COMET

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

ANNUAL REPORT
2019 / 2020

British Geological Survey

Natural Environment Research Council

CONTENTS

INTRODUCTION

The Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) delivers world-leading science in Earth Observation, 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 2019-21, the first 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 2019 – 31st March 2020.

DIRECTOR'S WELCOME

COMET's sixth annual report comes at a strange time as we are getting used to a new way of working in the midst of a global pandemic. We were disappointed not to be meeting in person in June 2020, but our annual meeting was held online and we learned from successes such as the EGU meeting so that we could try to enable as much virtual interaction as was possible.

We have completed the first year of our current 2-year funding period and you can read about progress towards our goals in this report. One major achievement has been reaching agreement with NERC and the BGS on a document describing the future closer working relationship with BGS. To quote from the agreement, *"In putting together this document, COMET and BGS recognised that COMET now encompasses a national-scale community whose size and impact builds on, but surpasses, its National Capability (NC) funding (e.g. through co-funded and externally-funded research). Our vision is for COMET to remain an independent entity with its own leadership aiming to deliver world-leading science in Earth Observation, Tectonics and Volcanism, but to develop closer integration of NC activities delivered by COMET and BGS."* As part of this agreement we have recently submitted our proposed NC work plan for the 5 year period from April 2021.

COMET has seen several new arrivals as staff scientists in the last year. We welcome Yasser Maghsoudi, who joins Leeds to lead the development of the InSAR facility, Scott Watson, who takes on a role in Geoinformatics at Leeds, co-funded through the Tomorrow's Cities GCRF Hub, Isabelle Taylor, who takes on a position at Oxford in the volcanic emissions team, Tamarah King, who is working on faulting and geomorphology, also at Oxford, and Charlie Royle, who has taken over from Debbie Rosen as COMET General Manager (shared with CPOM). We also welcome some new members to the Advisory Board, including Philippa Mason from Imperial College and former COMET staff member Elisa Carboni, now at RAL, who will be representing the National Centre for Earth Observation. We 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 several award winners (listed later in the document) at all levels within COMET: Marie Edmonds (Cambridge) was selected to present the Daly Lecture at AGU 2019, Tamsin Mather (Oxford) was invited to act as Theme Chair for Magmas and Volcanoes at the 2019 Goldschmidt meeting. Andy Hooper (Leeds) and Tamsin Mather (Oxford) were awarded large ERC consolidator grants and David Pyle (Oxford) won the Thermo-Fisher Scientific Award 2020 at the 2020 VMSG meeting.

Professor Tim Wright,
COMET Director

ADVISORY BOARD COMMENTS 2019

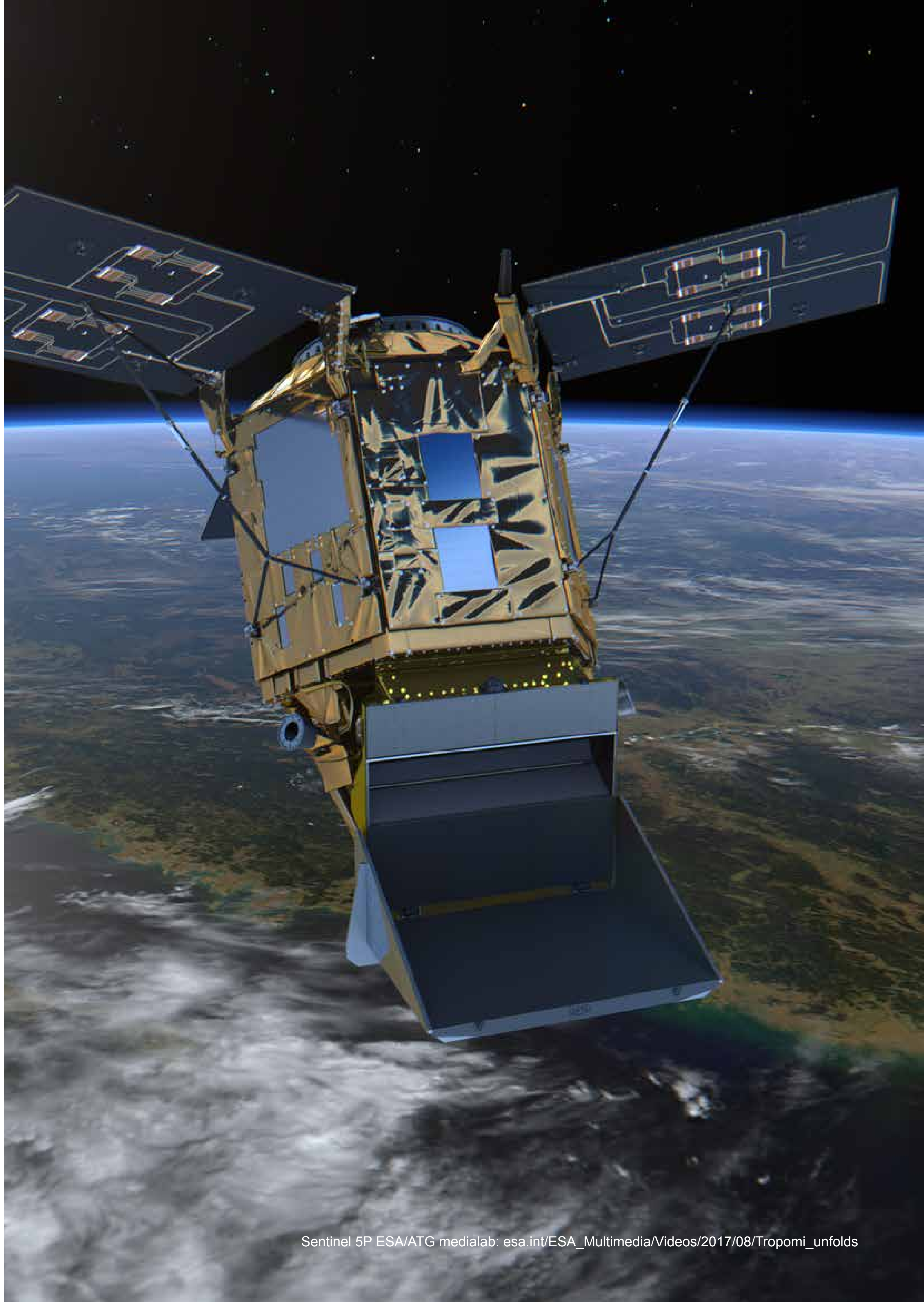
The 2019 COMET Annual meeting was held in person at the National Railway Museum, York. The Advisory Board were, again, struck by the global impact and the high quality of research conducted within COMET. The impacts of COMET research travel well beyond the high quality of the publications produced; they also influence society through improved understanding of hazards, and by providing training for a new generation of scientists in the UK and abroad. COMET is widely regarded as a focal point for Earth science in the UK, as well as in the rest of the world.

The scope of the research achieved by COMET is striking. Their success is due in part to careful prioritization of tasks and the consistently high quality of the resulting science. A particularly valuable aspect of COMET's efforts is their ongoing commitment to provide data and computer services to the national and international community. These products include unwrapped Sentinel-1 interferograms over tectonically active regions of the world; GBIS, a geodetic Bayesian inversion software; and GACOS, an online service for atmospheric corrections for InSAR that is increasingly used by researchers worldwide.

An exciting development has been the application of data science to aid in detection of relevant processes in the increasingly large volumes of available satellite imagery. COMET researchers used both principal components analysis and machine learning to automatically detect and monitor unrest at volcanoes. These efforts included outreach to scientists with expertise in machine learning, and were instrumental in training a new generation of earth scientists in the use of these tools.

We particularly appreciated the high quality of presentations at the 2019 Annual Meeting, with efficient talks and a dynamic poster session. The ability of the students to clearly communicate their research speaks highly of the quality of the mentoring and the success of the frequent meetings where the students can work on their presentation skills. COMET provides an environment where students can receive mentoring not only from their advisors, but also from other researchers.

A notable feature is the diversity of countries of origin of students. Because of this international environment, the skills gained by the students do not only benefit the British academic system or BGS, but also enhance research overseas when COMET PhD and post-doctoral researchers are hired outside of Great Britain.



Sentinel 5P ESA/ATG medialab: esa.int/ESA_Multimedia/Videos/2017/08/Tropomi_unfolds

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.

Volcano Tungurahua

COMET ANNUAL REPORT 2020

SCIENCE UPDATE: EO DATA AND SERVICES

1. Deformation from satellite geodesy

Research Highlight: Deformation results for much of the Tibetan Plateau, with interesting implications for where strain is accumulating on the Altyn Tagh Fault.

Lin Shen, PhD Candidate, University of Leeds

The 1600 km-long Altyn Tagh Fault (ATF) is a major intra-continental strike-slip fault in the Northern Tibetan Plateau, the slip rate of which has significant implications for our understanding of the tectonic processes of the Tibetan Plateau region. Previous studies of interseismic deformation over the ATF have only focused on specific portions, without providing the overall picture of the variation of localised strain accumulation along the fault. The operational nature and radar characteristics of the Sentinel-1 Synthetic Aperture Radar (SAR) mission makes it suitable for using Interferometric SAR (InSAR) to accurately constrain deformation for large regions, which has been difficult to achieve with previous SAR sensors.

In this research, we derive the InSAR velocity field over 1200 km of the ATF from 80˚E to 95˚E using the first 5 years of Sentinel-1 interferograms spanning the period between late 2014 and 2019 (Fig. 1). As the ATF is located at the border between the low Tarim Basin and the high Tibetan Plateau, the long wavelength deformation signal is strongly masked by tropospheric delay variation across the 4 km topographic relief. To improve the retrieval of small tectonic signals, we have developed a new spatially varying scaling method[1] for InSAR tropospheric corrections that combines the use of both external weather model data and the interferometric phase. Our method better reduces the tropospheric effects and leads to a clearer deformation signal over the ATF. We remove long wavelength trends from the InSAR velocity fields using GPS observations and then transform the velocities into the fault-parallel profiles at intervals of 0.5˚ along the fault.

The fault-parallel profiles show clear strain concentrations on the ATF. Of particular note, profiles to the west of 83˚E indicate that the strain accumulation occurs on the southern strand of the ATF, which is structurally linked to the Longmu-Gozha Co strike-slip fault, on which the 2008 Mw 7.2 Yutian earthquake occurred. The asymmetric pattern of interseismic velocities shown in the profiles suggests a decrease in rigidity from the Tarim basin to the Tibetan Plateau. The profiles also show that additional strain localisations are distributed over southern strands near the western portion of the ATF from 84˚E to 85.5˚E and the eastern portion from 91˚E to 92˚E.

We derive the slip rate and locking depth for the individual fault-parallel profiles along the ATF using an elastic half-space model, accounting for rotation and variation in rigidity (Fig. 2). The results reveal a systemic decrease in fault slip rate from 12 mm/yr to 8 mm/yr along the western portion to the central portion of the fault, whereas it rebounds to 10 mm/yr over the eastern portion. We also calculate strain rates at the surface from the estimated slip rate and locking depth and the results show that higher strain is accumulated at the surface over the western portion of the ATF especially from 81.5˚E to 83.5˚E. These results are significant for us to understand the distribution of the strain localization along the ATF and so to assess the future seismic hazards over the region.

References

Shen, L., Hooper, A., & Elliott, J. (2019). A spatially varying scaling method for InSAR tropospheric corrections using a high-resolution weather model, *Journal of Geophysical Research: Solid Earth,* doi:10.1029/2018JB016189

1. We have published the codes at https://github.com/Lin1119/ASVS

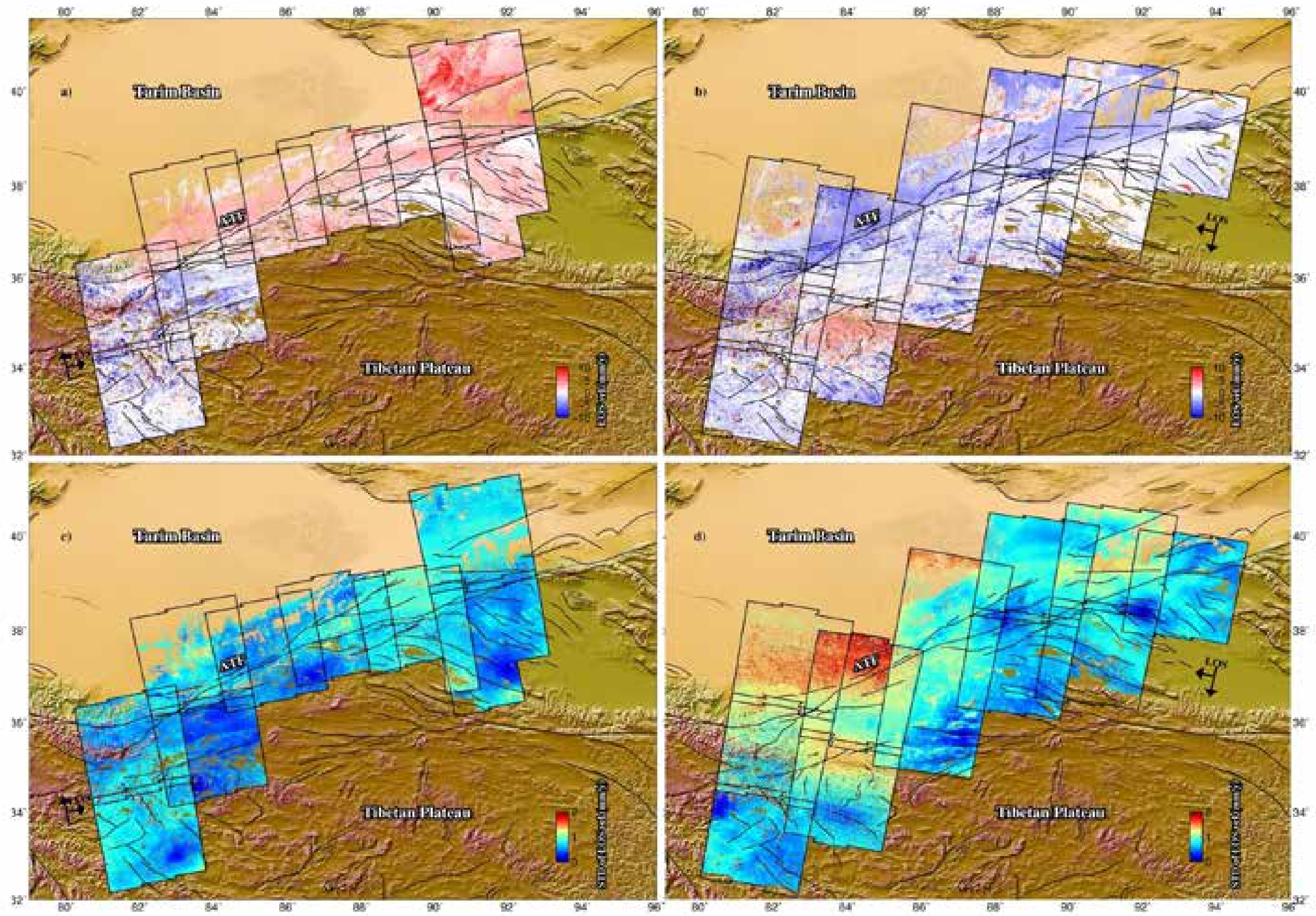


Figure 1: InSAR derived line-of-sight (LOS) velocity fields along the Altyn Tagh Fault in (a) ascending and (b) descending, and their respective standard deviations (c and d) estimated by the percentile bootstrapping technique. Positive values in (a) and (b) indicate the motion towards the satellite, whereas the negative values show the motion away from the satellite. The polygons indicate regions of InSAR frames.

SCIENCE UPDATE: EO DATA AND SERVICES

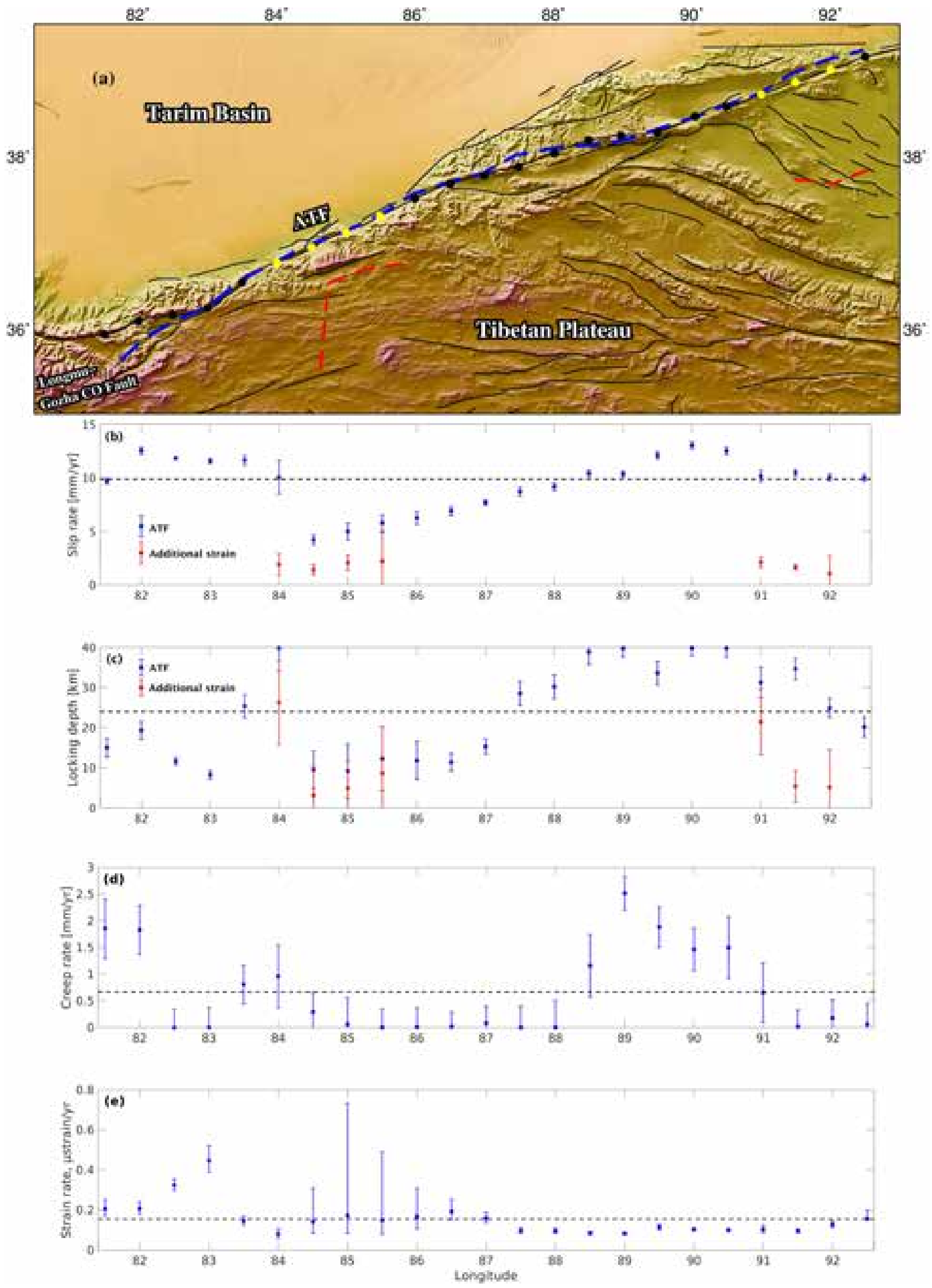


Figure 2: The variation in fault slip rate (b), locking depth (c), rigidity (d) and strain rate (e) along strike of the Altyn Tagh Fault (ATF) estimated from the fault parallel velocity profiles that derived from the decomposed east-west velocity map (a). The yellow points in the map (a) indicate the estimated fault dislocation along the ATF. The black dashed lines in (b) and (c) show that the mean fault slip rate is 10 mm/yr, with an average locking depth of 24 km. The error bars represent the 68% confidence bound on the parameter estimates. The focal mechanism solution in (a) indicates the 2008 Mw 7.2 Yutian earthquake.

