College London)

Ramon Hanssen (Delft University of Technology)

Valérie Cayol (University Clermont-Auvergne)

Elisa Carboni (RAL Space - NCEO).

NEW STARTERS

COMET Research Staff: Dr Matthew Gaddes, European Space Agency Living Planet Fellow, University of Leeds

Matthew was previously a PhD student at the University of Leeds where he was funded by the Looking inside the Continents from Space (LiCS) project. During this and a subsequent short COMET postdoc, he and Andy Hooper developed a prototype of a machine learning based algorithm for monitoring subaerial volcanoes using Sentinel-1 data (named LiCSAlert). During his fellowship, he aims to both improve several aspects of this algorithm through the use of deep learning, and to develop it into a service that is freely available to parties concerned with volcano monitoring.

COMET Associate: Professor Chris Jackson, Chair in Sustainable Geoscience, University of Manchester

Chris is Chair in Sustainable Geoscience at the University of Manchester. His research interests are rather broad, spanning the structure and stratigraphy of sedimentary basins, and the processes and products of crustal magmatism. He uses a range of data types in his research, including seismic reflection and borehole data, field data, and physical and numerical models. Past and ongoing research includes the analysis of the geometry and growth of normal faults, and the mechanics of magma emplacement in the brittle upper crust. Other research of potential relevance to COMET is his work in submarine landsliding; although submarine, terrestrial landslides, which share some geometric and kinematic similarities to their submarine counterparts, are a significant geohazard.

COMET Research Staff: Dr Tamarah King, University of Oxford

Tamarah joined COMET in April 2020 as a postdoctoral researcher in the Department of Earth Sciences at the University of Oxford, part of the Earthquakes and Active Tectonics research group. The group primarily investigate active faults through Central Asia using a combination of field-based, seismological, and remote-sensing techniques. She is also interested in the use of geological data in seismic hazard assessments, and quantifying near-fault ground motion intensities. She's originally from Katherine, a small remote town in northern Australia situated on Jawoyn and Dagoman country. She has lived in Melbourne (Australia) on the lands of the Wurundjeri people while completing her degrees at the University of Melbourne, and shes also lived in Glasgow (Scotland) and Yogyakarta (Indonesia).

COMET Postdoctoral Researcher: Lin Shen, Post-doctoral Researcher (Leeds)

Following completion of her PhD at the University of Leeds, Lin is now a postdoctoral researcher at Leeds researching volcanic deformation using InSAR techniques. She works on the European research project DEEPVOLC, applying InSAR from multiple satellites to image volcano deformation. In addition, Lin works closely with the Looking inside the Continents from Space (LiCS) teams to monitor seismic risk of active faults in Tibet.

Artist's impression of Sentinel-1B, Credit: ESA-P Carril

COMET OBJECTIVES

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.

We also aim to work closely with BGS to deliver against our mutual aims of better understanding both hazard and risk.

Specific science objectives for 2019-2021 are:

EO data and services

1. Deformation from satellite geodesy:

- Continue the long-term development of our Sentinel-1 InSAR processing facility at Jasmin/CEDA, focusing on producing consistent, reliable, and accessible long-term rates of deformation and time series globally for the tectonic belts and subaerial volcanoes.
- Produce 3D velocities by exploiting burst overlaps in Sentinel-1.
- Automate the production of time series, improving our atmospheric correction service, to enable rapid response following volcanic or seismic events using data from multiple satellites.

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

- Automate the production of displacement measurements from Sentinel-2 data.
- Develop methodologies to exploit the ongoing expansion in high-resolution optical satellite images (e.g. from CubeSats and satellite video).
- Produce datasets as required by the hazard teams.

3. Retrievals of volcanic emissions from satellite spectrometers:

- Develop methods to derive SO2 fluxes at quiescent degassing volcanoes (back to 2007 for IASI; 2017 for Tropomi).
- Incorporate laboratory measurements of ash optical properties of volcanic ash into IASI retrievals so we can estimate SiO2 composition.

4. Geoinformatics and machine learning:

- Consult with end users and build a unified, integrated portal to simplify COMET data access.
- Develop Machine Learning algorithms to identify anomalous behaviour at volcanoes.
- Trial Machine Learning algorithms with stakeholders towards real-time operation at volcanoes.

Tectonics and Volcanism

1. Tectonics and seismic hazard

- Construct the first global high-resolution strain-rate map, from InSAR and GNSS, of the Alpine-Himalayan Belt and East African Rift.
- Produce and deliver (to GEM), maps of active faults and their rates of activity, initially in Central Asia.
- Assess temporal variations in strain across distributed fault networks, in Central Asia, Turkey and Italy.
- Begin development of next-generation of geodynamic models of continental deformation linking short and long timescales.

2. Magmatism and volcanic hazard

- Produce deformation time series for all subaerial volcanoes, beginning to build a long term (decadal) view of processes occurring at volcanoes in different stages of the eruptive cycle.
- Construct the first global assessment of current volcanic SO2 flux from IR and UV data.
- Build models of magmatic systems that can explain gas and deformation observations, initially in Iceland.
- Develop near real-time tools for monitoring volcanic unrest, using machine learning approaches for analysing large volumes of satellite data.

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

Mount Nyiragongo, DRC

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

Research highlight: Sentinel-1 derived surface velocity map covering the entire afar rift, highlighting active volcanic deformation and the accommodation of extension over rift segments

Chris Moore, PhD Graduand, University of Leeds

The Afar region of Ethiopia provides a unique example of a sub-aerial volcanic dominated rift in a transitional phase between continental and oceanic style rifting. Although processes that facilitate the transition between continental rifting and sea-floor spreading remain unclear, variations in the spatial distribution of extension through Afar and into the Red Sea are indicative of the temporal evolution of the rift.

In this research, we develop a time series of Sentinel-1 interferometric synthetic aperture radar (InSAR) observations of ground deformation covering the whole Afar Rift from 2014-2019, to study the distribution of extension across all magmatic segments. We implement a misfit weighted atmospheric correction to clean the time series, and produce average line-of-sight velocity maps for each Sentinel-1 frame. By incorporating a sparse network of observations from Global Navigation Satellite Systems (GNSS), we are able to reference the InSAR velocities to the stable Nubian plate. We then resolve 3D average velocities in the vertical, rift-perpendicular, and rift-parallel directions across the entire rift, whilst retaining the original Sentinel-1 100 x 100 m pixel resolution (Figure 1).

Our results show the long-term motion of the Danakil micro-plate with rift-perpendicular velocities of up to 25 ± 5 mm/yr, with negligible motions in the rift-parallel direction. From cross-rift profiles, we find that extension in northern Afar is largely focussed to within ± 15-30 km of the rift-axis on the active magmatic segments. While in southern Afar, near the Nubia-Arabia-Somalia triple junction, amagmatic extension is distributed across 80-160 km of the rift. This trend of increased focussing of extension with magmatic rift maturity is consistent with strain localisation assisting the transition into oceanic spreading centres.

We are able to resolve deformation at individual volcanic centres, with rapid subsidence at Dallol volcano consistent with the deflation of a shallow sill at 0.9-1.3 km depth (Figure 2F); and edifice uplift at Nabro volcano, which we infer is sourced from a magma chamber at 5.5-6.8 km depth (Figure 2G), consistent with the source of post-eruption subsidence observed between 2011-12.

We also observe rapid surface uplift and rift-perpendicular extension at the Dabbahu-Manda-Hararo (DMH) segment with velocities of 33 ± 4 mm/yr and 37 ± 4 mm/yr respectively (Figure 2I). These are higher than the background extension rate of 18-20 mm/yr, but have decreased by 55-70% since 2006-10. The data suggests that this is due to an on-going long-lived response to the 2005-10 rifting episode on the DMH segment, with potential continued processes below the segment including a lower-crustal viscous response and magma movement. Continued long-term observations of surface deformation provide key constraints on tectono-magmatic processes in Afar.

The work is in review but it is available online as a pre-print here: **https://doi.org/10.1002/essoar.10503895.1**

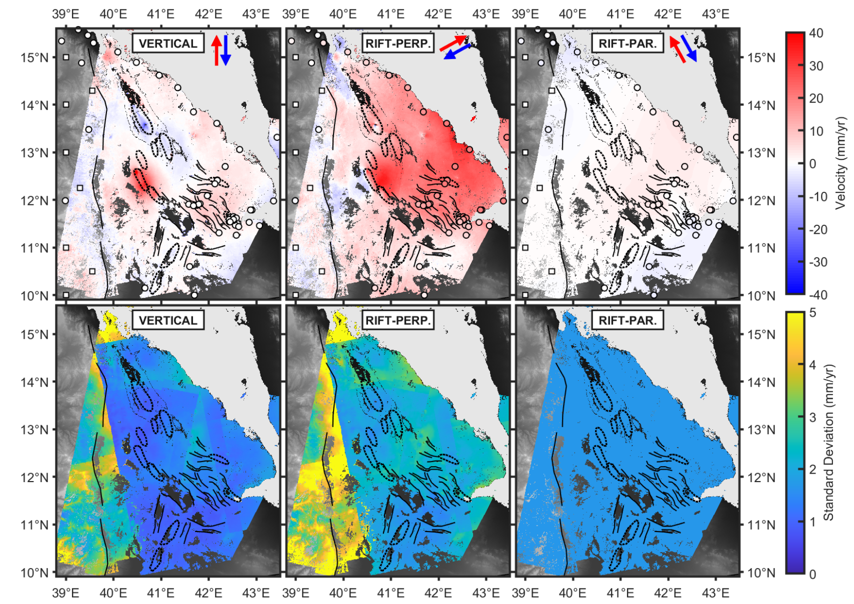

Figure 1: Vertical, rift-perpendicular, and rift-parallel average velocities and standard deviation over the Afar region between November 2014 and August 2019. All velocities are referenced to a stable Nubian plate. Vertical velocities are positive upwards, rift-perpendicular velocities are positive to the NE (61°N), and rift-parallel velocities are positive to the NW (-29°N). Real (circles) and fabricated (squares) GNSS stations used in the inversion are shown, with GNSS velocities shown as the fill colour. Volcanic segments and key faults are shown as black dashed outlines and black solid lines respectively.

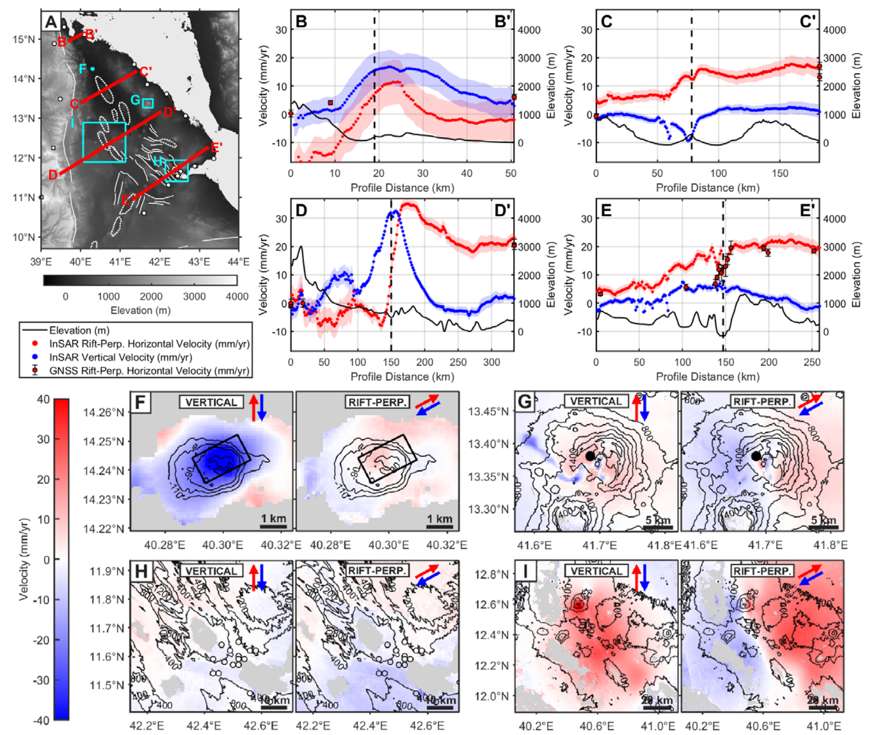

Figure 2: (A) The location of profiles (B-E) and subsets (F-I), with rift segments shown by white dashed outlines, and faults by solid white lines. The location of GNSS sites (white circles) used in (B-E) are shown in (A). Where GNSS sites are beyond the extents of the profiles, they are displayed at the profile limits on (B-E). (B-E) Vertical (blue, positive up) and rift-perpendicular (red, positive towards 61°N) velocities over four 10km-wide cross-rift profiles marked on insert map, covering (B) the northern tip of the Afar triangle, (C) the Erta ’Ale segment, (D) the Dabbahu-Manda-Hararo segment, and (E) the Asal-Ghoubbet segment. Black lines show surface elevation along the profiles, with vertical dashed lines indicating the location of the major rift axis on the profile. (F-I) Vertical and rift-perpendicular velocity maps at (F) Dallol volcano, (G) Nabro volcano, (H) the Asal-Ghoubbet segment, and (I) the Dabbahu-Manda-Hararo segment. Velocities in each subset are referenced to the local background mean value, with contours indicating elevation, and circles indicating GNSS velocities. The location of modelled deformation sources at Dallol (F) and at Nabro (G) are shown as black outlines.

COMET ANNUAL REPORT 2020

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

Research highlight: sub-centimeter resolution imaging of earthquakes: new insights into complex ruptures in the western us

Ian K.D. Pierce, Postdoctoral Fellow, University of Oxford

Many fine details of surface rupturing earthquakes are perishable: they are rapidly eroded and destroyed following an earthquake, so documenting these features is time sensitive. As only four surface rupturing earthquakes have occurred in the Western US during the 21st century, they offer a rare opportunity to study the effects of earthquakes on the landscape. As observational scientists, it is our duty to archive and preserve what we can for future generations to study.

On May 15 2020, the Mw 6.5 Monte Cristo Range earthquake occurred in the western desert of Nevada. It produced a strike-slip focal mechanism and generated a complex pattern of distributed surface ruptures over a 20km-wide zone. The maximum displacements measured in the field were generally <20 cm left-lateral and <15 cm of vertical. In the weeks following the earthquake, we collected aerial photographs over portions of these ruptures using small hobbyist UAVs. We processed these photos using structure-from-motion (SfM) software to produce 7 mm/pixel resolution orthoimages of over 3 km2 of the rupture area, or nearly 200 billion pixels. This resolution and volume of data quickly becomes a “big data” problem. We then used these resulting orthoimages to map over 15,000 individual fractures. Mapping this complicated rupture was incredibly difficult in the field, and vastly improved by these images.

The resulting fracture patterns are incredibly unusual for a strike-slip earthquake, forming discontinuous, anastomosing, and distributed zones that in places reach widths over a kilometre. In a geologic sense, this broad deformation would certainly be considered off-fault deformation, and would be difficult to account for by standard paleoseismic or geomorphic techniques. This provides a clear example of some of the difficulties facing slip rate comparisons made between studies that use geologic versus those that use space- or GNSS-based geodetic measurements.

We observed another unusual phenomenon both in the field and from this imagery: for a given field of cracks, generally all of only one side of the cracks were cleared of small pebbles. However, this dominant clearing side varied throughout the 20-km rupture zone. We interpret this to be a result of the directionality of crack opening, with one side of each crack popping free and experiencing much higher ground accelerations.

Both of these observations - the width of off-fault deformation and the directionality of coseismic fracture opening - would not have been possible at the overall rupture scale without this resolution of imagery, and likely have important implications for not only scientific understanding of rupture processes, but also for earthquake engineering and seismic design.

Image 1: Satellite image of part of the rupture area showing mapped fractures (black lines) and SfM orthoimagery extents (light blue). It is clear that the SfM orthoimagery improved the detail and quality of the rupture mapping.

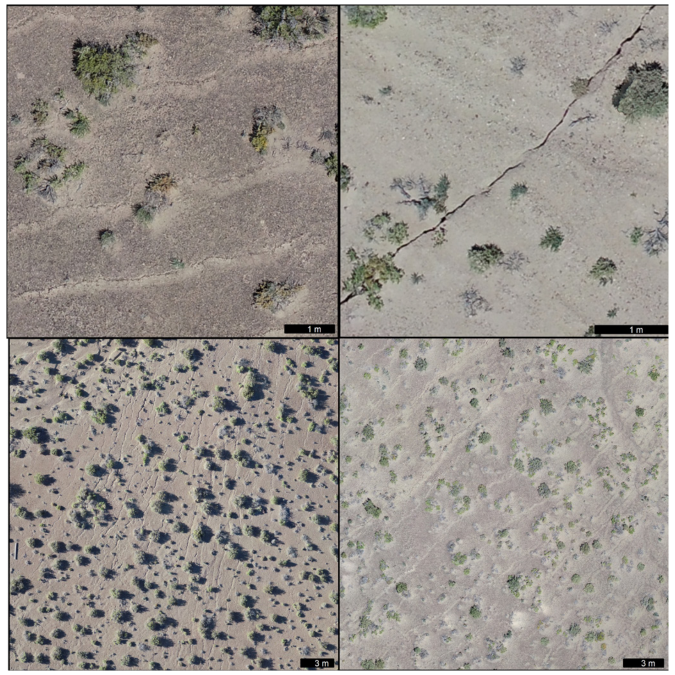

Image 2: Details of 7mm/pixel SfM derived orthoimages of ruptures from the Monte Cristo event. The upper right image shows the area of maximum lateral offset, with ~20 cm of left-lateral slip measured across the various channel features.

