COMET

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

Annual Report
2022/2023

British Geological Survey

Natural Environment Research Council

Cover photo: Winning image of the COMET 2023 Photography competition.
La Palma, Canary Islands, fieldwork June 2023 assessing building damage following the volcanic eruption in 2021.
Credit: Ben Ireland, University of Bristol

Runner up in the COMET 2023 Photography competition.
Castle Geyser in Yellowstone NP, Wyoming, USA.
Credit: Mark Bemelmans, University of Bristol

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INTRODUCTION

The Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) delivers cutting-edge 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 leading scientists across the British Geological Survey (BGS) and 8 UK partner universities: Bristol, Cambridge, Liverpool, Leeds, Manchester, Newcastle, Oxford, and University College London (UCL). In addition to this, we have associate members across a number of other UK institutions, including: Cardiff University, University of Exeter, Imperial College London, Newcastle University, University of Plymouth, University of Portsmouth, University of Sheffield, and the University of East Anglia. We provide scientific leadership in EO, while also bringing together a vibrant community of postgraduate students and early career researchers.

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

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

This report gives an overview of COMET's activities during the second year of our current 5-year programme of work. Following a 2-year transition, COMET is now delivered in partnership with BGS and managed as part of the BGS medium-term business cycle. The report highlights major scientific achievements, as well as progress against our key objectives covering the period 1st April 2022 – 31st March 2023.

DIRECTOR'S WELCOME

Welcome to the 20th anniversary edition of the COMET annual report! Over the last two decades, COMET has grown in size, scale, and scientific ambition. Each year, we expand and improve our long-term datasets and operational products, widely disseminate the findings of our research to scientific and public audiences, increase our international collaborations and networks, offer support for volcanic and tectonic events around the world, and work with strategic partners to drive forward scientific development in COMET's core areas of capability.

In Year 2 of the 2021-2026 programme, COMET has continued to work on scientific objectives that were jointly developed with BGS and are aligned with BGS's strategic priority of "Multihazards and Risk" to deliver national-level science in the observation and modelling of geohazards. Our Earth Observation Data and Services work has included the continued growth of the COMET-LiCSAR Sentinel-1 InSAR processing facility, with approximately 1,147,000 interferograms processed by April 2023, which is a significant increase from last year. COMET also launched the COMET-LiCS Land Subsidence Portal to document ninety-nine subsiding regions across Iran identified using Sentinel-1 InSAR. In our earthquakes and tectonics theme, we have made significant progress across our objectives, including our aims to map active faults and to develop a geodetically-based earthquake hazard model in partnership with the Global Earthquake Model foundation. Within our volcanology and magmatism theme, work has included continuing to produce our global dataset on volcanic plumes (2007- present), making adaptations and improvements to our codes and products, and developing a volcano database (VolcNet) that can be used to train deep learning models to detect volcanic deformation. In addition to the programme of National Capability work addressed in this report, our scientists continue to lead and contribute to a wide range of aligned projects and programmes.

This year, COMET scientists worked closely with partners across the globe and officials in the UK to provide information and support for the devastating Türkiye-Syria earthquake in February 2023. COMET were also involved in a NERC funded urgency project focused on the response to the 15th January 2022 Hunga Tonga-Hunga Ha'apai Volcanic Eruption to improve understanding of the volcanic mechanism and impact of the tsunami.

The work COMET does relies on the scientific excellence of its 160+ members and students. This year we welcomed a number of existing COMET members into new positions. Dr Pui Anantrasirichai recently joined COMET as an Associate at the University of Bristol, after working with COMET as a COMET Research Staff member; Dr Edna Dualeh (University of Bristol) was appointed a COMET Research Staff member after completing her PhD with COMET in 2022 at the University of Leeds; Dr Qi Ou also started a job as COMET Research Staff (University of Leeds) after completing her PhD with COMET supervisors at the University of Oxford; Sam Wimpenny (University of Leeds) was a COMET-funded PhD student and then a COMET Associate whilst a Research Fellow in Cambridge, and is now working with COMET Scientists at the University of Leeds as a COMET Postdoctoral Researcher. New COMET members include Peter Rowley (University of Bristol), a physical volcanologist, who joined as a COMET Associate to increase collaborations in volcanology; Victoria Anne Smith (BGS), who joined as a COMET Associate to work with us on Earth Observation techniques; and Gang Zheng (University of Leeds), a Newton International Fellow who is funded by the Royal Society to work with COMET Scientists at the University of Leeds. You can find a list of all our members at the end of this report.

The awards listed in this report every year highlight the exceptional talent within our membership. I would like to congratulate all of the recipients of these honours this year on their successes both nationally and internationally. They include Samantha Engwell's selection to sit on the WMO/ICAO Volcanic Science for Aviation Advisory Group, a ESA-EGU 2023 Earth Observation Excellence Award and AGU John Wahr Early Career Award (Geodesy) for Susanna Ebmeier, Oxford University MPLS (Maths, Physical, Life Sciences) Division awards in Teaching and Societal impact for Tamarah King and Rickard Walker, respectively, an invitation from the British Geophysical Association (BGA) to present the Bullerwell Lecture for Zoe Mildon, Cindy Lim being awarded a place on the Alan Turing Institute's 2022 Enrichment Community Scheme, Tamsin Mather being honoured with the Geochemistry Fellow title from the Geochemical Society and the European Association of Geochemistry, and Jessica Payne's Outstanding Student Presentation Award (OSPA) for the AGU.

Professor Tim Wright,
COMET Director (April 2023)

DIRECTOR'S COMMENT: HOW AND WHY DOES COMET RESPOND TO EARTHQUAKES?

A personal view from COMET Director, Tim Wright, originally published on 14th February 2023

We have all been shocked and horrified by the pictures coming from Türkiye and Syria following the two large earthquakes that happened on 6 February 2023. COMET aims to generate and freely distribute robust scientific satellite deformation data sets following all moderate-large earthquakes on land. These can assist the humanitarian and scientific response.

Here I want to briefly explain COMET's approach to responding to an event like this from my perspective, not just as COMET Director, but also as a scientist who has been involved in responding to many earthquakes using satellite deformation data and who has been working on active faulting in Türkiye for my entire career.

Deformation data from satellites are now a fundamental data set for understanding what happened in an earthquake, complementing the information that is available from seismology and from field studies. Deformation data shows, very precisely, which faults moved in an earthquake and by how much. Earthquakes are not point sources – they involve slip on faults. As earthquakes get larger, they involve larger/longer faults with increasing amounts of slip. Understanding how much and where slip occurred on a fault helps us understand the amount of shaking that is likely to have been experienced in different locations – distance to the fault is a primary control on the intensity of shaking.

In COMET, we have been developing a service to automatically produce ground movement data sets from radar satellites following all earthquakes bigger than Magnitude 5.5 that are likely to impact the land surface, and are now a trusted source for these data sets. This is possible because the Sentinel-1 satellites, part of the European Commission's Copernicus programme, have a systematic acquisition strategy over tectonic and volcanic areas, something that COMET worked with the European Space Agency to help define. We produce results from satellite data as fast as possible following the satellite acquisition, make them available to the public via a dedicated portal, and typically let people know about them using the @NERC_COMET and @COMET_database accounts on twitter.

In the case of the Türkiye earthquakes, the data sets that we produced in COMET, which were also analysed by other international groups, show that the fault that ruptured in the initial Magnitude 7.8 earthquake was a 300 km long section of the East Anatolian Fault, and the fault that ruptured in the second large earthquake, a magnitude 7.5, was over 100 km long and occurred along a different branch of the same fault system. In UK terms, the length of the first fault is about the same as the distance from Bristol to Hull; and is close to the distance from London to Paris. This great extent is one of the reasons why the devastation has been so widespread and horrendous. Both earthquakes occurred on mapped faults and in areas where national maps of seismic hazard required the strictest building codes.

We believe it is important to analyse satellite data as quickly as possible and to be open and transparent with the results, sharing them with the wider community and allowing people to use them in whatever way they wish. For most earthquakes, we now have data within a few days of the event, and we post results within a few hours of the satellite data acquisition, whether there is any media interest in an event or not. We would like to be able to do this within a few hours of every event, and with new satellite systems from the Europe, the US/India, Japan, Canada, China, and others coming on stream, there is good prospect of being able to provide results within a day of most events in the second half of this decade.

However, even if the results are not yet always available within the 72-hour window required for initial search and rescue efforts, the analysis of satellite deformation data can still be useful. Various groups around the world are using these types of data (provided by COMET or processed by other groups) to build models of the event – these can in turn be used to help understand how an earthquake influences the activity on nearby faults. More directly, the data, and information derived from it such as the location of individual fault ruptures, can help responders understand the potential impact on key infrastructure such as bridges and roads, which are vital for the relief effort but might have been impacted by the surface rupture, or other slope failures resulting from the earthquake. The data also help guide field geologists to sites in the field where they can study the earthquake fault rupture up close – such features can degrade very quickly in poor weather conditions; documenting them is important for understanding what palaeoseismologists see when they are investigating records of ancient earthquake ruptures and for understanding the detail of what happened in the causative earthquake. In turn, detailed surface rupture mapping can help to add constraints to models of the earthquake based on geodetic data. In the longer-term, forensically understanding every earthquake helps us prepare for future events in different regions.

As well as providing data sets, COMET scientists, including myself, often discuss the meaning of these data sets with colleagues in open fora like twitter, and respond to queries from colleagues and the media. Leading on from comments by American seismologist and science communicator Dr Lucy Jones, my view also is that this information sharing is vital so that scientists involved directly in the response, or those involved in communication to the public, have access to the latest data and can understand what happened during an event. Often this understanding evolves quite quickly during the hours and days that follow the earthquake. Having reliable information communicated directly in platforms like twitter, and indirectly via the media, is vital for combatting misinformation and conspiracy theories that can unfortunately proliferate in the absence of reliable scientific comment. Twitter has become a key platform for many of those discussions.

Behind the scenes, we also are passing on information to local and international partners directly, so that they have the data they need to respond, and we are responding to queries to help people use the data. We are also providing data and information to help assist with the UK government's emergency response via our partners in the British Geological Survey. We are of course acutely conscious that our scientific responses to events like the recent earthquakes are happening in the context of humanitarian tragedies. If you are able, I encourage you to give generously to organisations such as the Disasters Emergency Committee in the UK, who are helping survivors in urgent need of aid and assistance.

Thanks to Wendy Bohon, Ruth Lawford-Rolfe, and Laura Gregory for providing input on early drafts of this text.

ADVISORY BOARD COMMENTS 2022

COMET Objectives and Scientific Programme

The influence of COMET products goes beyond the COMET community, people all over the world use the COMET products, as well as the analysis tools provided online. We acknowledge the release of a comprehensive volcano deformation database, as well as the impressive development and extension of LICSAR on magmatic activity and global volcanic emissions. As the number of processed interferograms increases exponentially, a future challenge is the storage and processing of incoming data. The mapping of tectonic strain allowed by the LICSAR database is providing astonishing results for the Alpine-Himalayan belt, North and South America, the East African Rift and other parts of the world, with significant implications for the understanding of continental deformation and associated seismic hazard. We also enjoyed the long term time series of gas emissions. Cutting edge research is unifying the gas and deformation data in a consistent, physics based model, improving our understanding of volcano plumbing systems.

Annual Science Meeting

This year's COMET annual meeting (July 4-6, 2022) was organised in presence, after two years of online meetings, in the delightful village of Castleton.

The Advisory Board acknowledges the efficient and smooth meeting organisation by Lucy Sharpson and Ruth Lawford-Rolfe. We enjoyed the informal and relaxed atmosphere, and the inclusive aspect of the meeting, testified by the presence of families, babies and a helpful dog. In the future, if needed, we suggest having day care, as it would perhaps make life easier for parents. The meeting was as covid safe as possible without limiting communication, through the use of tests, masks, ventilation and use of the outdoor space whenever possible. There was a nice balance between talks given by students, postdocs, senior scientists as well as gender and nationality balance. We feel that COMET is exemplary in many ways and we hope that this inclusion model can be exported elsewhere in the scientific community.

Science, both presented at the meeting, through talks and posters, and delivered by products and publications, is of outstanding quality, driven by the high quality of the data and products. Outstanding keynote talks by Greg Houseman, University of Leeds, and Chris Rollins, GNS Science, were given remotely to the audience. Virtual talks are an interesting option which should be kept in future COMET meetings as it allows inviting distant scientists at a reduced carbon footprint. However, for talks in hybrid mode, the quality of sound is fundamental. The recommendations for fieldwork and Equality, Diversity and Inclusion discussed during the breakout sessions are exemplary and we believe they could be used by other communities of researchers throughout the world. We support the production and diffusion of documents and videos of recommendations and code of conduct during field work. We suggest that a well identified member of the steering committee may act as a mediator, in case of failure to properly address the recommendations.

This year again, we appreciated the large number of awards, fellowships, grants and publications by COMET scientists. Particularly noteworthy is the balance between fundamental science, and responses to ongoing volcanic eruptions and earthquakes.

Despite the active link with international committees, agencies and initiatives, and the success of COMET at hiring international postdoctoral fellows, we still have a concern about maintaining the link with European partners, without European funding.
We acknowledge the online training, which following our recommendation, allowed a worldwide participation of 358 people. We also appreciate the webinar series which delivered a large number of popular on-line seminars throughout the year.

Advisory Board Members 2022

Valerie Cayol (University Clermont Auvergne, France)
Elisa Carboni (RAL Space, UK)
Nicola D'Agostino (INGV, Roma, Italy)
Philippa J. Mason (Imperial College London, UK)

Runner up of the COMET 2023 Photography competition.
A child riding a donkey and they are heading to the mountains.
(July 2019 in Tien Shan)
Credit: Chia-Hsin Tsai, University of Oxford

NEW STARTERS

Pui Anantrasirichai, COMET Associate, University of Bristol

Pui has recently joined COMET as an Associate Scientist, although she has been working with COMET since 2019. She currently holds the position of Senior Lecturer in Computer Science at the University of Bristol. Her research interests encompass computer vision, image analysis and enhancement, medical imaging, and remote sensing. Within COMET, her research involves the application of image processing techniques, including denoising and deconvolution for sparse data. Additionally, she has developed a machine learning method for detecting volcanic deformation using InSAR data. For more information about Pui, please visit her website: https://pui-nantheera.github.io/

Edna Dualeh, COMET Research Staff, University of Bristol

Edna completed her PhD in 2022 at the University of Leeds, which was focused on using SAR backscatter to monitor volcanic eruptions. She is now a postdoctoral researcher at the University of Bristol looking at volcanic deformation using InSAR. She is working as part of the European Research Project *Imaging Magmatic Architecture using Strain Tomography (MAST)*, and is currently producing deformation timeseries for calderas globally and using these to understand the long-term evolution of the magmatic system and separating signals from different processes.

Qi Ou, COMET Research Staff, University of Leeds

Qi is a postdoctoral researcher, who joined the COMET team at the University of Leeds in June 2022. Qi has been a member of COMET since her PhD at the University of Oxford where she mapped the crustal strain over the northeast Tibetan Plateau using 5 years of Sentinel-1 data. Now she is working with COMET Scientist, John Elliott, and COMET Director, Tim Wright, mapping the large-scale velocity and strain rate fields over the entire Tianshan mountain range to understand the deformation of mountain belts and the associated seismic hazard.

Peter Rowley, COMET Associate, University of Bristol

Pete is a physical volcanologist, with interests in how pyroclastic density currents behave, how the resulting deposit stratigraphies accumulate, and what that means for the structure, shape and strength of the wider edifice. He works to tie scaled experimental models to field observations, particularly within fluidised grainflow conditions. Pete is increasingly interested in the risks posed by submarine and ocean island volcanoes to offshore infrastructure and shipping.

Victoria Anne Smith, COMET Associate, British Geological Survey

Victoria works at the NERC Space Geodesy Facility (SGF), operated by BGS. The SGF provides high precision geodetic data from the complimentary techniques of satellite laser ranging, Global Navigation Satellite Systems and Absolute Gravimetry. Victoria manages the Absolute Gravity Laboratory (AGL), at the SGF, and completed her PhD in Geodesy whilst working at the facility. Her research focus remains absolute gravimetry, maintaining the data, expanding the reference sites, working towards providing the UK data for the International Terrestrial Gravity Reference Frame (in development), and providing a reference site for new generation absolute gravimeters within the UK.