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
Daniel Juncu, COMET Postdoctoral Researcher, University of Leeds

The long-term development of the COMET Sentinel-1 InSAR processing facility at Jasmin/CEDA has continued over the last year. As of May 2020, the system had processed around 88,000 Sentinel-1 acquisitions and generated more than 270,000 interferograms. Figure 1 shows the number of generated interferograms from 2016 to present. A significant increase in the number of generated interferograms can be seen over the past year.

We divided the whole Alpine-Himalayan (AH) belt into 3 priority tectonic zones. The first zone covers Turkey, west of Iran, East of Tibet and the east African Rift. The second priority zone includes east of Iran, Caucasus and west of Tibet and the third priority zone covers the rest of the AH belt. We have now completed the processing of Zone 1 and 2. The frames over these priority zones are currently being updated to a 'rolling' status so that they will be updated on a monthly basis. This is now operational for more than 300 frames.

Among the 1507 LiCSAR frames, 470 frames are related to 1024 volcanoes. Frames covering active volcanoes are processed on a short-term basis (three updates per week), with specific processing structures being developed that should allow for the generation of interferograms over all active volcanoes as soon as Sentinel-1 SLC data are available (a 'live' status).

We also developed a quality assessment module in the LiCSAR system. This module can automatically check the quality of the generated interferograms. It is based on the coherency and the percentage of unwrapped coverage. The script can also detect any geometrical artefact in the interferograms.

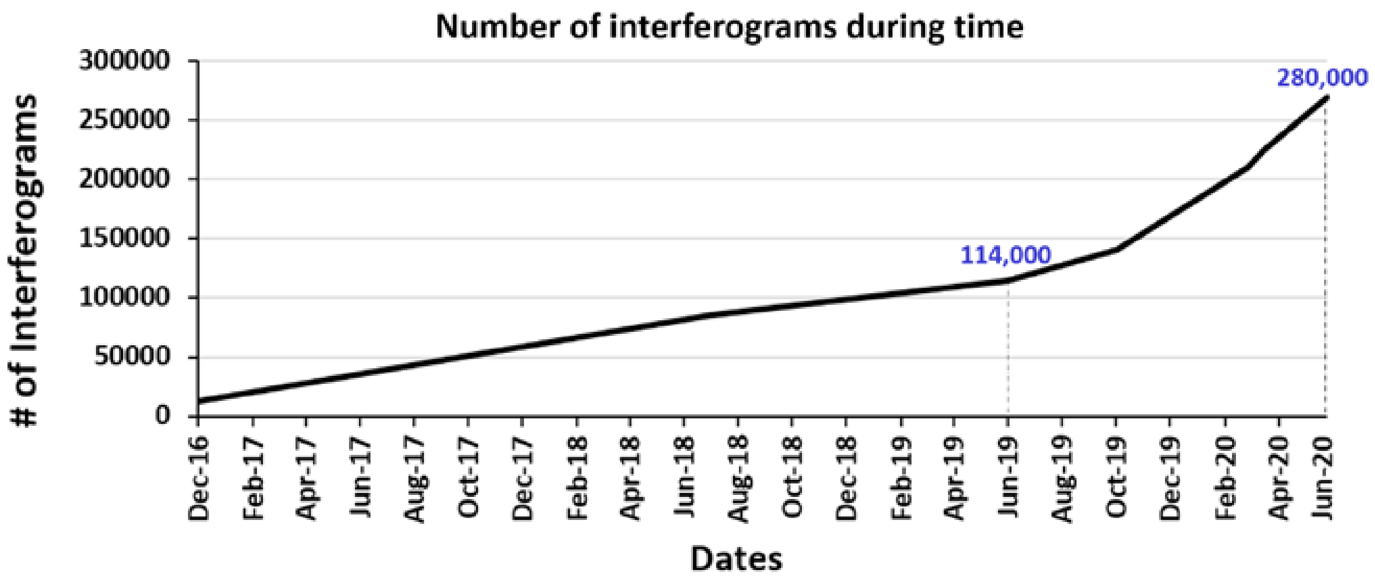


Figure 1: number of interferograms during time

SCIENCE UPDATE: EO DATA AND SERVICES

We are currently working on the automatic generation of the velocity fields in the AH belt. In essence, the quality of the velocity fields highly depends on the number and quality of the generated interferograms. We, therefore, are working on an iterative approach, which aims to fill the gaps in the time-series network and reprocess the 'bad' interferograms prior to the time-series module. An initial velocity field in the AH belt based on the current LiCSAR products can be seen in figure 2. We are continuing to improve this service.

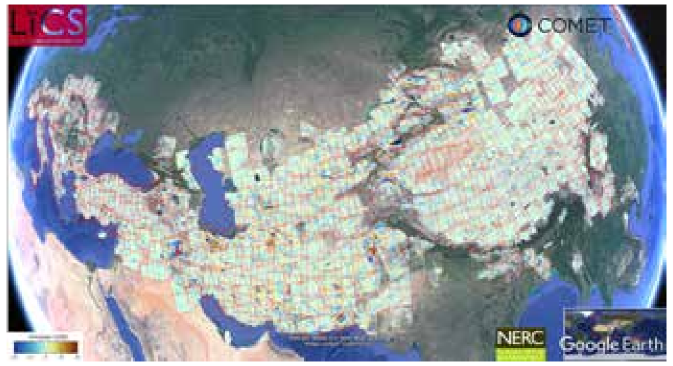


Figure 2: A preliminary velocity field in the AH belt

Progress Report: Work towards producing 3D velocities by exploiting burst overlaps in Sentinel-1.

Pawan Piromthong, PhD Candidate, University of Leeds

InSAR from ascending and descending geometries only provide two components of the 3D velocities, but burst overlaps can be exploited using the spectral diversity technique to determine offsets in the along-track direction, allowing constraint of the full 3D motion. However, significant noise contributions from decorrelation and propagation through the ionosphere make it challenging to retrieve the subtle variations in along-track velocity associated with low-straining regions undergoing interseismic deformation.

In the past year, we have developed an algorithm that can extract along-track velocities with a precision of 3 mm/yr approximately in high coherence areas. Using ascending data, the technique is able to detect the slip rate of 4 mm/yr across the West-Lut Fault in Eastern Iran, and the velocity profile agrees well with a previous GPS data study. Our algorithm uses a small baseline time-series approach to estimate the velocities, and improves on previous approaches to reducing ionospheric signal, through improved detection of unwrapping errors and spatial filtering techniques.

This study uses a low spatial resolution (1.5x1 km) in order to mitigate the significant decorrelation noise. However, with the ability to retrieve the north-south component independently, this work presents the first steps that will enable the full three components of deformation for tectonics to be extracted from the Sentinel-1 satellites.

Furthermore, we have applied the technique with the Chaman fault, where we have processed stacks of SAR images from both ascending and descending data. The along-track velocity maps agree well with each other and with other values in the literature.

Exchange visits provide further opportunities. COMET Bristol researchers were part of a team travelling to Guatemala to teach local scientists how to use drones to map the Fuego volcano after it erupted violently in June 2018, resulting in several hundred deaths[8]. The four-day workshop provided training in safe flight protocols, data acquisition and image processing using quadcopters and 3D modelling software.

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
Daniel Juncu, COMET Postdoctoral Researcher, University of Leeds

LiCSAR earthquake data provider

The rapid availability of Sentinel-1 data following acquisition (a few hours), together with the short revisit period of 6 days for many areas, provides a unique opportunity to develop an automatic Earthquake InSAR Data Provider (EIDP) system using the LiCSAR infrastructure. The main objective of EIDP is to form co-seismic interferometric pairs in a rapid manner, as well as pre- and post- seismic interferograms, and to make these data widely and freely available to the community. We anticipate that these products have applications for the scientific understanding of events as well as for operational crisis management and disaster mitigation.

We have developed routines for an early identification, download and processing of the first post-earthquake Sentinel-1 data within a few hours after the data appears available. These LiCSAR EIDP routines are activated for frames covering expected extent of earthquake events of at least Mw 5.5 (in case of depth of hypocentre at least 10 km), as identified by USGS Earthquake Catalog. We export co-seismic and post-seismic interferograms as KMZ files (Google Earth data format), in addition to standard LiCSAR outputs. We link the EIDP-generated interferogram products to our web based map and prepare structures for their automatic ingestion to other community systems (e.g. CEDA Archive, EPOS).

We aim towards integration of GACOS atmospheric phase screen correction estimates to the final interferograms, noting that GACOS data should be available with a 24 hour delay. We also plan to extend the system to respond to volcanic activity.

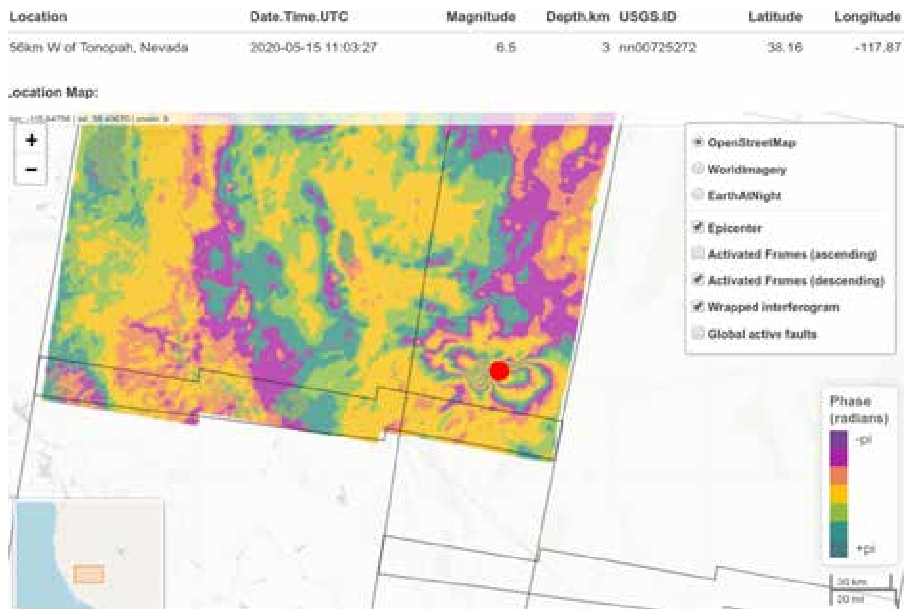


Figure 1: An example of EIDP products generated automatically for Mw6.5 event in Nevada, May 15, 2020: http://gws-access.ceda.ac.uk/public/nceo_geohazards/LiCSAR_products/EQ/nn00725272_map.html

SCIENCE UPDATE: EO DATA AND SERVICES

LiCSAR strip map processing module

We have incorporated processing functionality for Sentinel-1 StripMap images into the LiCSAR processing chain. StripMap images are acquired for islands that are not covered by the TOPS (Terrain Observation with Progressive Scan) acquisition mode, adding the volcanic islands of La Réunion (French territory, Indian Ocean), Fogo (Cabo Verde), Tristan da Cunha (British Overseas Territory, south Atlantic Ocean) and Marion Island (South Africa, sub-antarctic Indian Ocean) to the product database. The processing produces multi-looked interferograms at ~30x30 m resolution.

LiCSAR GACOS module

One of the major limiting factors of the use of the InSAR in most of tectonic and volcanic applications is the spatiotemporal variability of tropospheric properties. This is of importance especially in cases where deformation and topography are correlated. To address this limitation, we have developed tools for including products for an atmospheric correction, based on the COMET GACOS system developed at the University of Newcastle. GACOS uses an iterative tropospheric decomposition interpolation model that decouples the elevation and turbulent tropospheric delay components estimated from high-resolution ECMWF and GPS data. GACOS corrections are computed for each LiCSAR frame with the same image sizes to facilitate direct use.

GACOS tropospheric delay maps are provided per epoch in GeoTIFF format in the same resolution as the other LiCSAR products and in both vertical and LOS direction. It should allow the user to readily apply the correction to the LiCSAR phase products, using the LiCSBAS software. Additionally, we archive the original GACOS tropospheric delay map files. Currently only few frames have GACOS products generated during the testing phase.

Dolomieu Crater of the Piton de la Fournaise volcano on Réunion Island

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SCIENCE UPDATE: EO DATA AND SERVICES

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

Research Highlight: Two Billion Points: DEM generation for Tomorrow's Cities (UKRI GCRF Urban Disaster Risk Hub) Summary of DEM generation and intended use for each city in the Hub

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

Tomorrow's Cities is an interdisciplinary research hub working to address multi-hazard disaster risk management in Istanbul, Quito, Nairobi, and Kathmandu, funded through the Global Challenges Research Fund (GCRF). COMET is supporting the hub by providing and analysing earth observation data from the 1960s to present day. We are generating both science communication and research content using our experience in optical and radar data processing. Examples of content generated so far for the cities, such as topographic datasets and land use change, are available on the COMET website.

City models

Visualising a city's landscape and topography is key to understanding and communicating information on its development and intersection with hazards. We worked with a specialist map maker to create 3D relief models for each city, which were cut out of high-density foam. We have also used 3D printing to display smaller areas in greater detail. Image overlays are projected onto the models to show a wide range of datasets including land cover, population and infrastructure distribution, volcanoes and faults, and climate. City teams are encouraged to use the models for public and stakeholder engagement events.

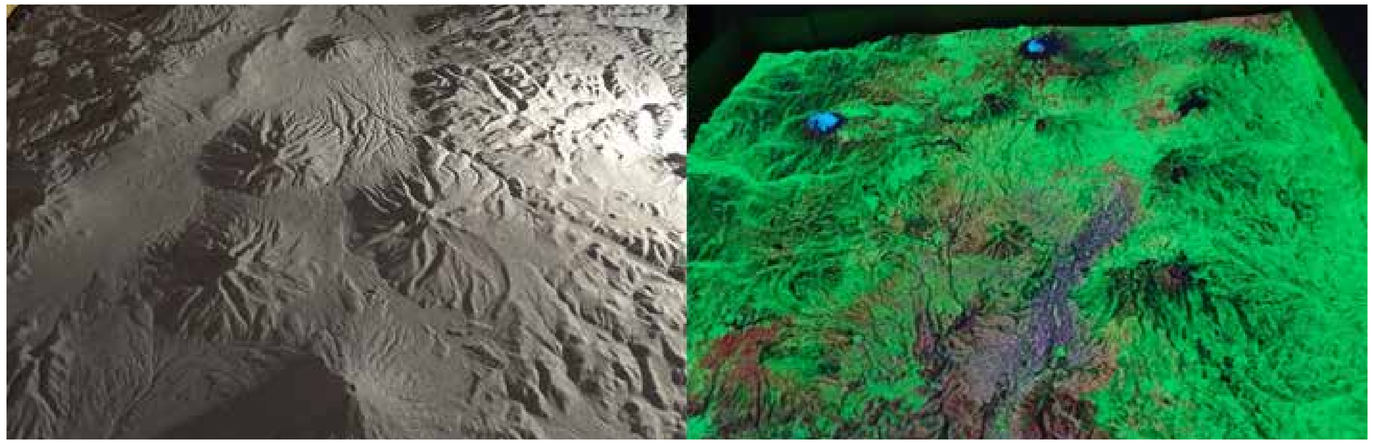


Figure 1: 3D city model of Quito with an illuminated hillshade (left) and projected Landsat composite satellite image overlay (right). The model measures 80 × 80 cm.

City topography

Through collaboration with the Committee of Earth Observing Satellites (CEOS), the Pléiades satellite constellation was tasked to acquire high-resolution tri-stereo city imagery. Capturing three images (tri-stereo) during each acquisition increases the coverage and data quality in areas of high relief and amongst high-rise buildings. The imagery is processed using photogrammetry software to generate digital elevation models (DEMs) at 2 m resolution and orthoimages. The data will be used to address seismic, volcanic, landsliding, and flooding hazards affecting the cities.

Initial processing of four Pléiades acquisitions over Kathmandu produced a point cloud of over 2 billion points. After quality checks and post-processing, the points cloud will be rasterised into discrete pixels to create a 2D DEM. DEMs have significantly lower data storage requirements and are easier to utilise in further analyses than raw point data. So far, we have post-processed a 10 km river reach in Kathmandu, which will be used by collaborators in a fluvial flood model.