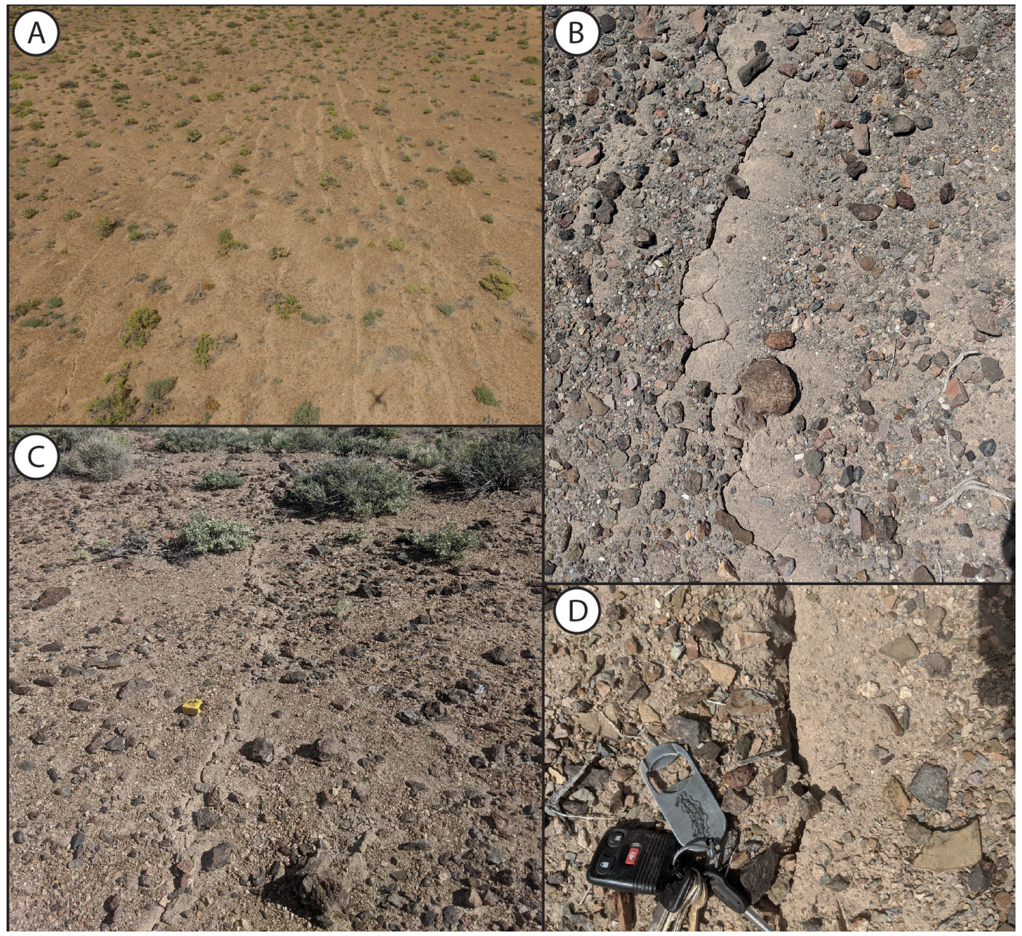

Image 3: Photos of cleared crack phenomena. A: oblique UAV photo of a crack field with clearings on the right. B-D: field photos of cracks showing clearings to image-right sides.

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

Research highlight: Seismogenic potential of the Philippine fault creeping section uncovered

J.D. Dianala, COMET PhD candidate, University of Oxford

The distribution of earthquake-rupturing and creeping sections of faults relates directly to seismic hazard and continues to be investigated for better understanding of earthquake mechanics. Fault creep involves slow and gradual slip over time, preventing interseismic stress accumulation that could otherwise be released suddenly to cause earthquakes. One such kind of fault known to creep is the Philippine Fault on Leyte Island (Figure 1a), a segment of the 1,200-km long fault that has been thought to be aseismic - that is, until a destructive magnitude 6.5 earthquake occurred there on 6 July 2017. This event surprised geoscientists and raised questions on what has been assumed about the fault.

To address the problem, we have mapped the surface deformation on Leyte Island using InSAR and present the first probabilistic interseismic and coseismic slip models of the Philippine Fault. Thanks to the coordination of COMET with the European Space Agency (ESA), an emergency Sentinel-1 pass was made across the island just a day after the July 2017 mainshock, providing us more coherent data than would have been available otherwise with the regular 12-day acquisition strategy in the region.

ALOS satellite InSAR data before the earthquake (from 2007 to 2011) allow us to track the surface deformation across the island, and we can identify creep right on the known fault trace for at least 100 km of the fault (Figure 1b). Modelling the interseismic slip rates from the InSAR data shows that the creep rates across the seismogenic zone of the Earth's crust reaches more than three centimetres per year. This is close to the long-term fault deformation rates on the island, which in this case generally means the fault would primarily slip aseismically. Most strikingly, however, the interseismic slip model highlights a shallow, 25-km long locked section in the middle of the island (Figure 2), which was previously unrecognized by previous studies based on sparse GPS data. With interferograms from Sentinel-1 and ALOS-2 satellites, modelling the coseismic slip in the July 2017 earthquakes shows that the recent seismic rupture was constrained to the same locked section identified from the interseismic model.

Different aspects of the geology of Leyte are known to promote aseismic slip on faults based on laboratory experiments, like the presence of hydrothermal fluids and rate-strengthening minerals in the fault zone. The reason for locking in a specific section of the fault is more enigmatic. More detailed work should be done to uncover the inner workings of the fault zone. The consequences of the unexpected hazard in Leyte have unfortunately directly affected the island's more than 2 million people and critical infrastructure. Both our models and the historical record suggest that similar seismic events could recur, and thus should be considered in the region's continued development. And with observations of creeping faults becoming more ubiquitous with the help of InSAR, like in Leyte, careful analysis of the causes of such variability in fault behaviour should drive further research in the scientific community.

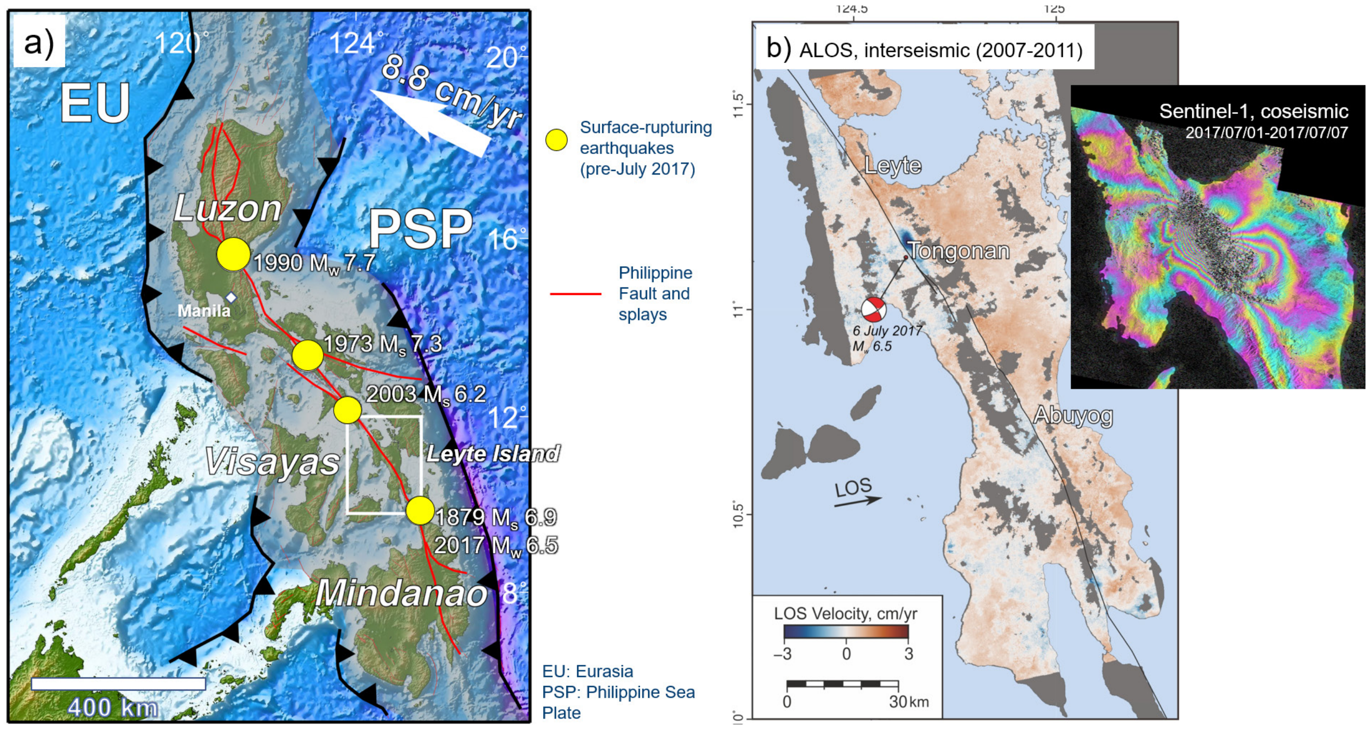

Figure 1: a) Tectonic setting of the Philippines, highlighting the Philippine Fault (red) and known surface rupturing earthquakes (yellow circles). The creeping fault section on Leyte Island is in the white box. **b)** Interseismic surface deformation map of Leyte in ALOS ascending track line-of-sight (LOS). Inset: Sentinel-1 interferogram spanning the 6 July 2017 mainshock obtained with the emergency acquisition from ESA.

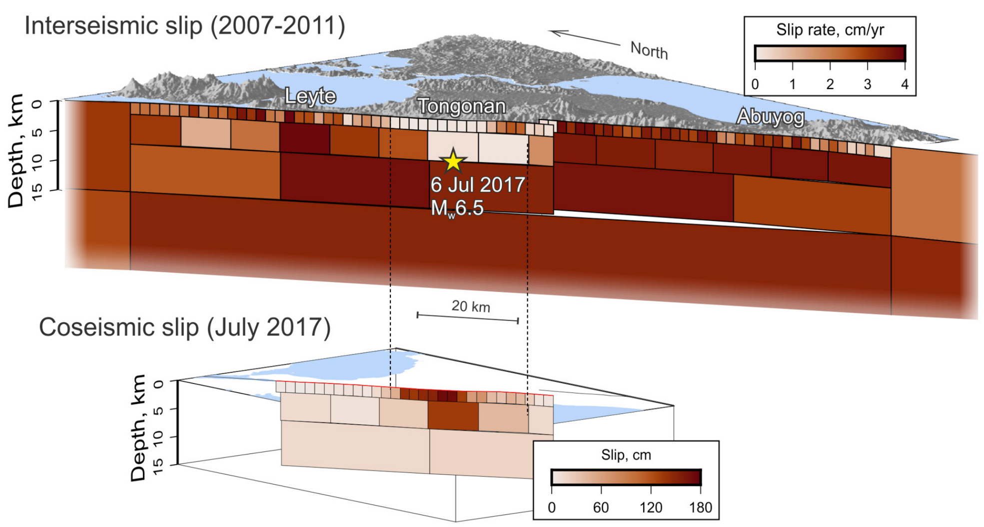

Figure 2: Interseismic and coseismic slip models of the Philippine Fault in Leyte (top and bottom diagrams, respectively). Darker patches indicate more slip on the fault. Fault patches closer to white in the interseismic model, between the dashed lines, comprise the locked Tongonan segment. Note that primarily only the locked patches slipped in the July 2017 earthquake, as shown by the coseismic model.

SCIENCE UPDATE: EO DATA AND SERVICES

1. Deformation from satellite geodesy

Progress report: continue the long-term development of our Sentinel-1 Insar processing facility at Jasmin/ Ceda, focusing on producing consistent, reliable, and accessible long-term rates of deformation and time series globally for the tectonic belts and subaerial volcanoes

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

During the current reporting period, we aimed at further developing the COMET-LiCSAR facility to complete the processing of the Alpine-Himalayan Belt, East African Rift and the volcanic priority zones. Considerable progress has been made toward these goals. As of March 2021, the system has processed about 136,000 Sentinel-1 acquisitions and generated more than 430,000 interferograms in 1774 frames. Figure 1 shows the number of generated interferograms from 2016 to present. For the current reporting period, we had a significant increase of 55,000 in the number of processed Sentinel-1 acquisitions and 203,000 in the number of generated interferograms.

Like any automatic system that provides services to the end-users, a quality check module is very important to make sure that the interferograms are correctly generated. In the past year, by using a large number of training samples, we were able to improve the quality check module. The module is mainly based on using some morphological image processing techniques and edge detection algorithms to identify the artefacts in the interferograms.

Since the last year, we have updated various parts of the system including visual representation of the COMET LiCSAR portal, interferogram previews generated by GMT using recommended scientific colour maps, automatised ingestion of GACOS data for correction of tropospheric delay, an improved Earthquake InSAR Data Provider (EIDP) for fast processing and delivery of especially co-seismic interferograms, and so on. From the technical side, we have improved our processing routines in various parts of the system. For example, we have significantly decreased both processing time and memory demands by optimising our phase unwrapping procedure. We have further optimised algorithms for an automatic check of the quality of generated LiCSAR products, used prior to their final ingestion to the CEDA Archive and EPOS system.

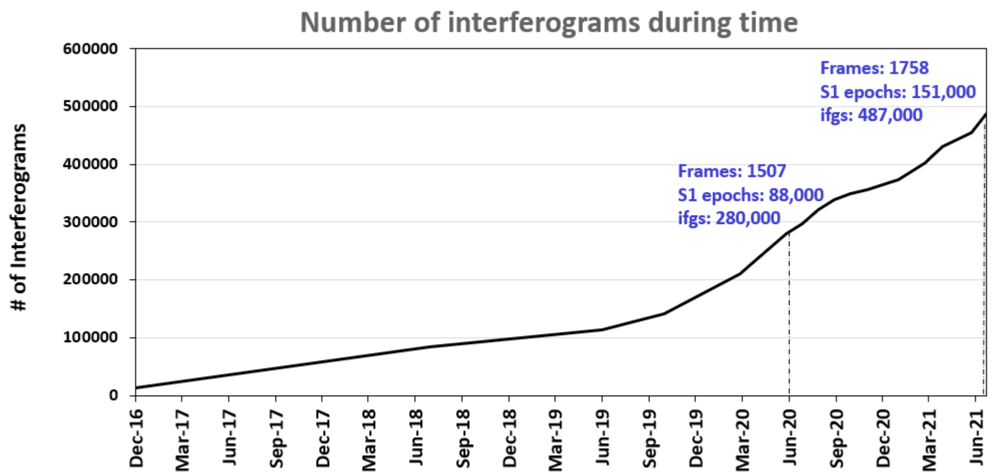

Figure 1: Number of interferograms over time

SCIENCE UPDATE: EO DATA AND SERVICES

Progress report: work towards producing 3d velocities by exploiting burst overlaps in Sentinel-1.

Andy Hooper, COMET Scientist, University of Leeds
Milan Lazecky, COMET Scientific Programmer, University of Leeds
Pawan Piromthong, COMET Postgraduate Researcher, University of Leeds

Continuing work from last year on extracting along-track velocities, we have combined these velocities for ascending and descending data over the Chaman Fault in Afghanistan/ Pakistan with InSAR line-of-sight velocities, to estimate the 3D velocity field (Figure 1).

Another advantage of along-track, measurements is that they can be extracted in a global reference frame, as opposed to InSAR line-of-sight measurements, which are relative to some other point in the coverage area. We have calculated mean along-track velocities for each LiCSAR frame in the Alpine-Himalayan Belt and they compare well to model values from ITRF (Figure 2). Combining this work with the estimation of high-resolution 3D velocities (above) will provide valuable data for strain rate estimation, not only by providing north-south motions in high resolution, but also in tying InSAR results to a global reference frame where GNSS data are sparse.

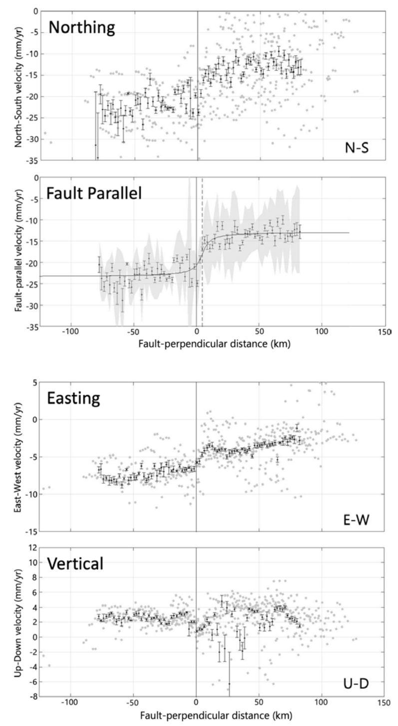

Figure 1: Profiles of decomposed velocities crossing the Chaman Fault estimated from along-track and line-of-sight InSAR observations at latitude 31ºN. The vertical line represents the fault trace. The grey dots are the average of decomposed velocities of each grid point projected from within ±40 km from the perpendicular profile. The error bars present mean velocities and one standard deviation for each 2-km bin. (Piromthong PhD thesis, 2021)

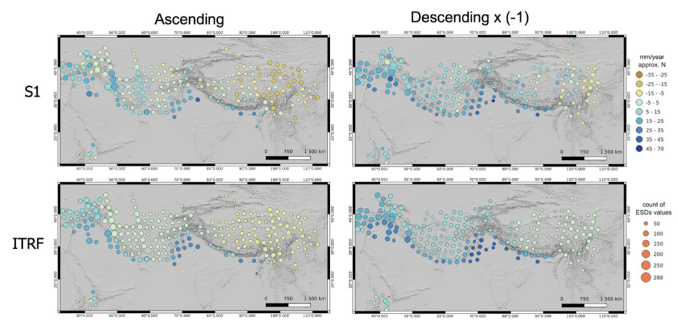

Figure 2: Mean along-track velocities estimated for each LiCSAR frame over the Alpine-Himalayan belt (above) and mean along-track velocities for same areas from ITRF2014 assuming no-net-rotation (below). The InSAR velocities have been corrected for solid earth tides and gradients of ionospheric total electron content (TEC).