Sam Wimpenny, COMET Postdoctoral Researcher, University of Leeds

Sam is a geophysicist and geologist who studies the properties and behaviour of faults, and their role in tectonic processes. Sam was a COMET-funded PhD student and then a COMET Associate whilst a Research Fellow in Cambridge. He has more recently moved to the University of Leeds to work with Tim Craig and is now a COMET Postdoctoral Researcher. Sam is currently working on using temporal variability in earthquake occurrence to study the mechanics of faulting in different settings.

Gang Zheng, COMET Associate, University of Leeds

Gang is a Newton International Fellow funded by the Royal Society, and is working with Tim Wright at the University of Leeds. His research mainly focuses on developing the use of geodetic data for measuring continental deformation, and using the results to understand active tectonics and assess seismic hazard. His current work focuses on the India-Eurasia collision zone. He has processed and analyzed massive volumes of GPS data from thousands of stations collected during the last two decades, and will combine the GPS solution with the latest InSAR data to produce a 3D velocity field, in order to test kinematic and dynamic models for the India-Eurasia collision.

COMET OBJECTIVES

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

Our science objectives for 2021-2026 are:

EO data and services

1. Deformation from satellite geodesy:

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

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

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

3. Retrievals of volcanic emissions from satellite spectrometers:

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

4. Geoinformatics and machine learning:

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

Tectonics and volcanism

1. Tectonics and seismic hazard

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

2. Magmatism and volcanic hazard

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

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

Aisling O'Kane pondering deformed rocks in the foothills of the Himalayas (in Jammu and Kashmir, NW India). These rocks have been rotated to the observed steep dips by motion on a range-bounding fold, underlain by an active thrust fault.
Credit: Alex Copley, University of Cambridge

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

RESEARCH HIGHLIGHT: COMET-LICS SUBSIDENCE PORTAL

Jessica Payne, COMET Research Student, University of Leeds
Richard Rigby, CEMAC, University of Leeds
Andrew Watson, COMET Research Student, University of Leeds
Yasser Maghsoudi, COMET Research Staff InSAR Scientific Developer, University of Leeds
Milan Lazecký, COMET Research Staff Scientific Programmer, University of Leeds
John Elliott, COMET Scientist, University of Leeds

In May 2022, COMET launched the COMET-LiCS Land Subsidence Portal to document ninety-nine subsiding regions across Iran identified using Sentinel-1 InSAR (Figure 1). The portal provides tools for the online analysis of automatically processed LiCSAR Sentinel-1 interferograms and subsequent LiCSBAS time-series on a region-by-region basis across the country. All explanatory text on the Portal pages is provided in both English and Farsi, the national language of Iran. Portal tools are designed to allow key stakeholders to search quickly through processed imagery and make critical assessments related to the extents and rates of basin subsidence.

Depletion of Iran's non-renewable groundwater has contributed to land-surface deformation across the country (Motagh et al., 2008)[1].Such depletion has been enhanced by regional droughts, but basin-scale depletions are driven mainly by extensive human groundwater extraction (Ashraf et al., 2021)[2]. Continued unsustainable groundwater management in Iran could lead to irreversible environmental impacts that threaten the country's water, food, and thus socio-economic security.

In terms of data, the Portal pulls over eight years (2014-present) of Sentinel-1 interferogram products from the main COMET-LiCS Portal. These interferograms were produced using the COMET LiCSAR automated processing system (Lazecký et al., 2020)[3].LiCSBAS time-series analysis tools (Morishita et al., 2020)[4] then use these interferograms to calculate line-of-sight (LoS) time-series displacements clipped to the extent of each subsiding region. This analysis reveals maximal cumulative LoS displacement near Tehran exceeds 120 cm since October 2014. Land subsidence LoS velocities therefore 150 mm/year in this region.

Both interferograms and displacements are available to view and download on the homepage of each region hosted on the COMET-LiCS Land Subsidence Portal (Figure 2). Users can decide whether to apply corrections and filters to calculated displacements. For example, an atmospheric correction via the GACOS system (Yu et al., 2018)[5] can be applied, as well as a spatiotemporal filter.

Initially the portal characterises Iranian subsidence but will increasingly have a global focus. Ongoing updates will be made to the portal's interferograms and timeseries extended as more Sentinel-1 data is acquired, as well as validation through further testing of rates from overlapping tracks.
The Subsidence Portal was launched during the ESA Living Planet Symposium 2022 with Jess Payne presenting a poster about the Portal.

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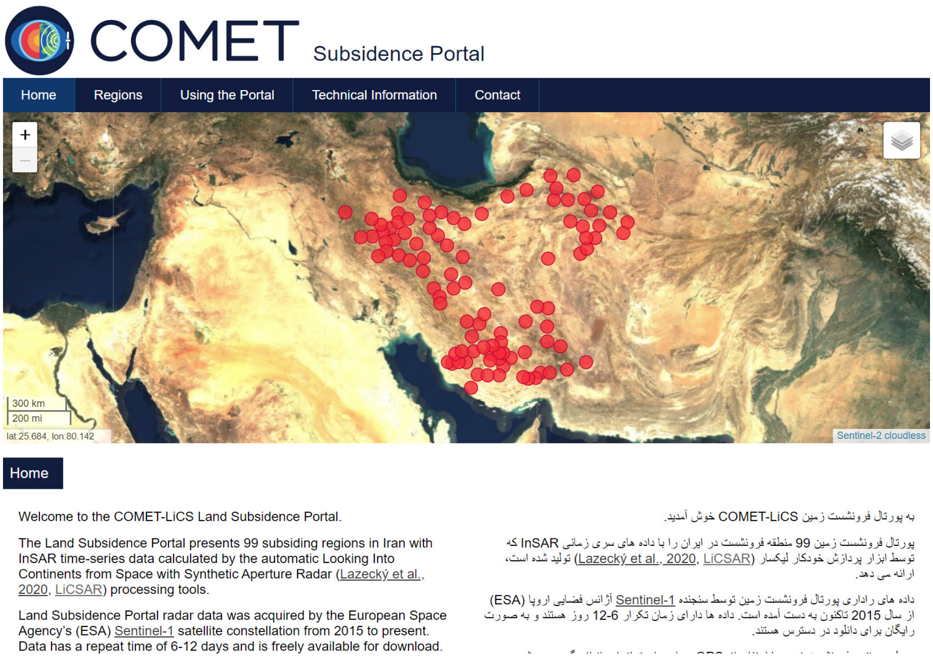

Figure 1: COMET-LiCS Land Subsidence Portal homepage showing 99 subsiding regions across Iran identified using Sentinel-1 InSAR.

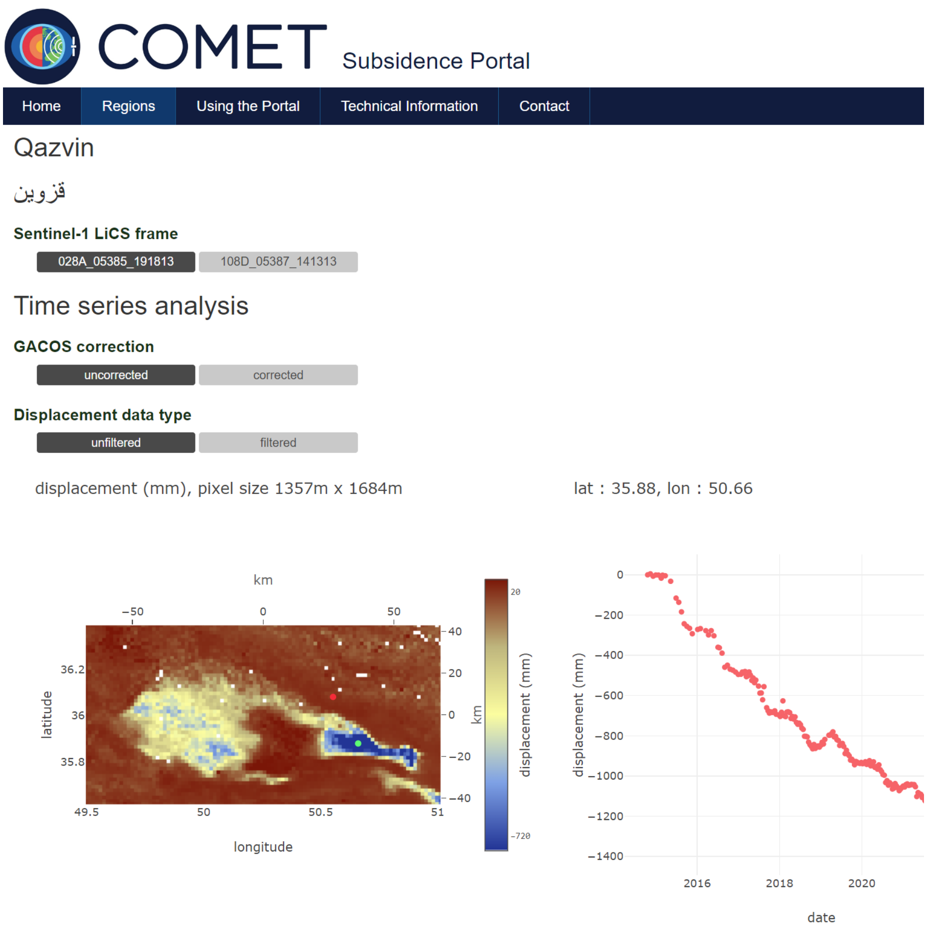

Figure 2: Homepage for Qavzin subsiding region in northern Iran. Map of time-series displacement and selected time-series of displacement calculated using LiCSAR interferogram products and LiCSBAS time-series analysis tools are available to analysis online by users.

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

RESEARCH HIGHLIGHT: THE 2020 – 2021 DOME GROWTH AT LA SOUFRIÈRE, ST. VINCENT QUANTIFIED FROM SAR BACKSCATTER

Edna Dualeh, COMET Research Staff Magmatic Deformation and Modelling, University of Bristol

Quantifying lava domes can be challenging due to the limited visibility (e.g., cloud coverage) and accessibility to the active dome. However, extrusion rates are critical for monitoring eruptions and forecasting their development. At the end of 2020, after 41 years of quiet, La Soufrière volcano on St Vincent entered a new phase of activity when a lava dome formed within the summit crater. This effusive activity continued for over three months before the eruption transitioned from effusive to explosive in early April 2021, completely removing the newly emplaced dome.

We developed a method to extract topography from individual Synthetic Aperture Radar (SAR) backscatter images and used this to measure extrusion rates through time for the 2020 - 2021 La Soufrière dome. We used 32 images from multiple SAR sensors (COSMO-SkyMED, CSK; TerraSAR-X, TSX; Sentinel-1, S1) that spanned the 3.5 months dome building phase from December 2020 to April 2021 (Figure 1). An advantage of satellite-based SAR backscatter is that it can provide frequent information about changes to the ground surfaces during an eruption when other datasets (e.g., optical, thermal imagery) are limited.

For the eruption at La Soufrière, we estimated an average extrusion rate of 1.8m3s-1 between December 2020 and March 2021 before an acceleration in extrusion rate to 17.5m3s-1 in the two days before the first explosive eruption (Figure 2). This increase in extrusion rate was also observed in photos acquired by a remote camera on the crater rim (Joseph et al., 2022) [6].

Based on the assumption that this increased extrusion rate remained constant until the eruption (which may not have been the case), we estimated a final dome volume of 19.4 million m3. Evidence from other studies indicate a magmatic change before the transition in eruption styles (Figure 2c), these included changes in seismicity (Joseph et al., 2022; Camejo-Harry et al., 2023)[6,7], detection of SO_2 emissions (Joseph et al., 2022; Esse et al., 2023)[6,8] and ash venting from fractures (Stinton, 2023)[9]. Therefore, a possible explanation for the acceleration in extrusion rate would be consistent with the combined emptying of the conduit and reservoir of older material before the ascent of gas-rich magma.

We found that our method was able to provide accurate measurement of topographic change during the 2020-2021 La Soufrière eruption. Further, by applying it to multiple SAR sensors we were able to test how different viewing geometries, polarisation and resolution affect our extracted topography. This suggested that the ideal geometry would be a high-resolution sensor with like-polarisation and a large incidence angle to reduce the layover contribution with frequent acquisitions. However, in practice during an eruption when it is hard to know what the most appropriate geometry will be, analysing data from different SAR instruments will provide better constraints on SAR extracted topography. This work (Dualeh et al., 2023)[10] and collaborations were established during the eruption response coordinated by University of the West Indies Seismic Research Centre (UWI-SRC).

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9. Stinton, A. J. (2023). Growth and evolution of the lava dome and coulée during the 2020-21 eruption of La Soufrière, St Vincent. *Geological Society, London, Special Publications*, 5, https://doi.org/10.1144/SP539-2022-304
10. Dualeh, E. W., S. K. Ebmeier, T. J. Wright, M. P. Poland, R. Grandin, A. J. Stinton, M. Camejo-Harry, B. Esse, and M. Burton. (2023). Rapid pre-explosion increase in dome extrusion rate at La Soufrière, St. Vincent quantified from synthetic aperture radar backscatter. *Earth and Planetary Science Letters*, 603, 117980, https://doi.org/10.1016/j.epsl.2022.117980

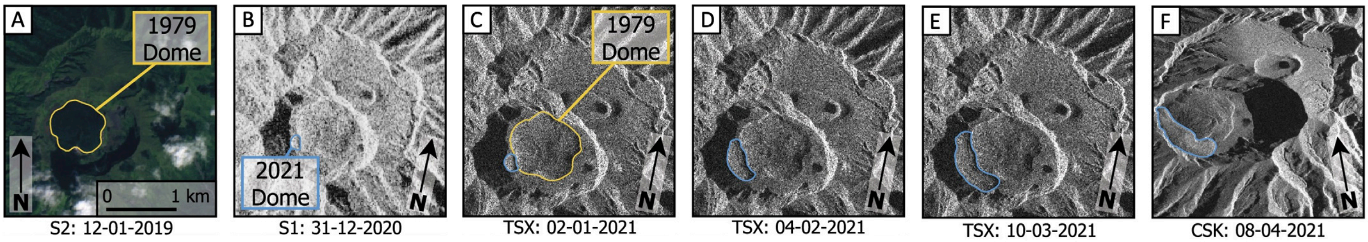


Figure 1: Dome growth (outlined in blue) in La Soufrière crater between December 2020 to April 2021 observed in (A) optical and (B-F) SAR images in radar geometry from different sensors.

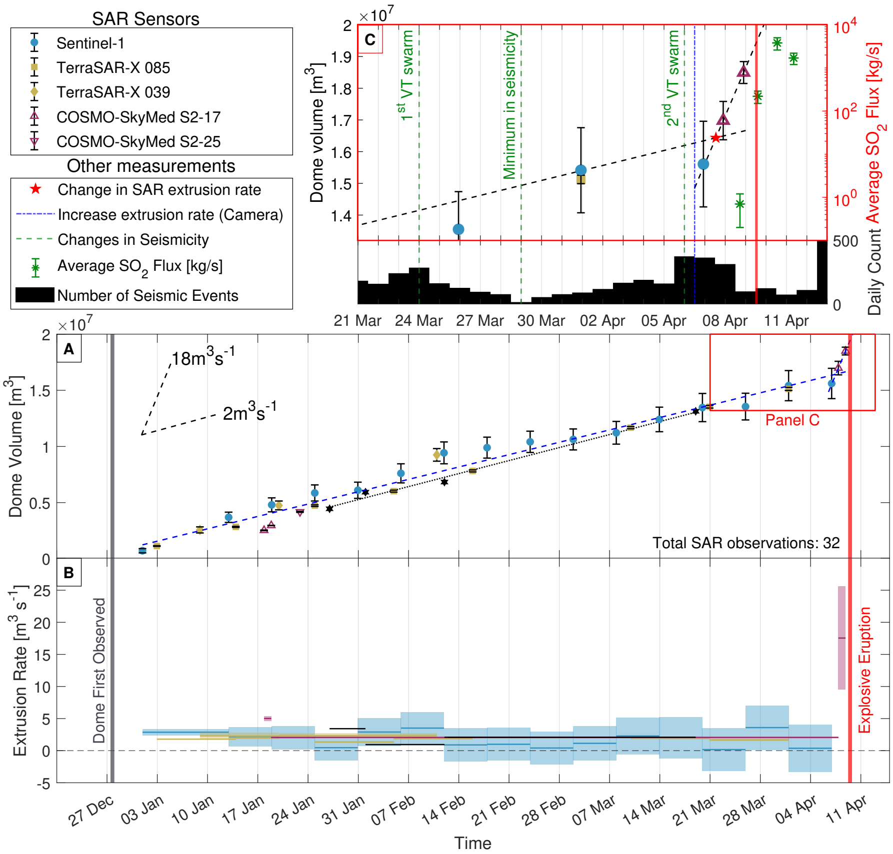


Figure 2: Time series of (A) cumulative volumes and (B) time-averaged extrusion rates of the dome at La Soufrière from December 2020 and April 2021 extracted from SAR backscatter data. The SAR backscatter data extend the photogrammetry observations showing the sudden increase in dome volume and extrusion rate in the days prior to the transition from extrusive to explosive eruption. (C) Enlarged time series of the two weeks prior to the eruption, with important changes seen in other datasets (i.e., seismicity, SO_2 emissions, visual observations superposed). SO_2 measurements are time-averaged fluxes over periods of 5–20 hours for the corresponding days (Esse et al., 2023)[8]. Date format is shown as 'Day Month' starting in December 2020 until April 2021.