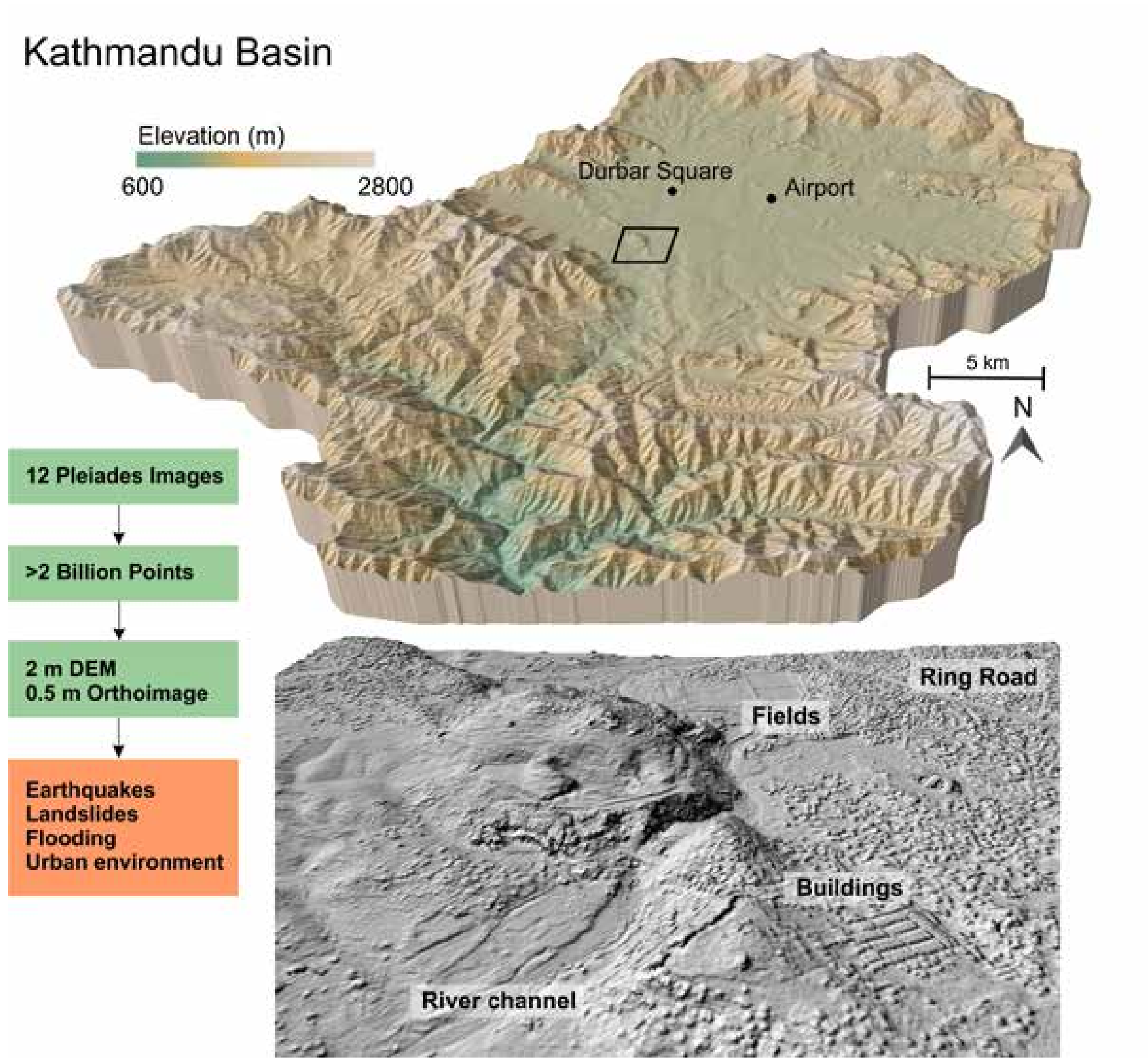


Figure 2: 3D elevation model of the Kathmandu Basin generated from tri-stereo Pléiades satellite imagery. The lower panel shows a subset of the hillshaded DEM.

SCIENCE UPDATE: EO DATA AND SERVICES

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

We have developed and documented workflows for producing digital elevation models (DEMs) from high resolution optical satellite imagery. We used both a traditional photogrammetry package (ERDAS IMAGINE), and Agisoft Metashape software, the latter of which emerged to exploit Structure from Motion with multi-view stereo techniques. Denser point clouds and Python based scripting in Agisoft Metashape indicate potential for the exploitation of an expanding archive of CubeSat imagery (e.g. Planet Labs). Future work will focus on cross-comparison of topographic datasets for quality assessment and automating elements of the workflow.

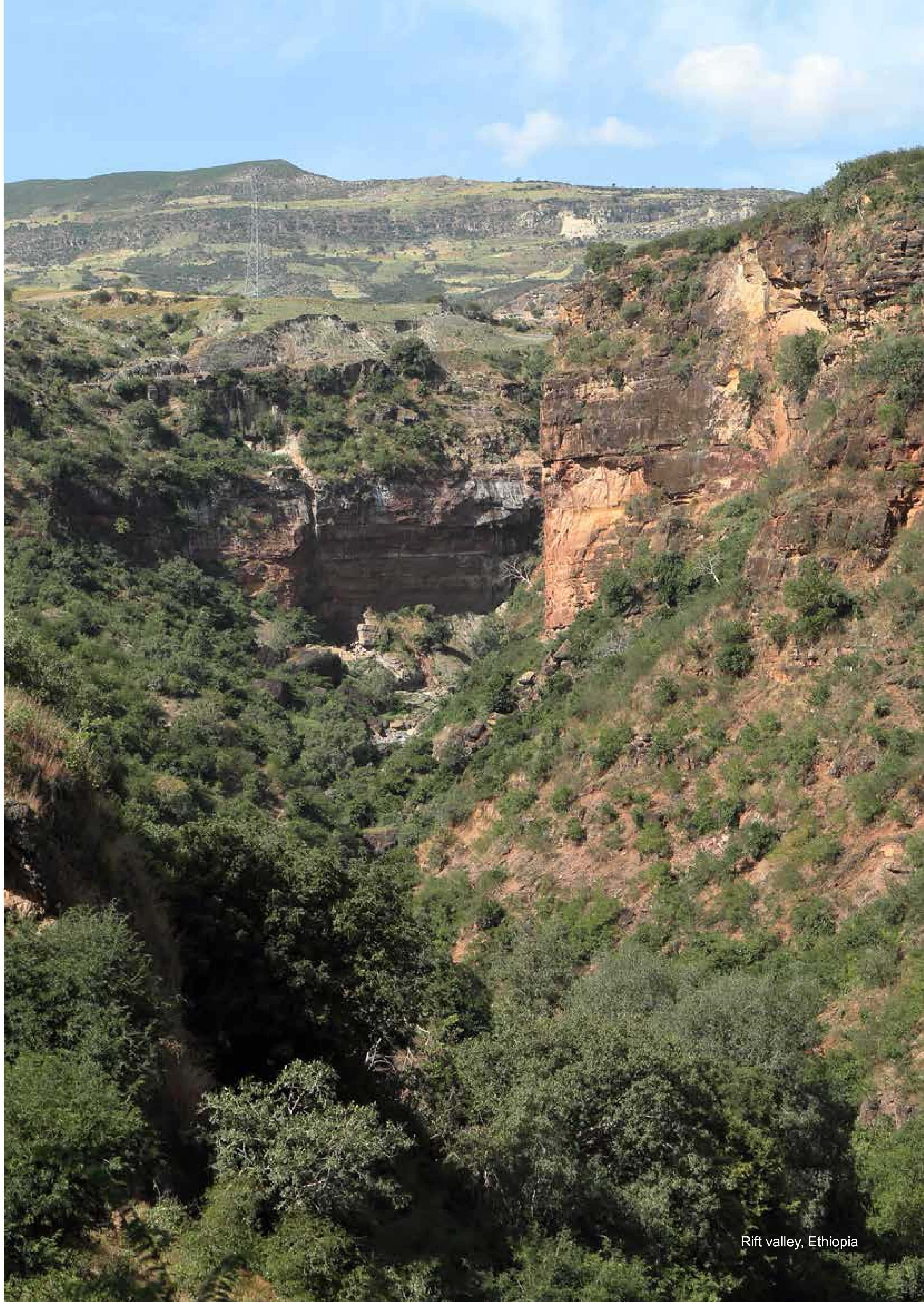
Progress Report: Produce datasets as required by the hazard teams.

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

Several publications involving COMET scientists have continued to exploit high-resolution satellite imagery (e.g. Pléiades) to generate topographic data for assessing tectonic and volcanic processes. Hodge *et al*. (2019)[1] analysed the Bilila-Mtakataka fault, Malawi, using scarp and river profile topography to reveal evidence of multiple earthquakes. Hunt *et al*. (2020)[2] used high resolution topographic data to analyse morphometric parameters of two volcanic fields in the Main Ethiopian Rift, revealing insights into volcanic processes and timescales. These and other topographic datasets generated by COMET scientists or with COMET support are available at OpenTopography[3].

COMET is also supporting the Tomorrow's Cities project (UKRI GCRF Urban Disaster Risk Hub) through the provision and analysis of earth observation data including high-resolution optical satellite imagery and topography to investigate multi-hazard disaster risk management.

1. https://doi.org/10.1029/2019TC005933
2. https://doi.org/10.1016/j.jvolgeores.2019.106732
3. https://portal.opentopography.org/dataSearch?search=COMET


Rift valley, Ethiopia

SCIENCE UPDATE: EO DATA AND SERVICES

3. Retrievals of volcanic emissions from satellite spectrometers

Research Highlight: Observations of the Raikoke eruption with the IASI instrument.

Isabelle Taylor, COMET Postdoctoral Research Assistant, University of Oxford

Raikoke, a volcano in the Kuril Islands, began erupting on the 21st June 2019. The eruption emitted significant quantities of SO_2 and volcanic ash into the atmosphere. These plumes were observed by numerous satellite instruments including the Infrared Atmospheric Sounding Interferometer (IASI): an instrument which has sensitivity to both SO2 and ash.

Initially, we observed the development of this plume using the Walker et al. (2011, 2012) IASI linear SO_2 retrieval. This is a quick method for detecting elevated levels of SO_2 making it suited to observations of volcanic plumes in near real time (NRT) and initially it was possible to watch the plume's evolution on the Earth Observation Data Group's NRT webpage. The IASI linear retrieval showed elevated amounts of SO_2 for at least two months following the eruption: with the plume circulating in the northern hemisphere above 30°. The figure below shows the effective SO_2 column amount averaged over July 2019.

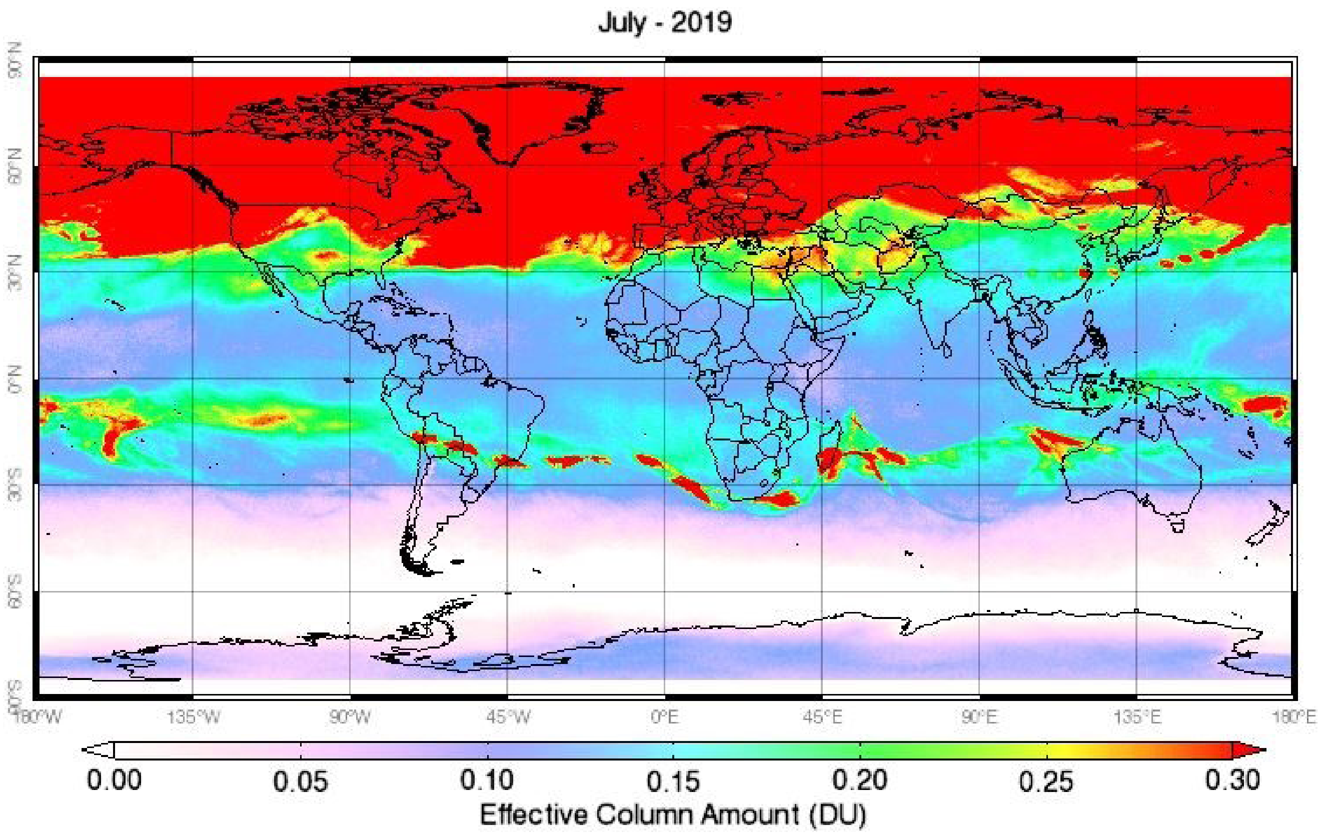


Figure 1: July 2019 monthly average of the Walker et al. (2011, 2012) linear retrieval with the output of each orbit gridded to a 0.125 by 0.125° grid. Within this it is possible to see plumes from two eruptions. In the northern hemisphere is the large plume from the eruption of Raikoke on the 21st June. In the southern hemisphere it is possible to see a plume from 26th June 2019 eruption of Ulawun in Papua New Guinea.

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Using the Carboni *et al.* (2012) iterative retrieval, it is possible to estimate both the column amount and altitude of the SO_2 plume and observe how this evolves with time. The complex nature of the Raikoke plume made it an excellent test of the retrieval technique. The figure below shows retrieval results for the first few days after the eruption. Initially, very high column amounts are estimated: in some cases, values are greater than 600 DU. The column amount can be combined to give a preliminary estimate of roughly 1.6 Tg for the total SO_2 mass (on the 23rd June 2019). The eruption creates two distinct plumes separated in height: they are shown as A and B in the figure below. SO_2 in box A, the southern most part of the plume, is at a relatively low altitude within the troposphere (generally less than 7 km). In contrast, the SO_2 in box B, lies between 8 and 20 km: placing some parts of the plume in the stratosphere. This implies that SO_2 was emitted at multiple heights during the course of the eruption. As the higher portion of the plume evolves with time some parts reach heights greater than 20 km. This raises some interesting questions regarding the impact of this eruption on climate which we plan to study further.

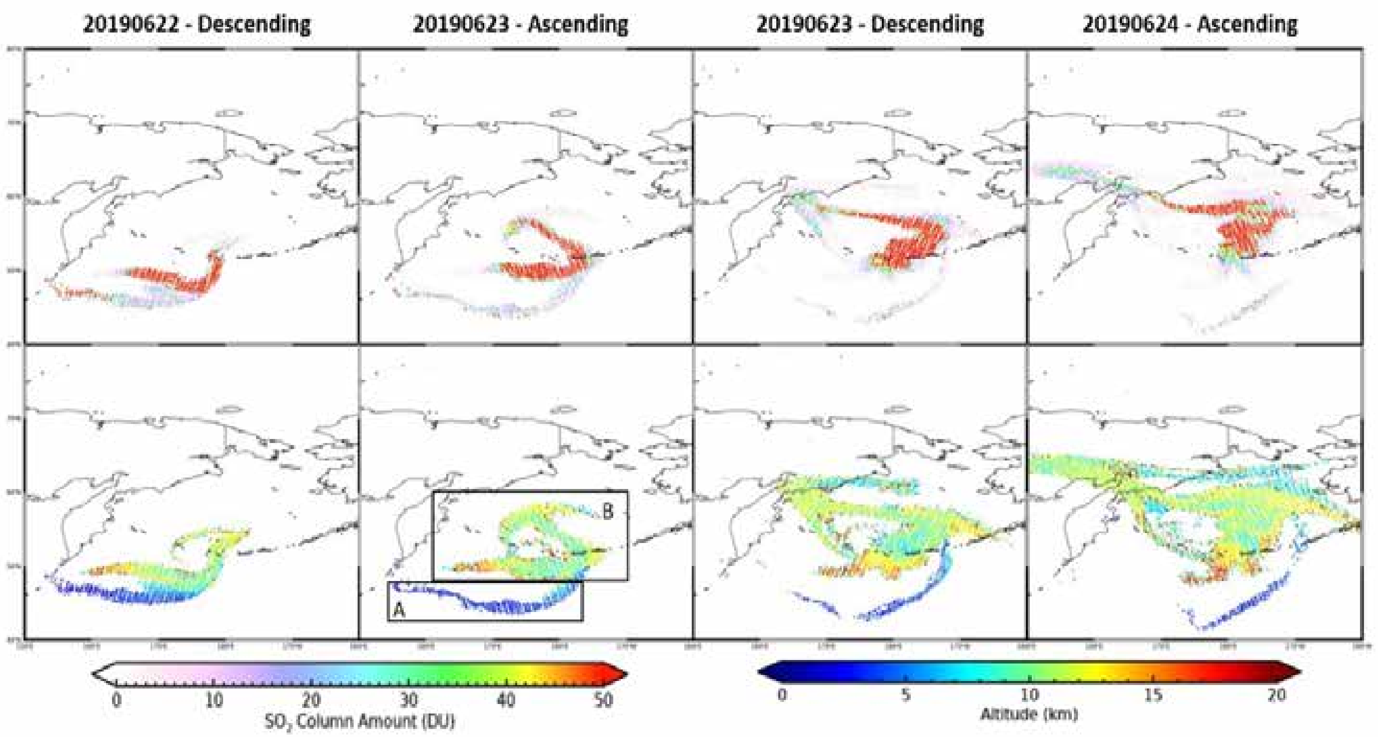

Figure 2: SO_2 column amounts (top row) and heights (bottom row) retrieved with the Carboni et al. (2012) IASI SO_2 retrieval from the first few days after the Raikoke eruption.

References

Data Acknowledgement: Both retrievals were applied to IASI level 1c spectra which were obtained from EUMETSAT, and the iterative retrieval also uses atmospheric profiles from ECMWF.