SCIENCE UPDATE: EO DATA AND SERVICES

Progress report: automate the production of time series, improving our atmospheric correction service, to enable rapid response following volcanic or seismic events using data from multiple satellites

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

LiCSAR Earthquake InSAR Data Provider (EIDP)

The EIDP system checks for earthquake events of at least Mw5.5 from USGS database every 30 minutes, and performs several operations leading to the generation and sharing of co-seismic and post-seismic interferograms within the first few hours after a new relevant Sentinel-1 acquisition is offered to the public. The system combines both the CEDA JASMIN facility, which houses the COMET LiCSAR system, and ARC4 HPC at University of Leeds with reserved computing resources to allow for this fast response. The processed interferograms are compatible with LiCSAR frame units, thus allowing their further use e.g. for time series analysis. The outputs are accessible on a dedicated EIDP web page within the COMET LiCS-Portal. We additionally include selected frames of interest (e.g. covering erupting volcanoes) to this fast response autonomous processing system.

LiCSAR-LiCSBAS Time-series module

Upon the completion of InSAR processing for each frame, the LiCSBAS open-source InSAR time series analysis package, integrated with the LiCSAR processing system, is used to derive InSAR LOS displacement time series and velocities. The top panel in Figure 2 shows a preliminary velocity field in the Alpine-Himalayan Belt (AHB) using the current LiCSAR products. The middle panel represents the average coherence map, and the bottom panel illustrates the maximum length of the connected network. The availability of a long-term connected network is very important in the time-series analysis. As can be seen, most of the frames in the AHB have a fairly good (>4yrs) connected network. However, there are still some frames, which need to be further processed. We aim to fill all the gaps in the time-series for all our priority zones.

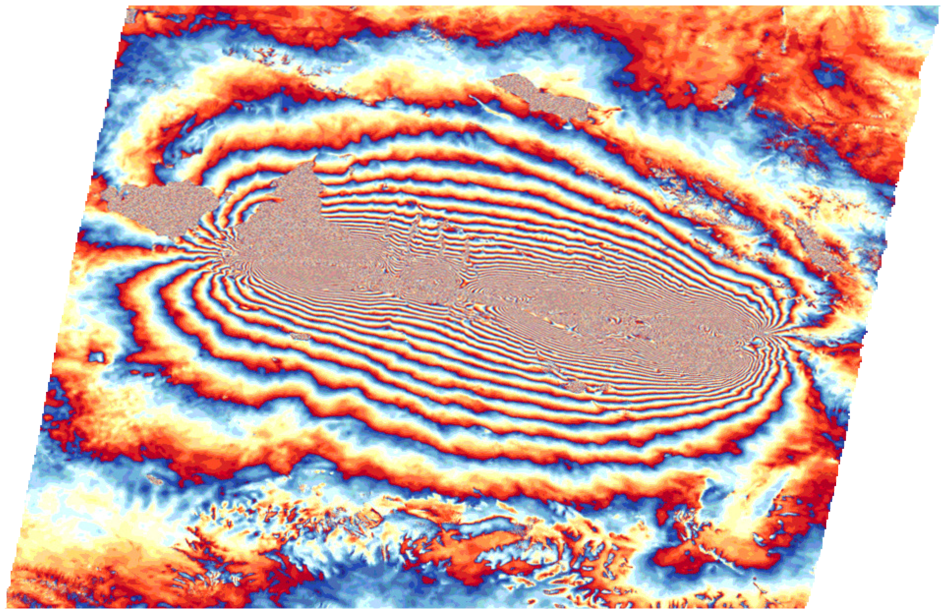

Figure 1: Automatic Twitter post showing an interferogram generated by EIDP

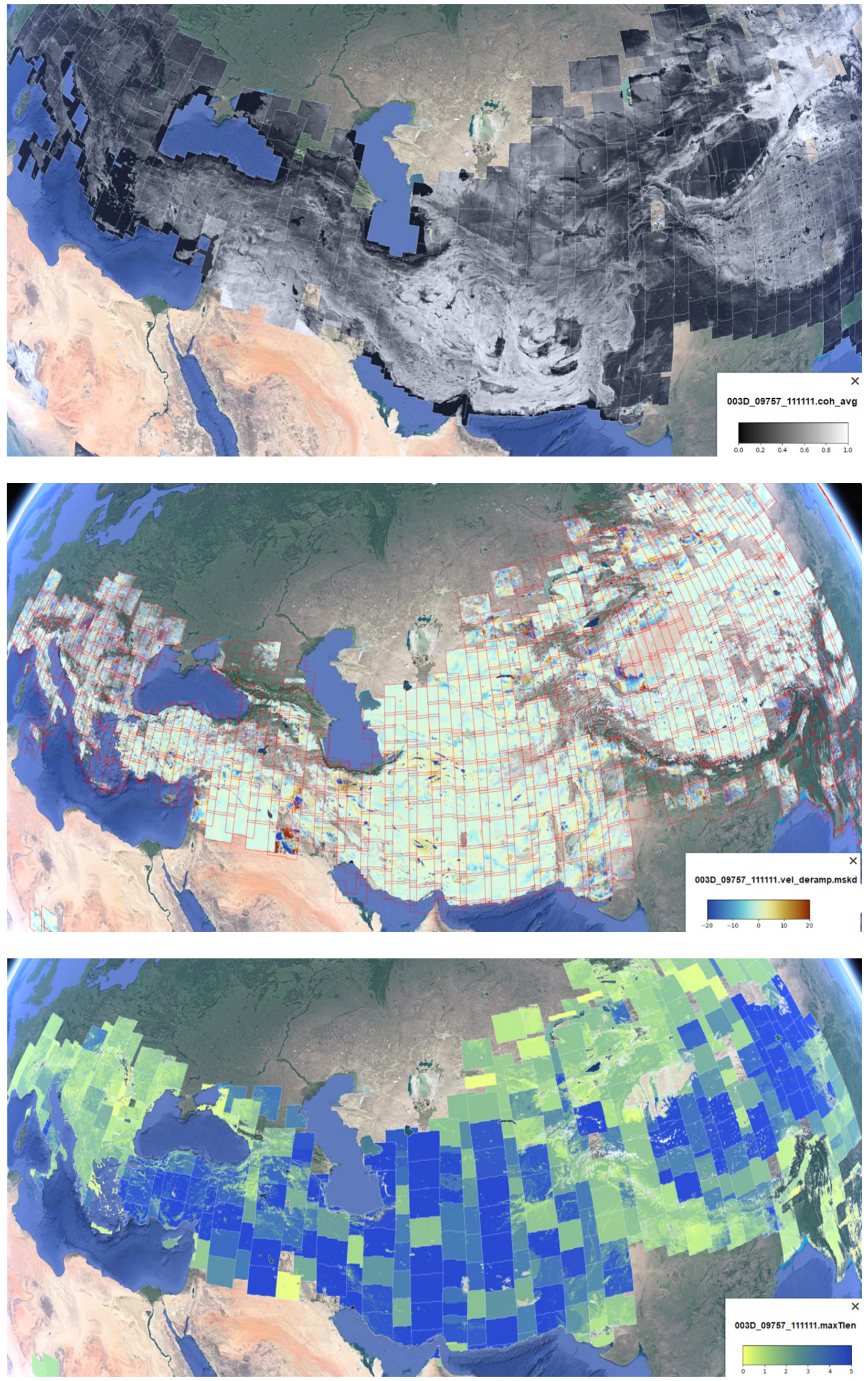

Figure 2: The preliminary velocity field (top), average coherence map (middle) and the maximum length of the connected network (bottom) in the AHB

SCIENCE UPDATE: EO DATA AND SERVICES

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

Progress report: automate the production of displacement measurements from Sentinel-2 data.

There has been no progress on this objective this year as work is planned for later in the scientific programme.

Progress report: develop methodologies to exploit the ongoing expansion in high-resolution optical satellite images (e.g. From cubesats and satellite video).

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

A workflow was developed to generate digital elevation models (DEM) using optical PlanetScope satellite data, which is collected at 3 m resolution using over 100 cubesat satellites that image the Earth's landmass daily. The data are not open access but monthly quotas are available for scientific research. The near-nadir imagery incidence angle is not ideal for DEM generation. Nonetheless, using images collected over 1–2 months from different orbit paths allows topographic reconstruction where surface conditions are relatively static. We are currently evaluating the workflow using a high-resolution Pleiades elevation model (~2 m spatial resolution) and ICESat-2 altimetry data over the city of Bishkek, Kyrgyzstan.

COMET ANNUAL REPORT 2021

Progress report: produce datasets as required by the hazard teams

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

High-resolution digital elevation models were generated using optical and synthetic aperture radar data to support hazard assessments. Hussain et al. (2020)[1] used SPOT and Pleiades imagery to generate digital elevation models to characterise the San Ramón Fault and fault splays within Santiago, Chile. This data is openly available on OpenTopography[2,3]. OpenQuake Engine was then used to calculate damage and losses for realistic earthquake scenarios on the mapped faults. Albino et al. (2020)[4] used TanDEM-X acquisitions of Fuego Volcano, Guatemala, to generate digital elevation models for assessing topographic changes associated with pyroclastic density currents following the 2018 eruption. The derived datasets could help refine models of future hazard at the volcano.

COMET researchers support the Tomorrow's Cities project (UKRI GCRF Urban Disaster Risk Hub), which aims to reduce disaster risk in future urban developments for Quito, Kathmandu, Istanbul, and Nairobi. High-resolution (2 m) digital elevation models were produced for Kathmandu and Quito using Pleiades satellite data acquired through the Committee on Earth Observation Satellites (CEOS) Seismic Hazard Demonstrator. Additionally, interactive data visualisations were developed to help communicate elements of disaster risk and embed this knowledge within a digital platform, which will form part of a school teaching curriculum in Quito, Ecuador.

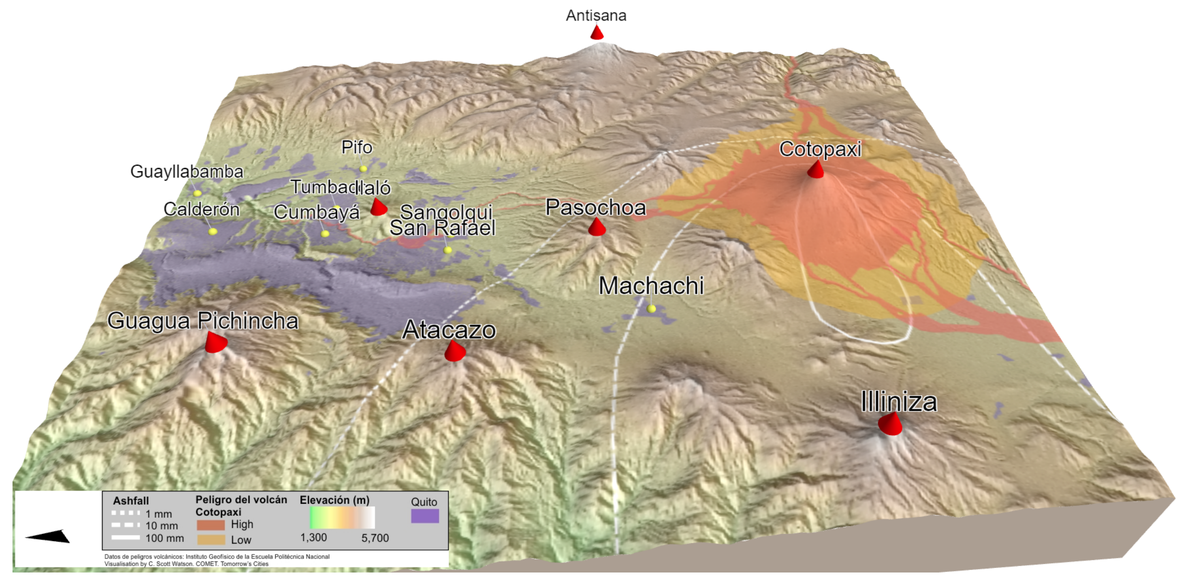

Figure 1: 3D interactive map showing ashfall and lahar hazards associated with Cotopaxi Volcano, which is close to the city of Quito, Ecuador.

1. https://doi.org/10.5194/nhess-20-1533-2020
2. https://portal.opentopography.org/dataspace/dataset?opentopoID=OTDS.022021.32719.2
3. https://portal.opentopography.org/dataspace/dataset?opentopoID=OTDS.022021.32719.1
4. https://doi.org/10.1016/j.jvolgeores.2020.107063

SCIENCE UPDATE: EO DATA AND SERVICES

3. Retrievals of volcanic emissions from satellite spectrometers

Progress report: develop methods to derive so2 fluxes at quiescent degassing volcanoes (back to 2007 for iasi; 2017 for tropomi)

Isabelle Taylor, COMET Postdoctoral Research Assistant, University of Oxford

The linear and iterative SO2 retrievals developed at Oxford for the IASI instrument have now been applied to majority of IASI spectra between mid-2007 and mid-2019. There are some gaps in this record, which will be processed over the next year. We will also extend the record to include more recent eruptions. Currently, we are preparing a manuscript that looks at this dataset in detail. We will archive the dataset to provide a valuable resource for other researchers. As well as including a number of large eruptions, elevated emissions are also visible from smaller sources including anthropogenic emissions, smaller eruptions and ongoing degassing. This dataset can then be used within Manchester's PlumeTraj technique to obtain flux information. Together with Manchester, we've selected two eruptive case studies (Sierra Negra in 2018 and La Soufriere in 2021) to test the use of PlumeTraj with IASI data which will also be compared with results from Tropomi.

Cat Hayer, Postdoctoral Researcher, University of Manchester

- PlumeTraj method has been further developed:
  - o Additional flux density analysis.
  - o Improvements in the altitude assignment.
  - o Average daily flux calculation.
- Long-term analysis on multiple volcanoes (inc. Bagana (PNG), Nyiragongo (DRC)) has continued.
- We have continued NRT analysis and direct collaboration with local volcano observatories for:
  - o Fagradalsfjall, Reykjanes, Iceland
  - o La Soufrière, St. Vincent
  - o SHV, Montserrat
  - o Nyiragongo, DRC
  - o Mt. Etna, Italy
- And we have also worked directly with respective volcanic observatories.

Progress report: incorporate laboratory measurements of ash optical properties of volcanic ash into iasi retrievals so we can estimate sio2 composition.

Isabelle Taylor, COMET Postdoctoral Research Assistant, University of Oxford

We've continued to collaborate with researchers at the Université libre de Bruxelles looking at the differences in IASI ash retrieval outputs when different refractive indices are used. As part of this, we've run our ash retrievals using a number of different look up tables generated from different refractive indices. This investigation has highlighted the need for further developments to the ash retrieval to improve the fit between the IASI measured spectra and the modelled spectra. This will be an area of future work in 2021 and 2022.

Erta Ale volcano, Ethiopia

SCIENCE UPDATE: EO DATA AND SERVICES

4. Geoinformatics and machine learning

Progress report: consult with end users and build a unified, integrated portal to simplify comet data access.

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

The COMET website provides online dissemination and analysis of a growing number of datasets and services. The Looking inside the Continents from Space (LiCS) Portal1 includes access to Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) products processed through the LiCSAR system for active tectonic and volcanic regions. Data are downloadable through an interactive map and from the Centre for Environmental Data Analysis (CEDA) archive. LiCSAR data also underpin the Volcanic and Magmatic Deformation Portal2 and Earthquake InSAR Data Provider (EIDP).[3]

The Volcanic and Magmatic Deformation Portal was redesigned in collaboration with the Centre for Environmental Modelling and Computation (CEMAC) at the University of Leeds to create a new volcano database and InSAR analysis tools. The web tools include time series analysis of deformation, viewing of individual interferograms, and machine learning detections of deformation events. Registered users can also contribute to editing volcano catalogue entries. The tools were demonstrated at the Cities on Volcanoes workshop, where users were invited to follow a tutorial walk-through for Erta Ale Volcano.

COMET's Earthquake InSAR Data Provider produces InSAR products to detect surface deformation associated with earthquakes (Lazecky et al. 2020).4 Events are plotted on a queryable interactive map, which links to individual website pages for each earthquake. LiCSAR data for activated Sentinel-1 frames are processed on ARC4, part of the High Performance Computing facilities at the University of Leeds, UK. InSAR products are downloadable through the website event pages, which also provide an interactive view of the wrapped and unwrapped interferograms covering the earthquake epicentre. Once processed, an image of the wrapped interferogram and event page link is automatically tweeted through @COMET_database. InSAR data tweets from @COMET_database following the May 2021 M 7.3 earthquake in China had over 50,000 impressions.