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

RESEARCH HIGHLIGHT: UTILISING ICESAT-2 IN ACTIVE TECTONICS: EXAMPLE STUDY ACROSS AN ACTIVE FAULT SCARP IN GREECE

Rebecca Tanner, MA Student, University of Oxford
Tamarah King, COMET Research Staff High Resolution Imagery/Topography, University of Oxford
Richard Walker, COMET Scientist, University of Oxford

NASA's Ice, Cloud, and Land Elevation Satellite 2 (ICESat-2) provides globally available space-born lidar data which are currently underutilised in geomorphology and geology research. As part of a 4th year master's project, a new semi-automated programmatic method was developed to use ICESat-2 elevation profiles for active fault studies and geomorphic analysis. This method provides an efficient and inexpensive way of mapping scarps and landforms, studying inaccessible faults, and densifying high-resolution measurements across scarps.

ICESat-2 has a near-polar orbit and a repeat time of 91 days along each of its 1,387 reference ground tracks (RGT). Onboard is the Advanced Topographic Laser Altimeter System (ATLAS), which produces six high-resolution lidar profiles per pass (three weak, and three strong) (Figure 1). At lower latitudes the beams shift to either side of the RGT per pass, which results in a dense grid of coverage.

As part of this project, a Python-based user-friendly Jupyter Notebook was produced, which allows a user with little to no programming experience to download, processes, analyse, and visualise ICESat-2 data across geomorphic features (e.g. active fault scarps). The workflow is semi-automated, allowing for minimal input from the user, whilst also retaining the ability for the user to verify each stage of data processing and analysis.

The Jupyter notebook identifies, downloads and processes available ICESat-2 profiles over the region of interest (e.g. a fault scarp). The user can then use the notebook to semi-automate calculating net-slip across an identifiable scarp, and slip-rate (if the age of offset surfaces is known/estimated). The final outputs of the Jupyter Notebook are: an interactive map showing available profiles, net-slip and/or slip-rates; a table of slip statistics; and histogram plots of slip-rate. Net-slip and slip-rates are calculated using the Monte Carlo Slip Statistic Toolkit developed by Wolfe et al. (2020)[11].

The method was tested using the Kaparelli fault in Central Greece. This fault was responsible for a surface rupturing Ms 6.4 earthquake in 1981. It is well-orientated (east-west) to the ICESat-2 ground tracks (north-south). Mis-orientation of faults/features of interest relative to the ground-tracks is otherwise a main limitation of ICESat-2 data.

Along a ~2.5km length of the rupture, six viable ICESat-2 profiles were available, providing high-resolution scarp height measurements of between 5-15m (Figure 2). Some ICESat-2 profiles were unusable due to low-photon counts from a weak-beam, which is a known limitation of this data. The ICESat-2 profiles identify scarps otherwise unmappable on globally available DEMs due to low-resolution, or satellite imagery due to heavy vegetation (ICESat-2 beams penetrate vegetation).

The Jupyter Notebook allows for quick and easy remote analysis of ICESat-2 data for identifying and analysing both large and small-scale topographic features in higher resolution than global DEMs. We aim to publish this work and the Jupyter Notebook soon, to enable geomorphology and active-tectonics researchers to more easily access and use this data in their work.

Reference
11. Wolfe, F. D., Stahl, T. A., Villamor, P., and Lukovic, B.: Short communication: A semiautomated method for bulk fault slip analysis from topographic scarp profiles, Earth Surf. Dynam., 8, 211–219, https://doi.org/10.5194/esurf-8-211-2020, 2020.

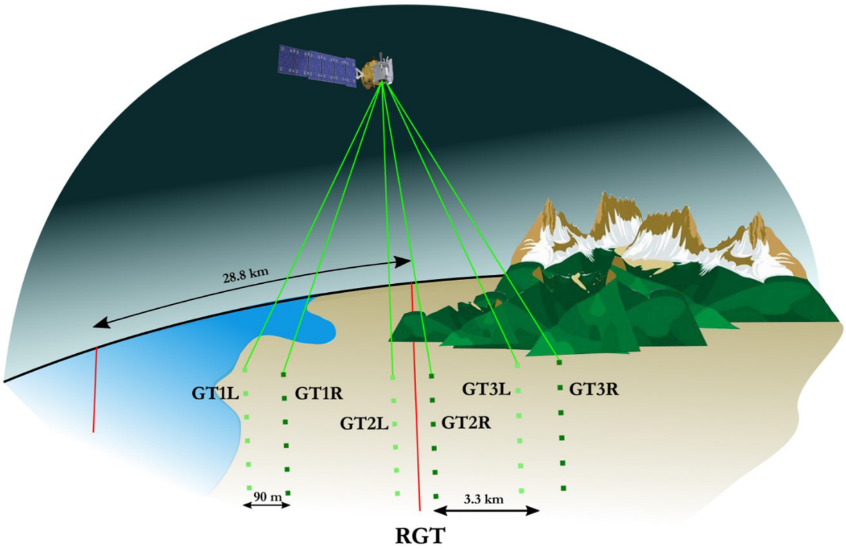


Figure 1: Schematic illustrating the setup of ICESat-2: six beams are centred over the RGT which produce six elevation profiles.

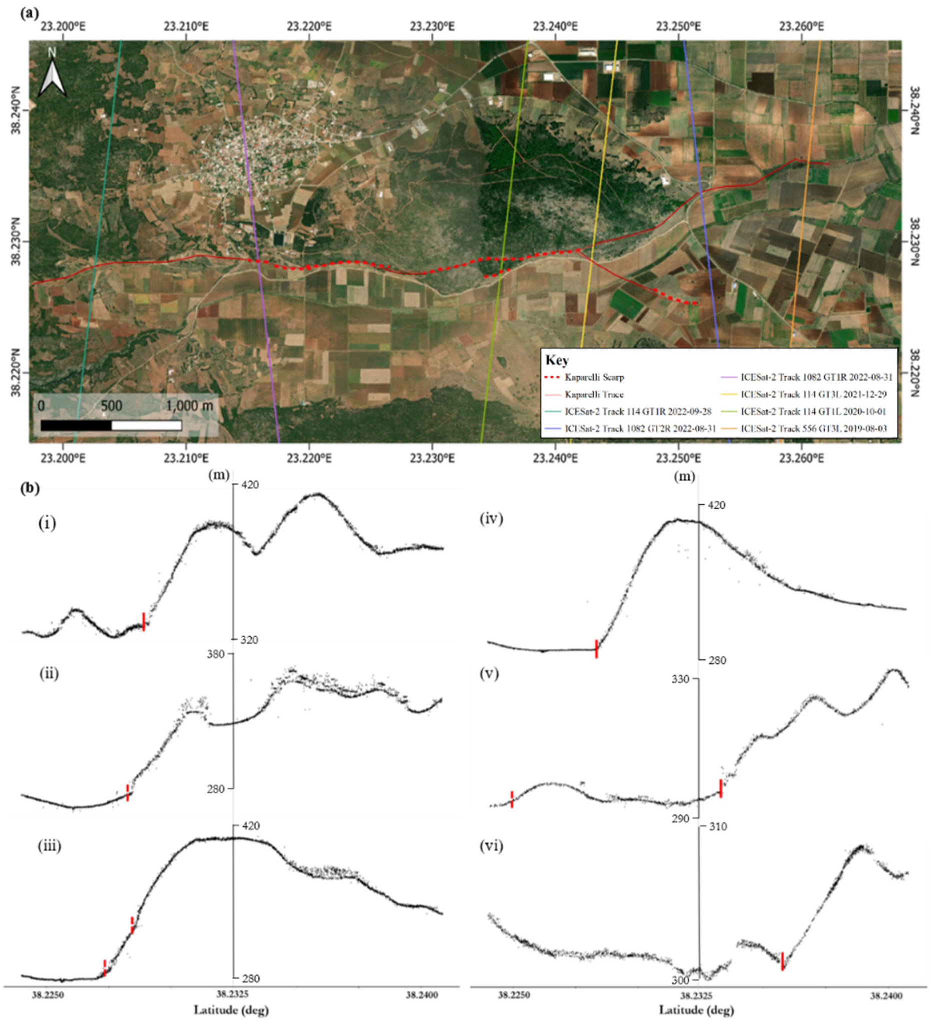


Figure 2: (a) ICESat-2 profiles (coloured lines) are shown relative to the Kaparelli fault scarp (red dashed lines). These scarps are mapped using satellite imagery and ICESat-2 profiles (b) shows the available and viable ICESat-2 elevation profiles across the scarp, with red solid and dashed lines indicating the fault and scarp locations respectively. Profiles (i) to (iii) go from west to east and are the westerly profiles, whilst (iv) to (vi) are the easterly profiles, also from west to east.

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

RESEARCH HIGHLIGHT: SATELLITE OBSERVATIONS OF PLUMES FROM THE APRIL 2021 LA SOUFRIÈRE ERUPTION

Isabelle Taylor, COMET Research Staff Volcanic Gas and Ash, University of Oxford

On 9th April 2021, following a few months of effusive activity, La Soufrière on St Vincent began erupting explosively. The eruption consisted of a series of explosive events over a 14-day period. We studied the plumes from this eruption using two satellite instruments: the Infrared Atmospheric Sounding Interferometer (IASI) on the MetOp satellites, and the Advanced Baseline Imager (ABI) on the Geostationary Operational Environmental Satellite (GOES).

The ABI instrument typically obtains data every 10 minutes, but for a large part of the La Soufrière eruption, a mesoscale region was moved over the volcano, which increased measurements to every minute. We examined true and false colour images (example in figure 1) to construct a chronology of the plumes emitted during the eruption. In total we counted a minimum of 35 explosive events during the 14-day period. Analysing the events we divided the eruption into four phases: (1) an initial explosive event, (2) a sustained event with significant ash emission lasting more than nine hours, (3) a pulsatory phase with 25 events lasting around 65 hours and (4) a waning phase.

Each of the three IASI instruments obtains near global coverage twice a day, and with these instruments we were able to study the evolution of the plume as it was transported across the globe, examples shown in figure 2. Our iterative SO_2 retrieval can quantity the column amount and height of SO_2 in each pixel, which when combined allows us to look at the vertical distribution of the gas. Our results showed that the majority of SO_2 was emitted into the upper troposphere and around the height of the tropopause, with some emission into the stratosphere. The total mass loading of SO_2 measured with IASI peaked at 0.31±0.09 on 13th April 2021, a few days after the first eruption. Converting our total mass timeseries to fluxes showed that the greatest emission occurred on 10th April with that measurement incorporating the sustained phase and beginning of the pulsatory phase. The flux was then shown to fall during the remainder of the eruption. By summing the fluxes, we estimated a total emission of 0.63±0.5 Tg of SO_2.

There are several similarities between the 1979 and 2021 explosive eruptions at La Soufrière, including that both eruptions consisted of a series of explosive events. Our study highlights the value of satellite data for helping to characterise the plumes and sequence of events during eruptions, which may help to be better prepared for future activity.

We are grateful to the NOAA Big Data Program for access to the GOES ABI data, to EUMETSAT for access to the IASI level 1c data and to ECMWF for the meteorological data used in the IASI retrievals.

This study was conducted in collaboration with Don Grainger, Andrew Prata, Simon Proud, Tamsin Mather and David Pyle. The paper is in review in *Atmospheric, Chemistry and Physics*.[12]

Reference

12. Taylor, I. A., Grainger, R. G., Prata, A. T., Proud, S. R., Mather, T. A., and Pyle, D. M.: Satellite measurements of plumes from the 2021 eruption of La Soufrière, St Vincent, Atmos. Chem. Phys. Discuss. [preprint], https://doi.org/10.5194/acp-2022-772, in review, 2022.

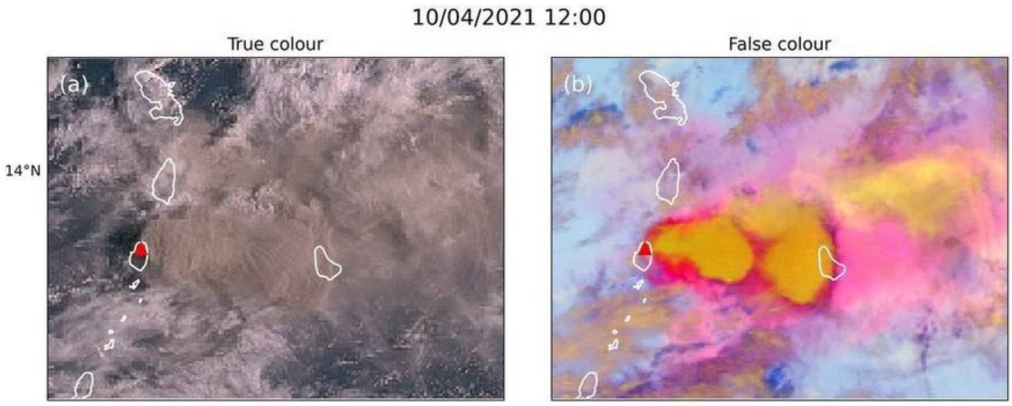


Figure 1: Images at 12:00 10th April 2021 constructed with the ABI data showing the ash clouds from La Soufrière travelling to the East of the volcano. (a) True colour image. (b) False colour image. In the false colour image, the orange/brown colours show the location of thick volcanic ash, and the pink colours show the optically thin ash.

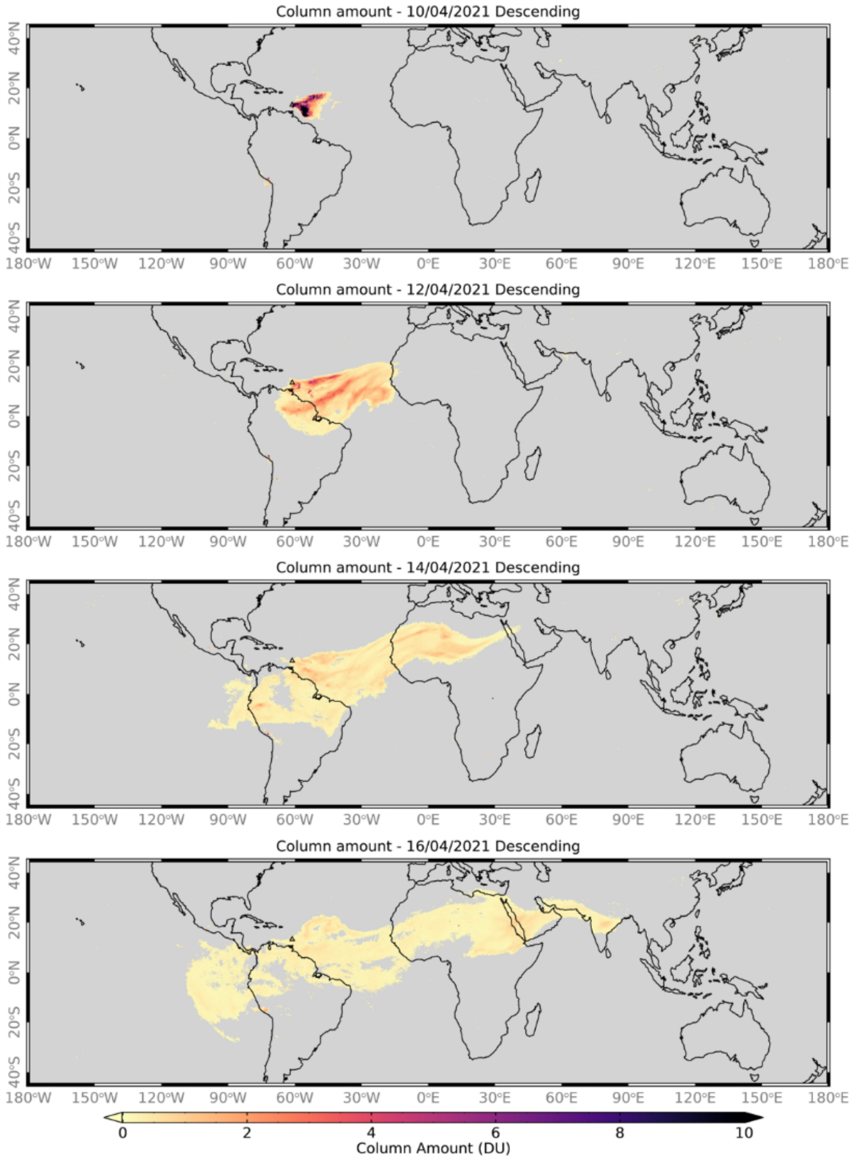


Figure 2: Maps of the SO_2 column amount output from our IASI SO_2 retrieval showing the plume from the La Soufrière eruption. Also visible is a plume from Sangay in Ecuador which erupted on 12th April.