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SCIENCE UPDATE: EO DATA AND SERVICES

Progress Report: Develop methods to derive SO_2 fluxes at quiescent degassing volcanoes (back to 2007 for IASI; 2017 for Tropomi).

Isabelle Taylor, COMET Postdoctoral Research Assistant, University of Oxford

We have been exploring a new method for deriving long-term time averaged flux estimates from our IASI SO_2 retrieval. This new approach averages our iterative retrieval output for different time periods such as a month, year or for a predefined activity period (e.g. an episode of quiescent degassing or lava fountaining). Then a model is fitted to the average retrieved column amount with distance from the volcano (in concentric circles). In this way it is possible to obtain a time averaged flux for the defined time period. This has been trialled on data from Etna with promising results. We are presently drafting a paper on this topic.

Cat Hayer, Postdoctoral Researcher, University of Manchester

We have further developed a method of sub-daily SO_2 flux analysis, using back trajectory modelling, first described by Pardini *et al*. (2017) and Quißer *et al*. (2019). The PlumeTraj method uses the HYSPLIT trajectory model to calculate the origin location of air parcels within a satellite pixel, allowing us to calculate sub-daily SO_2 fluxes, by finding the release time and the altitude at both measurement and release. The method has been applied to several eruptions during the Sentinel- 5P/ TROPOMI lifetime (since 2018) including Mt. Etna (December 2018), Krakatau (December 2018), White Island (December 2019), and Piton de la Fournaise (April 2020). In the near future, we are aiming to produce daily, automated, near real-time SO_2 fluxes for various target volcanoes around the globe.

References

Pardini, F., Burton, M., Arzilli, F., La Spina, G. and Polacci, M. (2018) SO_2 emissions, plume heights and magmatic processes inferred from satellite data: The 2015 Calbuco eruptions, *JVGR*, 361, 12-24, https://doi.org/10.1016/j.jvolgeores.2018.08.001

Queißer, M., Burton, M., Theys, N., Pardini, F., Salerno, G., Caltabiano, T., Varnam, M., Esse, B. and Kazahaya, R. (2019) TROPOMI enables high resolution SO2 flux observations from Mt. Etna, Italy, and beyond, *Sci. Rep.,* 9, 957,https://doi.org/10.1038/s41598-018-37807-w

Progress Report: Incorporate laboratory measurements of ash optical properties of volcanic ash into IASI retrievals so we can estimate SiO_2 composition.

Isabelle Taylor, COMET Postdoctoral Research Assistant, University of Oxford

Using laboratory measurements of the optical properties of a number of volcanic ash samples (Reed et al., 2018; Deguine *et al.,* 2020) we have constructed several more look up tables which can be used within the Oxford IASI ash retrieval and also for ORAC (Optimal Retrieval of Aerosols and Cloud) ash retrievals for several instruments including MODIS. A larger number of look up tables means we can select the most appropriate one for the eruptions we are studying, which will improve our retrieval outputs.

We have been collaborating in a study led by Alexandre Deguine at the University of Brussels who is looking at how IASI ash retrievals are affected by different measurements of ash refractive indices. As part of this, we ran our ash retrieval using look up tables created from different refractive indices. These refractive indices were measured from ash samples from the Eyjafjallajökull eruption but were measured using different methods. A manuscript is in preparation and will be submitted in the near future.

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Reed, B.E., Peters, D.M., McPheat, R., and Grainger, R.G. (2018) The complex refractive index of volcanic ash aerosol retrieved from spectral mass extinction. *Journal of Geophysical Research: Atmospheres*, 123, 1339– 1350. *https://doi.org/10.1002/2017JD027362*

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Anak Krakatau mountain

SCIENCE UPDATE: EO DATA AND SERVICES

4. Geoinformatics and machine learning

Research Highlight: Forecasting Volcanic Eruptions with Artificial Intelligence.

Matthew Gaddes, COMET Postdoctoral Researcher, University of Leeds

A diverse set of hazards are posed by the world's ~1500 subaerial volcanoes, yet the majority of them remain unmonitored. Measurements of deformation provide a way to monitor volcanoes, and synthetic aperture RaDAR (SAR) provides a powerful tool to measure deformation at the majority of the world's subaerial volcanoes. However, the volume of data created by this is too large for analysis by human domain experts, so we have developed an algorithm at Leeds to detect signs of volcanic unrest in times series of interferograms.

To determine the baseline behaviour of a volcano, we split a time series of interferograms into a set of pairs of spatial patterns and time histories (i.e. how strongly each spatial pattern contributes to each interferogram). This can be performed using a variety of algorithms, but the results presented in Ebmeier *et al.* (2016) showed that independent component analysis (ICA) is suitable for use with InSAR time series, and so this was used in our monitoring algorithm. However, quantifying the robustness of the sources recovered by ICA has traditionally been challenging, and to address this we developed an algorithm and Python package to apply ICA to InSAR data robustly. The algorithm, termed ICASAR, compares the result of multiple bootstrapped runs of an ICA algorithm in order to determine which sources are recovered consistently, and are therefore unlikely to be spurious. When applied to Sierra Negra (Galapagos Archipelago, Ecuador), the algorithm isolated the intra-caldera deformation, a topographically correlated atmospheric phase screen, and several other signals that are likely to characterise the behaviour of the atmosphere at the volcano.

To determine if a volcano has deviated from the behaviour observed during the baseline stage, we developed a second algorithm and Python package termed LiCSAlert. This algorithm performs a simple inversion to fit each new interfeorgam using the spatial patterns learned by the ICASAR algorithm, and detects changes in the results of this inversion through time. When applied to a time series of interferograms imaging Sierra Negra, a change in rate of the intra-caldera inflation was detected approximately one year before the 2018 eruption. Should the algorithm have been running in real-time, it would have flagged this previously steady deformation as having accelerated, and indicated that the volcano had entered a period of unrest.

Code Repositories

https://github.com/matthew-gaddes/ICASAR
https://github.com/matthew-gaddes/LiCSAlert

References

Ebmeier, S. K. (2016). "Application of Independent Component Analysis to multitemporal InSAR data with volcanic case studies". In: *Journal of Geophysical Research: Solid Earth*, pp. 8970–8986. http://doi.wiley.com/10.1002/2016JB013765.

Gaddes, M., Hooper, A., and Bagnardi, M. (2019), Using machine learning to automatically detect signs of volcanic unrest in a time series of interferograms, *Journal of Geophysical Research: Solid Earth.*

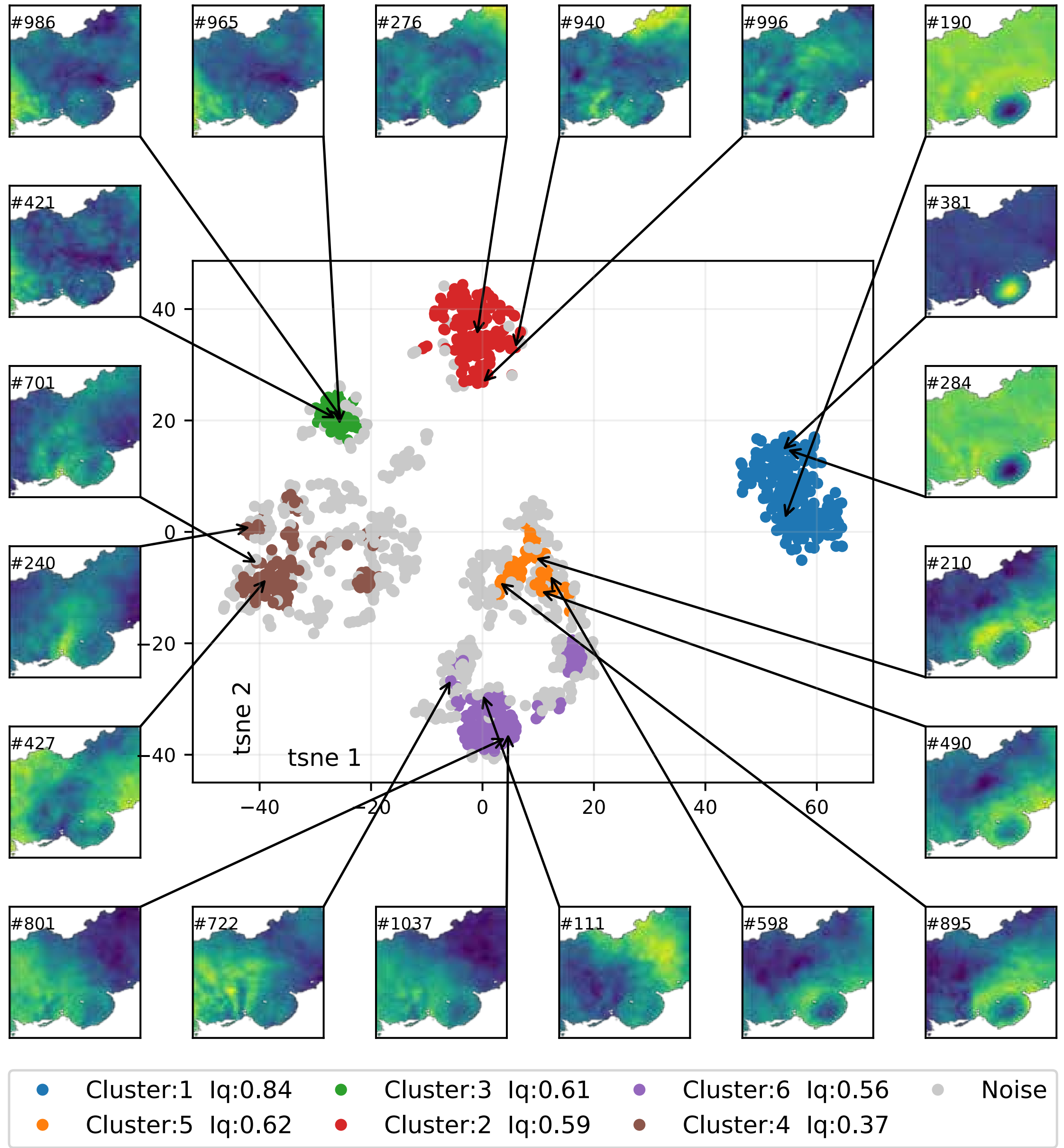

Figure 1: The results of applying the ICASAR algorithm to a time series of Sentinel-1 interferograms at Sierra Negra. Each point represents a spatial signal that is isolated from the time series during repeated runs of the ICA algorithm, and their position in the 2D plot represents their similarity to each other. Independently, a clustering algorithm is also used to determine which sources are similar. Close agreement can be seen between the 2D representation and the clustering algorithm, with the intra-caldera deformation recovered by the blue cluster.

SCIENCE UPDATE: EO DATA AND SERVICES

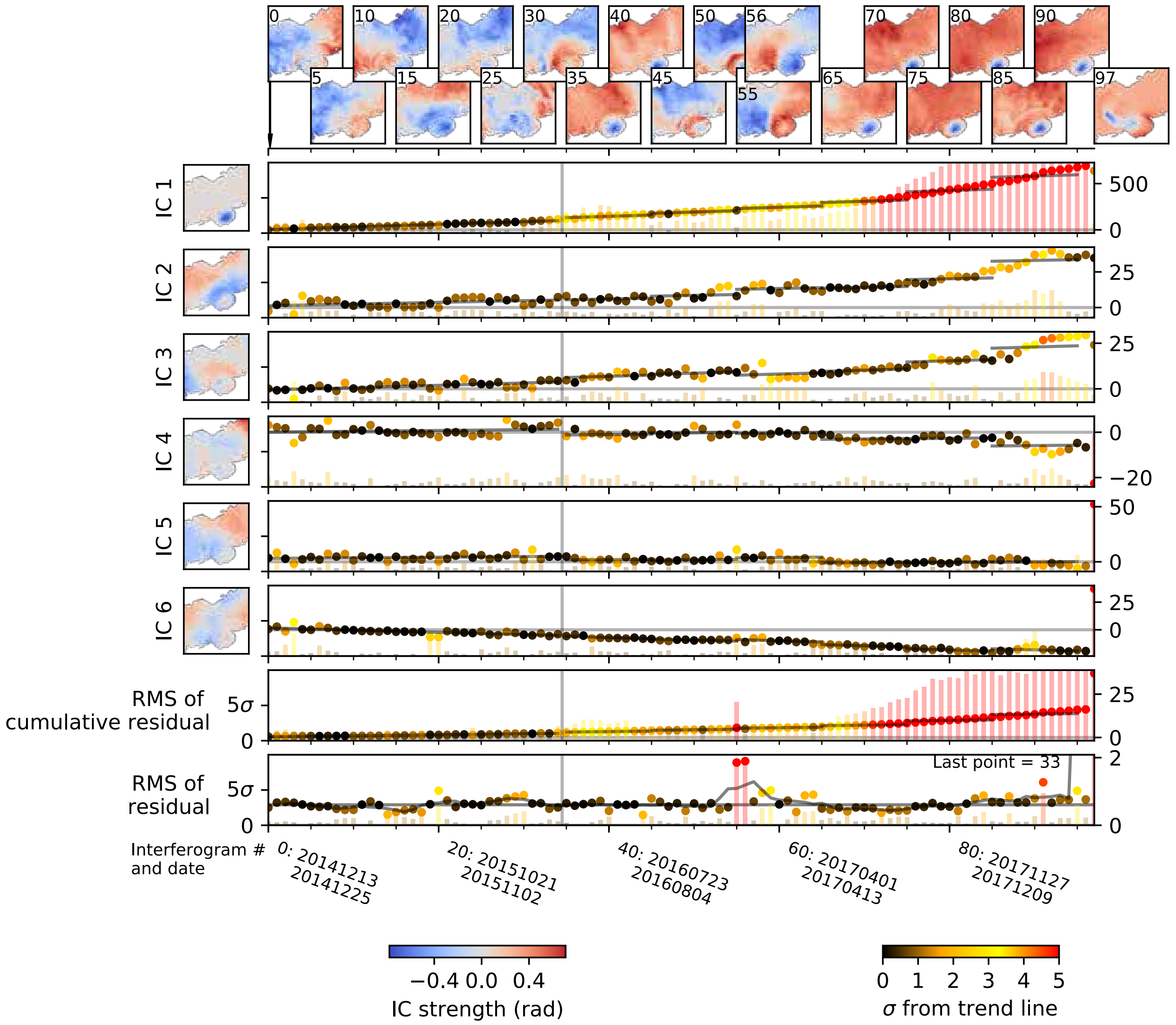

Figure 2: The results of applying the LiCSAlert algorithm to a time series of Sentinel-1 interferograms at Sierra Negra. The intra-caldera deformation isolated by ICASAR is visible as IC1, and the change in rate that occurs in the latter third of the time series is flagged when the algorithm begins to switch to red points.

Sierra Negra, Isabella Island

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SCIENCE UPDATE: EO DATA AND SERVICES

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

We are developing a data portal (https://comet.nerc.ac.uk/COMET-LiCS-portal/) that will simplify access to all COMET datasets and services. Recent updates have focused on expanding the LiCSAR portal, which is the point of entry for users searching and downloading LiCSAR InSAR data, and developing the capacity to efficiently process and serve InSAR data following earthquake events. The COMET Datasets & Services Twitter handle was established to communicate new datasets and developments. We also conducted a user feedback survey to determine how LiCSAR data are used in the wider community and how to better meet end user needs.

The LiCSAR data portal features an interactive map utilising the open source *Leaflet* library. Users can search and download LiCSAR data that is hosted at The Centre for Environmental Data Analysis (CEDA) and is being ingested into the CEDA Archive for permanent storage. LiCSAR metadata and links to additional processing workflows, such as the Generic Atmospheric Correction Online Service (GACOS) model and time-series processing using LiCSBAS, are described on the 'Product details' webpage.

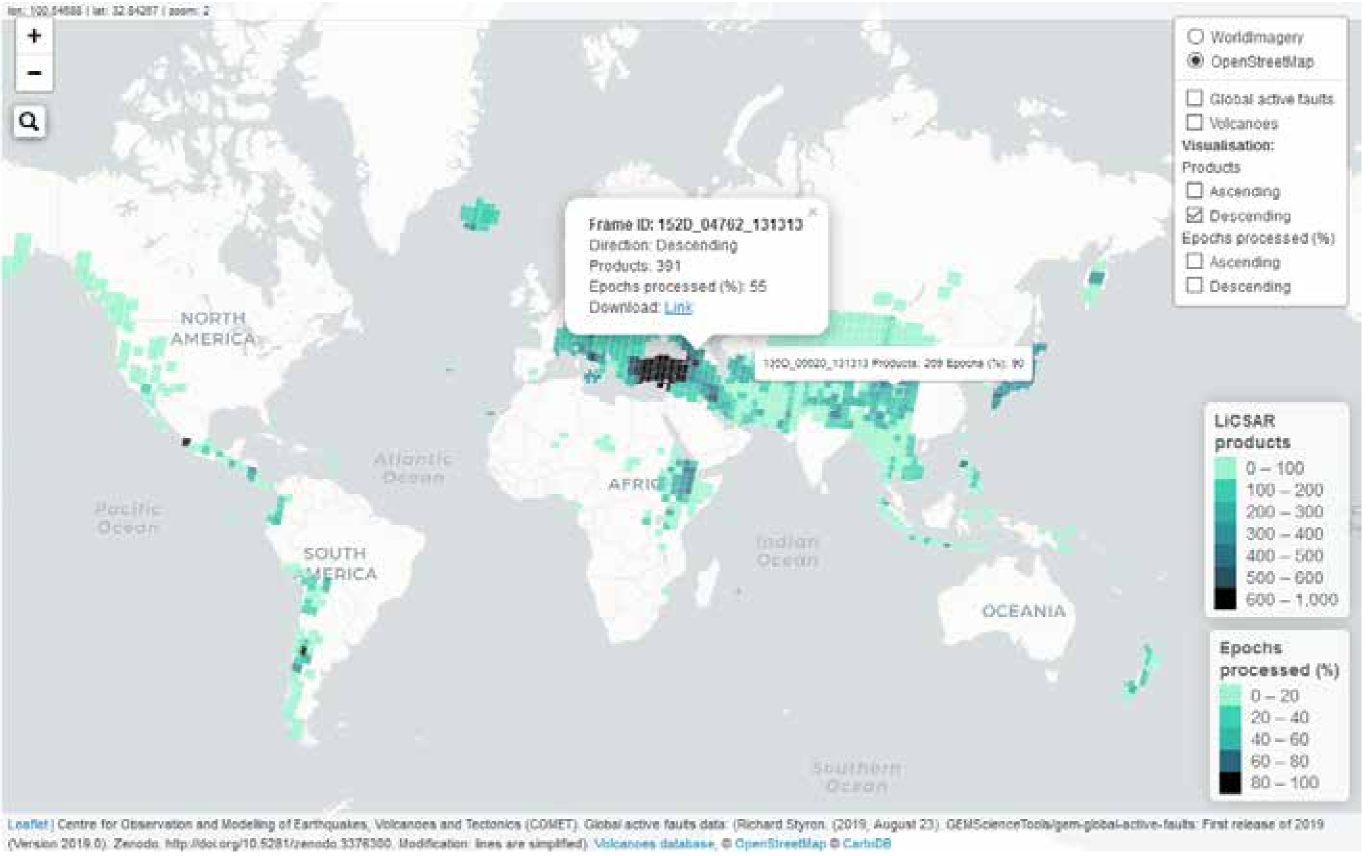

Figure 1: The LiCSAR portal shows a visual representation of the number of InSAR products available to download for all active LiCSAR frames (n = 1485). Users can also view supplementary overlays for volcanoes and global active faults.