Updates were made to the Global Waveform Catalogue5 (gWFM) v1.0, which is a database of point-source fault-plane solutions and focal depths for moderate-magnitude earthquakes that have been modelled by an analyst using synthetic seismograms. The dataset is now querable using filters and displayed using linked interactive maps and a data table.

User feedback on COMET's Datasets and Services was sought through workshop discussions and online forms located on each data portal, where users can rate functionality, provide details on how they use COMET data, and suggest future improvements. To date, feedback from users of LiCSAR data spans 25 countries and 82% of users were academics. Applications of LiCSAR data include studies of ground deformation, landslides, lava lake and lava flows, and disaster events.

1. https://comet.nerc.ac.uk/comet-lics-portal/
2. https://comet.nerc.ac.uk/comet-volcano-portal/
3. https://comet.nerc.ac.uk/comet-lics-portal-earthquake-event/
4. https://doi.org/10.3390/rs12152430
5. https://comet.nerc.ac.uk/gwfm_catalogue/gWFM_catalogue.html & https://doi.org/10.1785/0220200218

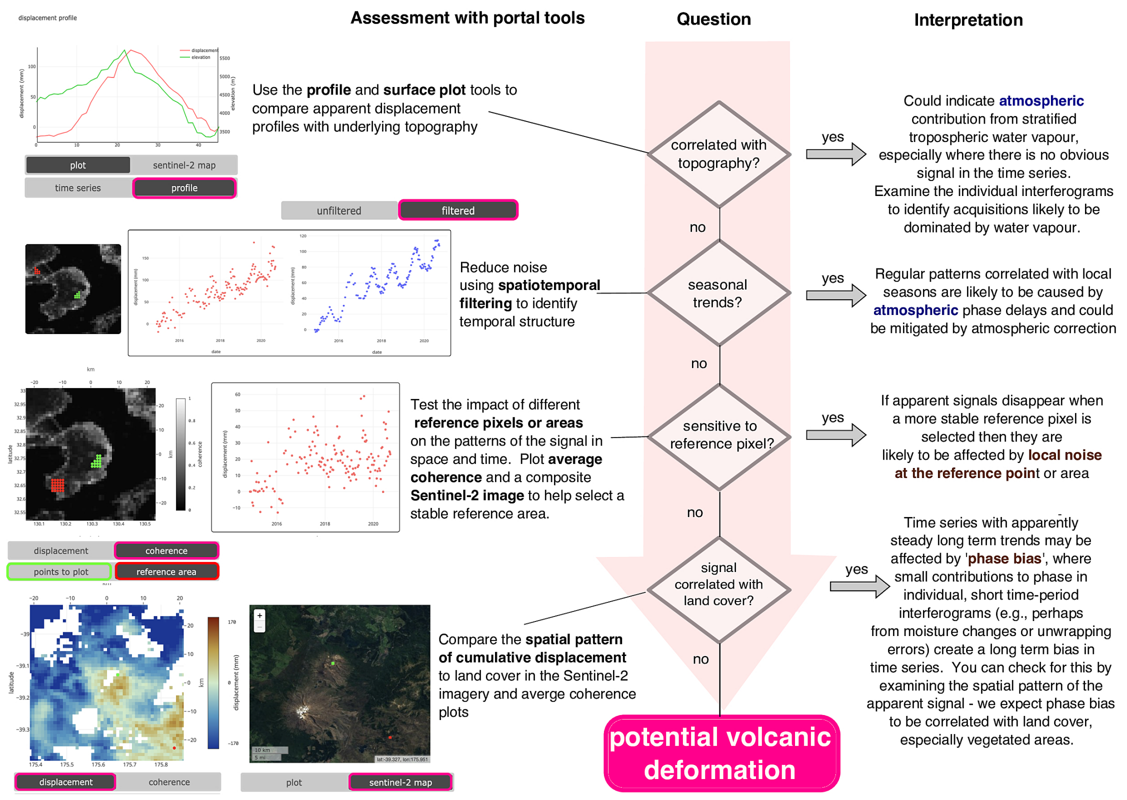

Figure 1: The Volcanic and Magmatic Deformation Portal includes flowcharts created by Susanna Ebmeier to aid interpretation of the online analysis tools.

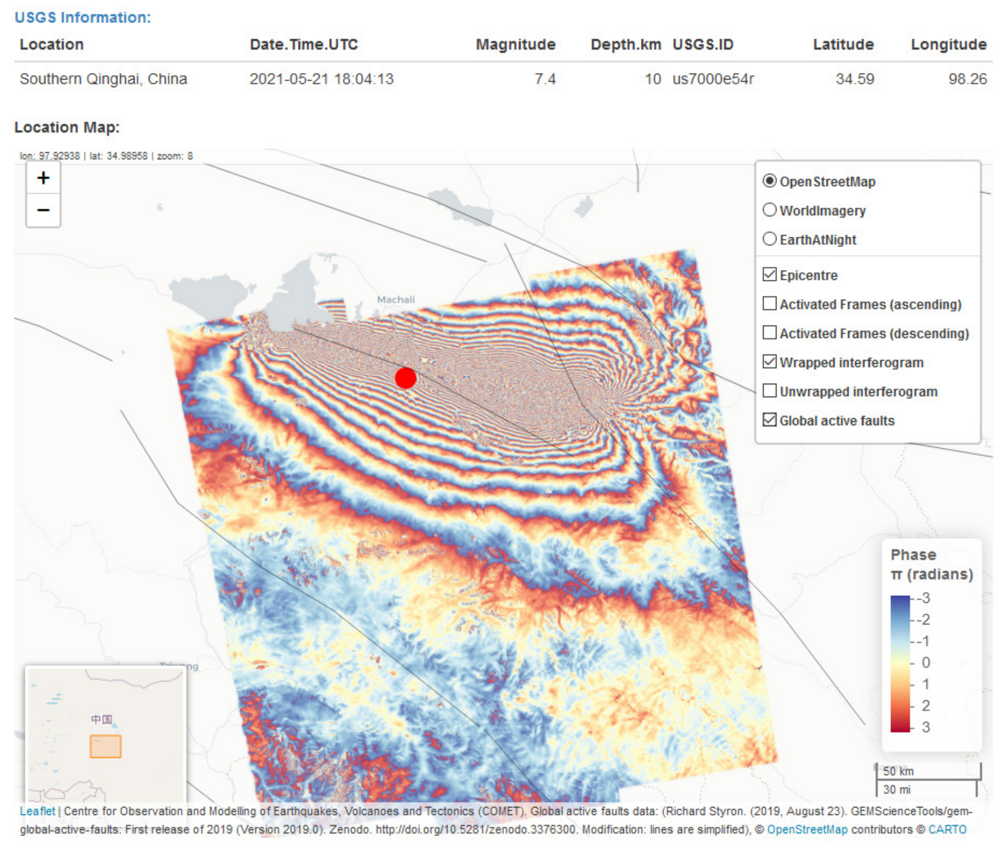

Figure 2: Wrapped interferogram displayed on the EIDP event page for the May 2021 earthquake in China.

SCIENCE UPDATE: EO DATA AND SERVICES

Progress report: develop machine learning algorithms to identify anomalous behaviour at volcanoes

This work was funded by the COMET co-funding project NERC Innovation Award “Making Satellite Volcano Deformation Analysis Accessible” (NE/S013970/1, PI: J. Biggs). In recent years, different approaches have been developed for performing automated detection of ground deformation signals in InSAR datasets. These algorithms may contribute to the early flagging of new volcanic unrest and as a result they support hazards assessment during volcanic crisis. Before their final implementation in the forecasting systems of Volcano Observatories, there is a need for comparative studies to evaluate the performance of different approaches using the same testing datasets. Here, our goal is not to develop new methods but to apply and to test on the EARS volcanoes the three following approaches: 1) anomaly detection algorithm CUSUM (Albino et al, 2020a), 2) blind separation method based on the Independent Component Analysis (ICA) (Gaddes et al., 2018, 2019) and 3) machine learning using Convolutional Neural Network (CNN) (Anantrasirichai et al., 2019). We compared the performance of these approaches for detecting volcanic unrest for 4 deformed volcanoes in the EARS: Erta Ale, Suswa, Tullu Moje and Corbetti. We discuss the results in a paper that is in preparation.

Progress report: trial machine learning algorithms with stakeholders towards real-time operation at volcanoes.

(This objective is in closely linked with the following objective: Consult with end users and build a unified, integrated portal to simplify COMET data access)

This work has been conducted under the COMET co-funding project “Making Satellite Volcano Deformation Analysis Accessible” (NE/S013970/1, PI: J. Biggs). We have been working towards the implementation of the new COMET Volcano Database portal (https://comet-volcanodb.org). The main objective is to provide to Volcano Observatories an easy access to the Sentinel-1 InSAR products generated by the LiCSAR/LiCSBAS for all the active volcanoes in the world. The web portal consists of 3 panels: 1) the time series analysis: the user can plot time series of displacements for any point, change the reference point, apply filtering, and plot profiles of displacements; 2) Individual LiCSAR Interferograms: the user is able to see all individual interferograms (wrapped/unwrapped) and coherence maps produced for an area of 0.5x0.5 degree centred on the volcano’s centre; 3) Probability of high magnitude deformation: the user can explore the map of probability of deformation associated with each interferogram, provided by our Machine Learning algorithms. Each interferogram with a maximum probability above 0.5 is flagged, which enables the user to easily identify periods of unrest.

During the implementation on the web portal, we considered that it was important to have feedback from our ODA partners. Therefore, J. Biggs and F. Albino organized an InSAR online workshop with our Ethiopian partners working at the University of Addis. S. Ebmeier did something similar with Ecuadorian partners. Our workshop consisted of 3 sessions of 2 hours:

- the first one was an introduction about InSAR techniques
- the second one was a presentation that focussed on the applications of InSAR on Earth Sciences and especially the use of InSAR for monitoring natural hazards
- the third one was a presentation of our COMET Volcano Database portal and how to use it.

After this workshop, we collected feedback from our partners and discussed ways to improve the portal before its official release. Initially, we were planning to present our new COMET Volcano Database web portal during the InSAR workshop at the Cities of Volcanoes conference in Greece (initially planned in June 2020). As the conference was postponed and then cancelled, we reschedule the InSAR workshop as an independent event during February 18-23, 2021. The presentation of our web-tool was a success, with approximately 128 participants from 25 different countries. At the moment, the portal shows 86 volcanoes for which gap filling and time series analysis have been completed. With the current effort being made by the LiCSAR team, we hope to increase this number by three in the coming months in order to be able to show all the most active volcanoes (~300 according to the Powell list).

Tien Shan mountains

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

Research highlight: the relationships between metamorphism, the strength of continental interiors, and the characteristics of ground shaking in earthquakes

Alex Copley, Andrew Whyte, and Aisling O'Kane, University of Cambridge

All of the world's continents contain large regions of low-lying terrain that experience little earthquake activity, despite being surrounded by mountain ranges, basins, and associated earthquakes. These regions, commonly termed cratons, are usually composed of rocks that have experienced high pressures and temperatures in the past. Such conditions lead to the removal of chemically volatile components (such as water), and leave behind strong, inert rocks. Research by two PhD students based in Cambridge has been investigating two aspects of continental cratons: how they manage to survive for such geologically long periods, and what effect they have on the ground-shaking due to earthquakes on the edges of mountain belts.

Cratons heat up when they collide with, and thrust beneath, mountain belts (see research highlight by Tim Craig). If the strength of these cratons is governed by temperature, we would therefore expect them to be deformed during mountain-building events they are involved in, which contrasts with their apparently unchanged nature since they formed (mostly early in Earth's history). Andrew Whyte and colleagues (Whyte et al, in review) investigated this question by examining a two-billion-year old mountain belt in arctic Canada, where we can see exposed at the surface the remains of what was the middle-crust when the mountains were being built. By examining how water was transferred from the volatile-rich mountain belt to the underthrusting strong craton, it was possible to estimate how fast water can be transported by diffusion along the boundaries between the individual crystals that form the rocks, and the rate at which it reacts with those crystals. Additionally, it was possible to establish that the rocks only became deformed once a significant amount of water had been added to them. These results show that the limiting factor in controlling the strength of cratons is the very slow rate of water transport through them, rather than the faster rate of heating (Figure 1). These results provide an explanation for the strength and geological persistence of cratons, including when they are involved in mountain-building events.

Aisling O'Kane studied the implications of the strength of the plates bounding mountain belts (e.g., whether they are made of strong cratons or weaker crustal blocks) on the characteristics of earthquake-induced ground shaking (O'Kane and Copley, 2021). The strength of the bounding plates controls the depths and widths of the sedimentary basins that form on the edges of mountain belts as the crust is bent beneath them. The duration and severity of ground shaking produced by earthquakes adjacent to these basins is governed by the wavelength of the waves produced by the earthquake (itself dependent on the characteristics of the fault that ruptures) compared to the geometry of the sedimentary basin. Deep and wide basins result in earthquakes producing strong pulse-like ground motions, rather than shallower and narrower basins that result in longer-duration but lower-amplitude shaking.

When taken together, these studies show the connections between the strength of cratons, the grain-scale diffusion of water, and the ground-shaking produced by earthquakes. Further work is underway to continue investigating the causes and consequences of the lateral variability of continental deformation, geological evolution, and earthquake characteristics.

References:

Aisling O'Kane and Alex Copley, The controls on earthquake ground motion in foreland-basin settings: the effects of basin and source geometry, Geophysical Journal International, 225, 512-529, doi:10.1093/gji/ggaa599, 2021

Andrew Whyte, Owen Weller, Alex Copley, and Marc St-Onge, Quantifying water diffusivity and metamorphic reaction rates, and their implications for the rheology of cratons, in review.

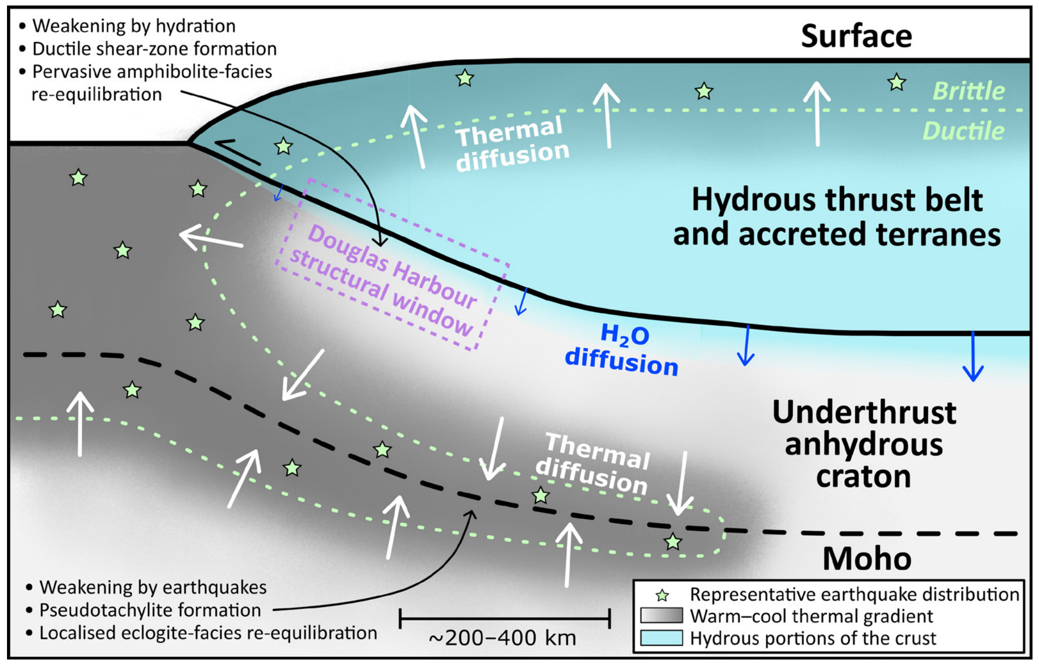

Figure 1: The evolution of temperature, water content, and strength on the margin of a mountain belt.

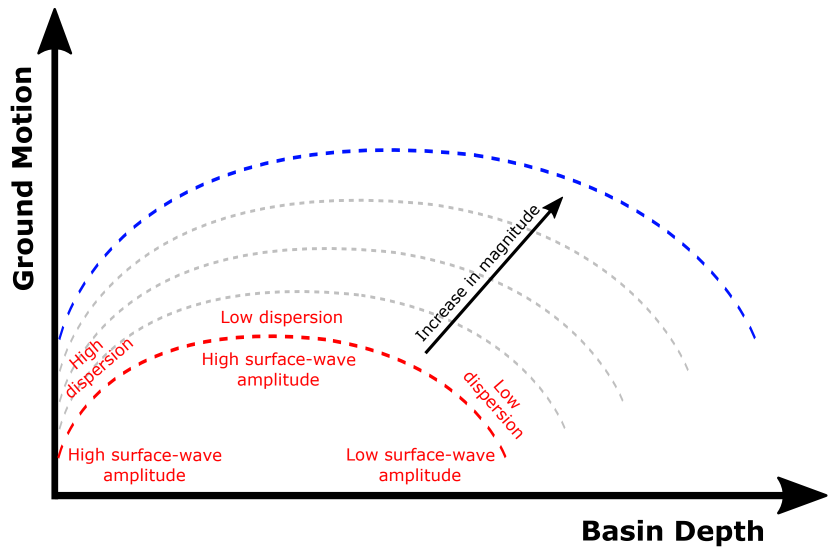

Figure 2: The influence of sedimentary basin depth and earthquake magnitude on the severity of ground shaking due to the earthquakes that occur on the margins of mountain belts.