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

RESEARCH HIGHLIGHT: INVESTIGATING VOLCANIC DEGASSING PROCESSES DURING THE 2021 ERUPTION OF LA SOUFRIÈRE, ST VINCENT, USING SATELLITE SO_2 IMAGERY

Ben Esse, COMET Postdoctoral Researcher, University of Manchester

After several months of effusive, lava dome building activity, La Soufrière volcano on the island of St Vincent underwent an explosive eruption beginning on 9th April 2021 and lasting until 22nd April. The volcano was well monitored, with the local infrastructure being upgraded after the uptick in activity leading up to the eruption by staff from the Seismic Research Centre of the University of the West Indies (UWI-SRC), the National Emergency Management Organisation of St. Vincent and the Grenadines (NEMO) and the Montserrat Volcano Observatory (MVO). The lava dome grew steadily from December 2020 to the side of an existing lava dome that was left after the previous 1979 eruption. The day before the explosive eruption began, an increase in the seismic activity and observed steam and gas emissions from the vent triggered an evacuation order for residents closer to the volcano. This evacuation was a great success, with no recorded direct fatalities resulting from the eruption. The explosive phase of the eruption began with an initial explosion at 12:40 (UTC) on 9th April, followed by a period of sustained ash venting from roughly 18:00 (UTC). The explosive activity continued overnight and into the following days, with individual explosions becoming more spread out as time passed, until the final explosion on 22nd April.

We were interested in the SO_2 emissions from this eruption, both in terms of how these could be used to monitor future eruptions and what we could learn about the eruptive processes. Notably, there was very little SO_2 emitted during the dome building phase, with SO_2 only being detected using sensitive in-situ sensors from 1st February and not at all by either ground- or satellite-based remote sensing until the day before the explosive activity began. Therefore, we decided to investigate this eruption using satellite SO_2 imagery from TROPOMI, and analysed with PlumeTraj, a back-trajectory analysis toolkit developed at the University of Manchester, to unpick the degassing and eruptive processes.

The SO_2 emissions from La Soufrière during the explosive phase were extensive, with the detected plumes spreading across the Atlantic Ocean and wrapping around the world. Figure 1 shows the plumes measured by TROPOMI during the eruption. One issue that arose was the fact that some of the SO_2 was recirculated back to the volcano location, meaning that old emissions were impossible to distinguish from new ones. This meant that we focused on the initial phase of the eruption where the emissions were clearly fresh.

Using PlumeTraj, we were able to take the raw TROPOMI SO_2 imagery and calculate the emission rate and altitude throughout the first few days of the eruption, as well as the precursory emissions detected the day before the explosive activity began (Figure 2). This shows low level emissions (in agreement with emission rates measured on the ground) on 8th April, the impulsive initial explosion on 9th April and the continuous emissions on the 10th and 11th.

One point to note is that the mass eruption rate of an eruption is correlated with the injection height of the eruption plume. This means that since they were injected at similar heights the eruption rate of magma would be roughly the same. As the emissions on 9th April during the initial explosion were an order of magnitude lower than on the 10th, the initial explosion was sulphur poor relative to the rest of the eruption.

These results allow us to produce a picture of the eruption process. At the beginning of the eruption the conduit was filled with the remaining magma from the previous eruption in 1979. The arrival of fresh magma at depth slowly forced this degassed but still mobile magma out, forming the new lava dome while producing little-to-no SO_2 emissions. As the old magma was depleted, its resistance to movement decreased, leading to an acceleration of lava effusion and the low level SO_2 emissions seen on 8th April. Analysis of Synthetic Aperture Radar (SAR) data by Dualeh et al. (2023)[13] also shows a rapid increase in the lava effusion rate prior to the explosive eruption, supporting this theory. This produced a run-away process, culminating in the initial explosion which cleared the conduit of the previously degassed magma, allowing the eruption of the fresh magma in the main phase a few hours later.

This research was conducted in collaboration with UWI-SRC and MVO. It has been published in a Special Publication on the eruption of La Soufrière by the Geological Society of London (https://doi.org/10.1144/SP539-2022-77).

Reference

13. Dualeh EW, Ebmeier SK, Wright TJ, et al (2023) Rapid pre-explosion increase in dome extrusion rate at La Soufrière, St. Vincent quantified from synthetic aperture radar backscatter. Earth Planet Sci Lett 603:117980. https://doi.org/10.1016/j.epsl.2022.117980

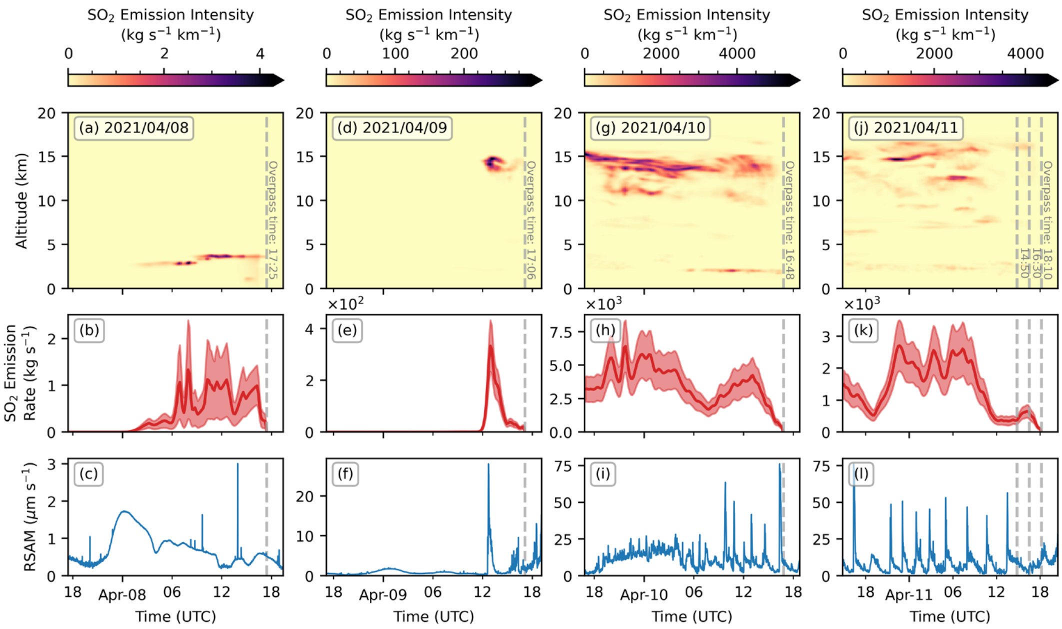


Figure 1: SO_2 plumes measured by TROPOMI during the eruption of La Soufrière.

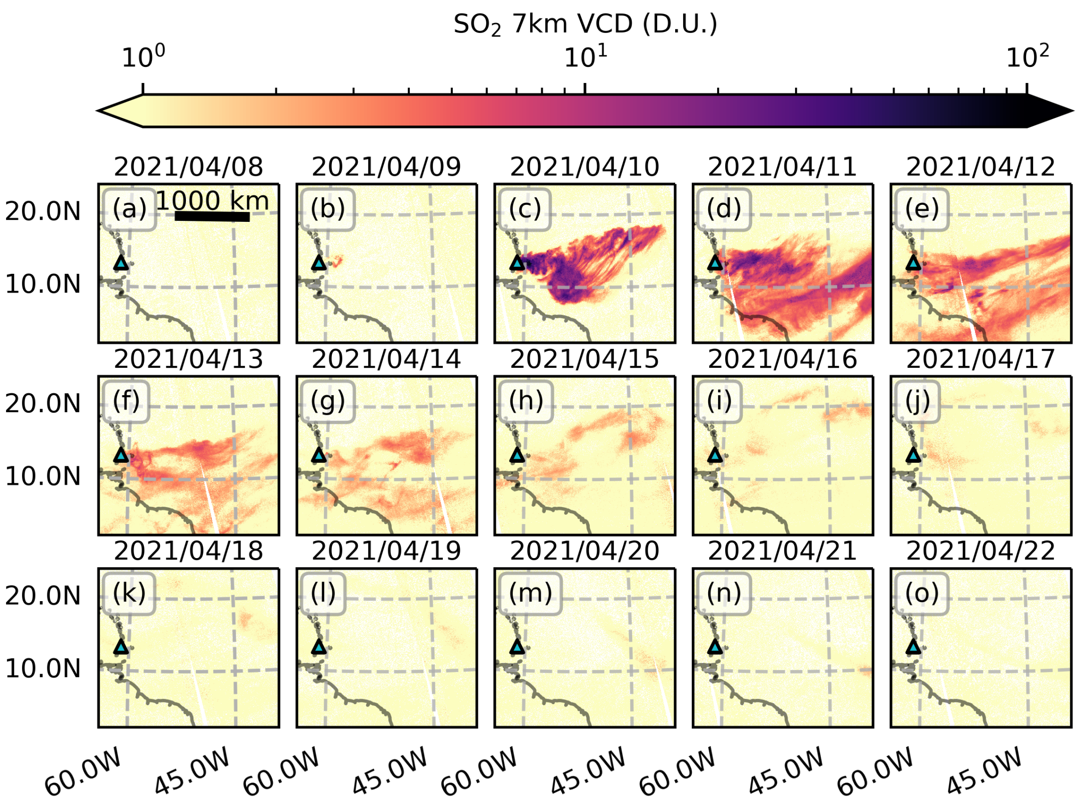


Figure 2: Reconstructed SO_2 emissions from 8th-11th April 2021. Top row shows the emission intensity, with darker colours representing a stronger emission at that time and altitude, the middle row shows the total integrated emission rate with time, and the bottom row shows the seismic activity (data provided by UWI-SRC).

RESEARCH HIGHLIGHTS: EO DATA AND SERVICES

RESEARCH HIGHLIGHT: 3D DISPLACEMENTS AND STRAIN OF THE 2023 FEBRUARY TÜRKIYE-SYRIA EARTHQUAKES FROM SENTINEL DATA

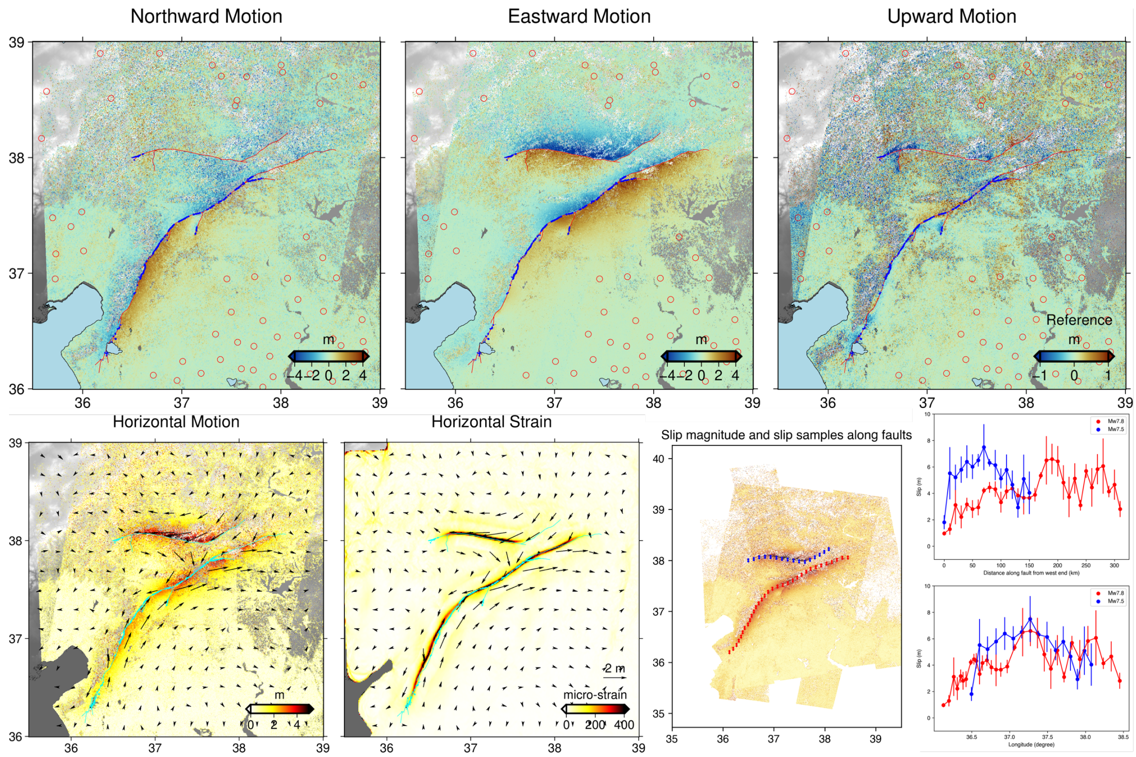
Qi Ou, COMET Research Staff Tectonic Strain, University of Leeds

This February witnessed two devastating Türkiye-Syria earthquakes which happened back-to-back. In support to the humanitarian rescue effort and to facilitate research by the scientific community, COMET presented ~100 m resolution 3D displacements, horizontal strain and surface slip distributions, with associated uncertainties, jointly inverted from four tracks of Sentinel-1 range and azimuth offsets and a set of north and east displacements from Sentinel-2 pixel tracking (Ou et al., 2023)[14].

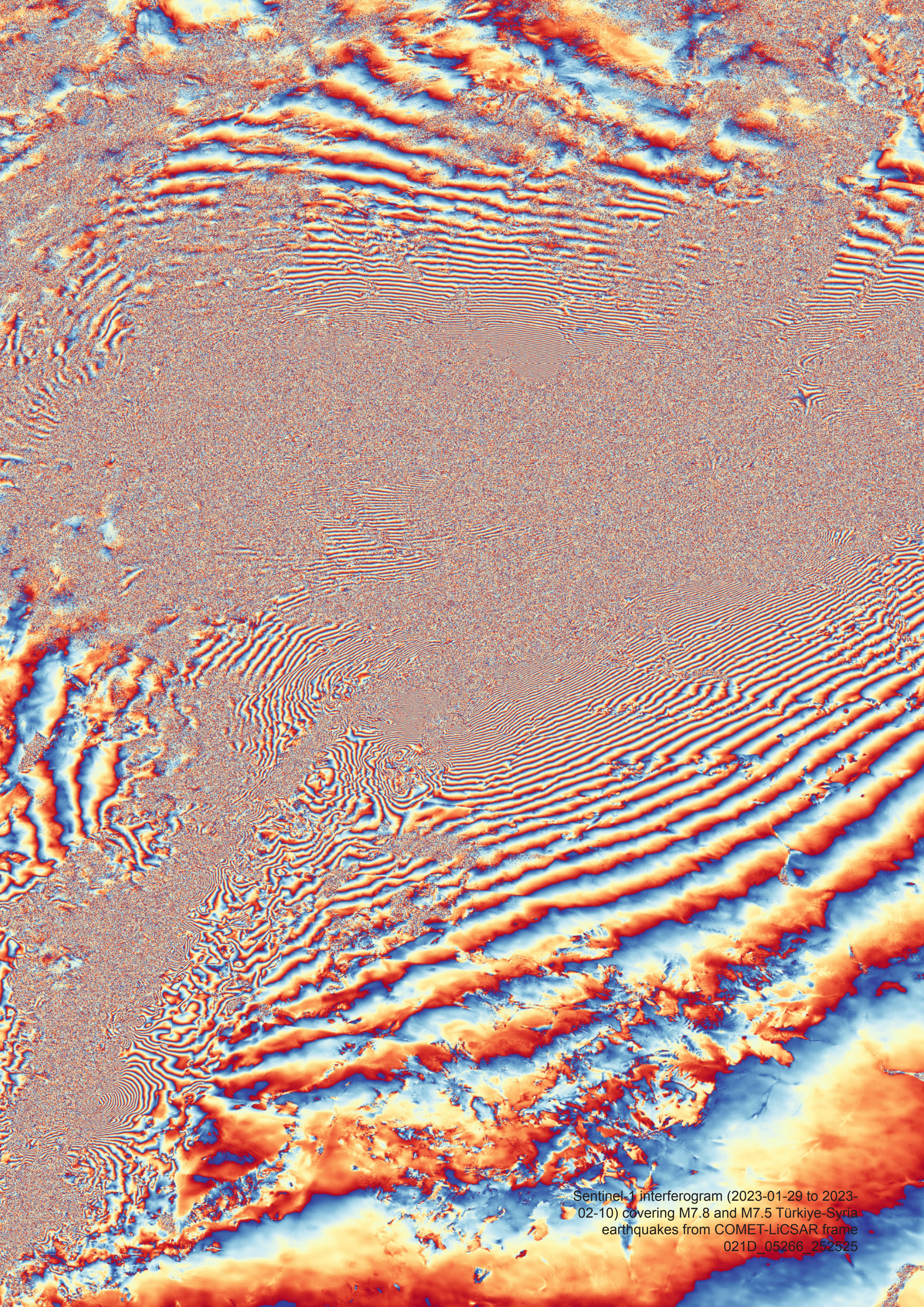
The Mw7.8 earthquake generated over 310 km of surface rupture with peak surface slip of 6.6 ± 1.2 m, whereas the Mw7.5 earthquake generated over 150 km of surface rupture with peak surface slip of 7.5 ± 1.7 m.