LiCSAR InSAR data are automatically generated following earthquake events with a minimum magnitude of Mw 5.5. Links to the data are served through an interactive map, which is currently in a testing phase on the LiCSAR Portal. Webpages will soon be generated for each earthquake, featuring an interactive map, details of the USGS earthquake parameters, and quick-look images of LiCSAR interferograms.

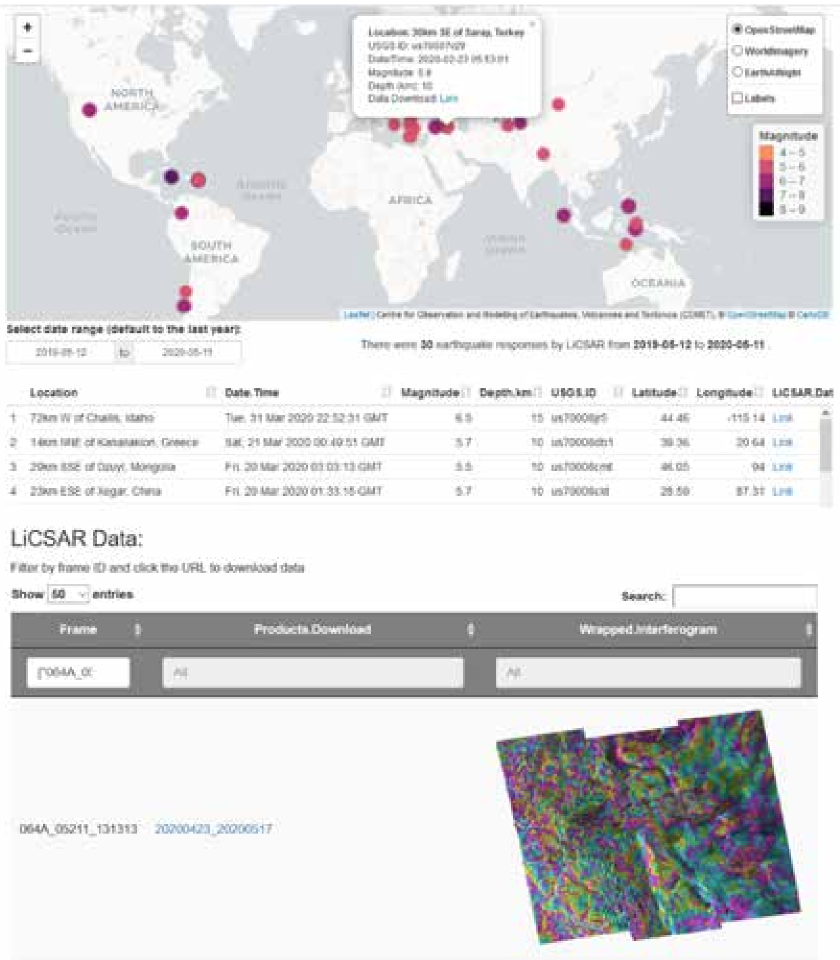

Figure 2: An interactive earthquake event map shows LiCSAR processing responses and provides data download links. Users will also be able to search and download InSAR data using a dedicated webpage for each event.

Progress Report: Develop Machine Learning algorithms to identify anomalous behaviour at volcanoes

See 'Research Highlight: Forecasting Volcanic Eruptions with Artificial Intelligence' by Matthew Gaddes.

Further work on this specific research objective is planned for later in the scientific programme.

Progress Report: Trial Machine Learning algorithms with stakeholders towards real-time operation at volcanoes.

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

SCIENCE UPDATE: TECTONICS AND VOLCANISM

1. Tectonics and Seismic Hazard

Research Highlight: Global Waveform Catalogue

Sam Wimpenny, Denman Baynes Junior Research Fellow, University of Cambridge

The simplest parameters we can use to describe the earthquake source are the location, size and orientation of the fault that slipped to generate the earthquake. Since the 1960's a global network of digital seismometers has made routine determination of these fault parameters possible for moderate-magnitude earthquakes, resulting in widely-used catalogues of seismicity, such as the Global Centroid Moment Tensor Project (Dziewonski *et al.*, 1981) and the ISC-EHB Bulletin (Engdahl *et al.*, 1998). These catalogues provide globally-consistent and standardised estimates of earthquake source parameters, but a continuing sticking-point for both is that they struggle to determine the depths and mechanisms of crustal earthquakes (e.g. McCaffrey, 1988), which are key to understanding seismic hazard, and the rheology and dynamics of Earth's lithosphere.

For nearly 40 years COMET researchers and students have performed careful seismological source studies of moderate-magnitude earthquakes using long-period teleseismic body-wave modelling to accurately determine their depths, source mechanisms and magnitudes. These studies have typically been regional in scope, and many of the results remain buried in hard-copy tables. Recently I compiled these data tables into a global catalogue of all-known waveform-modelled earthquakes (Figure 1), forming a resource for researchers to search and download carefully-determined earthquake source parameters. This catalogue, known as the Global Waveform Catalogue (gWFM), is hosted on Github at: https://github.com/samwimpenny/Global-Waveform-Catalogue and is available to visualise on the COMET website at: https://comet.nerc.ac.uk/gwfm_catalogue/

References

McCaffrey, R. (1988). Active tectonics of the eastern Sunda and Banda arcs. *Journal of Geophysical Research*, 93(B12):15163–15182.

Engdahl, E. R., van der Hilst, R., and Buland, R. (1998). Global Teleseismic Earthquake Relocation with Improved Travel Times and Procedures for Depth Determination. *Bulletin of the Seismological Society of America*, 88(3):722–743.

Dziewonski, A. M., Chou, T.-A., and Woodhouse, J. H. (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. *Journal of Geophysical Research: Solid Earth*, 86(B4):2825–2852.

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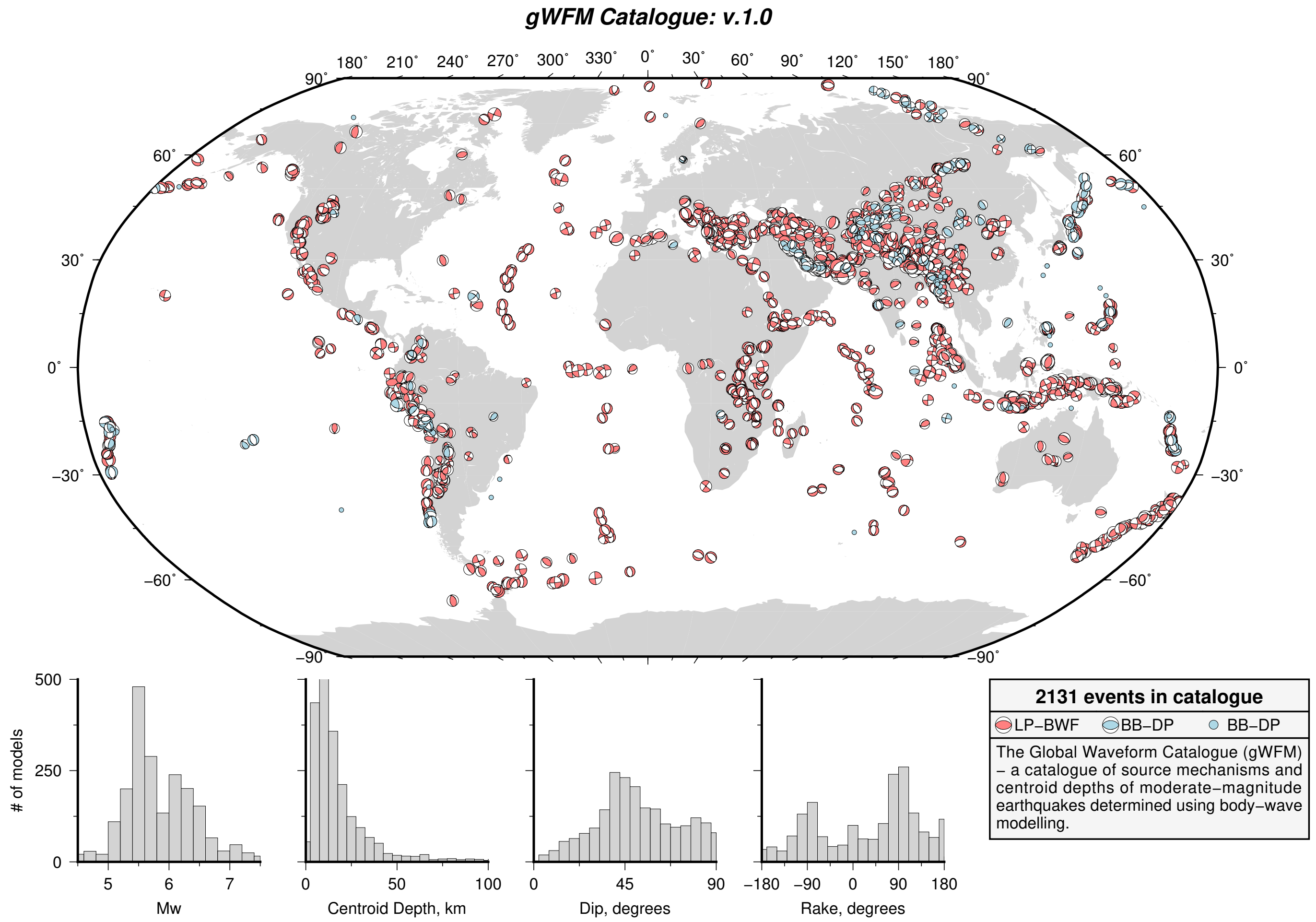

Figure 1: Global distribution of seismicity in the gWFM catalogue. An interactive version of this map is available on the COMET data sets and services page.

SCIENCE UPDATE: TECTONICS AND VOLCANISM

Research Highlight: Resolving a century-long mystery about earthquake rupture in the Pamir using satellite observations from before and after a 2015 M7.2 earthquake

Austin Elliott, Visiting Research Fellow, University of Oxford

In the Pamir Mountains of eastern Tajikistan, continental collision, delamination, and subduction have repeatedly crumpled and stretched the upper crust like an accordion, leading to both the highest plateau and some of the deepest earthquakes on the planet.

A major, shallow strike-slip earthquake (M_W=7.2) ripped across these accreted terranes on 7 December 2015, reigniting a century-long puzzle about the structures responsible for shallow strike-slip earthquakes in the Pamir.

COMET researchers Austin Elliott (University of Oxford, now at the U.S. Geological Survey) and John Elliott (University of Leeds) used satellite image pixel-tracking and InSAR (Sentinel-1) analysis to derive the most detailed fault model and slip distribution to date for this earthquake. Their analysis of pre- and post-event 1.5-meter SPOT satellite imagery supplemented these slip measurements with detailed maps of surface rupture along the inaccessible high-altitude Sarez-Karakul fault.

Our investigation of the deformation field from this earthquake and of scarp morphology elsewhere along the fault revealed evidence for a *sequence* of large surface ruptures that have taken place on distinct reaches of the fault, totalling at least three separate identifiable events. One of these ruptures may have been the instrumentally recorded M7.3 strike-slip earthquake of 1911. Working with historical seismologist Galina Kulikova (University of Potsdam), the team confirmed that seismic records from 1911 were most compatible with rupture of the southern-most reach of the SKF, revising the long-debated understanding of which tectonic structure may have caused that earthquake.

The boundaries between these different ruptures, and indeed strong gradients in the 2015 event slip distribution, coincide with bedrock structures—faults, shear zones, and sutures—inherited from the long history of continental collision, suggesting that rupture length and thus event size along the shallow faults of the Pamir may be modulated by lithologic contrasts and structural complexities in the surrounding bedrock.

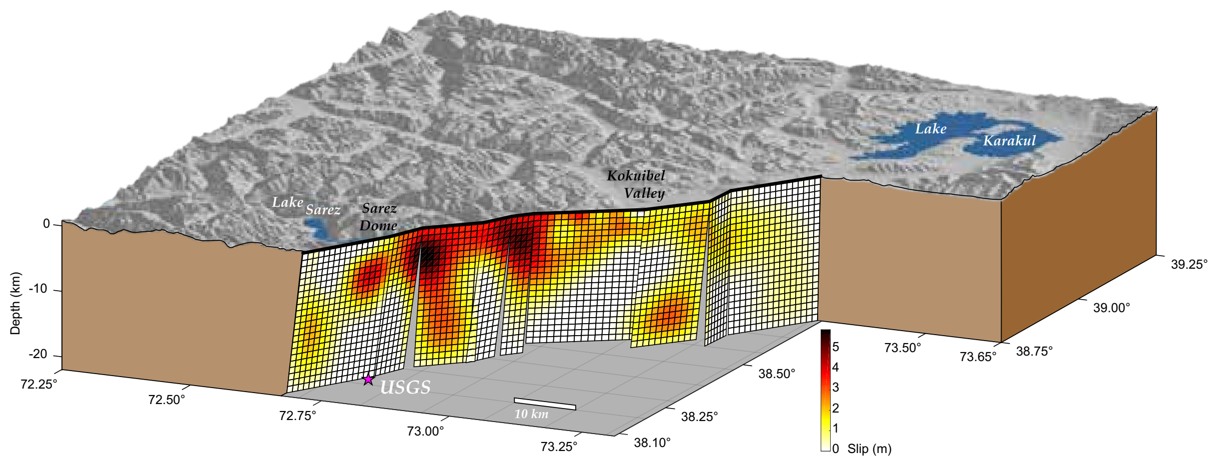

Figure 1: Perspective view of the modelled fault plane and slip distribution at depth, derived through a joint inversion of InSAR & optical pixel-tracking surface displacement measurements.

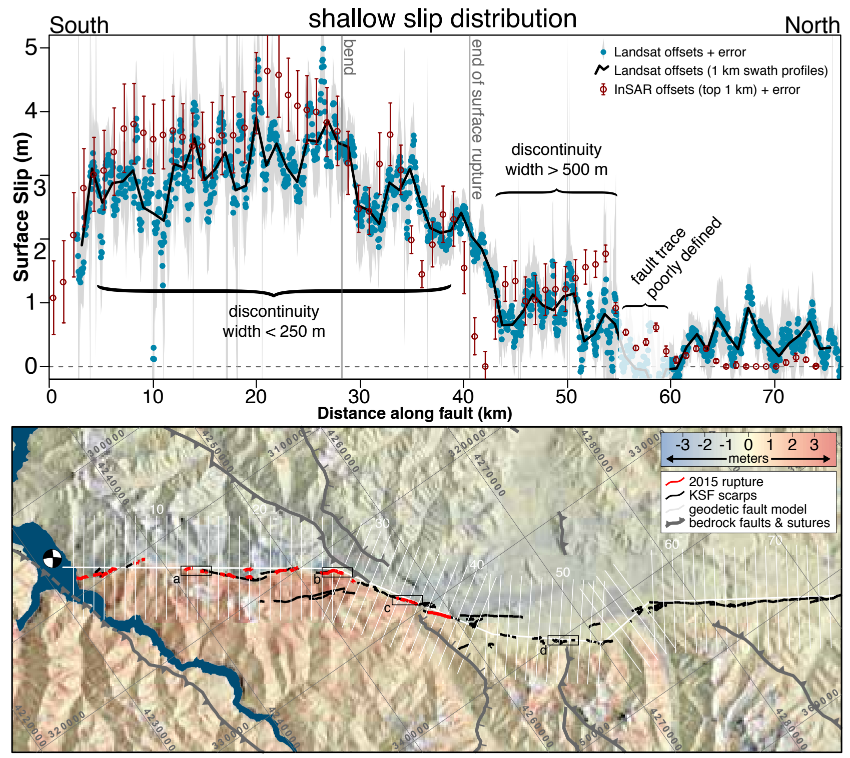

Figure 2: Distribution of horizontal surface slip along the Sarez-Karakul fault during the 2015 earthquake, measured from a Landsat-8 image pixel-tracking map of displacement and surface rupture (below).

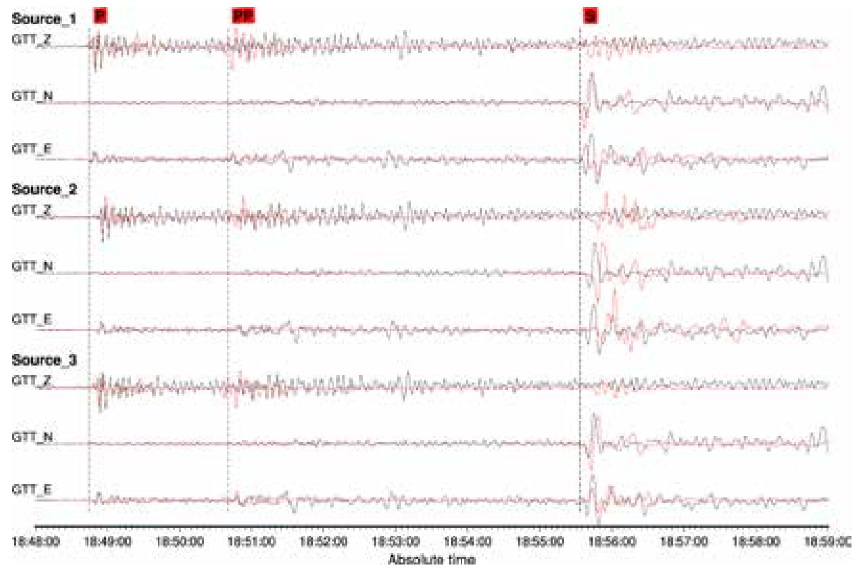

Figure 3: Matching synthetic seismograms (red) from three plausible sources for the 1911 earthquake, with observed seismic records (black) in Göttingen, Germany, we find that rupture of the southern portion of the Sarez-Karakul Fault is more compatible with seismological evidence than other possible epicenters along the SKF.