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

Research highlight: the temperature structure beneath tibet

Tim Craig, COMET Scientist, University of Leeds

The Tibetan Plateau is the largest modern orogenic system, and provides a range of vital information about the geological and geodynamic evolution of large collisional zones, and how these are expressed in seismological, geochemical, and geological data. The deep thermal structure of the Plateau plays a dominant role in governing its deformation and evolution – yet little is known about the present-day temperature field, and even less about how that temperature field has evolved over the recent past.

In a 2020 paper (Craig et al., 2020), we bring together a suite of observational data that help to constrain the geological, geodynamic, and thermal structure of southern Tibet over the last 30+ Myrs, including geophysical (earthquake thermobarometry, seismic tomography, shear wave splitting, head-wave propagation) and geochemical/petrological (xenolith thermobarometry, volcanic geochemistry) data, and ask the question – can we construct a thermal model that can fit all these data consistently, and if so, what range of parameters do these data allow?

We built a two-dimensional advective-diffusive thermal model for the collision zone, under the assumption that east-west variation along the Himalayan front is small compared to the north-south variation imposed by the direction of collision. We tested a range of scenarios for the evolution of the thermal structure of southern Tibet, and various boundary conditions (e.g., collision rates, incoming thermal structures, underplating, radiogenic heat production). All models that are capable of fitting the available data (Figure 2), have three features in common: (a) all models require a cold underthrusting Indian lithosphere, much of which survives intact beyond the Himalayan prism to be emplaced under southern Tibet, (b) fitting the available geochemical data requires the removal of large volumes of older Indian lithospheric mantle from beneath the plateau at some stage during the Miocene, and (c) to match both the southward extent of ultramafic magmatism in the Miocene, and also the present day geophysical structure of southern Tibet, the rates of underthrusting of Indian material beneath the southern plateau must have been, on average, greater since the Miocene than they are at the present day.

References:

T.J. Craig, P.B. Keleman, B.R. Hacker, and A Copley (2020). Reconciling Geophysical and Petrological Estimates of the Thermal Structure of Southern Tibet, Geochemistry, Geophysics, Geosystems, doi:10.1029/GC008837.

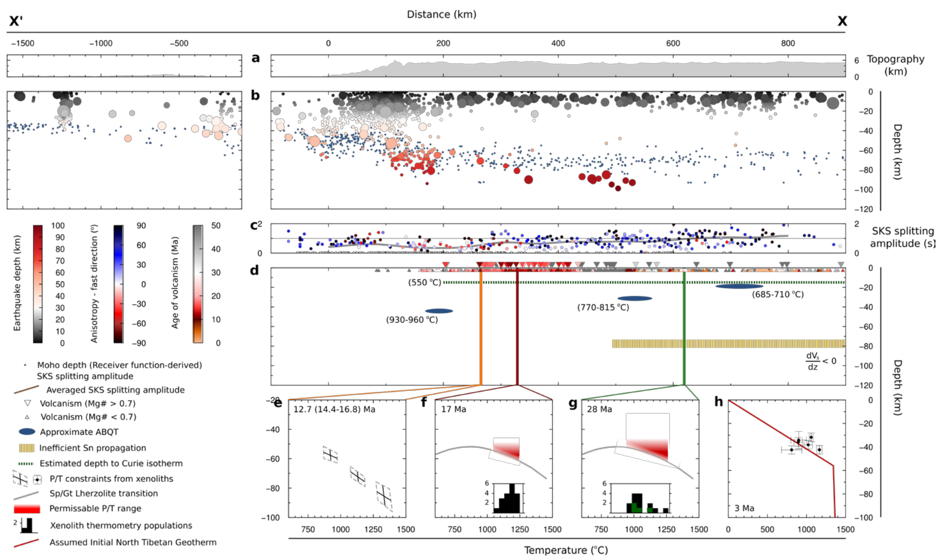

Figure 1: Compilation of available geophysical, geochemical, and petrological data for the structure and thermal structure of southern Tibet.

COMET ANNUAL REPORT 2021

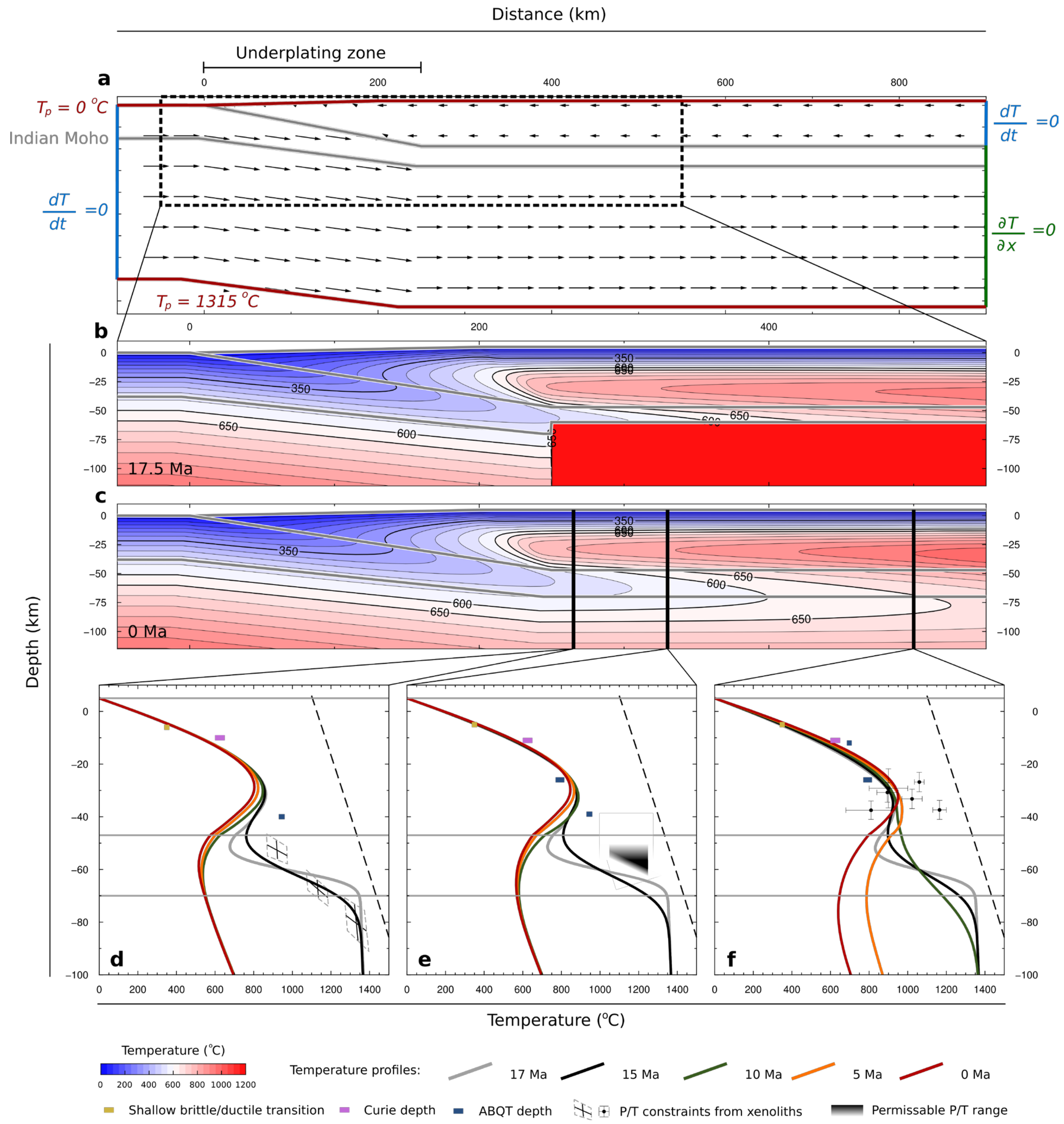

Figure 2: Example model for one set of parameters capable of fitting all data for the thermal structure over the last 30 Myrs reasonably well. Such solutions are, inevitably, non-unique. This model incorporates the removal of much of the Indian lithospheric mantle from beneath the plateau at 17.5 Ma. Cross-sections show the snapshots of the spatial temperature field, profiles show the evolution of the temperature field for a given point in the Indian lower crust through time.

COMET ANNUAL REPORT 2021

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

Research highlight: the earthquake ruptures of Iran and Central Asia

Richard Walker, COMET Scientist, University of Oxford

The last century has seen unprecedented urban growth in regions of earthquake hazard within the continental interiors. The active faults are widely distributed across large regions, and there can be intervals of hundreds, or even thousands of years between large earthquakes in any one area. The long recurrence intervals pose challenges for the assessment of earthquake hazards, and the small database of recent large earthquakes limits our understanding of fault rupture processes in such regions.

These challenges motivated a team of COMET researchers and partners in several countries to expand and enlarge the database of earthquake surface ruptures across the Asian continental interior, both to address the general issues of earthquake scaling and clustering, as well as to provide information that is useful to earthquake hazard assessment at a local scale. We are aided by the pristine landscape that can retain evidence for discrete surface ruptures for very long periods of time, and also by the available of modern sub-metre stereo optical satellite imagery, which allow us to make measurements and identify sites for field investigation.
Many of the large cities of Asia have historical records of destructive earthquakes, including a significant number through the late 19th and early to mid 20th centuries. For example, Almaty, Kazakhstan, with a population of 2 Million, was badly damaged by a magnitude 7.3 event in 1887, and two extremely large events of magnitude >8 that struck the city in 1889 and 1911. Ashgabat, the capital city of Turkmenistan, was destroyed with much loss of life in a poorly understood earthquake in 1948. The major 20th century earthquakes are of particular importance for us, as we are able to study them (1) using seismology, to gain direct constraints on their magnitudes, as well as other important details of their sources such as depth extent, and (2) using geomorphology, by mapping the extent of the surface ruptures and measuring the amount and variability of surface slip along those ruptures (e.g. Abdrakhmatov et al., 2016; Ou et al., 2020). These earthquakes help to calibrate our findings for historic and prehistoric events, for which we are limited to observations from the geomorphology.

Historical records in regions such as Iran and China extend far back in time, and yet the geological context of many of the historical earthquakes is not well resolved (e.g. Middleton et al., 2016; Feng et al., 2020). A number of prominent faults close to major population centres have no documented historical record of earthquakes near them, and yet display evidence in the landscape for rupture in the recent past. Forensic study of these faults, such as the example shown in the figure, is essential for determining the completeness of the historical record and the hazard posed to population centres across the region.

The work began within the Earthquakes without Frontiers consortium and is currently supported by grants from the Leverhulme Trust, the NATO Science for Peace and Security program, UKRI, and the CEOS Seismic Hazards Demonstrator. The project contributes to COMET objectives in delineating active faults, assessment of hazard, and in assessing temporal variations in strain.

Project website: **quakesincentralasia.org**
Twitter: **@QuakesCentAsia**

Selected references:

Feng, X., Ma, J., Zhou, Y., England, P., Parsons, B., Rizza, M.A. and Walker, R.T., 2020. Geomorphology and Paleoseismology of the Weinan fault, Shaanxi, central China, and the source of the 1556 *Huaxian* earthquake. *Journal of Geophysical Research: Solid Earth,* 125(12), p.e2019JB017848.

Ou, Q., Kulikova, G., Yu, J., Elliott, A., Parsons, B. and Walker, R., 2020. Magnitude of the 1920 Haiyuan earthquake reestimated using seismological and geomorphological methods. *Journal of Geophysical Research: Solid Earth*, 125(8), p.e2019JB019244.

Abdrakhmatov, K.E., Walker, R.T., Campbell, G.E., Carr, A.S., Elliott, A., Hillemann, C., Hollingsworth, J., Landgraf, A., Mackenzie, D., Mukambayev, A. and Rizza, M., 2016. Multisegment rupture in the 11 July 1889 Chilik earthquake (Mw 8.0–8.3), Kazakh Tien Shan, interpreted from remote sensing, field survey, and paleoseismic trenching. *Journal of Geophysical Research: Solid Earth*, 121(6), pp.4615-4640.

Middleton, T.A., Walker, R.T., Parsons, B., Lei, Q., Zhou, Y. and Ren, Z., 2016. A major, intraplate, normal-faulting earthquake: The 1739 Yinchuan event in northern China. *Journal of Geophysical Research: Solid Earth*, 121(1), pp.293-320.

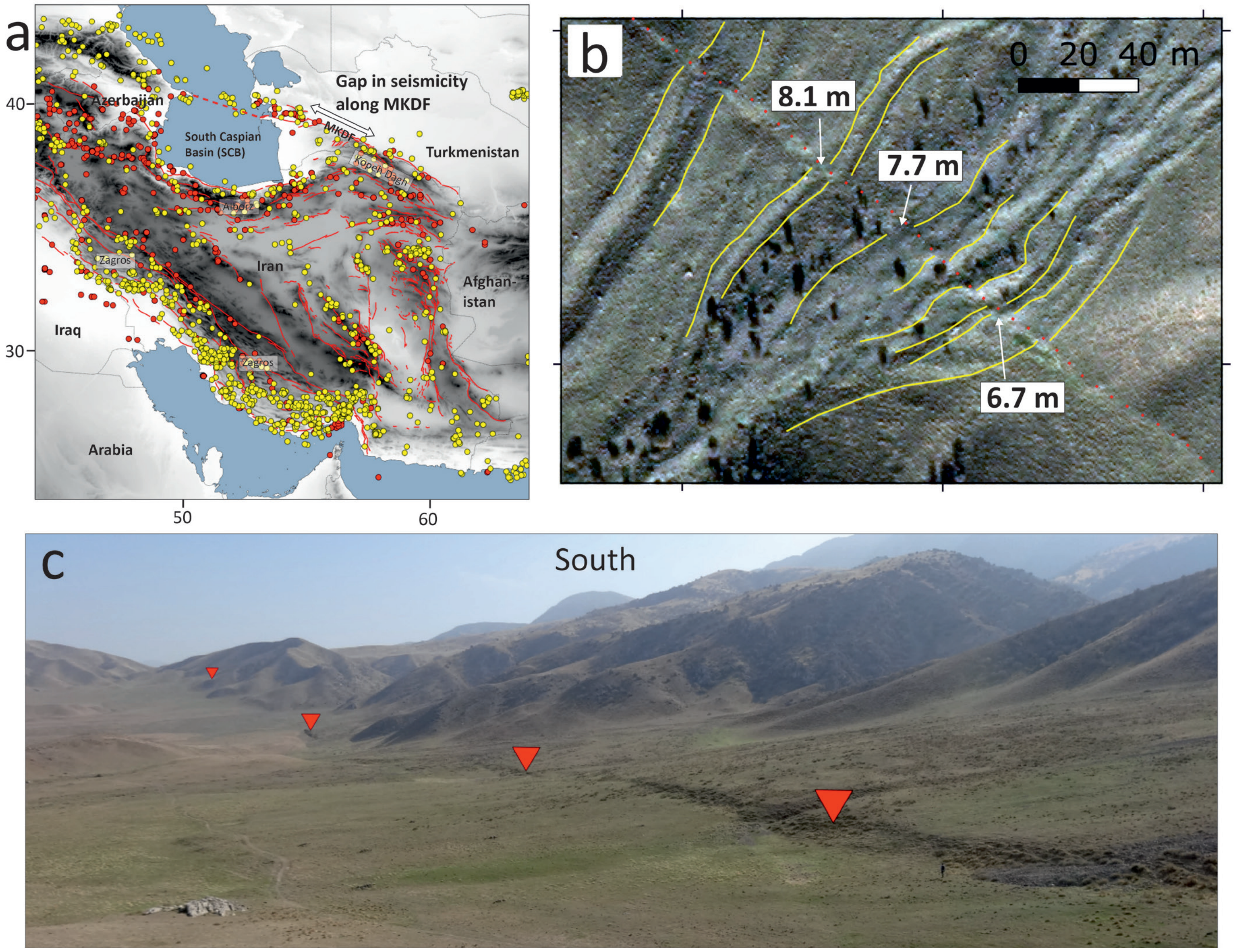

Figure (a) Instrumental (yellow) and historic (red) earthquakes within the Arabia-Eurasia collision. There is a gap in seismicity along the Main Kopetdag fault (MKDF) in Turkmenistan. (b) Sub-metre Worldview-3 imagery (obtained through the Digitalglobe foundation) shows evidence for multiple ~6-8 m right-lateral offsets which are likely to have bene caused by a single large earthquake. (c) Fieldwork allows observations to be validated, and trench investigations allow the earthquake to be dated to the Medieval period. This large magnitude earthquake is not present in any catalogue of earthquakes. All figures from Dodds et al., in preparation.

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

Research highlight: eruption fieldwork at Fagradalsfjall, Iceland: dispersion and deposition of volcanic metals

Evgenia Ilyinskaya, COMET Associate, University of Leeds

Collaborator team (in alphabetical order): Andri Stefansson, Barbara I Kleine, Brock Edwards, Clive Oppenheimer, Elin Jónasdottir, Emily Mason, Emma Liu, Fran Jenners, Gerdur Stefansdottir, Johann Gunnarsson Robin, Marie Edmonds, Martin J. Voigt, Melissa Pfeffer, Mike Burton, Moritz Schramm, Penny Wieser, Rikey Kjartansdottir, S. Rakel Gudjonsdottir, Sam Hammond, Sara Barsotti, Sydney Gunnarsson, Tamsin Mather, Thorsteinn Johannesson, Tryggvi Stefansson.