We have made the data available to the community for use in modelling, which are downloadable at https://catalogue.ceda.ac.uk/uuid/df93e92a3adc46b9a5c4bd3a547cd242.

3D displacements are important for understanding and modelling surface deforming events. Decomposing range and azimuth offsets from satellite data measured in different lines-of-sight into the standard Cartesian displacement fields allows easy integration of InSAR and optical pixel-tracking offsets with data from different sources for further modelling and applications.



Reference
14. Ou, Q.; Lazecky, M.; Watson, C.S.; Maghsoudi, Y.; Wright, T. (2023): 3D Displacements and Strain from the 2023 February Turkey Earthquakes, version 1. NERC EDS Centre for Environmental Data Analysis. doi:10.5285/df93e92a3adc46b9a5c4bd3a547cd242. https://dx.doi.org/10.5285/df93e92a3adc46b9a5c4bd3a547cd242



Sentinel-1 interferogram (2023-01-29 to 2023-02-10) covering M7.8 and M7.5 Türkiye-Syria earthquakes from COMET-LiCSAR frame 021D_05266_252525

SCIENCE UPDATE: EO DATA AND SERVICES

1. DEFORMATION FROM SATELLITE GEODESY

PROGRESS REPORT: IMPROVE COMET-LICSAR SENTINEL-1 SERVICE.

Objective Coordinators: Tim Wright (Leeds), Luke Bateson (BGS), Juliet Biggs (Bristol)
COMET Research Staff: Yasser Maghsoudi (Leeds), Milan Lazecky (Leeds)

During this reporting year, we have continued the long-term development of our COMET-LiCSAR Sentinel-1 InSAR processing facility at JASMIN, further improving quality of both products and the LiCSAR processing chain. As of March 2023, we have processed 274,000 Sentinel-1 acquisitions in 2031 LiCSAR frames, resulting in the generation of approximately 1,147,000 interferograms. This represents a significant increase from March 2022, during which we processed approximately 430,000 interferograms for this reporting year. The figure below illustrates the number of generated interferograms during time.

Our primary focus for processing zones has been on the Alpine-Himalayan Belt (AHB) and volcanic frames. Within the AHB region, we have successfully processed the frames located in Tibet, Turkey and Caucuses and Iran and they have been added to our monthly list of updates. As for the volcanic frames, we have given priority to those on the A1 list of volcanoes. We recently started the processing of the B1 list of volcanoes. Table 2 shows the number of LiCSAR products in AHB and A1 as of March 2023.

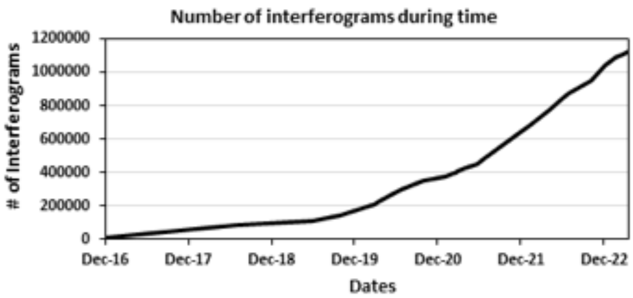


Figure 1: presents a performance comparison of the LiCSAR system between March 2022 and March 2023. The comparison is based on the number of frames, Sentinel-1 epochs, and interferograms

	frames	Sentinel-1 epochs	Interferograms
March 2022	1855	200,878	715,899
March 2023	2031	274,278	1,147,622
		73,400	430,723

Table 1: Comparison of the LiCSAR system in March 2022 with March 2023

AHB frames	Epochs	IFGs	Ave. Tmaxlen	Total epochs	Percentage processed
645	135,022	538,195	6.3 yr	171,487	79%

A1 frames	Epochs	IFGs	Ave. Tmaxlen	Total epochs	Percentage processed
276	48,752	201,410	5.7 yr	63,734	76%

Table 2: The number of various LiCSAR products in AHB as of March 2023

PROGRESS REPORT: IMPROVE ATMOSPHERIC CORRECTION SERVICES.

Objective Coordinators: Tim Wright (Leeds), Luke Bateson (BGS), Juliet Biggs (Bristol)
COMET Research Staff: Yasser Maghsoudi (Leeds), Milan Lazecky (Leeds)
Contributors: Fei Liu, COMET Research Student (Leeds)

The COMET-developed tropospheric correction service GACOS continues to supply the LiCSAR system. As of March 2023, we store those important interferometric phase corrections for 72% of our 274,278 processed temporal epochs and apply them routinely in our time series inversion procedures.

Lately, several scientific works focused the possibility of extracting accurate measurements from Sentinel-1 in the global reference frame. Thanks to very high precision in the satellite orbit determination products, this is possible once the radar signal delay through the atmosphere is also mapped accurately. We tested experimental S1_ETAD products that include tropospheric and ionospheric corrections, and realised we reach very similar correction terms using GACOS for troposphere, and IRI2016 model for ionosphere, as demonstrated in Figure 1.

In case of strong ionospheric fluctuations, the split-spectrum method to extract ionospheric phase screen directly from Sentinel-1 measurements reveals more significant differences with regards to the existing coarser ionospheric models. Yet, the models should satisfy accuracy needs in time series inversion and are to be further investigated to improve COMET atmospheric correction services.

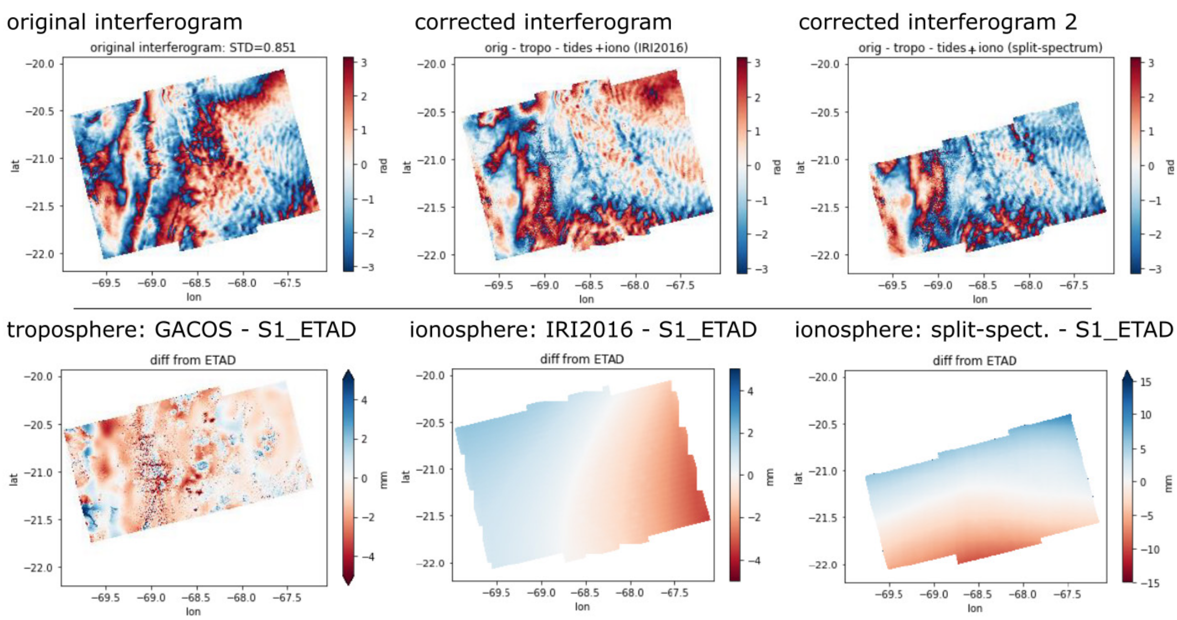


Figure 1: Selected Sentinel-1 LiCSAR interferogram over Chile capturing strong atmospheric signals that can be reduced using either experimental S1_ETAD data or COMET products (current GACOS products, planned ionospheric correction products based on IRI2016 model and/or ionospheric signal derived from Sentinel-1 data using split-spectrum).

SCIENCE UPDATE: EO DATA AND SERVICES

PROGRESS REPORT: EXTEND THE COMET-LICSAR SYSTEM TO OTHER SATELLITES.

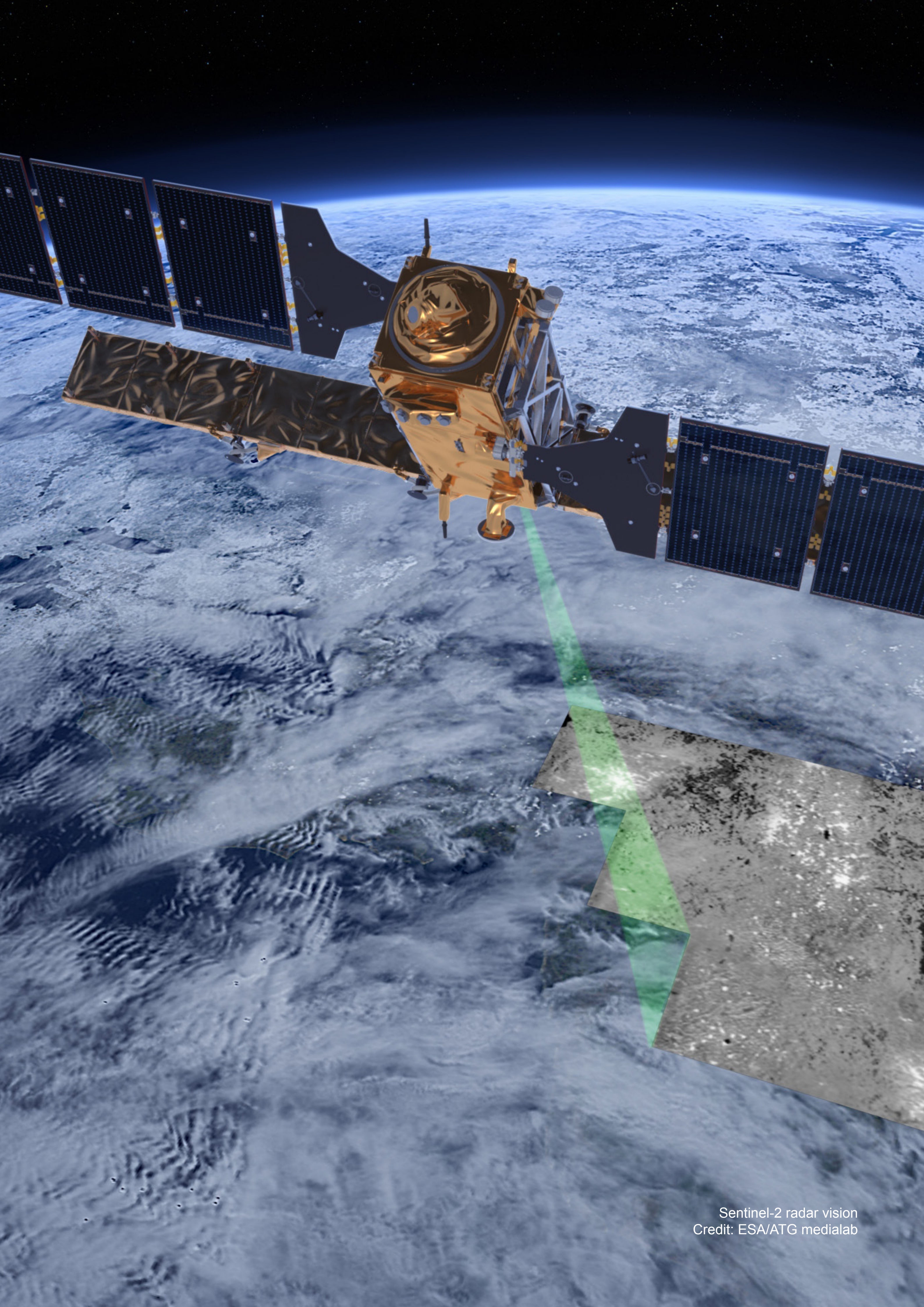
Objective Coordinators: Andy Hooper (Leeds), Alessandro Novellino (BGS), Juliet Biggs (Bristol)
COMET Research Staff: Yasser Maghsoudi (Leeds), Milan Lazecky (Leeds)
Contributors: Lin Shen, COMET Postdoctoral Researcher (Leeds), Mark Bemelmans, COMET Research Student (Bristol), Eva Zand, COMET Research Student (Leeds)

So far, we have started testing new satellite capability. Mark Bemelmans from Bristol has been testing the use of high-resolution CSK and TSX data for detecting shallow eruption precursors in this paper: https://doi.org/10.1029/2022JB025669[15] Eva Zand (University of Leeds) has processed ALOS-2 data in the last year and Lin Shen (University of Leeds) has processed various SAR datasets over Hekla (not yet published).

In the short-term, we are planning to add ERS and ENVISAT catalogues to the LiCSAR archive. Following this, over the next year we will be exploring the possibility to include CSK and TSX data for the supersites via CEOS. An option could be to use the NASA JPL-released software tool ISCE for the coregistration of the X-band data.

Long-term, we plan to systematically add NISAR interferograms on LiCSAR. In this case we are investigating the frames and orbit passes of the satellite and how we can use its acquisitions to cover Sentinel-1 area with poor coherence/coverage.

Reference
15. Bemelmans, M. J. W., Biggs, J., Poland, M., Wookey, J., Ebmeier, S. K., Diefenbach, A. K., & Syahbana, D. (2023). High-resolution InSAR reveals localized pre-eruptive deformation inside the crater of Agung volcano, Indonesia. *Journal of Geophysical Research: Solid Earth*, 128, e2022JB025669. https://doi.org/10.1029/2022JB025669



Sentinel-2 radar vision
Credit: ESA/ATG medialab

SCIENCE UPDATE: EO DATA AND SERVICES

2. TOPOGRAPHY, DEFORMATION, AND SURFACE CHANGE ANALYSIS FROM HIGH-RESOLUTION IMAGERY

PROGRESS REPORT: SEMI-AUTOMATION OF SATELLITE-DERIVED DISPLACEMENT MAPS OF LARGE GROUND DEFORMATION SIGNALS, AND OF TOPOGRAPHY AND TOPOGRAPHIC CHANGE

Objective Coordinators: Richard Walker (Oxford), Ekbal Hussain (BGS), John Elliott (Leeds)
COMET Research Staff: Tamarah King (Oxford), Scott Watson (Leeds), Milan Lazecky (Leeds)

The 2016 Kaikōura earthquake was used as a test case to evaluate the horizontal displacements retrieved using pre- and post-earthquake Sentinel-2 imagery processed using COSI-Corr software. We will continue to explore displacement retrieval using different sources of optical satellite imagery and processing methods. We subsequently used Sentinel-2 imagery to derive horizontal displacement maps for the 2023 Turkey–Syria earthquake, which were disseminated online and were complemented by displacements derived from Sentinel-1 data. We quantify topographic change using multi-temporal digital elevation models derived from SAR and optical data. For example, SAR backscatter data were used to quantify dome growth and extrusion rate during the 2021 eruption at La Soufrière, St. Vincent.