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SCIENCE UPDATE: TECTONICS AND VOLCANISM

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

This year, Jonathan Weiss (former COMET Research Fellow, now at the University of Potsdam) and a team at COMET completed work on a high-resolution map of surface strain rates across the Anatolia (Turkey) region based on COMET-LiCSAR InSAR products and GPS (Global Positioning System) data. This success, and the methods that were worked out in building it, lays the groundwork for COMET's initiative to build these strain maps across the Alpine-Himalayan Belt (stretching from Europe to southeast Asia) and the East African Rift. In Anatolia, Jonathan and collaborators used approximately 30,000 COMET-LiCSAR interferograms covering the first five years of Sentinel-I data over a ~800,000 km^2 area, making this (to our knowledge) the largest InSAR-based measurement of tectonic processes ever carried out. These InSAR data contain many deformation signals, some time-varying and some from noise, but the signal of interest in this line of work is the steady motion of the surface due to tectonic motion and fault loading, which occurs at tens of millimeters per year (the speed at which your fingernails grow!). The team parsed the large suite of LiCSAR products and extracted these steady motions using the newly developed LiCSBAS timeseries algorithm (Morishita *et al*., 2020), also developed at COMET, and then combined these InSAR motions with a refined GPS dataset to further tie down how they vary from place to place and from plate to plate. Jonathan and collaborators then used the VELMAP method, developed by Hua Wang and collaborators at COMET, to digest these datasets and estimate the underlying pattern of tectonic motions and strain accumulation across Anatolia. The team published their work and findings in Geophysical Research Letters this year (doi.org/10.1029/2020GL087376). In the coming year, we aim to expand this strain-rate map from Anatolia to an area covering the Caucasus, Iran, and the Aegean Sea. As one of many uses of this strain map, we are comparing these strain maps to the rates and magnitudes of recorded earthquakes to estimate how often earthquakes of each magnitude are needed to release the strain that is gradually accruing. These estimates of earthquake potential, given high enough spatial resolution, can then be used directly for seismic hazard assessment.

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

The COMET Central Asia Fault Database proto-type is set to be released to COMET researchers in June 2020. Over the past year, former COMET postdoctoral researcher Austin Elliott moved on from his position and this role was filled by Tamarah King. Both Tamarah and Austin are working hard to complete this work.

The proto-database is composed of mapped faults hosted as attributed line vectors in primarily an ArcGIS geodatabase, and will be made available in a variety of geospatial formats. Preliminary metadata includes fault and segment names, structural detail (slip mechanism) and reference information.

Work is ongoing to produce a final database for public release. This includes populating the database with additional structural detail (dip, rake), palaeoseismic information (slip rate, most recent event, seismic recurrence interval), and reducing line data to consistent mapping scales applicable to multiple purposes (e.g. simplified seismogenic sources for seismic hazard modelling; continuous, faithful lines for kinematic analysis and modelling; and highly detailed scarp traces for paleoseismic and neotectonic investigations).

These are necessarily manual and user-intensive improvements as faults cannot be automatically re-scaled without expert decision making, and palaeoseismic data are single location datapoints which require expert interpolation to map onto a fault line. Ultimately we aim to deliver a highly functional database, and to complete these improvements efficiently to expedite public release of the database. Contributions and review of fault parameters are being undertaken with current and former COMET researchers involved in fault studies in this region, and Austin and Tamarah are working with partners in other institutions and agencies to establish practices, formats, and standards to align this with other databases for maximum versatility.

These efforts will be conducted with two objectives in mind: (i) to provide accurate seismic source inputs to the GEM seismic hazard map, in collaboration with GEM scientists and (ii) to provide a comprehensive map of active faults and palaeoseismic data to improve understanding of the spatial and temporal distribution of active faults and earthquakes in this region, with implications for tectonic and risk-reduction applications.

Following internal peer-review processes, the final database will be released to the public with an open-access publication describing the methodology of data collation, and reduction, used to produce this consistent and accurate fault map.

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

Richard Walker, Professor of Tectonics, University of Oxford

This theme assesses to what extent the instantaneous velocity field measured with geodesy is representative of kyr-timescale earthquake cycles, and the importance of transient behaviour and off-fault deformation for the assessment of seismic hazard. Activities over the past year have included measurements from the central Asia region. In a joint project between COMET researchers in Oxford and researchers in France and Iran, we have compared InSAR and GPS derived measurements of strain accumulation with 10 kyr and 100 kyr geological slip rates on the Doruneh fault of NE Iran. This fault has previously been described as exhibiting spatial and temporal changes in slip-rate. In our study (Mousavi *et al*., paper in review) we show agreement between decadal to 100 kyr timescales. We are currently compiling a country-wide comparison of geodetic and geological measurements across Iran, as well as building detailed measurements of the Ashgabat fault in neighbouring Turkmenistan (papers in preparation). In the Tien Shan we have measured N-S transects of geological shortening across the major structures with the aim of comparing to GPS and InSAR measurements.

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

Dr Alex Copley, University of Cambridge

The temperature structure of the lithosphere plays a first-order role in the long- and short-timescale deformation of the continents through the controls it exerts on the seismogenic thickness, the viscosity of the ductile lithosphere, and the important lateral variations of these quantities. Likewise, the presence of fluid, as either free phases or as water structurally bound in minerals, has a strong control on the strength of the lithosphere. Therefore, as a first step towards building geodynamic models of the lithosphere that can link short and long timescales, COMET has been developing our understanding of the thermal structure of the lithosphere and the distribution of fluids within it. This work has so far been undertaken in three complementary strands.

We have developed a new model for the thermal structure of Tibet, the underlying methodology for which can be used as a template for similar studies in other mountain ranges. Geophysical and petrological observations (e.g. well-determined earthquakes depths derived by COMET, seismic velocity structure, seismic anisotropy, ages and compositions of erupted lithospheric melts, pressure and temperature conditions experienced by exhumed metamorphic rocks) can be simultaneously used as constraints on a thermal model in order to establish a thermal structure that is consistent with all geophysical and petrological observations. This model can, in turn, provide information about the geological history of the collision zone, and provide an understanding of the present-day temperature distribution.

In addition to focussed studies of individual mountain ranges, COMET has also been running hundreds of thousands of thermal models to simulate a wide range of potential mountain-building scenarios, material properties, and distributions of radiogenic heating. These models can then be compared with the metamorphic record of the pressure and temperature conditions experienced in mountain ranges, and the present-day constraints provided by the seismogenic thickness and heat flow in the range of global mountain belts. Such work allows us to narrow down the possible range of model parameters that are consistent with observations from modern and exhumed mountain ranges. The modern-day observations and the information that can be gleaned from rocks exhumed from old mountain ranges have different controls on the range of allowable model parameters, so combining them gives a well-constrained picture of the effects of mountain building on the thermal structure of the continental lithosphere.

In order to explore the distribution of fluids within the lithosphere, we have been undertaking fieldwork focused on regions where fluid infiltration has weakened the lithosphere and promoted deformation. We have quantified the distribution of fluid-bearing minerals, and by modelling this distribution have been able to understand the mechanism and rate of fluid transport through the lithosphere. Figure 1 shows an example of the effect of hydration state on rock deformation.

Using our new understanding of the temperature and fluid distribution in mountain ranges that we have acquired from these studies, we are now investigating the implications of

SCIENCE UPDATE: TECTONICS AND VOLCANISM

these results for the dynamics of mountain ranges. We are developing models that can investigate both the long-term controls on the geometry and rate of motion, and the short-timescale deformation observed in earthquake cycles. Our aim is to develop a consistent view of forces and material properties that can simultaneously explain observations from across the timescales, and therefore give us new insights into lithosphere rheology and the dynamics of continental deformation.
The thermal aspects of this work is described in two papers that are under review at the time of writing. The fluid distribution in the lithosphere is described in manuscripts currently in preparation (by Andrew Whyte):

References

1. **T. Craig, P. Kelemen, B. Hacker and A. Copley**, Reconciling geophysical and petrological estimates of the thermal structure of southern Tibet, in review, *G-cubed*.

2. **A. Copley and O. Weller,** The controls on the thermal evolution of continental mountain ranges, in review, *Journal of Petrology*

Figure 1: weakening by water input in the continental middle crust. The striped rocks in the lower left (amphibolites) are hydrated and highly deformed, whereas the anhydrous rocks in the upper right (granulties) have remained rigid. From NW Scotland.

Fault in the Caucasus mountains

SCIENCE UPDATE: TECTONICS AND VOLCANISM

2. Magmatism and Volcanic Hazard

Research Highlight: Using high-resolution TanDEM-X Digital Elevation Model in order to quantify the thickness and the volume of the pyroclastic deposits associated with the 2018 Fuego eruption in Guatemala.

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

Volcan Fuego, March 2019 (Photo courtesy A. Naismith)

On June 3rd, 2018, Fuego volcano, Guatemala, erupted violently producing pyroclastic density currents (PDC), which killed hundreds of people living near the volcano. From TanDEM-X bi-static interferometry, we produce a high-resolution Digital Elevation Model (DEM) after the eruption to quantify the source location, thickness and volume of the flow deposits.

On active volcanoes, the accurately mapping of the thickness distribution of volcanic deposits and the estimates of erupted volumes is required to understand the growth and collapse of volcanic edifices during eruptive cycles. In addition, such information provides new constraints for the parametrization of numerical simulations of volcanic flows and participate to improve our understanding on flow mechanism and the forecasting of present and future hazards.

Because field surveys only measure the thickness of the flow edges and are limited especially during explosive eruptions, there is a need to use remote sensing datasets for producing up-to-date high-resolution Digital Elevation Model (DEM) prior, during and after an eruption in order to detect and quantify topographic changes related to flow emplacement. Although previous studies have shown the ability of TanDEM-X bi-static interferometry to derive the thickness and the volume of lava flows during effusive eruptions[1-3], the method has not been explored for pyroclastic flows.

For the first time, we process and analysis TanDEM-X data for deriving the thickness and volume of pyroclastic flows, using the case study of the deadly eruption of Fuego volcano on June 3rd, 2018. Pyroclastic Density Currents have destroyed the town of San Miguel Los Lotes (Figure 1a) and is estimated to have resulted in hundreds of fatalities. From differencing pre- and post-eruptive TanDEM-X DEMs (10m resolution), we identify negative elevation changes caused by significant substrate erosion and vegetation destruction (Figure 1c) as well as positive elevation changes in narrow channels caused by the accumulation of the pyroclastic deposits (Figure 1d). The identification of these area where volcanic deposits accumulates are important as they are likely to be the source of lahars during future rainy seasons. We estimate the volume of the 2018 PDC to be 15.1±4.2 x10^6 m^3. More interestingly, we detect large topographic changes up to 60 m near the summit (Figure 1b). Our interpretation is that the source 2018 PDC was predominantly composed of material which had gravitationally collapsed from a location close to the vent. The bulking and erosion of materials tends to increase the PDC volume (15.1 x10^6 m^3) and more importantly the mobility of the flow, which explains why the run-out distance of the 2018 PDC (~12 km) was twice larger than the ~6 km usually observed for previous eruptions during the period 1999-2017.

This study highlights the importance of remote sensing techniques for actively monitoring mass accumulation/erosion at the summit of steep-sided stratovolcanoes, as it sheds new light on the mechanisms of pyroclastic flows and the growth and collapse of volcanic edifices.

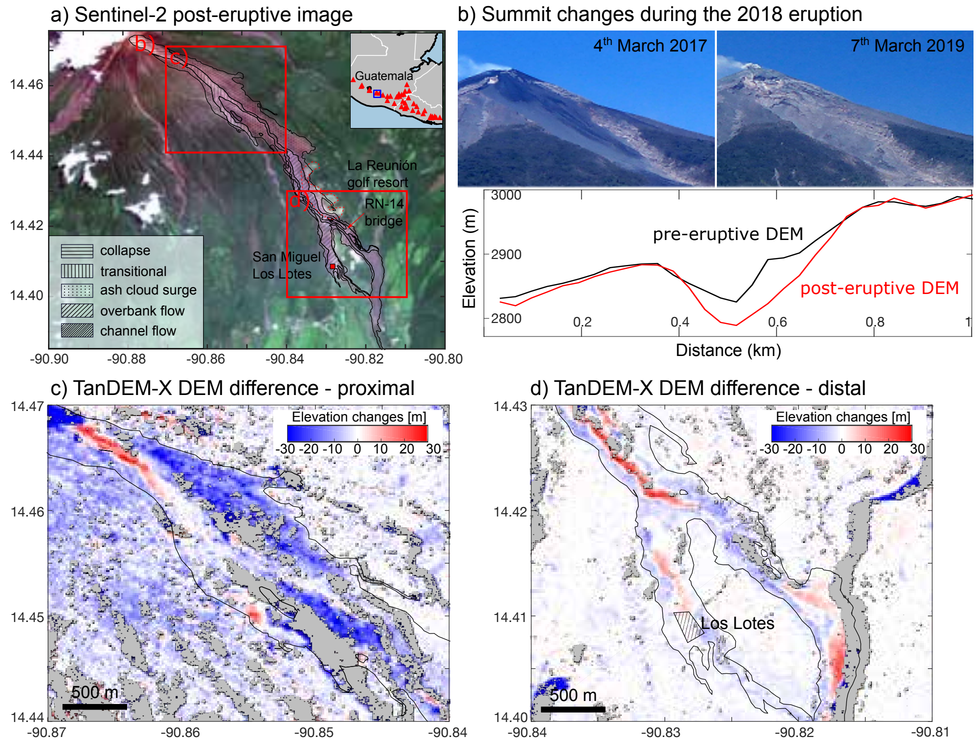

Figure 1: Evaluation the topographic changes associated with the 2018 Fuego eruption. a) Sentinel-1 post-eruptive image showing the extend and the different facies of the 2018 Pyroclastic Density Currents (PDC); b) Top: pre and post-eruptive photographs of Fuego's summit showing the removal of volcanic materials that occurred during the 2018 event; Bottom: TanDEM-X profiles across the valley show the negative elevation changes associated with the mass removal. c) TanDEM-X DEM difference at the proximal section of the PDC showing negative elevation changes caused by the destruction of the vegetation; d) TanDEM-X DEM difference at the distal section of the PDC showing positive elevation changes associated with deposition.

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SCIENCE UPDATE: TECTONICS AND VOLCANISM

Research Highlight: A new model that explains Montserrat inflation without new magma influx or pressurisation

Jurgen (Locko) Neuberg, Professor of Physical Volcanology, COMET scientist, Leeds University

A new visco-elastic deformation model can explain the ongoing, island-wide inflation of Montserrat without new magma influx or pressurisation. Instead, the deformation pattern is explained as a visco-elastic response of the crust to a magma intrusion that has ceased several years ago.

Since the eruption began in 1995, Soufrière Hills volcano on Montserrat has been characterised by five phases of magma extrusion and corresponding pauses. Despite a lack of eruptive surface activity since 2010, the volcano continues to show signs of unrest in the form of ongoing outgassing, and inflation of the entire island of Montserrat. Using numerical modelling, we compared a set of contrasting deformation models in an attempt to understand the current state of Soufrière Hills volcano, and to gauge its future eruption potential.

Previous modelling attempts explained the ongoing inflation by fresh magma influx of 0.15 m^3/s or 4.7×10^6 m^3/year into a reservoir at about 6 km depth. Such accumulation of magma and the corresponding pressurisation would most probably lead to a new eruptive phase in the near future. Encouraged by a recent petrological study (McGee et al., 2019), and in contrast to previous modelling attempts, Neuberg compared elastic- with visco-elastic models that take temperature models, tectonic components and mass balance data into account. A Maxwell rheology is used that shows a linear deformation pattern caused by a constant pressure acting on the viscous surrounding of the volcano. Fig. 1 illustrates the main features of the Maxwell rheology.

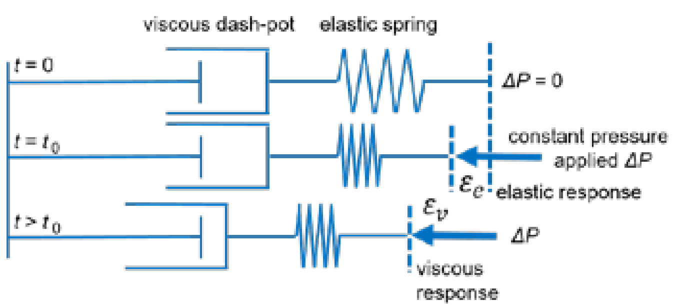

Figure 1. A Maxwell rheology comprises an elastic and viscous element. Once a force or pressure is applied to the system, it reacts in the first instance elastically, i.e. the "spring" is squeezed. Due to the viscous element, here pictured as a "dashpot", the system continues deforming over a long time as long as the pressure is applied.

In order to model the viscous behaviour of the crust around the volcano we used a thermal model for Montserrat that takes results from the geothermal drilling on the island into account. From this temperature model we derive a range of average viscosities that we use in our numerical deformation models (Fig. 2).

Fig. 3 depicts in the upper panel the horizontal displacement of a GPS station (MVO1) about 7 km north of the volcano showing the classic zig-zag behaviour monitored by the Montserrat Volcano Observatory. During eruptive phases the entire island deflates and the radial displacement decreases as the station moves closer to the volcano. In contrast, the displacement increases and the station moves away when magma extrusion pauses. This pattern had been interpreted as caused by deflation and inflation of a magma reservoir at about 6 km depth. In the lower panel we show the modelling results of one of our visco-elastic models, which offers a new interpretation.