Photographs by team members.

Volcanoes are a globally important source of environmentally-reactive trace elements classified as 'heavy metal pollutants' but there are many unknowns about their fate after emission and associated environmental and health hazards. During the large fissure eruption of Kīlauea volcano in Hawaii 2018 our team collected samples of the volcanic plume across the island (fieldwork funded by COMET) to better understand these processes.1–3 We discovered that metals with the highest potential toxicity appear to be deposited from the plume very rapidly after emission; this process has environmental and public health implications as it may disproportionately impact localised areas close to the vent.2 However, as tends to be the case with scientific research, even more questions arose based on these findings! One of the questions is why do volatile metals (including e.g., selenium, cadmium and lead) appear to deposit faster than refractory metals (such as aluminium and iron). Also, the rate of the rapid metal deposition is unconstrained beyond that it occurs within the first ~3-5 hours of the plume's lifetime. Our team were therefore very excited (to say the least) when an eruption began at Fagradalsfjall in Iceland as it was the perfect natural laboratory to answer these questions. COMET supported rapid-response fieldwork in March-April 2021.

Going on fieldwork in the middle of lockdown with a baby in tow

Krýsuvík volcanic system on Reykjanes peninsula in Iceland had been experiencing unrest. Elevated seismicity suggested a magma intrusion in early 2020, and another one started in February 2021. On 3 March, the unrest escalated and started to 'tremor' – a type of seismic signal that in many cases is a direct precursor for eruption onset. I had been following the unrest from the backbenches with no thoughts of traveling there myself: the UK was in the middle of a Covid-19 lockdown and I had a 9 month old daughter. Then I received a message from a colleague at the Icelandic Met Office: "Tremor detected, all contingency plans activated…!! We wait for the eruption.. good luck to all of us and you!!!!".

All notions of 'impossible' went out of the window and wheels set in motion to make fieldwork happen. It wasn't just the thrill of potentially seeing an eruption so close to the capital city of Reykjavik where I grew up (although I did have goosebumps just thinking about it). My colleagues and I had had our eyes on the volcanoes of Reykjanes peninsula since the discoveries we'd made in Hawaii. These volcanoes produce gas-rich fissure eruptions, and the flat terrain and proximity to towns and cities means that the eruption site would be relatively easy to access. This would be ideal for sampling the plume at multiple locations and shed light on what happens to the volcanic metals in the first minutes and hours of the plume's lifetime.

I was the only one from our usual field team who was going to travel to Iceland due to the Covid-related restrictions. This was a new challenge as it takes 4-5 people to do the time-consuming sampling at the crater, as well as at different distances downwind. But I would have help in Iceland from colleagues at the Institute of Earth Sciences at the University of Iceland and the Iceland Met Office, as well as remote support from those who could not travel. Getting ready for fieldwork was a mammoth team effort. The field equipment had been locked up in storage in various universities across the UK for over a year so we had to comply with a lot of new rules, paperwork and Covid tests to enter our departments, get it field-ready and get it to Leeds in time. Mike Burton speeding across the Pennines to deliver a huge drone directly to my house was one of the highlights! Icelandic colleagues took care of various paperwork since travel out of the UK was only permitted for critical work. Getting to Iceland from Leeds took two days because instead of multiple flights each day from several airports in the UK, now there was only one weekly crack-of-dawn-on-Sunday flight from Heathrow. It seemed like an impossible task at times but the puzzle was successfully solved as a team and myself, my husband and our little one – plus 200 kg of equipment – landed in Iceland within a fortnight.

Checking in at Heathrow

The calm before the storm

Minutes before the plane touched down a M5.4 earthquake within the volcano shook Reykjanes peninsula. And then it went quiet. There were small earthquakes here and there but nothing I could feel over in the apartment where I was quarantining for 5 days – a welcome change for the local residents who had been shaking for weeks. On Friday 19th March the general consensus was that it looked like the unrest period had reached its end. At 6pm I got my test result releasing me from quarantine. Oh well, I thought, I will use this trip to get background samples of the local atmosphere with no volcanic pollution. At 7:30pm, an Icelandic Met Office scientist appeared on the evening news saying that they "do not expect an eruption". At 9pm the eruption had started.

The eruption

I actually did not know that an eruption had started until early next morning because that night had been the first time in several weeks that I didn't check my phone for the whole evening. Needless to say, the morning was less than relaxing in order to get the equipment ready, find a lift to the eruption site, figure out how to leave a baby that hadn't ever been away from me for a whole day thanks to lockdown, but it was all worth it when our team arrived at the site.

The fissure eruption before us was remarkable. The amount of lava and sulphur dioxide gas (SO2) being erupted was small (2-4 kt/day of SO2) compared to the fissure eruptions of Holuhraun 2014-2015 (mean SO2 flux 50 kt/d) or Laki 1783-1784 (10 times larger than Holuhraun). But the composition of the magma and gas showed that it was coming from very deep (~20 km), directly from the mantle, which is very unusual. This also meant that the eruption was likely to continue for a long time since it was tapping a large reservoir. This has implications for the hazard of the volcanic pollutants such as SO2 and heavy metals. Acute health effects of SO2 are relatively well studied, but effects of long-term exposure less so. From studies of anthropogenic heavy metal emissions, it is known that health effects are associated with long-term exposure to contaminated water, food, and/or air.

Eruption site and crowds of people hiking in to see it, 21 March 2021

The fieldwork

We collected samples of gas and particulates in the volcanic plume, and are currently analysing these in a laboratory for composition. We can analyse for approximately 60 elements using a mass spectrometer (ICP-MS). Erupted rocks (matrix glasses and melt inclusions) will be analysed for the same elements to understand why some elements are degassed more easily than others, and why they form certain chemical compounds in the plume – which, in turn, could answer why some chemical compounds are deposited faster from the plume than others. The proximity of the eruption to the capital area means that we were able to start processing the plume samples very rapidly in the clean lab at the Institute of Earth Sciences.

We sampled the plume both at ground-level and when it was lofting, using an Unoccupied Aerial System (UAS). Flying a UAS in the rugged terrain and unpredictable Icelandic weather at a close range to a volcanic eruption is always a challenge, but even more so at Fagradalsfjall where there is heavy air traffic of sightseeing helicopters and low-flying planes, and thousands of people hiking in, many with their own drones for recreational purposes. We set up sampling right at the erupting vent, and at several increasing distances downwind from 0.5 to 30 km from the vent, in order to capture the changes in the plume composition as it drifts downwind. Some of the far-field sampling was set up in populated areas, including the capital area, where we set up our equipment at official air quality monitoring stations.

Attaching samplers to the UAS at the eruption site

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

For ground-level sampling close to the erupting vent we used 'Harry' – a backpack frame with all the instruments strapped to it. We designed Harry during the 2018 Hawaii campaign; it allows us to set up the sampling in a drop-and-run fashion and minimise the time spent in dangerous conditions.

Carrying Harry to sample the plume at the erupting vent. The full face gas mask proved useful not only against toxic gases but also against the Icelandic weather

First conclusions and next steps

First results show that Fagradalsfjall eruption is emitting volatile metals at a similar rate to Holuhraun. Although Holuhraun was a much larger eruption, Fagradalsfjall's emissions are relatively more concentrated in these pollutants. The emission rate of heavy metals is comparable to total anthropogenic emissions from the UK. When the plume is advected over the far-field populated areas in Iceland, the airborne concentration of heavy metals becomes similar to that in large cities, such as London and New York. At the moment, the exposure to volcanic heavy metals is unlikely to be causing measurable health impacts but it will be important to assess the long-term exposure if the eruption continues for years or decades. Funding dependent, we plan to test the toxicity of the volcanic metals, and assess the population exposures, assuming the eruption will become long-lived. Our results are being continuously shared with the monitoring and decision-making agencies in Iceland and used for relevant hazard assessments.

References:

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2. Ilyinskaya, E. et al. Rapid metal pollutant deposition from the volcanic plume of Kīlauea, Hawai'i. *Commun. Earth Environ*. 2, 1–15 (2021).
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Fagradalsfjall, Iceland

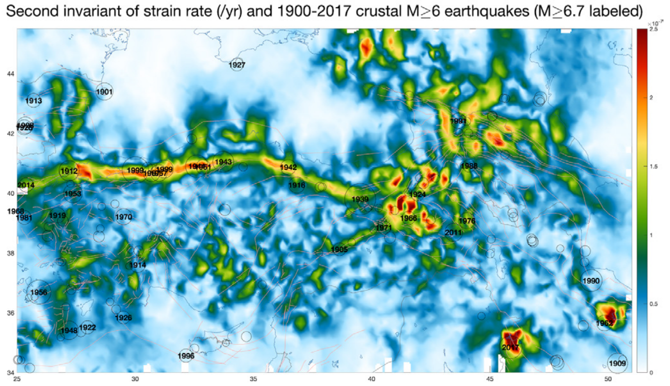
SCIENCE UPDATES: TECTONICS AND VOLCANISM

1. Tectonics and seismic hazard

Progress report: construct the first global high-resolution strain-rate map, from insar and gnss, of the Alpine-Himalayan belt and East African Rift

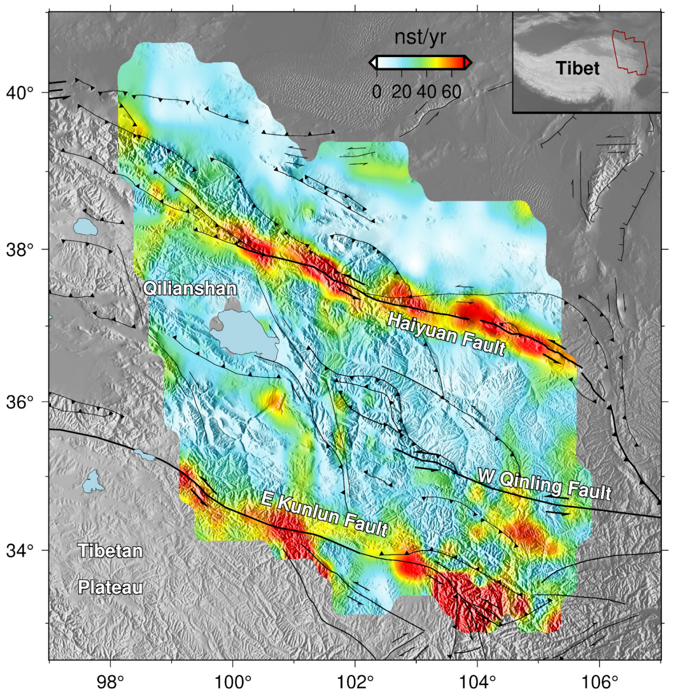
Chris Rollins, COMET Postdoctoral Research Fellow, University of Leeds

We have been working on this objective from several fronts. In the western Alpine-Himalayan Belt, Chris Rollins has expanded Jonathan Weiss' LiCSAR- and GNSS-based strain-rate analysis in Anatolia into a larger region encompassing the Caucasus and northern Syria, Iraq and Iran. Preliminary results (below) are encouragingly similar to Jonathan's results in Anatolia, with the North and East Anatolian Faults being the dominant features, and show a good correlation between high-strain-rate areas and recorded earthquakes throughout the region.



This strain rate map will be met on the southeast by Andrew Watson's work in Iran. Andrew and John Elliott have been using Sentinel-1A and GNSS data to assess strain accumulation across the Main Recent Fault, which runs through the Zagros Mountains, and have now begun work on an Iran-wide strain map.

In Tibet, Tim Wright has been using LiCSAR products and GNSS velocities to construct a strain rate map for Tibet. Preliminary results show an intriguing subsidence signal in the central Tibetan Plateau that may support the Bischoff and Flesch (2018) hypothesis of crustal buckling there. And along the northeastern Tibetan Plateau, Qi Ou has constructed a strain rate map along the Haiyuan, Qinling and Kunlun faults from Sentinel-IA and GNSS data (below).



Progress report: produce and deliver (to gem), maps of active faults and their rates of activity, initially in Central Asia.

Tamarah King, COMET Postdoctoral Research Assistant, University of Oxford
Austin Elliott, Visiting Research Fellow, University of Oxford

COMET researchers have compiled fault mapping across the broadly deforming Tien Shan, one of the highest seismic hazard regions in the world. An early version of the database has been released to collaborators at the Global Earthquake Model (GEM), to assist in COMET/GEM collaborative projects. Through consultation with stakeholders such as GEM, we are crafting a database that faithfully represents the state of knowledge on Central Asia's vast array of active faults, balances limitations of sparse data, and flexibly incorporates knowledge advances from ongoing field and geodetic investigations.

The database includes three resolutions of fault mapping to serve variable applications, and includes published and unpublished fault metadata including naming, kinematics, and neotectonic measurements. The database will support global research by seismic hazard practitioners, earthquake geologists, paleoseismologists, geodesists, and geophysicists, and illuminate where further studies are required. The database also directly assists in additional COMET objectives investigating temporal and spatial variations in strain across distributed fault networks.

Level 1 contains the finest scale (highest resolution) mapping available for identified faults, to guide site-specific scientific investigations and fault zone hazard assessments. Level 2 contains representations of through-going faults identified in the landscape through remote-sensing, field mapping, and/or historical earthquakes. This constitutes the most comprehensive level of the database, intended to represent all significant tectonic and seismogenic faults. Level 3 contains representations of the most significant throughgoing faults that, through consultation with GEM and a community of Central Asian active tectonics specialists, represent principal sources of seismic hazard and tectonic deformation.

We will hold workshops in late 2021 with specialists in Central Asian active tectonics across COMET, GEM, and the wider community to collaboratively assign slip-rates and geometries to seismogenic faults and discuss fault connectivity, continuity, activity, and the completeness of the database. Public release of the full database and associated publications will follow these consultation and vetting workshops.

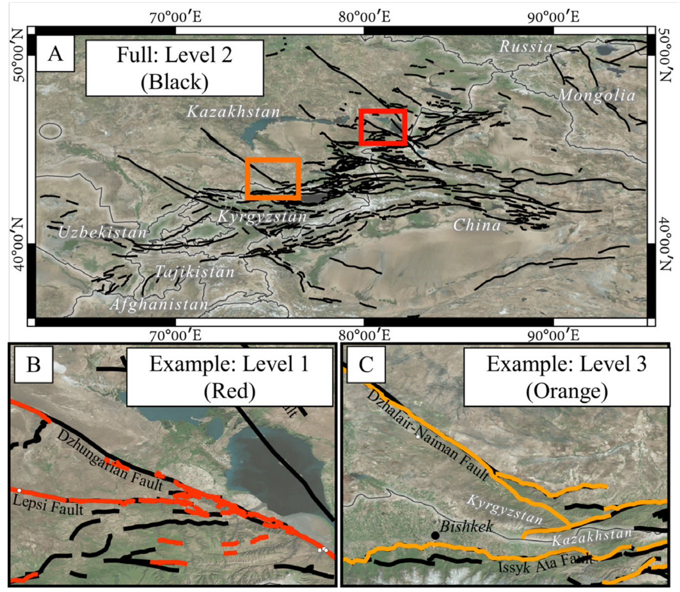


Figure 1: (A) Full extent of COMET Central Asia fault database (Level 2 lines); (B) comparison of Level 1 with Level 2; (C) Comparison of Level 3 with Level 2. Level 3 lines are from GEM regional fault model for illustrative purposes; subject to change through inclusion of additional information from COMET geodetic strain products & expert consultation.

SCIENCE UPDATE: TECTONICS AND VOLCANISM

Progress report: assess temporal variations in strain across distributed fault networks, in Central Asia, Turkey and Italy.

Tamarah King, COMET Postdoctoral Research Assistant, University of Oxford
Richard Walker, Professor of Tectonics, University of Oxford
Tim Wright, COMET Director, University of Leeds
Chris Rollins, COMET Postdoctoral Research Fellow, University of Leeds

This theme brings together and synthesises multiple COMET objectives by bringing together geological data on kyr-timescale earthquake cycles and geodetic data from InSAR and GNSS.

A major development is the establishment of a collaborative multi-year work program with the Global Earthquake Model (GEM). Through this collaboration we will address transient earthquake behaviour and off-fault deformation across vast distributed fault networks across Central Asia, from Turkey to the Tien Shan, to assist in the assessment of seismic hazard.

COMET researchers have recently published work on faults in Italy exploring dense geological data on individual faults (Goodall et al. 2021), and in Iran combining geological and remote-sensing strain-rate data (Mousavi et al. 2021). These studies both quantify and compare long-term geological slip-rate variations to address questions of temporal variation on individual and networks of faults.

References:

H.J. Goodall, L.C. Gregory, L.N.J. Wedmore, K.J.W. McCaffrey, R.M.J. Amey, G.P. Roberts, R.P. Shanks, R.J. Phillips, A. Hooper, Determining Histories of Slip on Normal Faults With Bedrock Scarps Using Cosmogenic Nuclide Exposure Data, Tectonics. 40 (2021). https://doi.org/10.1029/2020TC006457.Z.

Mousavi, M. Fattahi, M. Khatib, M. Talebian, E. Pathier, A. Walpersdorf, R.A. Sloan, A.L. Thomas, E. Rhodes, F. Clive, N. Dodds, R.T. Walker, Constant Slip Rate on the Doruneh Strike-Slip Fault, Iran, Averaged Over Late Pleistocene, Holocene, and Decadal Timescales, Tectonics. 40 (2021). https://doi.org/10.1029/2020tc006256.