PROGRESS REPORT: UTILIZE DIGITAL TOPOGRAPHIC DATA AT GLOBAL, REGIONAL, AND LOCAL SCALES TO AID THE FIELDWORK ACTIVITIES OF COMET MEMBERS AND THE MAPPING OF HAZARDS AT REGIONAL SCALE

Objective Coordinators: Richard Walker (Oxford), Luke Bateson (BGS), Laura Gregory (Leeds)
COMET Research Staff: Tamarah King (Oxford)

A new user-friendly method for accessing and analysing NASA ICESat-2 satellite lidar profiles has been developed to enable use of these data for geomorphic and geologic purposes. These provide much higher-resolution topographic data than freely available DEMs, enabling (for instance) remote measurement and mapping of earthquake scarps which are otherwise only measurable through expensive field investigations or commercial satellite imagery. This method is useful across COMET objectives (e.g. active tectonics, earthquakes, volcanoes, remote-sensing, fieldwork).
We have also continued to collect high-resolution drone imagery and DEMs across field sites in Central Asia, and are in the process of stock-taking and uploading all drone and commercial satellite-derived DEMs to Open Topography to make these available to the wider research community.

PROGRESS REPORT: DERIVATION AND ANALYSIS OF HIGH-RESOLUTION TOPOGRAPHIC DATASETS FOR SEISMIC HAZARD IN AND AROUND CITIES.

Objective Coordinators: John Elliott (Leeds), Ekbal Hussain (BGS), Richard Walker (Oxford)
COMET Research Staff: Tamarah King (Oxford), Scott Watson (Leeds), Milan Lazecky (Leeds)

We have continued to develop workflows using commercial (Agisoft Metashape, ArcGIS Pro, ERDAS Imagine) and opensource (Ames Stereo Pipeline) software to generate digital elevation models from high resolution satellite imagery such as Pleiades, Pleiades Neo, and WorldView-2. ICESat-2 altimetry data are used for independent validation in the absence of ground control points. We use workflows developed in the LAStools point-cloud processing software to derive the ground surface elevation and create digital terrain models (DTMs), which are used in hazard models and when deriving additional datasets such as building heights.

A detailed study of the faulting responsible for the 1948 Asgabat earthquake in Turkmenistan is currently in review. We combine contemporary mapping and reports, waveform modelling and epicentral relocations, with analysis of high resolution DEMs extracted from stereo Pleiades and Worldview 3 optical satellite data to determine the source of this enigmatic earthquake, which is one of the most deadly earthquakes of the 20th century. Using heritage satellite imagery from the 1960s we find evidence of surface faulting and displacement of archaeological remains within present-day Asgabat, on faults that are not recorded to have ruptured in 1948, pointing to continued hazard.

We continue to develop paleoseismic data and fault maps from high-resolution DEMs close to large cities, including Almaty (Kazakhstan), Dushanbe (Tajikistan), Shemakhi (Azerbaijan), Xian (China).

SCIENCE UPDATE: EO DATA AND SERVICES

3. RETRIEVALS OF VOLCANIC EMISSIONS FROM SATELLITE SPECTROMETERS

PROGRESS REPORT: ADAPT FAST LINEAR RETRIEVAL OF ASH AND SO_2 TO PROCESS DATA FROM IASI-NG AND IRS

Objective Coordinators: Don Grainger (Oxford), Tamsin Mather (Oxford), Samantha Engwell (BGS)
COMET Research Staff: Isabelle Taylor (Oxford)

The IASI-NG and IRS instruments are due to launch in 2024 and data will not be available for some time after. However, one of our project students, Ben Pery, has adapted our linear SO_2 retrieval for the Cross-track Infrared Sounder (CrIS).

This retrieval shows promise when applied to data from the La Soufrière, St Vincent, eruption in April 2021. Using both IASI and CrIS doubles our daily global coverage: a big improvement for hazard assessment.

PROGRESS REPORT: EXTEND EXISTING SO_2 AND ASH TIME SERIES AND INVESTIGATE RETRIEVALS FOR OTHER VOLCANIC SPECIES

Objective Coordinators: Don Grainger (Oxford), Tamsin Mather (Oxford), Samantha Engwell (BGS)
COMET Research Staff: Isabelle Taylor (Oxford)

We've looked at a number of eruptions this year with the Infrared Atmospheric Sounding Interferometer including the 2019 Raikoke, 2021 La Soufrière and 2022 Hunga Tonga-Hunga Ha'apai eruptions, as well as continuing to produce our global dataset on volcanic plumes (2007- present). We've also made some small adaptations to our iterative SO_2 retrieval code, so that it can be applied using standard atmospheric profiles, enabling us to get estimates of SO_2 column amounts and height soon after an eruption occurs.

We've also begun to explore using the MORSE retrieval developed by Anu Dudhia to retrieve information about other volcanic species including water vapour. Further work is needed.

PROGRESS REPORT: AUTOMATION OF SO_2 FLUX TIME SERIES RETRIEVALS

Objective Coordinators: Mike Burton (Manchester), Samantha Engwell (BGS), Marie Edmonds (Cambridge)

We are following two approaches for the automation of SO_2 flux retrievals from TROPOMI data. The first approach is to apply our standard PlumeTraj back-trajectory toolkit to regridded TROPOMI data, and this is now being completed for all of 2020. Using a new version of the SO_2 analysis called COBRA developed by Nicolas Theys in BIRA, Belgium, we are able to detect daily gas emissions from 20-25 volcanoes. This will be published for 2020 then extended to the entire available time series. We will propose a PhD to look at this dataset in comparison with the long-term deformation datasets for the measured volcanoes. The second approach is to use the MetOffice NAME back-trajectory model, which would then open the possibility of automating real-time analysis globally on JASMINE. This work is ongoing but we expect to see a first version working by end of 2023.

4. GEOINFORMATICS AND MACHINE LEARNING

PROGRESS REPORT: IMPROVE THE SHARING DATA AND TIME SERIES THROUGH THE DEVELOPMENT OF AN INTEGRATED COMET DATA PORTAL

Objective Coordinators: Susanna Ebmeier (Leeds), Luke Bateson (BGS), John Elliott (Leeds)
COMET Research Staff: Scott Watson (Leeds), Yasser Maghsoudi (Leeds), Milan Lazecky (Leeds), Isabelle Taylor (Oxford), Matt Gaddes (Leeds)

Several online data portals simplify user access to the Datasets and Services provided by COMET. The COMET LiCSAR Portal contains over 1,000,000 interferograms and is accessed over 1,000 times each month. The Earthquake InSAR Data Provider (EIDP) generates InSAR products following earthquakes and has a catalogue of over 500 events. The Volcanic and Magmatic Deformation Portal contains records for 1,480 volcanoes and allows users to analyse Sentinel-1 InSAR derived displacement timeseries. Finally, the COMET Subsidence Portal is under active development and uses InSAR data to quantify subsiding basins in Iran. We explored the dissemination of ground deformation measurements from Interferometric Synthetic Aperture Radar (InSAR) data through COMET's online portal and Twitter, which was summarised in a paper submitted to the EGU journal Geoscience Communication. New portals showing volcanic gas retrievals such as sulphur dioxide are also under development using the TROPOspheric Monitoring Instrument (TROPOMI) and Infrared Atmospheric Sounding Interferometer (IASI).

The IASI Near Real-Time processing is now back up and running again! The SO_2 results are currently displayed on the Earth Observation Data Group's webpage. And we hope they will soon be integrated within the COMET data portal.

PROGRESS REPORT: DEVELOP MACHINE LEARNING APPROACHES AND TOOLS THAT CAN BE APPLIED TO COMET SATELLITE DATA SETS

Objective Coordinators: Andy Hooper (Leeds), Ekbal Hussain (BGS), Juliet Biggs (Bristol)
COMET Research Staff: Matt Gaddes (Leeds)

This work was funded primarily by the COMET co-funding project ERC Consolidator Grant DEEPVOLC (Grant ID: 866085, PI: A. Hooper) and an ESA Living Planet Fellowship awarded to COMET Research Staff member Matthew Gaddes.

The LiCSAlert volcano monitoring algorithm has been improved to function at more challenging volcanoes in preparation for being applied globally. This included developing a method to maximise the variance of low-rate but persistent deformation, and the use of temporal independent component analysis (tICA) to separate deformation from topographically correlated atmospheric phase screens, particularly at stratovolcanoes (paper in review).

We have developed a database (VolcNet) that provides labelled Sentinel-1 InSAR time series, which can be used to train deep learning models such as those that can be used to detect volcanic deformation. The number of volcanoes contained within the database is currently 20, and we have developed a system to allow easy ingestion of time series that will be routinely created for volcanoes on the JASMIN service in the future. The enhanced database has been used to train a volcanic deformation detection convolutional neural network, and a modest increase in performance was achieved, which was attributed to the increase in diversity of deformation within the VolcNet database.

We have also developed ML methods to extract meaningful information and to aid clustering of deformation time series by fully exploiting variability in time. This work has resulted in a publication https://doi.org/10.1016/j.jag.2023.103276[16] with another paper about to be submitted.

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RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

RESEARCH HIGHLIGHT: WHAT HAS THE LOWER CRUST EVER DONE FOR US?

Alex Copley, COMET Scientist, University of Cambridge

Debates about the strength of the lower crust may seem somewhat academic: does it really matter if it is strong or weak, rigid or deforming, seismically active or ductile? It turns out that it does matter, because for something that we rarely see the lower crust plays a remarkably important role in our lives. Its material properties control the locations and characteristics of earthquakes, and also the sizes, shapes, and evolution through time of the mountain belts and basins that host many important resources. So if the lower crust matters, but we rarely see it, how do we go about studying it?

Fully understanding something requires knowing its origins and evolution. Much of the Earth's volume of continental lower crust is thought to be old, from the first half of the Earth's history. The only way to study the evolution of such rocks is by looking at the preserved geological record. Sophie Miocevich has recently done just that, and interrogated the oldest rocks in the UK (from NW Scotland) using a combination of field observations, geochemistry, and thermodynamic and geophysical modelling techniques. Sophie was able to show that the exotic tectonic configurations generally assumed to occur on early Earth are not physically viable, and that the early history of the continents seems to have been governed by the same tectonic processes that dominate at the present day (Miocevich et al 2022)[17]. This finding is supported by other recent COMET work that demonstrates that the evolution of the thermal structure in the Earth's oldest preserved deformation belts (Copley & Weller 2022; Figure 1)[18], and the large-scale evolution of the geological past's most significant mountain belts (Weller et al 2021; Figure 2)[19], both imply that mountain range behaviour is dominated by the under-thrusting of rigid crust on the margins of the belt, as we see today. This surprising finding that significant volumes of the continental lower crust were made strong early in the history of the Earth, and remained strong, is due to a combination of: (1) melting removing volatiles and leaving behind a strong residue (Jackson et al 2021)[20], coupled to (2) the newly-appreciated extremely slow transport and reaction of the water which could rehydrate and weaken this strong crust (Whyte et al 2021)[21].

The modern-day implications of crustal strength are diverse. Aisling O'Kane recently studied the tectonics of the NW Himalayas, by combining seismological studies of earthquakes, geomorphological mapping, and structural geology. She found that the strength of the Indian crust results in it being thrust far beneath the Himalaya on a low-angle active fault plane, which is cutting through a previously-formed crustal-scale fold (O'Kane et al 2022)[22]. Furthermore, Aisling's analysis of the ground-shaking that could be produced by future earthquakes in the region indicates that this fault geometry plays a key control on the distribution and severity of destructive seismic waves. The very nature of a mountain belt produced by the thrusting is governed by lower crustal strength, as shown by Lizzie Knight who used seismology, gravity anomalies, and thermal modelling to establish the role that spatial and temporal variations in crustal strength play in the early stages of mountain belt formation, of which New Guinea is an excellent example (Knight et al 2022, Figure 3)[23]. Indeed, dynamic modelling by Camilla Penney implies that the gradient of a mountain range-front may be a proxy for lower crustal strength (Penney & Copley 2021; Figure 4).[24]

A wide range of evidence has therefore allowed us to gain some new insights into the timing, causes, and consequences of the evolution of lower crustal strength. However, this story is not yet complete. Questions still remain regarding the initial formation mechanism for the continental crust, the amount of melting required to make it strong, the role of earthquakes in the rheological evolution of the crust, and the interplay between the brittle and ductile deformation within the crust. COMET has busy times ahead.

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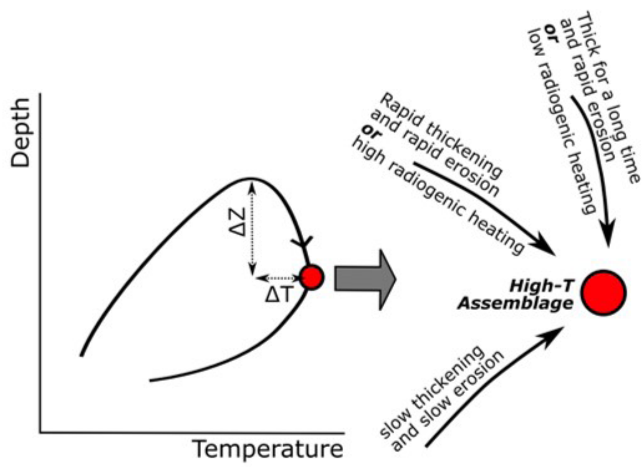

Figure 1: The factors controlling trajectory through temperature and depth of a suite of rocks experiencing a mountain-building event.

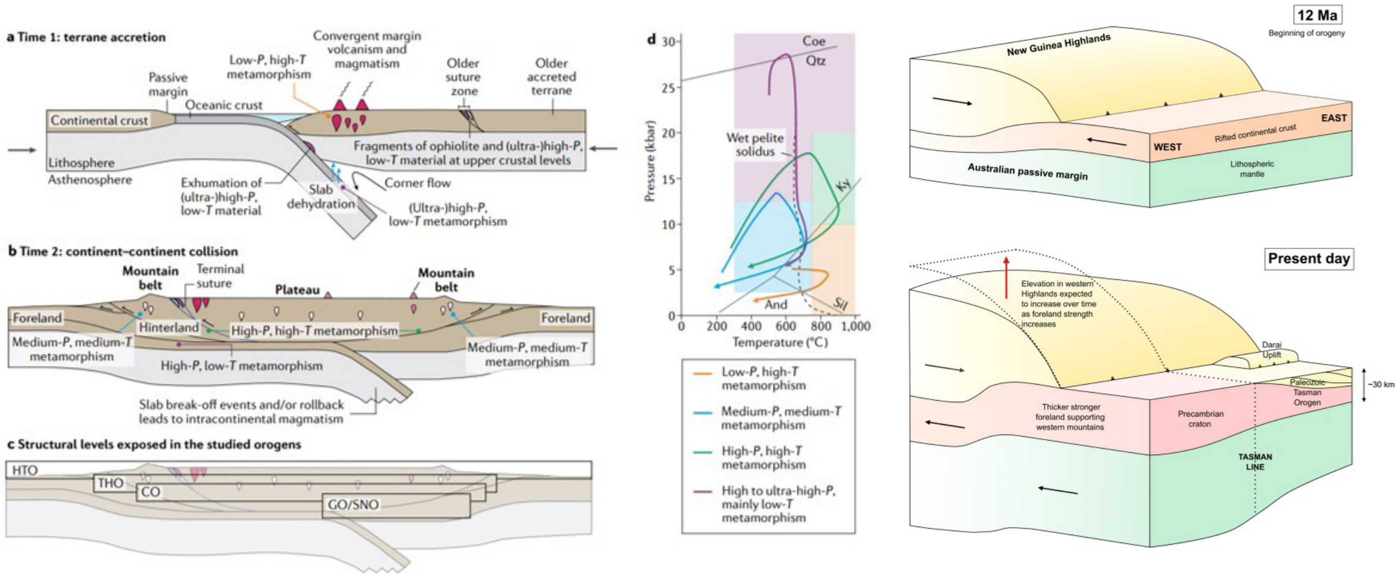

Figure 2: The locations and characteristics of different metamorphic environments within mountain belts.