The reservoir pressure is shown in the solid black line and starting off with a high value caused by magma intruding into a shallow reservoir. During an eruptive phase part of this magma is extruded and the pressure drops correspondingly. During the pause that follows, however, the pressure stays at a constant level controlled by the compressibility and volume of the remaining magma – no fresh magma enters the reservoir. While the deformation follows the pressure in the reservoir during an eruptive phase, it changes direction during the pause, even though the pressure remains constant. This is due to the delayed effect of viscosity, illustrated in Fig. 1 and modelled by a Maxwell rheology. It is the response to the initial magma intrusion that may have ceased after the eruptive phase in 2003. The almost linear behaviour with which the deformation responds to the reservoir pressure is typical for a Maxwell rheology used in our models. That means, the island will keep on inflating by about 1 cm/year (as measured at GPS stations 5-10 km away from the volcano) as long as there is a residual, constant pressure left in the magmatic reservoir. No new magma influx or pressurisation through other magmatic processes is necessary to explain this behaviour. As demonstrated in Fig.3 the visco-elastic model follows the classic zig-zag pattern very well and matches its main features.

The implications for the interpretation of the volcanic system in Montserrat and many other volcanoes showing a similar behaviour are significant. Rather than expecting renewed eruptive activity in the near future when ongoing pressurisation has reached a critical threshold, a status quo is much more likely and any decreasing trend in the deformation pattern translates directly into decreasing residual reservoir pressure. Research outputs like this feed directly into the discussions of the Scientific Advisory Committee on Montserrat Volcanic Activity and are a crucial contribution by COMET to support decision making by the British and the Montserratian Governments.

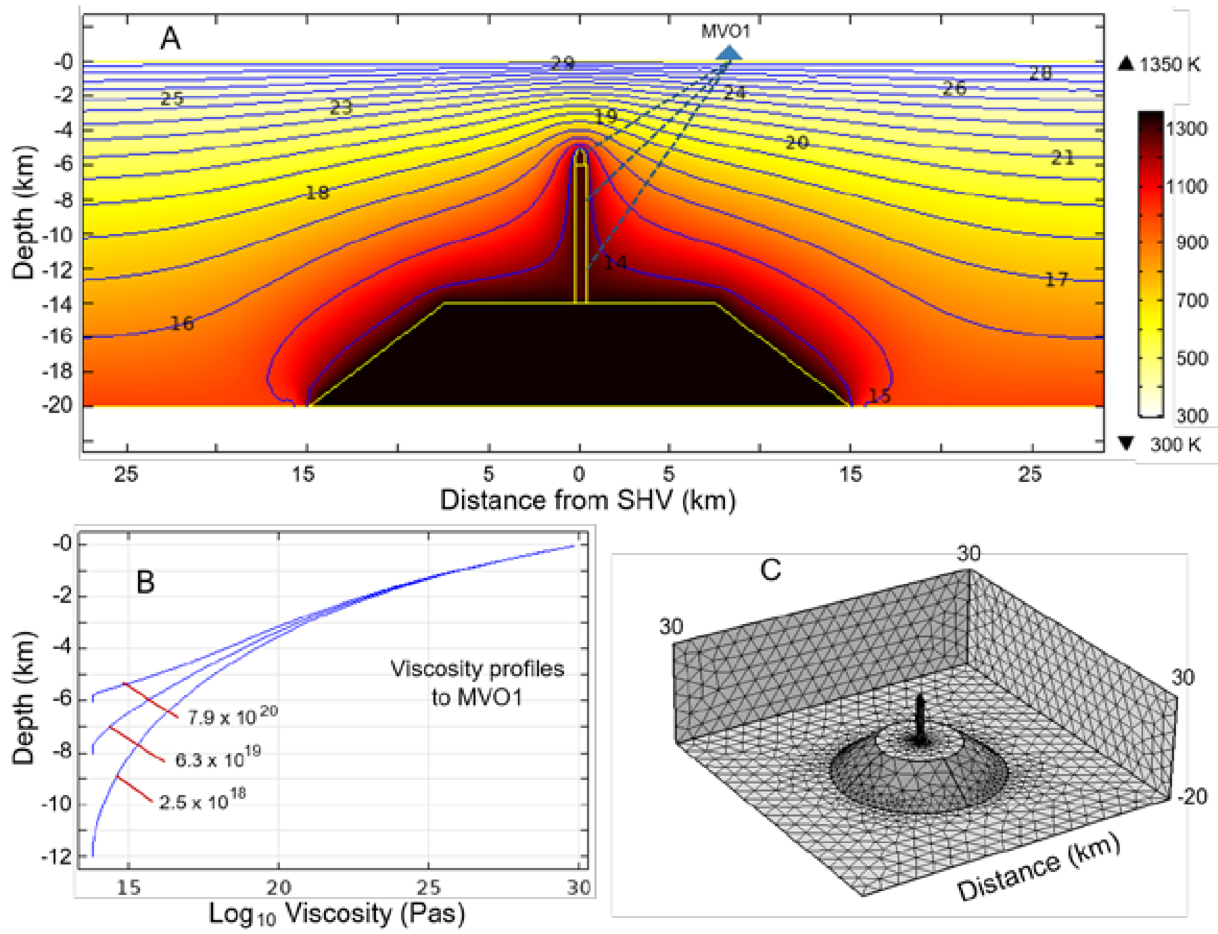

Figure 2. Temperature – viscosity model: (A) temperature distribution and contoured viscosity values (Log10). Dashed lines indicate where viscosity profiles have been calculated between the magmatic source at different depths and distal GPS stations where the deformation is monitored. (B) Viscosity profiles between one station (MVO1) and magmatic source at 12, 8 and 6 km depth. Viscosity averages over the profiles are indicated. (C) Temperature model comprising a cone shaped deep reservoir (30 km wide and 6 km high) and superimposed magma intrusion.

SCIENCE UPDATE: TECTONICS AND VOLCANISM

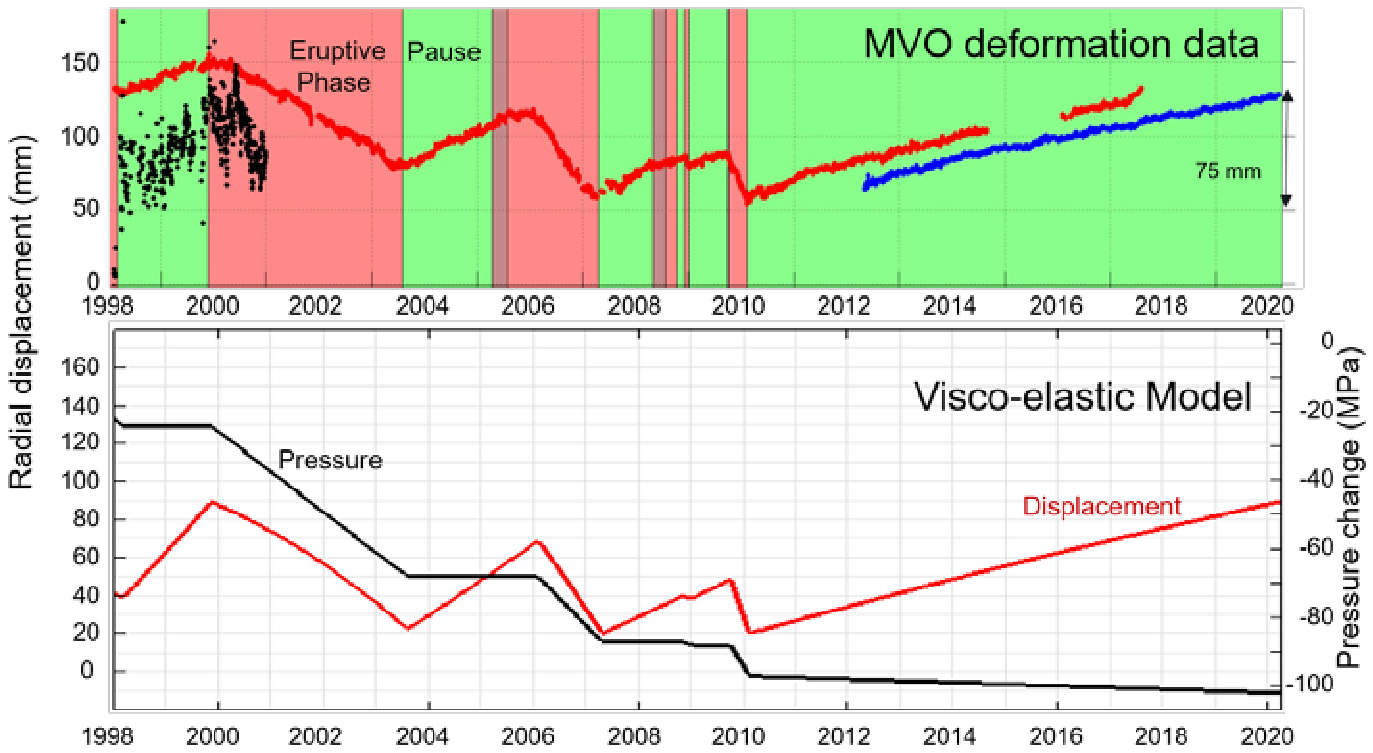

Figure 3. Upper panel: radial displacement of GPS station MVO1 (red) and NWBL (blue) relative to volcanic centre (adapted from Stinton et al., 2020). Eruptive phases depicted in red, pauses in green. During pauses the radial distance increases with declining trend, while eruptive phases show over time increasing trends of deflation. Lower panel: Visco-elastic model of stepwise depressurisation of the magma reservoir (black) and response of the radial displacement at station MVO1 (red).

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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

With ESA's Sentinel-1 mission launched in 2014, global monitoring of volcanic unrest is now feasible as data are freely available with a revisit time of 6-12 days. We start to carry out systematically time series analysis on active volcanoes using the InSAR products from the automated processing system LiCSAR. We test our approach on the East African Rift (EAR), where 80 volcanoes are considered active during the Holocene and half of them showed historical evidence of eruptive or unrest activity.

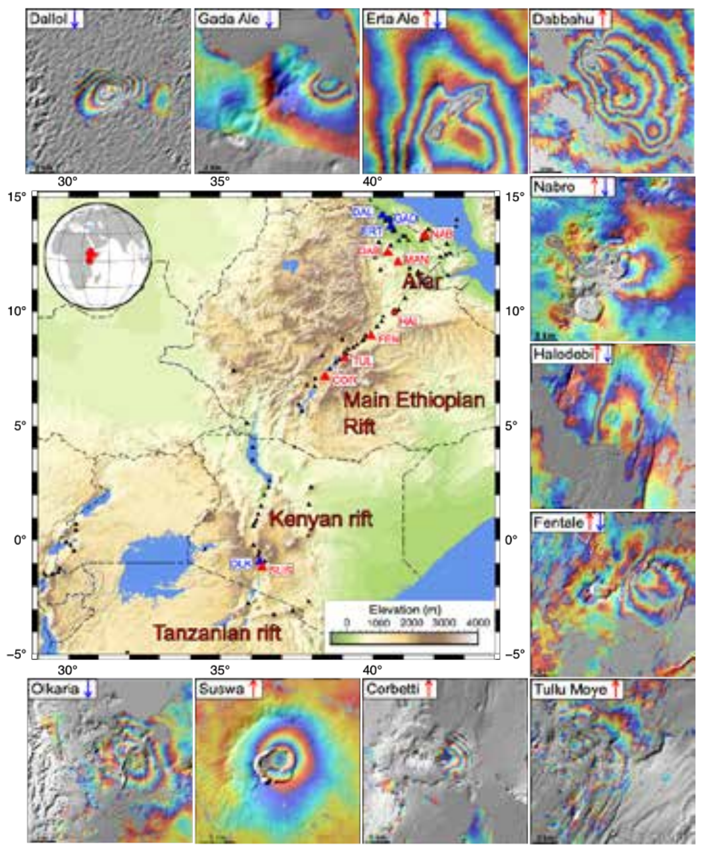

Figure 1: Map showing the Holocene active volcanoes along the East African Rift. The insets show all the ground signals detected (cumulative wrapped interferograms) by our 2014-2020 Sentinel-1 InSAR survey. Blue and red triangles indicate ground subsidence and ground uplift, respectively.

Our 2014-2020 Sentinel-1 survey shows ground unrest at 11 different volcanic systems:

(1) short-term inflation due to magma intrusions at Erta Ale and Fentale;

(2) post-eruptive deformation at Dallol and Nabro;

(3) large inflation signals due to the pressurization of magmatic systems at Dabbahu-Manda Hararo, Corbetti and Tullu Moje;

(4) new unrest at Suswa;

(5) subsidence due to geothermal exploitation at Olkaria;

(6) ground deformation related to fluid-tectonic interactions at Gada Ale and Haledebi.

In the near future, we will combine the Sentinel-1 time series with InSAR time series derived from previous SAR missions to build two-decadal time series, which will enable to better understand the dynamic of magmatic systems.

SCIENCE UPDATE: TECTONICS AND VOLCANISM

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

The first step to getting IASI global estimates of SO2 emissions was to identify the types of activity and volcanoes which can be identified with our retrievals. To isolate and enhance a volcano's SO2 signal we have used a simple technique which rotates the plumes so they always travel in one direction. This method was used to flag volcanoes where an elevated SO2 signal was present and to track changes in the magnitude of emission over time. This approach has identified a number of key flux targets and a manuscript based on this work is in preparation for submission in JVGR.

Cat Hayer, Postdoctoral Researcher, University of Manchester

Currently, PlumeTraj is run for individual case study events, rather than as a systematic program. A recent overhaul of the whole analysis package has been performed to improve the robustness of the technique and allow for integration of different trajectory models in the future. In the near future, we are aiming to automate the system, to produce daily SO2 fluxes at various target volcanoes around the world, with Mt. Etna and Papua New Guinea being the initial test cases. Once these data are being generated on a daily basis, it will be possible to analyse the dataset to improve our understanding of passive degassing and their volcanological implications.

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

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

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

Nantheera 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 network (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 the LiCSAR,which generates automatically the 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 different gain each time displacement map to 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 being deformation is the average of the four results.

Using with 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 test the 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 and at Dallol, deformation of 3.5cm/yr was detected after 310days. This corresponds to cumulative displacements of 3cm and 4cm consistent with estimates based on synthetic data.

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

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[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.

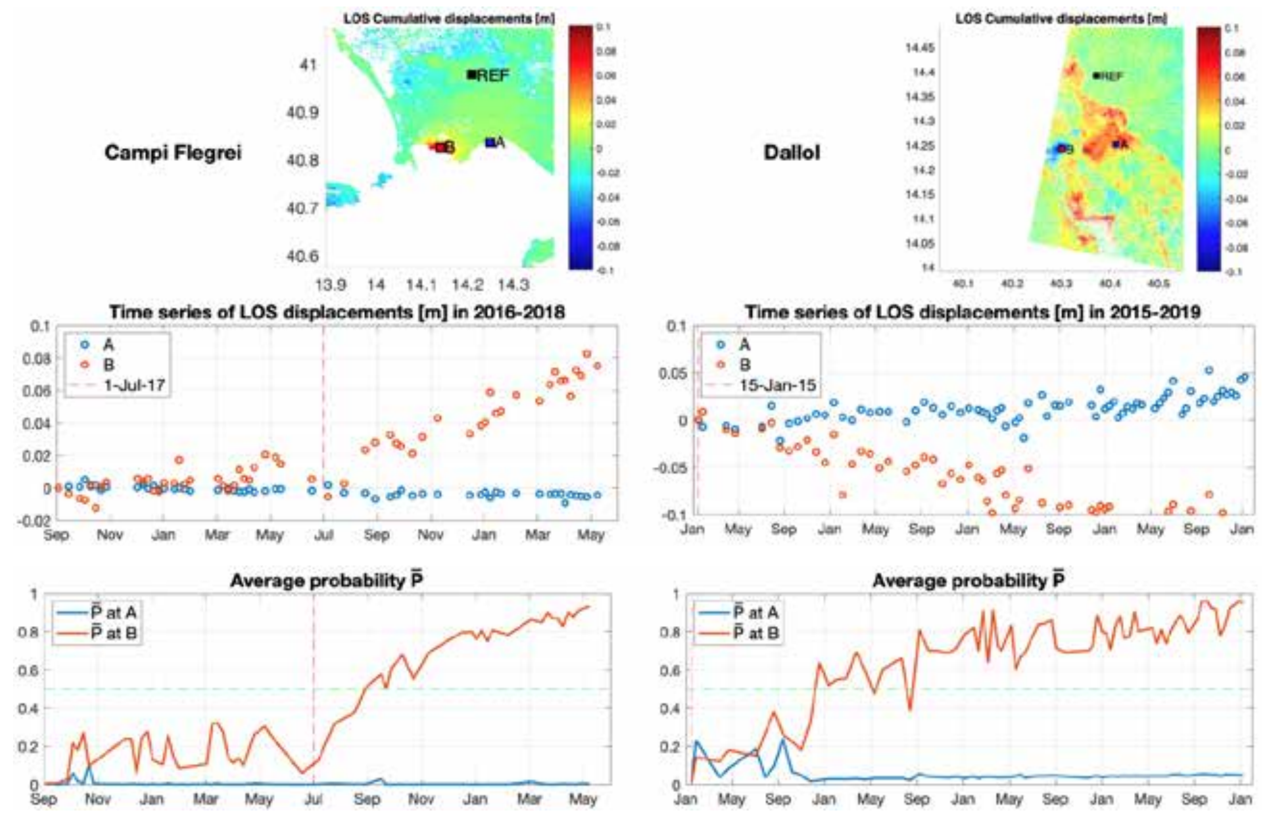


Figure 1: Examples using Sentinel-1 time-series from Campi Flegrei (left column) and Dallol (right column). Second-row figures show the cumulative displacements and two studied areas, A and B. The ground at area A is considered stable, whereas B is located at the volcanic centre is shows significant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

Over the last year, for example, COMET made important contributions to real-time response to a series of four significant earthquakes in the island of Mindanao in the south of the Philippines. Following a peculiar and devastating series of magnitude 6+ earthquakes between 16-31 October 2019 (all within 20 kilometers of each other) and a magnitude 6.7 earthquake in 15 December 2019 in the same region, Sentinel-1 and ALOS-2 satellite radar data processing to produce ground deformation maps was initiated by COMET. Coordination with ESA allowed rapid satellite tasking, data analysis, and discussion with colleagues at the National Institute of Geological Sciences of the University of the Philippines (UP) and the Philippine Institute of Volcanology and Seismology (PHIVOLCS). This collaboration was in aid of efforts to map the effects of the earthquakes and the search for usually elusive fault ground rupture. Remote sensing analysis by COMET was particularly helpful in targeting areas for detailed field investigation, especially as the surrounding volcanic terrain makes field work challenging. Preliminary findings were directly issued to and acted upon by the local government for disaster mitigation, and parallel scientific investigations by COMET and the Philippine colleagues are currently in the works.