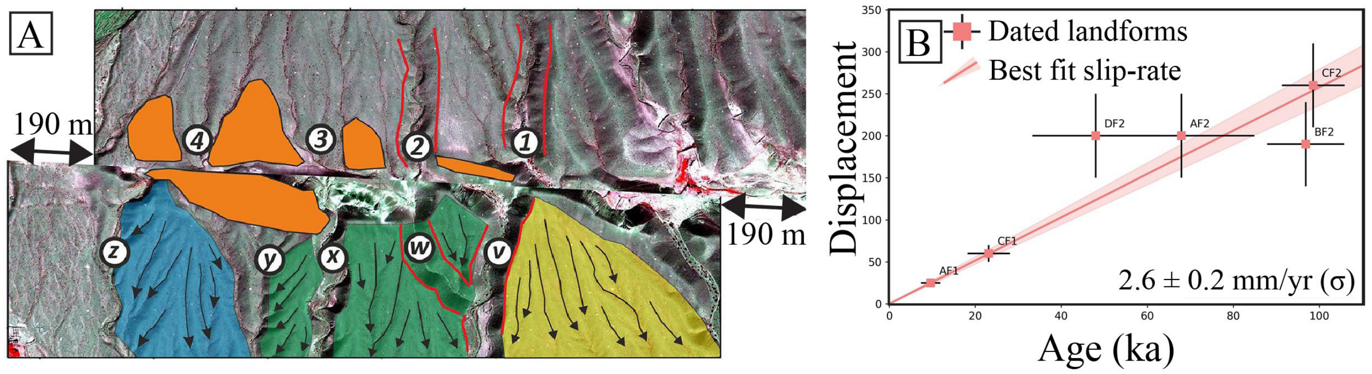


Figure 1: (2021) (A) restoring sinistrally faulted channels and IRSL dated alluvial fans along the Doruneh Strike Slip Fault, Iran, indicates 190 ± 50 m of slip over ~100 (B) Long-term slip-rate derived from age vs. displacement of dated landforms. This geological slip-rate is within error of the long-term slip-rate derived from geodesy (from Mousavi et al. 2021).

Progress report: begin development of next-generation of geodynamic models of continental deformation linking short and long timescales.

Dr Alex Copley, University of Cambridge

COMET researchers have been developing and applying a suite of observational and modelling techniques to investigate the dynamics of earthquakes and large-scale tectonics on a range of time- and length-scales. Newly quantified water contents as a function of depth within mountain belts, and the associated reactive-flow numerical models, have established some of the grain-scale controls on rheology (see research highlight on page 32-34). In tandem, observations, thermal models (Craig et al 2020, see research highlight on page 35-37) and mechanical models (Penney and Copley 2021) have revealed the controls on the temperature structure and deformation of mountain belts at the scale of the entire crust and lithosphere. Studies of earthquake locations and characteristics in the continents (Craig and Jackson 2021) and on subduction megathrusts (Greenfield et al 2021) have revealed more about the rheology of individual faults, and their role in controlling large-scale material properties. Work is now progressing on developing physically- and chemically-consistent models that can span these spatial and temporal scales. A new PhD student arriving in Leeds in October 2021 will contribute to work on this topic.

2. MAGMATISM AND VOLCANIC HAZARD

Progress report: produce deformation time series for all subaerial volcanoes, beginning to build a long term (decadal) view of processes occurring at volcanoes in different stages of the eruptive cycle.

Fabien Albino, COMET Research Associate in Satellite Observations of Volcanic Processes, University of Bristol

This work was funded by the COMET co-funding project RiftVolc (NE/L013649/1). We have achieved the objective to produce a 5-years Sentinel-1 time series on 65 active volcanoes along the East African Rift System (EARS). Our survey (2015-2020) shows ground unrest at 14 different volcanic systems associated with different processes: 1) short-term inflation due to magma intrusions (Erta Ale and Fentale); (2) post-eruptive deformation related to magma bodies (Erta Ale, Nabro, Alu-Dalafilla, Dallol and Dabbahu); (3) broad inflation on restless caldera systems (Corbetti, Tullu Moje, Suswa); (4) lava flow subsidence (Erta Ale, Nabro and Kone); (5) ground deformation related to pore-pressure changes with possible tectonic structures (Gada Ale, Alutu, Haledebi and Olkaria). Results of this study have been recently published in Geochemistry, Geophysics, Geosystems (*Albino et al*., 2021).

Progress report: construct the first global assessment of current volcanic So2 flux from ir and uv data. (A long term study of global So2 emissions with IASI?)

Isabelle Taylor, COMET Postdoctoral Research Assistant, University of Oxford

We've applied our IASI retrievals to over 10 years of spectra and in doing so have identified a number of potential targets worldwide. Together with the COMET group at Manchester, we are planning to test running PlumeTraj on a few case studies (Sierra Negra in 2018 and La Soufriere in 2021). After that we can begin thinking about extending this globally and to ongoing activity.

Cat Hayer, Postdoctoral Researcher, University of Manchester

- Initial run for global TROPOMI-PlumeTraj for one week, performed with L2__SO2___ operational SO2 dataset.
- Year-long analysis run in progress.
- Additional global analysis using novel low-noise COBRA dataset, developed by Nicolas Theys (BIRA). Developing a wind-rotation averaging approach.

SCIENCE UPDATE: TECTONICS AND VOLCANISM

Progress report: build models of magmatic systems that can explain gas and deformation observations, initially in Iceland.

Cat Hayer, Postdoctoral Researcher, University of Manchester
Ana Pardo, COMET Postgraduate Student, University of Manchester
Mike Burton, COMET Scientist, University of Manchester
Andy Hooper, COMET Scientist, University of Leeds

We have switched focus from Iceland and are now primarily targeting Piton de la Fournaise, Réunion Island, and Nyiragongo, Democratic Republic of the Congo. We have obtained timeseries covering several months for SO2 fluxes (from applying the PlumeTraj analysis toolkit to TROPOMI observations) and ground deformation (using Sentinel-1 InSAR data). A high-resolution deformation time series for Nyiragongo is currently underway, as is inverse modelling of the 2021 activity using the deformation data to investigate the geometry of the plumbing system. Working with scientists from the Réunion observatory, we have compared the SO2 and deformation time series to local seismic data and are collaborating on the interpretation. Efforts are underway to establish a similar working relationship with local scientists at the Goma observatory.

Progress report: develop near real-time tools for monitoring volcanic unrest, using machine learning approaches for analysing large volumes of satellite data.

Fabien Albino, COMET Research Associate in Satellite Observations of Volcanic Processes, University of Bristol.

This work has been conducted under the COMET co-funding project “Making Satellite Volcano Deformation Analysis Accessible”, NE/S013970/1. At the present time, our LiCSAR dataset is composed of half of millions of Sentinel-1 interferograms over 1300 volcanoes for the period 2015-2020. This enables us to test our Machine Learning (ML) algorithms at a global scale to identify anomalous behaviour at active volcanoes. We applied the ML-CNN algorithms initially developed for individuals interferograms (Anantrasirichai et al., 2018) to the large dataset, and we identified 16 active volcanoes with a large number of detection (> 25 or >10% of the total number of interferograms). Among them, a large proportion is located on Galapagos islands and related to recent eruptions/intrusions at Fernandina, Cerro Azul and Sierra Negra. We also detected unrest at two silicic volcanic systems in the Andes, Laguna de Maule and Domuyo, as well as volcanic deformation related to recent eruptions at Kilauea and Etna. For each of the 16 volcanoes, we performed a detailed analysis applying our ML-CNN to the time series for a 5-years period (Nov 2015 – Nov 2020) to characterize the onset of unrest. This work has been recently submitted to Nature.

Nantheera (Pui) Anantrasirichai, Research Fellow, University of Bristol

Automated systems for detecting deformation in satellite InSAR imagery could be used to develop a global monitoring system for volcanic and urban environments. Here we explore the limits of machine learning based on deep convolutional neural networks (CNN) for detecting slow, sustained deformations in wrapped interferograms [1].

Previous studies have shown that CNNs have the capability to identify volcanic deformation signals from a large dataset of wrapped interferograms [2,3]. The high-frequency content of wrapped fringes provides strong features for machine learning algorithms. The outputs are expressed as a probability, which can be used to flag deformation. For C-band satellites like Sentinel-1, one fringe corresponds to 2.8 cm and it is present only at high rates of deformation, such as dyke intrusions or eruptions. Yet there are many deformation signals that occur at lower rates, but for longer duration, such as sustained uplift at silicic volcanoes.

To tackle this problem, we employ two adaptations to enable a machine learning system to detect slow, sustained deformation:

1) Using a daisy-chain of interferograms to increase the time interval and hence the signal to noise ratio (SNR). For each volcano, we process Sentinel-1 SAR images using LiCSAR, which automatically generates three short-duration interferograms for each time acquisition. A linear least-square inversion is performed on the network of unwrapped interferograms to obtain the time series of cumulative ground deformation using singular value decomposition and assuming no deformation at the first date.

2) Rewrapping at a different gain each time displacement maps generate additional fringes, without altering the SNR. We generate a new phase ψ' with a wrap gain μ using $\psi' \equiv \mu\psi$ (mod 2π), where μ is a positive integer. The wrap interval is reduced by 1/μ of the original phase value, and the number of fringes increases μ times, e.g., μ=2 produces twice as many fringes. We use μ=1, 2, 4 and 8 and the final probability of there being deformation is the average of the four results.

Using synthetic data, we estimate a detection threshold of 3.9cm for deformation signals alone, and 6.3cm when atmospheric artefacts are considered. Over-wrapping reduces this to 1.8cm and 5.0cm respectively. We also test this approach on timeseries of cumulative deformation from Campi Flegrei and Dallol (Fig. 1), where over-wrapping improves classification performance by up to 15%. We propose a mean-filtering method for combining results of different wrap parameters to flag deformation. At Campi Flegrei, deformation of 8.5cm/yr was detected after 60days. At Dallol, deformation of 3.5cm/yr was detected after 310days. This corresponds to cumulative displacements of 3cm and 4cm, which is consistent with estimates based on synthetic data.

Our techniques [1-3] have shown the potential of machine learning to detect ground deformation in InSAR data. Currently we have started the implementation of our machine learning tools on CEMS to work routinely and flag interferograms on the COMET Volcano Database.

References

[1] N Anantrasirichai, J Biggs, F Albino and D Bull (2019). The Application of Convolutional Neural Networks to Detect Slow, Sustained Deformation in InSAR Time Series, Geophysical Research Letters 46 (21), 11850-11858.

[2] N Anantrasirichai, J Biggs, F Albino, P Hill and D Bull (2018). Application of Machine Learning to Classification of Volcanic Deformation in Routinely Generated InSAR Data, Journal of Geophysical Research: Solid Earth

[3] N Anantrasirichai, J Biggs, F Albino and D Bull (2019). A deep learning approach to detecting volcano deformation from satellite imagery using synthetic datasets, Remote Sensing of Environment 230, 111179.

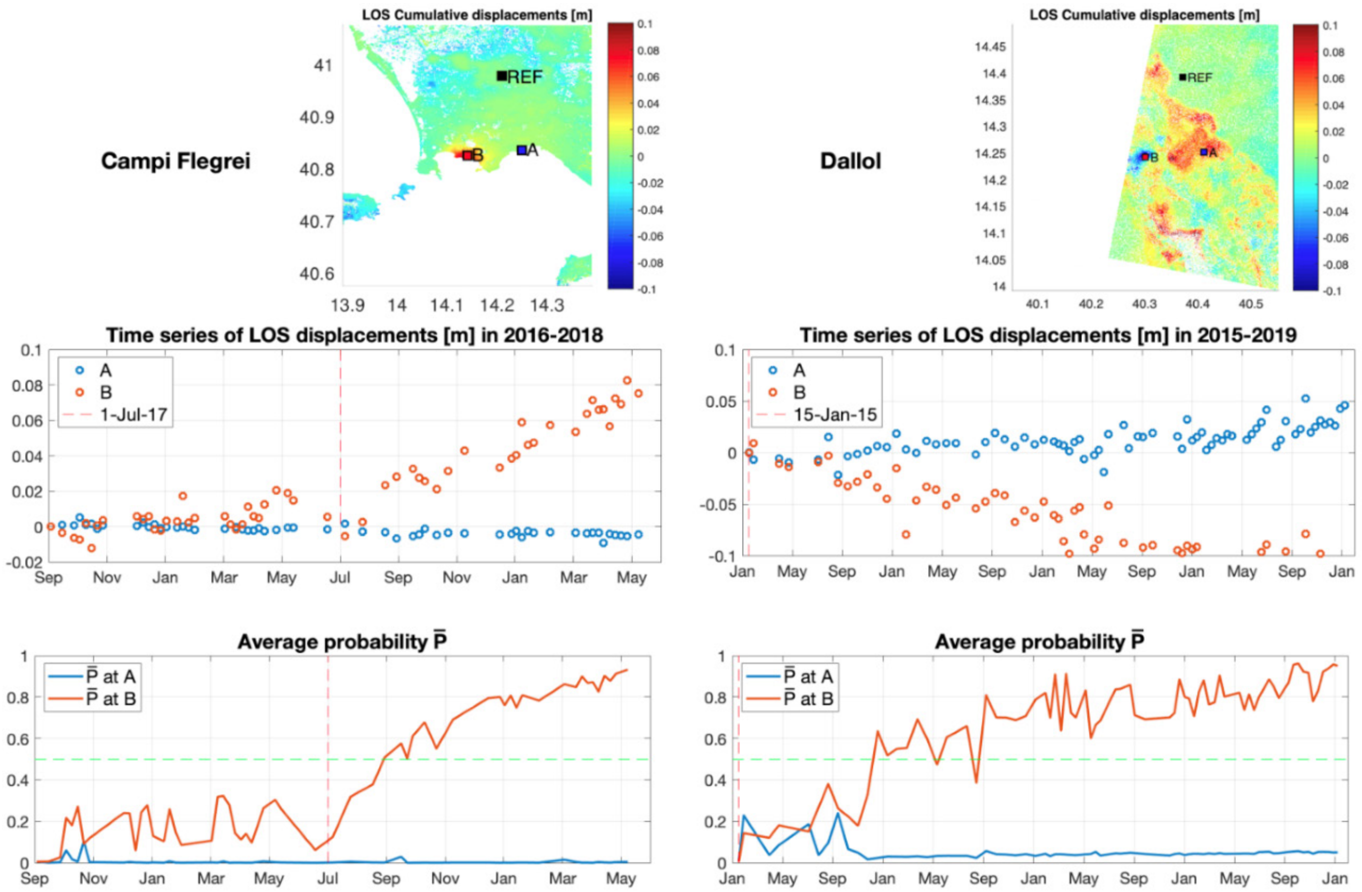


Figure 1: Examples using Sentinel-1 time-series from Campi Flegrei (left column) and Dallol (right column). Second-row figures show the cumulative displacements and two studied areas, A and B. The ground at area A is considered stable, whereas B is located at the volcanic centre is shows significant deformation. The average CNN-output probability for points A and B are shown in the bottom row.

IMPACT 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). COMET also feeds into the weekly advice on volcanic hazards and impacts that BGS provides to the Department for International Development (DfID) and other UK Government departments, and to the European Emergency Response and Coordination Centre.