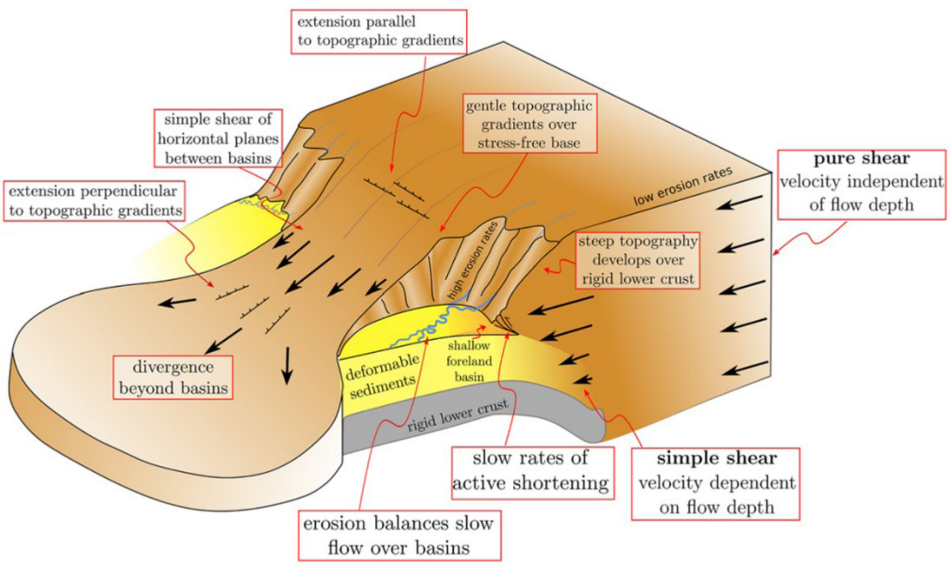

Figure 3: The effects of lateral variations in lower crustal rheology on the dynamics of the southeastern Tibetan Plateau.

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

RESEARCH HIGHLIGHT: THE FATAL ERUPTION OF VOLCAN DE FUEGO, GUATEMALA: A FIVE YEAR RETROSPECTIVE.

Matthew Watson, COMET Scientist, University of Bristol

Early in the afternoon of June 3rd 2018, pyroclastic flows started descending the valleys of the Easter side of Volcan de Fuego, Guatemala. Within a few hours the town of San Miguel Los Lotes has been inundated and several hundred people, at least, has lost their lives. Many more lost their homes and their livelihoods.

Several members of COMET responded quickly to the eruption. The International Charter was invoked by civil protection in Guatemala within twenty-four hours of the disaster and scientists scrambled to provide information to national agencies through the charter portal. We sent radar imagery (backscatter and InSAR), SO_2 and ash maps and high-resolution optical data used in search, rescue and recovery (e.g. Figure 1). In fact, nine of the first ten maps and images sent to Guatemala through the charter were from Bristol, Leeds, and Oxford.

The charter is designed to last for only a few days before disaster management moves from search and rescue to longer term recovery. A team from Bristol, armed with a range of UAVs, were amongst the first to arrive from overseas. We mapped the pyroclastic flow deposits on the Eastern flanks, smaller deposits on the Western flanks and the summit area (although the latter was hampered by the rainy season).

Several studies from COMET have illuminated the events of the disaster using a range of observations. Firstly, Naismith et al., 2019[25] postulated that the 3rd of June eruption might herald a change in eruptive frequency which has subsequently been borne out by observation. They used a range of observations, including the MIROVA dataset (Coppola et al., 2016)[26] from MODIS to relate precursory effusive activity to paroxysmal eruptions. Pardini et al., 2019[27], quickly followed, with an analysis of the 2018 eruption using IASI data. Here the authors quantified the mass eruption rate, the total mass of tephra and implicated injection of a fresh batch of magma as a potential triggering mechanism for a larger eruption.

Albino et al., 2020[28] published some of the first estimates of pyroclastic flow volumes, using Tandem-X data. They found that once changes associated with vegetation loss were accounted for in DEMs of difference, deposition and erosion of material roughly balanced at 15-17 million metres cubed, the deposits had a maximum thickness of nearly seventy metres, and the transition zone was at a slope angle between 20 and 29 degrees.

Two recent papers from other groups have discussed flow generation mechanisms at Fuego. It has long been known that the pyroclastic flows don't really fit in any of the conventional mechanisms. Columns rarely collapse and the magma isn't at a high enough viscosity to form a conventional dome. At Fuego, the mechanism has been suggested to be something of a hybrid, with material for the flows being sourced from lava flows, the ephemeral cone and from carapace build up during the pre-paroxysmal phase of the eruptive cycle. The perched, transient deposits (Risica et al., 2023)[29] constituted the source material for the eruption, with a range of temperatures suggesting residence times on order years, which were added to by a partial flank collapse (Charbonnier et al., 2019)[30]. Charbonnier et al., 2023[30] built on that work and detailed three separate failure events and identified multiple pulsed units within the flow deposits. They estimated that it took only ten minutes to backfill the lower section of the Las Lajas valley during the largest flows which caused the subsequent overspill.

Finally, another work from COMET, this time from a PhD student, Ben Ireland. Ben's paper, his MSc thesis, currently in review at JVGR, looks at satellite and UAV data of the Seca / Santa Teresa valley (barranca) on the Western flanks of Fuego [31].

This work was inspired by an ALOS image acquired almost immediately after the June 3rd eruption - (Figure 2(d)). The pyroclastic flow, delimited by the dark red colour, took a sharp right-hand turn in the Seca valley. Ben determined that a sequence of events shaped the direction of the 3rd of June flows. Firstly, a previous eruption on May 2017 produced a series of PDCs large enough to fill the upper sections of valley, 'resetting' the topography. This was followed by an unusually heavy rainy season, probably coupled with a la niña event, which downcut into the fresh deposit and carved a new channel. This then pushed the June 2018 PDC round the tight right-hand bend (at the location marked as "Collapses" in figure 3). The runout distance was probably shortened by up to several kilometres and may have avoided several population centres.

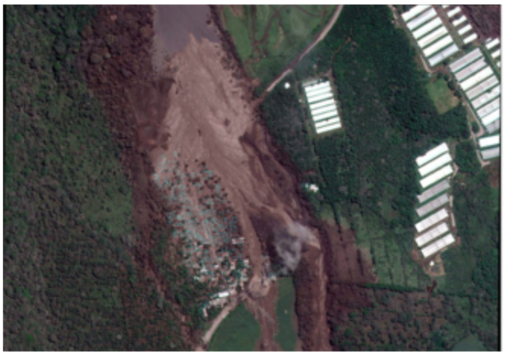

Figure 1: Image provided to civil protection in Guatemala delimiting the location of buried buildings in San Miguel Los Lotes, the town destroyed during the June 2018 eruption of Volcan de Fuego.

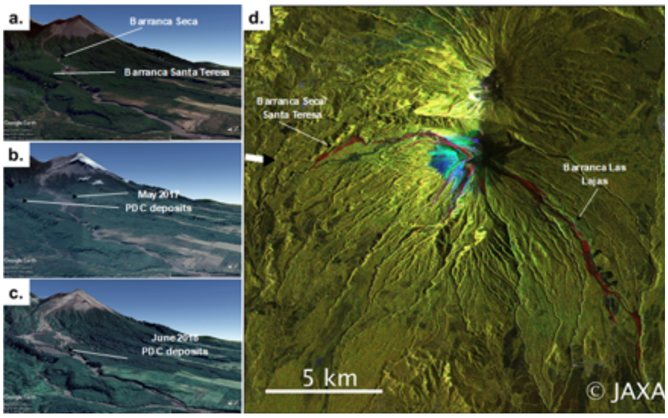

Figure 2: Google Earth perspective images of the May 2017 and June 2018 PDC deposits (a-c) and a post-eruption ALOS-2 radar image of the 2018 flow paths (d). This image immediately stood out as unusual as the PDC that travelled down the Seca valley took a rather tortuous (and unusual) path that deflected it away from population centres. [Ireland et al., in review[31]].

Figure 3: Photograph taken from a UAV looking west down the Seca valley at the point at which the PDC diverged from previous path and headed right. [Ireland et al., in review[31]].

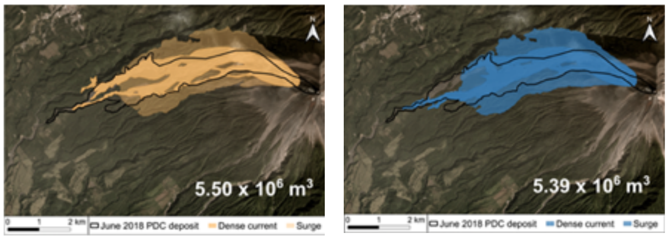

Figure 4: VolcFlow outputs for pre-2017 (left) and post-2018 (right) DEMs showing a change in direction and shortening of the flow runout. [Ireland et al., in review[31]]

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RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

RESEARCH HIGHLIGHT: A MONTH IN AZERBAIJAN: PROMISING NEW START TO A LONG PALEOSEISMIC CAMPAIGN

Ian Pierce, COMET Postdoctoral Researcher, University of Oxford
Richard Walker, COMET Scientist, University of Oxford

In April and May of 2022, researchers from the University of Oxford traveled to Azerbaijan to work with the Republican Seismic Survey Center of Azerbaijan to conduct paleoseismic studies of the major faults that control the fascinating tectonic region covering the western Caspian and Greater Caucasus.

Our satellite-based fault mapping reveals a series of very active strike-slip faults in the northeastern part of the Kura Basin (the foreland of the Caucasus), to the south of Baku. Yet basically nothing is known of these faults, and modern seismicity is relatively quiet along them. We excavated two trenches where a prominent strike-slip fault cuts through young marine sediments and wave-cut platforms. The first trench revealed a sequence of fluvial sands and aeolian silts stacked against highly sheared clays and sands. Within the young sediments was a nearly vertical flower structure.

Figure 1: Oblique aerial view of the West Kura trench site

Figure 2: trench revealing active strike-slip faulting.

Based on different levels of upward terminating fault strands, capped zones of sheared sediments, and buried fissures, we documented 6 paleo-earthquakes. It will take some time to analyze the ages of the sediments to determine the precise earthquake timing, but we expect that these are all Holocene aged ruptures (<10k yr).

The next fault we focused our work on was the Greater Caucasus Thrusts in the Kura basin. From GPS geodetic observations, we know that the Kura fault system accommodates nearly a cm/yr of compression. It has produced many historical earthquakes, including devastating events in 1667 and 1902 that destroyed the city of Shemakhi. This fault has built an impressive set of folds and water gaps as shown in the below satellite image. Yet surprisingly little is known of these faults' earthquake potential.

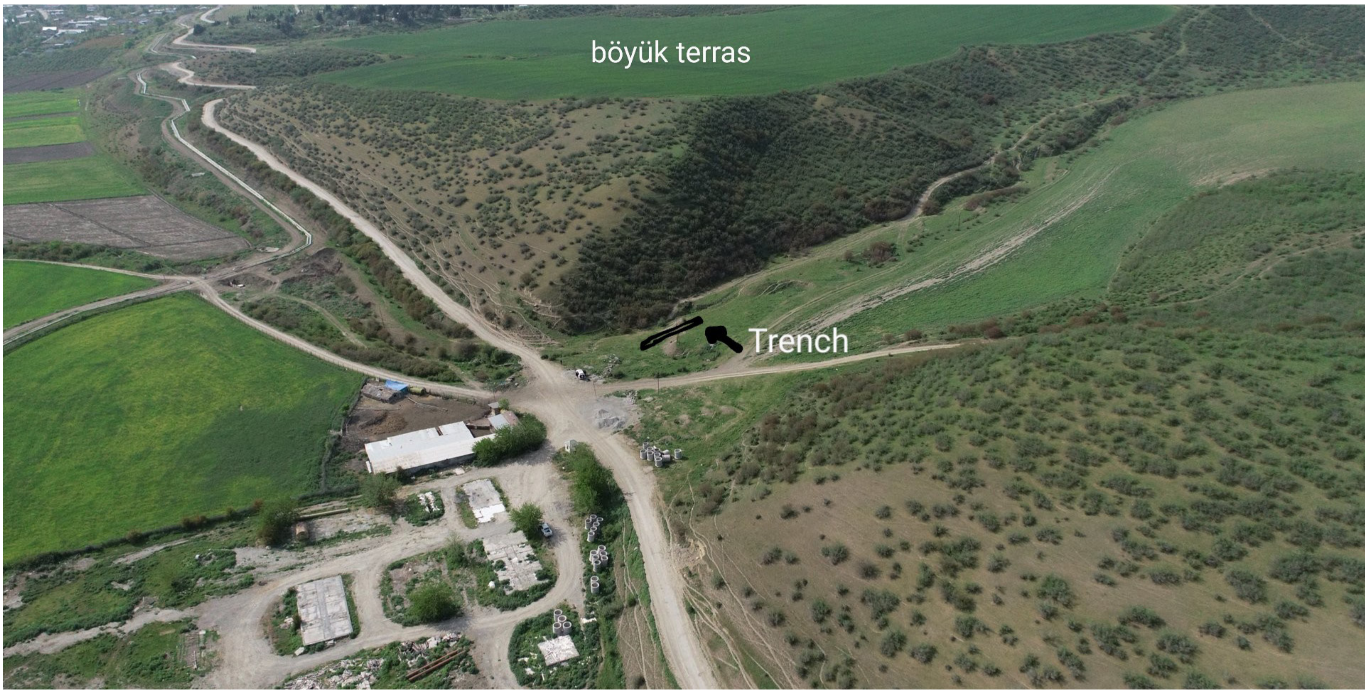

Figure 3: Trench location across a 1.5 m high scarp in a drainage that cuts through a folded terrace

Figure 4: View of the eastern trench wall

Our trench revealed a low angle fault that has displaced sedimentary layers approximately 7 m. Initial radiocarbon results shows that this rupture occurred in the late-18th to early-19th century, coinciding with the 1902 Shemakhi earthquake. This is the first trench to reveal the source fault of this pre-instrumental earthquake.

RESEARCH HIGHLIGHTS: TECTONICS AND VOLCANISM

RESEARCH HIGHLIGHT: CHARACTERISING GAS EMISSIONS FROM THE PERSISTENTLY ACTIVE BAGANA VOLCANO, PAPUA NEW GUINEA

Brendan McCormick Kilbride, COMET Associate, University of Manchester

Around our world, dozens of volcanoes are persistently releasing gases into the atmosphere. For most of these volcanoes, we lack a complete picture of how the chemical composition and mass flux of their gas emissions vary through time. An understanding of how gas emissions evolve as a function of subsurface processes like magma recharge or ascent is critical for volcano monitoring and eruption forecasting. Moreover, accurately quantifying global outgassing is necessary to evaluate volcano climate forcing or regional air pollution.

Bagana volcano, Papua New Guinea (PNG), has been among the most active volcanoes on Earth in recent decades. Previous COMET-supported research suggests the edifice has grown rapidly, in mere centuries (Wadge et al., 2018)[32], and that SO_2 emissions vary widely, though never cease, between episodes of lava extrusion and quiescence (McCormick Kilbride et al., 2019)[33]. In 2019, an international team visited Bagana to make the first measurements of CO_2 flux from the volcano. We combined airborne measurements of the summit gas plume, with gas sensors aboard unoccupied aerial vehicles (UAVs), and simultaneous ground- and satellite-based remote measurements of SO_2 flux. The fieldwork was conducted with valuable support from the Rabaul Volcanological Observatory (RVO), the Bougainville Disaster Office, and residents of the nearby Torokina and Wakovi communities.

We found that Bagana's gas emissions are relatively carbon-rich for oceanic arc volcanoes but that the overall CO_2 and SO_2 fluxes at the time of our measurements were low (McCormick Kilbride et al., 2023)[34], consistent with present low levels of unrest.

Figure 1: Bagana volcano, located on Bougainville Island, Papua New Guinea.

Our new multi-year observations of SO_2 emissions (via the TROPOMI satellite instrument) and thermal flux from Bagana (via the MODIS satellite instrument) support our earlier findings that the volcano alternates between multi-month extrusive episodes and longer non-eruptive periods. Further gas sensing flights, most feasibly using UAVs, are required to better understand how CO_2 emissions or gas composition may vary with activity. Our recent work in PNG using drones to measure volcanic gas emissions and our provision of equipment and training to our partners at RVO may provide the basis for future regular drone-based monitoring of remote and frequently erupting volcanoes such as Bagana.