Many of the activities that maximise the impact and reach of COMET expertise stem from the continued building of soft and hard linkages by COMET with scientists and academics in the international community. The response to the Philippine earthquakes and data analysis was led by UP faculty members, COMET student, J.D. Dianala (Oxford), and Yu Morishita, GSI Japan scientist and COMET Visiting researcher (Leeds) from 2018-2020

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. Much of our work continues to be focused in countries eligible for Overseas Development Assistance (ODA), with initiatives including the Global Challenges Research Fund (GCRF) Multi-Hazard Urban Disaster Risk Transitions Hub. This £20m initiative is using satellite data to assess seismic and volcanic hazard and vulnerability in cities at high risk.

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.

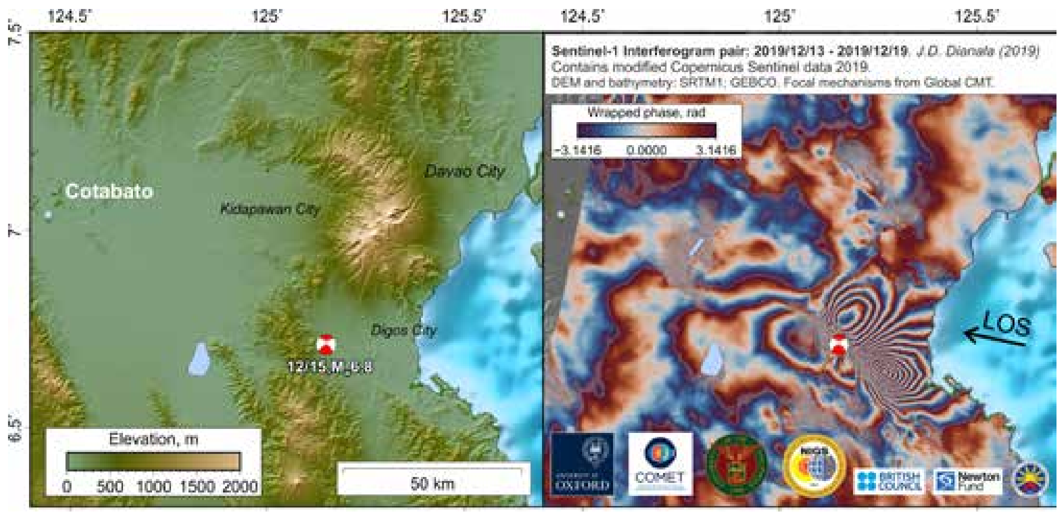
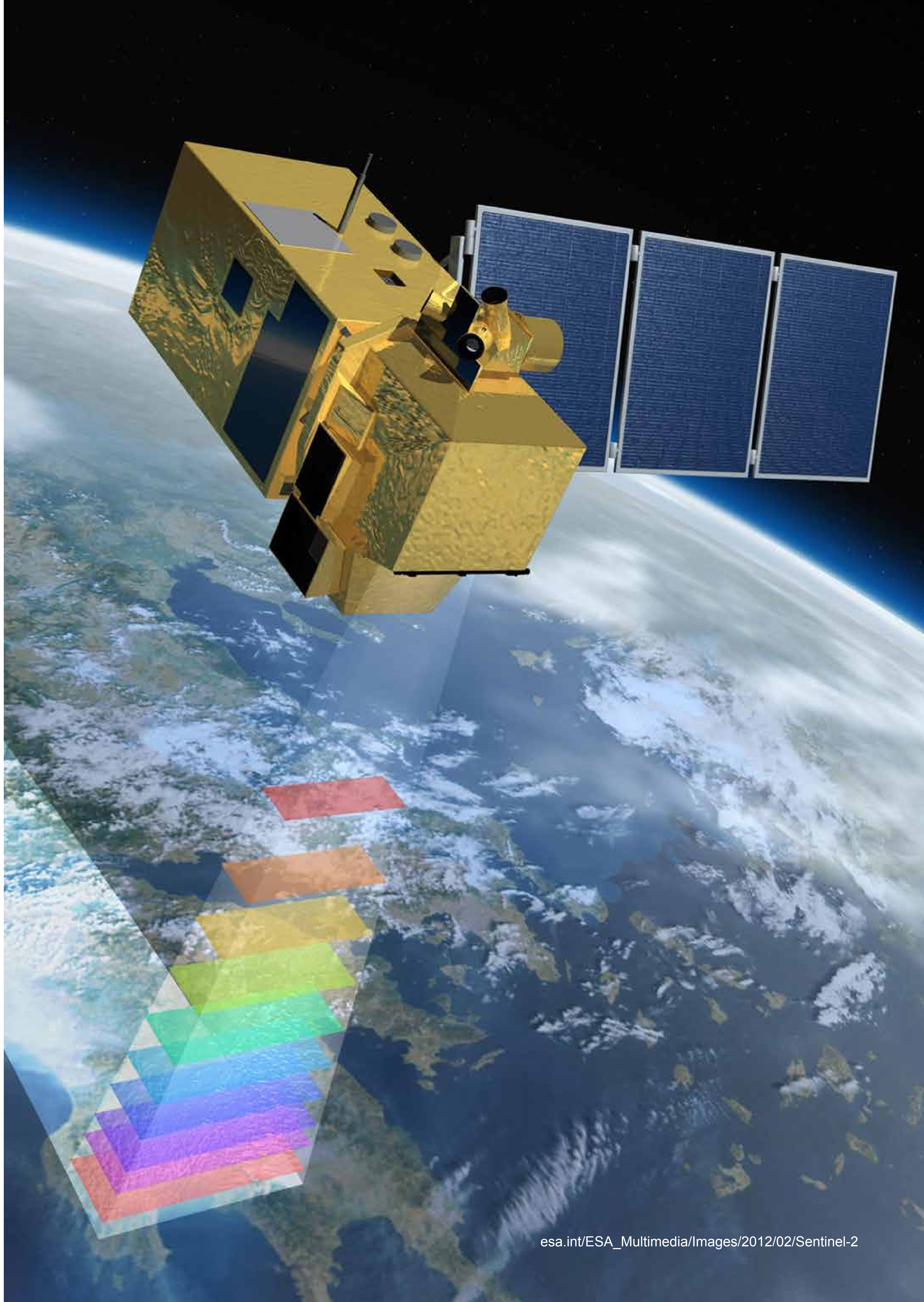


Figure 1: 15th December magnitude 6.8 event: Mindanao, Philippines.



esa.int/ESA_Multimedia/Images/2012/02/Sentinel-2

TRAINING AND EDUCATION

Our flagship training event is our annual InSAR course, held in Leeds over three days each autumn. The course aims to improve InSAR processing and analysis skills for students and early career researchers as well as those working in industry and the public sector, focusing on topics such as accessing and processing data, time series analysis and data modelling. The 2019 workshop was a great success with 29 participants from around the world at different stages in their careers.

Funded by the Royal Society, Tamsin Mather collaborated with the Oxford Sparks online outreach portal and three female PhD students at Oxford to develop a series of videos and teaching resources called 'Your Science Our There'. The project celebrates the 2020 International Day of Women and Girls in Science while providing a platform for the researchers to, as Tamsin explains, 'share our excitement about researching planetary-scale processes and to show students that the concepts that they are learning at school (or beyond!) are used daily by scientists at the knowledge frontier'.[1] A live Facebook Q&A launched the event.[2]

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.

1. https://www.oxfordsparks.ox.ac.uk/scienceoutthere
2. www.facebook.com/203041429773492/videos/2806900519393411/?__so__=channel_tab&__rv__=all_videos_card

John Elliott, University of Leeds – June 2019 field trip to assess seismic hazard and risk along the northern Tien Shan

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.

Our latest webinars[1] have covered a number of topics, including: velocity, strain and earthquake hazard models in Anatolia; the global importance of seismic sequences; impacts of volcanic gas on the environment and health; and work on algorithms for InSAR. In early 2020, we upgraded our webinar account to allow up to 500 audience members to join the sessions live. In February 2020 we had 174 registrations and this number had risen to over 300 since then. Our webinars uploaded to YouTube in this reporting period have reached over 750 views!

COMET website views have more than doubled from 20,000 in 2015, when the new website was launched, to 41,000 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 now have 2,128 followers on Twitter[3] and a new Instagram[4] account with 30 followers.



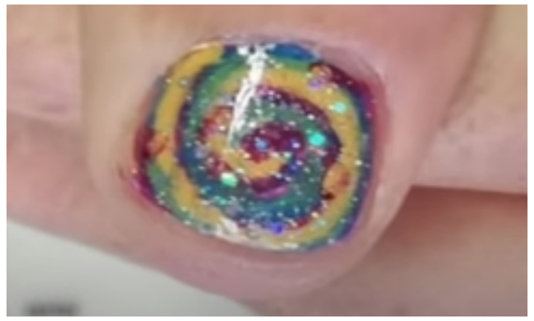



Our work is widely accessible online and in print. Results from the Deep Carbon Observatory (DCO) project, for example, which show that humans produce 40-100 times more carbon emissions than volcanoes, have been widely reported.[5] Research on monitoring volcanoes using satellite data[6] and the Tungurahua volcano in Ecuador -- known locally as "The Black Giant" – showing early warning signs of collapse have also been covered by the media.[7]

COMET members have commented on a wide range of topics in the media over the last year, such as the monitoring of airspace using satellite measurements of sulfur dioxide from volcanic eruptions,[8] the rise in volcano tourism,[9] hurricane formation,[10] contributions to an article on 'Sci-fi ways scientists could mimic volcanic eruptions to help avert climate disaster',[11] and insights into the secrets of Vesuvius.[12]

Over the last year we gave a number of public lectures, including the Tamsin Mather's Geological Society Public Lecture, Evgenia Ilyinskaya's "After Dark in the Park" talk at the Kilauea Visitor Center in Hawaii and Juliet Biggs's talk under Luke Jerram's magnificent touring art installation 'Gaia' in the University of Bristol's Wills Memorial Building:

COMET scientists are also involved in more innovative ways of communicating their research. A video of Tamsin Mather discussing her research while having a satellite, an interferogram, a volcano and tiny volcanologists painted on her nails has had over 11,000 views![13]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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:

The NERC-funded **Digital Environments: Dynamic Ground Motion Map of the UK** is exploring whether Sentinel-1 data can be integrated with sensors on the ground and embedded in the built environment to contribute to the UK Digital Environment. It is implementing cutting edge approaches to data handling, analysis and decision making, combining expertise in InSAR with image processing, machine learning, landslides, subsidence and onshore energy production.

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.

1. www.epos-ip.org/
2. eurovolc.eu

The NERC-funded **Looking inside the Continents from Space** (LiCS) project is using Sentinel-1 data to revolutionise our knowledge of how continents deform, how strain accumulates during the earthquake cycle, and how seismic hazard is distributed. LiCS is combining satellite data with ground-based observations to map tectonic strain throughout the Alpine-Himalayan Belt and East African Rift, using the results to inform new models of seismic hazard.

The LiCSAR service provides Sentinel-1 InSAR products for download, with interferograms and coherence maps produced automatically using the LiCSAR processor, and new interferograms available within two weeks of data acquisition. The initial focus on the Alpine-Himalayan tectonic belt is also being expanded with the aim of producing a complete archive for tectonic and volcanic areas globally, as well as development of a rapid event response facility.

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

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

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.

The UKRI **GCRF Urban Disaster Risk Hub** is a £20 million international collaboration aiming to provide new understanding of multi-hazard for four target cities (Istanbul, Kathmandu, Nairobi and Quito), and inform policy development on risk reduction as a result. The project includes using EO techniques, primarily satellite data, to produce data sets and information on hazard that can be used by Hub partners in achieving the wider project aims.[4]

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

3. riftvolc.wordpress.com/
4. https://www.tomorrowscities.org/

AWARDS AND RECOGNITION

Marie Edmonds (Cambridge) was selected by the VGP section President to present the Daly Lecture at AGU 2019 in recognition of her outstanding contributions to volcanology.

Matthew Gaddes (Leeds) has been selected to receive a prestigious European Space Agency (ESA) Living Planet Fellowship for his project ‘Volcano Monitoring using Deep Learning’. These fellowships are awarded to initiate a scientific career in the context of Earth Observation and Earth System Science.

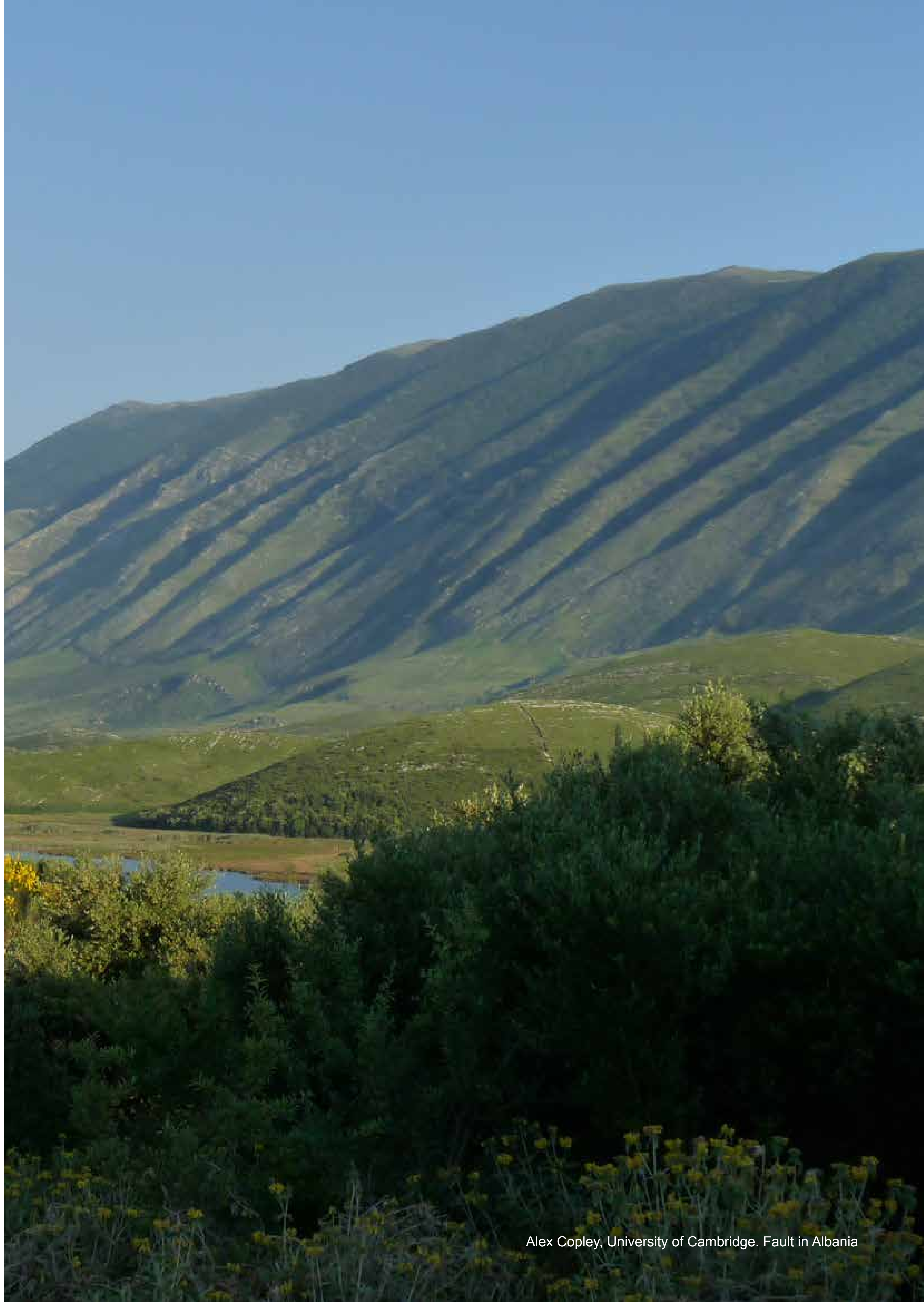
Andy Hooper (Leeds) was awarded an ERC consolidator grant of €2 million for his ‘Forecasting volcanic using deep learning’ (DEEPVOLC) project.

Tamsin Mather (Oxford) was invited to act as Theme Chair for Magmas and Volcanoes at the 2019 Goldschmidt meeting. This prestigious position was awarded in recognition of her international standing in the field.

Tamsin Mather (Oxford) was awarded an ERC consolidator grant of €2 million for research into ‘Revealing hidden volcanic triggers for global environmental change events in Earth’s geological past using mercury (Hg)’ (V-ECHO).

David Pyle (Oxford) won the VMSG Thermo-Fisher Scientific Award 2020, giving the keynote lecture entitled ‘Living with volcanoes: past, present and future’ at the 2020 VMSG meeting. This award is given annually to an individual who has made a significant contribution to current understanding of volcanic and magmatic processes.

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



Alex Copley, University of Cambridge. Fault in Albania

PUBLICATIONS - STUDENT PUBLICATIONS

COMET has a strong publication record: since 2014, COMET has published 395 papers in international scientific journals, including 33 in Science or Nature Research journals, attracting 7675 citations to date.[1] 121 (30.6%) of these publications are in the top 10% most cited publications worldwide and 78% of all publications are the result of international collaborations.

125 were published between 1st January 2019 and 31st March 2020 (Annex 1), and, of these, 23 had student first authors.

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Cotopaxi Volcano eruption

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GLOSSARY

AGU	American Geophysical Union
BGS	British Geological Survey
CAST	China Academy of Space Technology
CEOS	Committee on Earth Observation Satellites
COMET	Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics
DEM	Digital Elevation Model
EO	Earth Observation
EPOS	European Plate Observing System
ESA	European Space Agency
EwF	Earthquakes without Frontiers
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
GSRM	Global Strain Rate Model
GTEP	Geohazards Thematic Exploration Platform
GVM	Global Volcano Model
IASI	Infrared Atmospheric Sounding Interferometer
IGEPN	Instituto Geofísico de la Escuela Politécnica Nacional
InSAR	Synthetic Aperture Radar Interferometry
LiCS	Looking inside the Continents from Space
LOS	Line of Sight
NASA	US Space Agency (National Aeronautics and Space Administration)
NCEO	National Centre for Earth Observation
NERC	Natural Environment Research Council
NGO	Non-Governmental Organisation
OMI	Ozone Monitoring Instrument
RAS	Royal Astronomical Society
SAR	Synthetic Aperture Radar
UCL	University College London
USGS	US Geological Survey
VMSG	Volcanic and Magmatic Studies Group

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