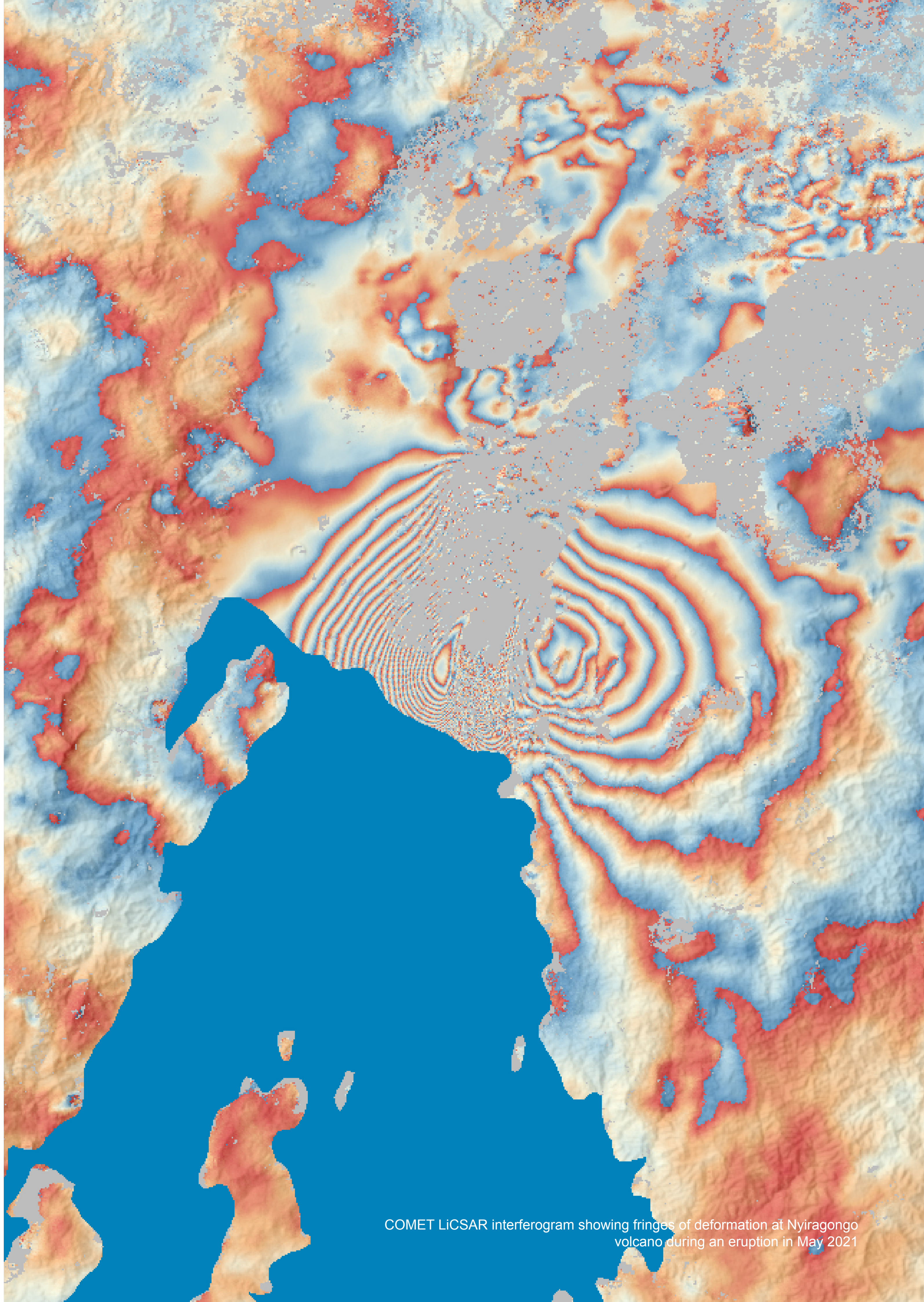
We have also developed close links with the Global Earthquake Model (GEM) and Global Volcano Model (GVM) as well as the US Geological Survey (USGS) and their Powell Centre Working Group. We sit on the Committee on Earth Observation Satellites (CEOS) Working Group on Disasters (leading the Pilot and Demonstrator 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, including two of the three missions chosen to compete as ESA's 10th Earth Explorer: Stereoid and G-Class.

TRAINING AND EDUCATION

Our flagship training event is our annual InSAR course, usually 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 2020 workshop was held online with participants joining virtually from around the world at different stages in their careers.

Our membership of the Copernicus Academy also 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 LiCSAR interferogram showing fringes of deformation at Nyiragongo volcano during an eruption in May 2021

COMMUNICATION, OUTREACH AND ENGAGEMENT

Communication and public engagement are important aspects of COMET's mission as we want 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 mins + questions), which are advertised to our wider COMET community, and uploaded to our YouTube channel, social media, and website.

Our latest COMET webinars[1] have covered a number of topics, including: what Australian surface ruptures tell us about intraplate faults and seismic hazard; measurements of the rheology of active faults; how active volcanism changes topography; LiCSAR for measuring tectonic & volcanic deformation; reinterpreting the historic and prehistoric ruptures of central Asia; and 101 Geodynamic Modelling Applied to Subduction.

COMET is committed to delivering practical changes that help increase equality, diversity, and inclusion within our community. Within this aim, we have started to develop a 'COMET+' webinar series to run alongside the COMET webinar series. 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.

Due to structural inequalities within our community, these researchers may not have as many opportunities to promote their work to a large audience, such as the COMET community. COMET+ aims to showcase research from these under-represented groups and promote the benefits of broad collaborative networks and a diversity of ideas.

COMET+ webinars occur whenever speakers are available (rather than a regular schedule) and are usually shorter than traditional COMET webinars (15 – 20 mins + questions). This will enable our webinar audience to watch more of these talks than they might for the longer webinars, interacting with a larger number of our COMET+ speakers.

The first COMET+ Webinars were given on Wednesday 3rd February 2021 by Xueming Xue and Connor Droof, Department of Earth and Environmental Sciences at Michigan State University.

We upgraded our webinar account last year to allow up to 500 audience members to join the sessions live. Over the last year, we have had between 200-300 registrations per webinar.

Our webinars uploaded to YouTube in this reporting period have reached a huge audience, with over 2500 views!

Website

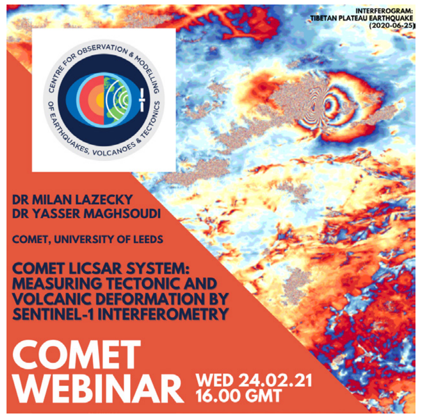
COMET website views have increased by around 20,000 from 2019-20, with 60,898 views in the last year. The website highlights our research and latest news but also access to our webinars, datasets and services, including the volcano deformation database.2 We are currently updating the look and content of the website to ensure that it is user-friendly and up-to-date.

We have gained around 500 Twitter followers over the last year – we now have 2,664 followers.[3] Our Instagram[4] followers have also risen by more than double to 78.

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 Associate Evgenia Ilyinskaya's research in Iceland, which was supported by a COMET Emergency Grant, led her to provide information about the volcanic activity in Iceland to various media sources.[5] The work of COMET Deputy Director Juliet Biggs was also featured in an article in *Science*.[6]

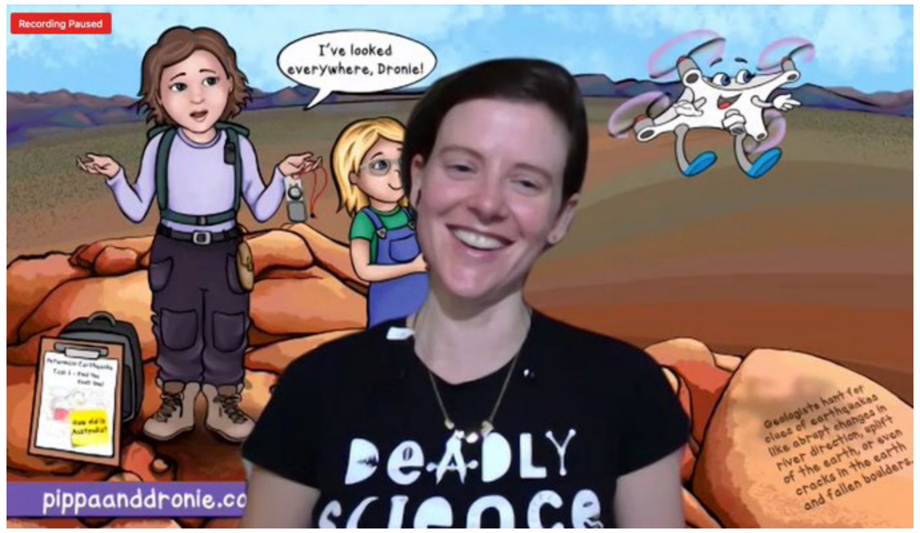
COMET members have commented on a wide range of topics in the media over the last year, such as Iceye's small radar satellites and InSAR,[7] earthquake models of California,[8] a £400m public bailout to rescue an imperilled satellite internet firm,[9] a 7.0 magnitude earthquake under the Aegean Sea,[10] and the Chamoli disaster (2021 Uttarakhand flood), India.[11] COMET Scientist Richard Walters also appeared in TV Documentary on BBC Earth.[12]

1 comet.nerc.ac.uk/comet-webinar-series/
2 comet.nerc.ac.uk/volcanoes/
3 @nerc_comet
4 www.instagram.com/comet_nerc/
5 www.nationalgeographic.com/science/article/eruption-in-iceland-may-mark-start-of-decades-of-volcanic-activity; https://www.bbc.co.uk/sounds/play/w3cszh1x; https://www.bbc.co.uk/sounds/play/w3cszh1x
6 www.sciencemag.org/news/2021/02/fleets-radar-satellites-are-measuring-movements-earth-never
7 www.bbc.co.uk/news/science-environment-52560809
8 www.nationalgeographic.com/science/article/southern-california-may-be-at-greater-risk-of-a-major-earthquake



Over the last year we gave a number of public lectures, such as: COMET Director Tim Wright presented a free public lecture, 'Monitoring our hazardous planet from space', as part of the Royal Astronomical Society's Bicentenary celebrations on 25th September 2020, Tamsin Mather did a live Q&A with Oxford Sparks Live 'Volcanoes!', COMET Scientist Tim Craig gave a talk as part of the Earth2Earth online seminar series that is being organised by a group of UK Earth/Geo-science departments in collaboration with Nature Geoscience, COMET Research Staff Fabien Albino presented as part of the International Volcanology Seminar series, and COMET Scientist Ekbal Hussain gave a talk to the Geoscientist Forum: Quakes, poverty and corruption: A recipe for disaster?.

COMET scientists are also involved in more innovative ways of communicating their research and engaging with the public. COMET Research Staff Tamarah King, for instance, features in a children's book 'Pippa and Dronie' to engage young children with geology and earthquakes![13]



9 https://news.sky.com/story/oneweb-dominic-cummings-and-the-400m-public-bailout-to-rescue-an-imperilled-satellite-internet-firm-12252863
10 www.nationalgeographic.com/science/2020/10/greece-and-turkey-earthquake-driven-by-wild-tectonics-of-aegean-sea/
11 https://news.sky.com/story/uttarakhand-dam-disaster-what-caused-indias-deadly-flood-12214731
12 www.cineflixrights.com/our-catalogue/539
13 www.pippaanddronie.com/characters

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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 and projects, including:

COMET has developed a formal collaboration with GEM, which is currently set to run from 2021-2026. COMET staff and scientists (in Oxford and Leeds) will work with scientists in GEM to deliver a technical proposal aimed at improving probabilistic seismic hazard and risk assessment in Central Asia.

The European Plate Observing System[1] (EPOS) 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.

EUROVOLC[2] is an EC 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 and companies from R&D, IT and geothermal industries.

RiftVolc[3], 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.

Tomorrow's Cities: The UKRI GCRF Urban Disaster Risk Hub is an 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.[4]

1. www.epos-ip.org
2. eurovolc.eu
3. riftvolc.wordpress.com
4. www.tomorrowscities.org
5 www.safernepal.net/

SAFER[5] - This landmark project draws on knowledge and experience from Nepal and around the world, incorporating earthquake, structural and geotechnical engineers, seismologists, earth scientists, computer scientists, social scientists, stakeholders, decision-makers and more. The project aims to save lives by making buildings safer – starting with schools. This work will provide diagnosis, testing and knowledge, but it's also preparing Nepal to mitigate the risk associated with future earthquake events.

Following on from this project, SAFER PREPARED is a UKRI funded GCRF project (2020-2021) led at University of Bristol in partnership with colleagues in Malawi. Earth scientists and engineers from Bristol and Malawi collaborate on the SAFER PREPARED project whose primary purpose is to contextualise the schools inspection app developed in the SAFER project for use in inspection of schools in Malawi.

RISE: Real-time earthquake rIsk reduction for a reSilient Europe[6] Earthquakes are the deadliest natural hazard. Developing tools and measures to reduce future human and economic losses is the aim of RISE. RISE is a three-year project financed by the Horizon 2020 programme of the European Commission. RISE is coordinated by ETH Zurich, it brings together 19 organisations from across Europe and five international partners.

V-PLUS[7] The NERC-funding 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.

Earthquake hazard and environmental security in Kazakhstan and Kyrgyzstan: This multi-year NATO funded project looking at active fault hazard, building on long-standing research collaborations between COMET members and colleagues in Kazakhstan, Kyrgyz Republic, France, Germany and USA

Making Volcano Deformation Data Accessible: This NERC Innovation Project 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.

R4Ash[8] (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.

DEEPVOLC aims to forecast volcanic activity by applying artificial intelligence to new data. Some 200 million people live within 30 km of a volcano but accurate forecasting of volcanic activity is problematic. It usually relies on human expertise at individual volcanoes, but volcanoes often behave in unexpected ways. A key indicator of volcanic activity is the deformation of a volcano's surface due to magma moving beneath the surface, and recent advances in satellite monitoring now allow us to record this deformation worldwide. 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.

6. www.rise-eu.org/home
7. http://gotw.nerc.ac.uk/list_split.asp?awardref=NE%2FS004025%2F1
8. http://wp.lancs.ac.uk/radar-forecasting-of-volcanic-ash/

AWARDS AND RECOGNITION, APRIL 2020 - MARCH 2021

Edna Dualeh (COMET Student, Leeds) was awarded Geological Remote Sensing Group (GRSG) student award. This national research prize was given to a GRSG student award to support collaboration with Mike Poland @USGSVolcanoes on the use of satellite radar amplitude imagery for monitoring active volcanoes.

Marie Edmonds (COMET Scientist, Cambridge) was presented with the prestigious AGU Joanne Simpson Medal for recognition of scientific research, education, communication, and outreach.

John Elliott (COMET Scientist, Leeds) was awarded the international AGU John Wahr Early Career Award, which recognizes significant advances in geodetic science, technology, applications, observations, or theory.

Ekbal Hussain (COMET Scientist, BGS) received the BGS Instant Recognition Award in recognition of his efforts in driving forwards the InSAR capability at the BGS.

Tamsin Mather (COMET Scientist, Oxford) was elected a member of the Academia Europaea in 2021 (https://www.ae-info.org/ae/Member/Mather_Tamsin).

Ailsa Naismith (COMET Student, Bristol) was selected to receive the Willy Aspinall award at the national Volcanic and Magmatic Studies Group (VMSG) awards for her outstanding paper on eruptive patterns at Volcan de Fuego.

Aisling O'Kane (COMET Student, Cambridge) was awarded the AGU Outstanding Student Presentation Award. This international research prize was awarded to Aisling for giving the most outstanding student presentation at the 2020 AGU Fall Meeting.

Tim Wright (COMET Director, Leeds) was invited to give a public keynote speech as part of the free and open to the public online lecture series for the Royal Astronomical Society's bicentenary celebrations.

COMET members have also given numerous invited talks and keynote lectures across the globe in recognition of their international standing in their respective fields.


Almaty, Kazakhstan

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STUDENT PUBLICATIONS, APRIL 2020 - MARCH 2021

COMET has a strong publication record: since 2014, COMET has published 539 papers in international scientific journals, including 43 in Science or Nature Research journals, attracting 13,574 citations to date and approximately 77% of all publications are the result of international collaborations.

114 were published between 1st April 2020 and 31st March 2021 (Annex 1), and, of these, 22 had student first authors.

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Iris van Zelst (Leeds)
Luke Wedmore (Bristol)
Chen Yu (Newcastle)

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)
Sarah Boulton (Plymouth)
Peter Clarke (Newcastle)
John Douglas (Strathclyde)
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David Ferguson (Leeds)
Matt Fox (UCL)
James Hickey (Exeter)
Anna Hicks (BGS)
Evgenia Ilyinskaya (Leeds)
Chris Jackson (Manchester)
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Margherita Polacci (Manchester)
Ed Rhodes (Sheffield)
Dylan Rood (Imperial)
Anja Schmidt (Cambridge)
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Tom Wilkes (Sheffield)
Sam Wimpenny (Cambridge)

OUR MEMBERS, APRIL 2020 - MARCH 2021

COMET STUDENTS

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.

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Stanley Yip (Bristol)
Eva Zand (Leeds)


Volcán de Fuego, Guatemala

GLOSSARY

AGU	American Geological Union
ABH	Alpine-Himalayan Belt
ALOS	Advanced Land Observation Satellite
BGS	British Geological Survey
CEDA	Centre for Environmental Data Analysis, NERC
CEMS	Copernicus Emergency Management Service
CEOS	Committee on Earth Observation Satellites
CNN	Convolutional Neural Network
COMET	Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics
DEM	Digital Elevation Model
EARS	East African Rift System
EC	European Commission
EDI	Equality, Diversity and Inclusion
EIDP	Earthquake InSAR Data Provider
EO	Earth Observation
EPOS	European Plate Observing System
ESA	European Space Agency
GACOS	Generic Atmospheric Correction Online Service for InSAR
GCRF	Global Challenges Research Fund
GEM	Global Earthquake Model
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRSG	Geological Remote Sensing Group
GVM	Global Volcano Model
gWFM	Global Waveform Catalogue
HEIs	Higher Education Institution
HPC	High Performance Computer
IASI	Infrared Atmospheric Sounding Interferometer
InSAR	Synthetic Aperture Radar Interferometry
IR	Infrared
ITRF	International Terrestrial Reference Frame
LiCS	Looking inside the Continents from Space
LiCSAR	Looking Into Continents from Space with Synthetic Aperture Radar
ML	Machine Learning
NCEO	National Centre for Earth Observation
NERC	Natural Environment Research Council
NGO	Non-Governmental Organisation
NRT	Natural Resonance Theory
ODA	Official development assistance
SAR	Synthetic Aperture Radar
SfM	Structure-from-Motion
SNR	Signal to noise ratio
SPOT	Satellite pour l'Observation de la Terre
TEC	Total electron content
UCL	University College London
USGS	US Geological Survey
UV	Ultraviolet
VMSG	Volcanic and Magmatic Studies Group

Tibetan Plateau

COMET

CENTRE FOR OBSERVATION & MODELLING
OF EARTHQUAKES, VOLCANOES & TECTONICS

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