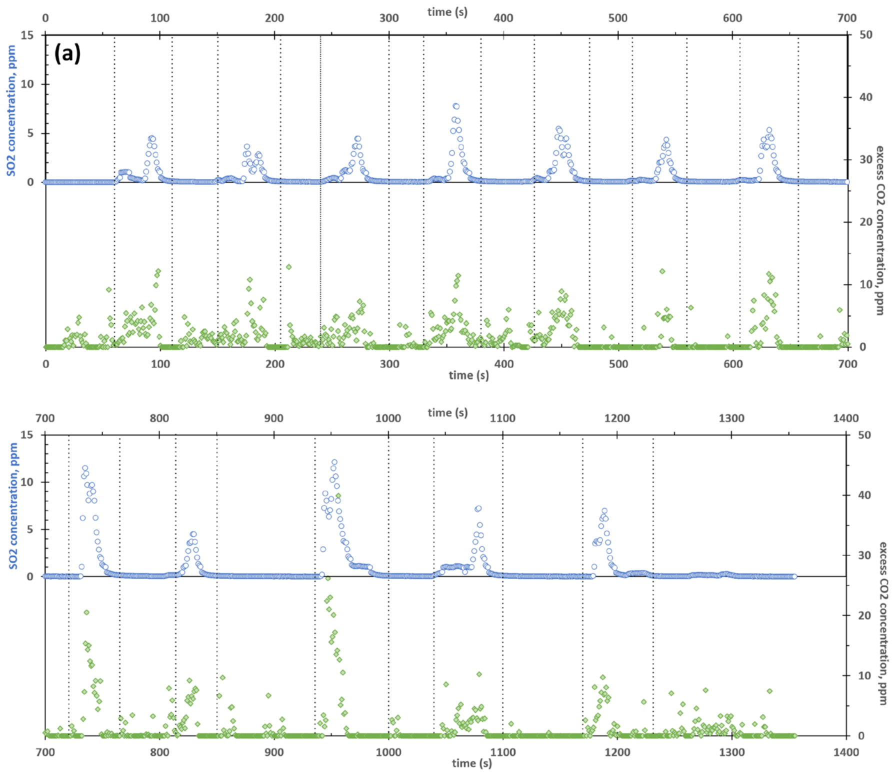

Figure 2: Time series of CO_2 (green) and SO_2 (blue) concentration, measured by airborne gas sensors onboard the UAV. Peaks indicate aircraft transits through the volcanic plume. For each peak, or entire flights, we use linear regressions between these two time series datasets to calculate CO_2/SO_2 ratios that characterise the volcanic gas composition.

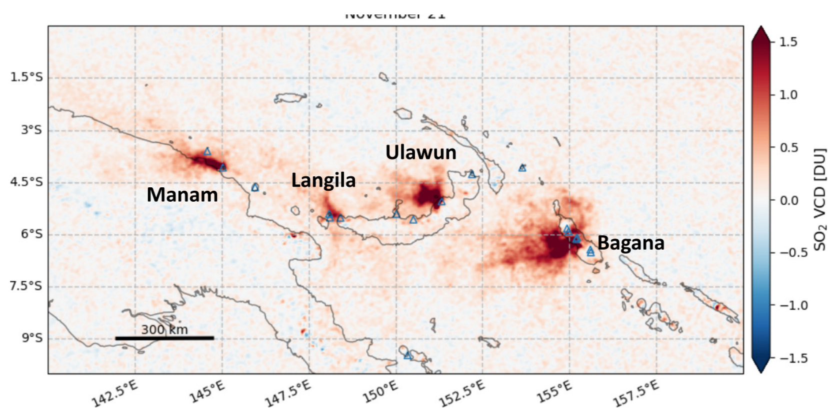

Figure 3: Satellite (TROPOMI) observations of atmospheric SO_2 concentration over Papua New Guinea, showing the relative strength of emissions from different volcanic sources. The data shown is from November 2021, when four volcanoes were actively outgassing.

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SCIENCE UPDATES: TECTONICS AND VOLCANISM

1. TECTONICS AND SEISMIC HAZARD

PROGRESS REPORT: DEVELOP AND DEPLOY A GEODETICALLY-BASED EARTHQUAKE HAZARD MODEL IN PARTNERSHIP WITH THE GLOBAL EARTHQUAKE MODEL

Objective Coordinators: Tim Wright (Leeds), Ekbal Hussain (BGS), Richard Walker (Oxford)
COMET Research Staff: Tamarah King (Oxford), Yasser Maghsoudi (Leeds), Milan Lazecky (Leeds), Qi Ou (Leeds)
Contributors: John Elliott (Leeds)

Mapping the present-day velocity over large mountain belts, such as the Tianshan, is important for understanding the kinematics and the dynamics driving continental deformation. For Tianshan, we have processed 7 years of Sentinel-1 data acquired between 2014 and 2022 to generate over 90,000 interferograms at 500 m resolution for 89 LiCS frames. From time series analysis on dense networks of interferograms with temporal baselines between 6 days to 1 year, we have generated interseismic line-of-sight velocities over an area of 2,280,000 km^2. In addition to the focused InSAR work, we have compiled GNSS data over Central Asia, and built a reliable fault data base for the region.

The generation of these key datasets has allowed us, in collaboration with Richard Styron at the Global Earthquake Model, to create a new 'block' or tectonic microplate model for Central Asia that is based on the fault database and calculates tectonic deformation rates for all faults in the fault database (Figure 1). The block model incorporates extremely high-resolution, regional-scale InSAR-based velocity fields produced by COMET's LiCSAR program, geologic slip rate measurements taken by COMET scientists and by others, and our compilation of GNSS velocity data. The broad-scale, high-resolution nature of the block model, as well as the integration of a huge quantity of high-quality data of many diverse types into the mathematical solution, is unprecedented among published studies in Central Asia and anywhere else on the globe. Furthermore, the block model links seamlessly with similar block models in development by GEM for China, Northeastern Asia, and Anatolia, yielding an integrated, high-resolution, fault-based deformation model for all of Asia.

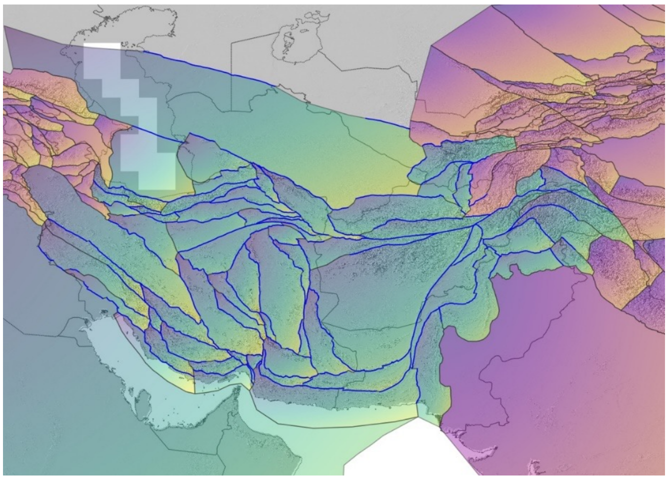

Figure 1: Block and fault model for Central Asia. Blocks in the Central Asia model are shown in purple to green, while adjacent models are shown in orange to pink. Central Asia faults are blue. This new product is being used to produce an updated probabilistic seismic hazard model for the region.

These data products are being incorporated into a Probabilistic Seismic Hazard Analysis (PSHA) model for Central Asia, which is progressing well toward completion in 2023, although some technical challenges remain to be overcome. The hazard model, which is a traditional classical, time-independent model, will serve as the basis for future development of an innovative time-dependent model that will incorporate more advanced earthquake physics and statistics, as well as a wider range of datasets produced by COMET for the region, such as palaeoseismic catalogs. Furthermore, the techniques developed here for incorporating InSAR-based velocity fields into block and fault modelling are being applied in other regions where COMET has produced the data.

PROGRESS REPORT: PRODUCE AND DELIVER MAPS OF ACTIVE FAULTS, INCORPORATING NEW RESULTS REGARDING THEIR RATES OF ACTIVITY AND PAST EARTHQUAKES

Objective Coordinators: Richard Walker (Oxford), Ilaria Mosca (BGS), Alex Copley (Cambridge)
COMET Research Staff: Tamarah King (Oxford)

Field and remote-sensing studies of individual and networks of faults continues in the Caspian, Pamir, Tien-Shan, and wider Alpine-Himalaya area. During the 2022 summer field season, six paleoseismic trenches were excavated across faults in the Kyrgyz Tien Shan, and two trenches were excavated in Azerbaijan to investigate earthquake histories and rates of activity in these regions. These studies contribute to broader remote-sensing studies of fault networks across the Caspian, Pamir, and Tien Shan. Through our collaborative project with GEM (The Global Earthquake Model) we are working to incorporate these studies into tectonic block-models to better understand rates of activity and seismic hazard across the region.

PROGRESS REPORT: ASSESS TEMPORAL VARIATIONS IN STRAIN ACROSS DISTRIBUTED FAULT NETWORKS

Objective Coordinators: Laura Gregory (Leeds), Brian Baptie (BGS), Richard Walker (Oxford)

We have made comparisons of long-term (10-100 ka) fault slip and decadal strain accumulation across Iran as measured by GNSS, with the two time periods of measurement showing close agreement. A paper is close to submission. In the Tien Shan we have continued to build paleoseismic data to assess time-dependent clustered earthquake behaviour. We also completed a detailed paleoseismic study of the 1911 Chon Kemin earthquake ruptures, to assess whether the complex multi-fault source has ruptured repeatedly in successive earthquake cycles. We are currently processing topographic survey data and age data.

PROGRESS REPORT: BUILD DYNAMIC MODELS THAT CAN EXPLAIN LITHOSPHERE DEFORMATION ACROSS TIMESCALES

Objective Coordinators: Alex Copley (Cambridge), Brian Baptie (BGS), Tim Craig (Leeds)

COMET has been continuing to work in linking observations and models across a wide range of timescales. A ‘science highlight’ elsewhere in this report (p.34-35) describes the linking of observations and models of earthquake cycle deformation with the long-term (millions of years) evolution of deformation belts (e.g. Knight et al 2022; O’Kane et al 2022; Copley & Weller 2022)[35, 36, 37]. Craig et al 2023[38] have modelled postglacial relaxation on timescales of tens of thousands of years to provide insights into the controls on seismicity in slowly-deforming continental interiors. On even shorter timescales, Wimpenny et al 2023[39] used observations and dynamic models to investigate the re-loading and re-rupture of active faults on timescales of years. When combined, these and previous studies are providing an increasingly clear view of the interplay between the timescales of tectonic deformation. Work will continue on this topic, with the eventual aim of a fully dynamic understanding of the processes and material properties that govern this interplay.

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SCIENCE UPDATES: TECTONICS AND VOLCANISM

2. MAGMATISM AND VOLCANIC HAZARD

PROGRESS REPORT: ANALYSE LONG-TERM (DECADAL) PATTERNS OF VOLCANIC ACTIVITY GLOBALLY

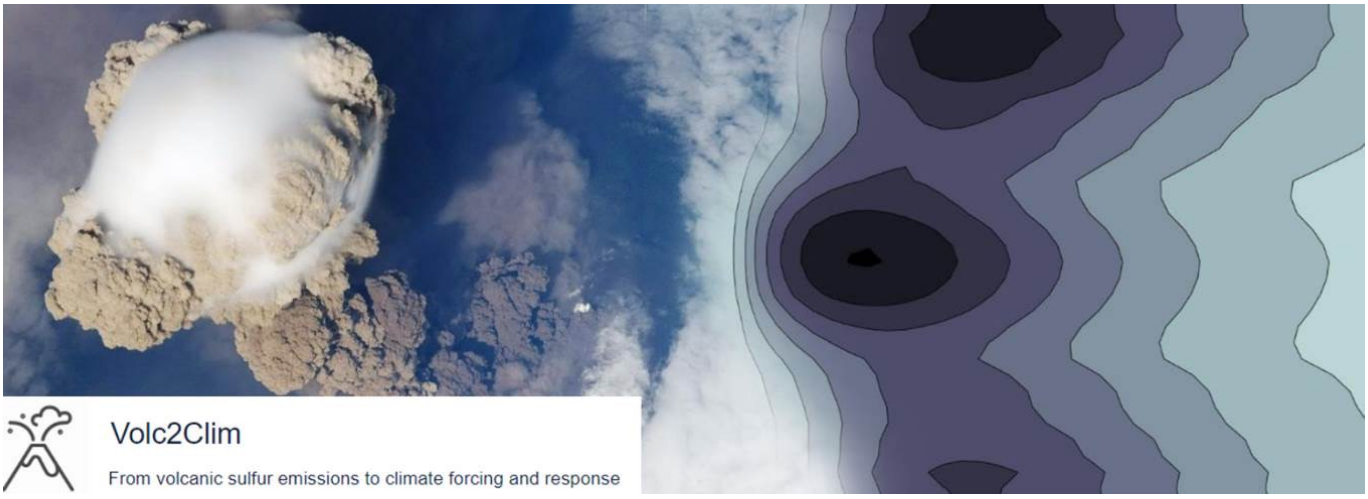
Objective Coordinators: Susanna Ebmeier (Leeds), Melanie Duncan (BGS), Marie Edmonds (Cambridge)

No work was completed in the reporting period. Work is planned for later in the science programme.

PROGRESS REPORT: ASSESS THE CONTRIBUTION OF VOLCANIC SO2 TO GLOBAL CLIMATE AND AVIATION

Objective Coordinators: Don Grainger (Oxford), Samantha Engwell (BGS), Matt Watson (Bristol)
COMET Research Staff: Isabelle Taylor (Oxford)
Contributors: Anja Schmidt (DLR & LMU Munich)

Volc2Clim (https://volc2clim.bgs.ac.uk/) is a webtool that enables the user to calculate volcanic radiative forcing and the global surface temperature response to an explosive volcanic eruption in an easy and accessible manner. The user needs to enter key eruption source parameters, such as the mass or height of sulfur dioxide (SO_2) injected, and the user can also modify some of the underlying model parameters in order to get an uncertainty estimate. The tool outputs values such as the predicted surface temperature to the screen and as downloadable file. It also calculates the so-called Volcano Climate Index (VCI, Schmidt and Black 2022, https://volcano-climate.github.io/vci/). The VCI is a scale that measures the magnitude of the volcanic climate response and takes values from 0 to 6+. It is similar to the Richter scale for the magnitude of earthquakes. Overall, the tool is suitable for use by scientists, policy makers and lay people.



PROGRESS REPORT: DEVELOP AND TEST THE MODELS NEEDED FOR INTERPRETING SATELLITE DATA DURING VOLCANIC CRISES

Objective Coordinators: Juliet Biggs (Bristol), Sue Loughlin (BGS), Andy Hooper (Leeds)
COMET Research Staff: Matt Gaddes (Leeds)

Two of the most widely observed co-eruptive volcanic phenomena - ground deformation and SO_2 outgassing - are fundamentally linked via the mechanism of magma degassing and the development of compressibility. In previous years, we developed thermodynamic models – constrained by petrological data - to reconstruct volatile exsolution and the consequent changes in magma properties. Now, COMET PhD Student Stanley Yip has extended these models to consider a wider range of magma compositions (basaltic to rhyolitic) and to consider changes that occur during eruptions due to either the removal of a degassed plug or gas-rich cap to the magma reservoir. We found that mafic systems exhibit higher co-eruptive volume changes and a wider range of SO_2 emissions than intermediate-silicic systems due to their high volatile diffusivity and tendency for effusive eruptions (co-eruptive degassing). Our results indicate that all magmatic systems undergo some degree of outgassing prior to an eruption – the gas content of the reservoir from an eruption is gas-rich when compared to predictions based on melt-inclusion data but partially depleted in gas content when compared to predictions based on fractional crystallisation. These findings have important implications for the interpretation of satellite data during volcanic crises, where the pre-eruptive gas content is a primary control on both deformation and SO_2 flux.

IMPACT, INNOVATION AND INFLUENCE

IMPACT

COMET members contribute to research in response to significant global events. This year, COMET scientists were involved in a NERC funded urgency project focused on the response to the 15th January 2022 Hunga Tonga - Hunga Ha'apai Volcanic Eruption. This funding was awarded to improve understanding of the Volcanic Mechanism and Impact of the tsunami[40].

Following the Türkiye-Syria earthquake in February 2023, which caused widespread destruction both in Türkiye and Syria, COMET worked closely with international partners, focusing initially on processing satellite data to measure how the ground moved during the earthquake. See 'Research Highlight: 3D Displacements and Strain of the 2023 February Türkiye-Syria Earthquakes From Sentinel Data (p.24-25) by Qi Ou for more information about the data processing we completed after the event. We also provided a technical briefing to the UK's Foreign, Commonwealth and Development Office (FCDO) and to the United Nations Relief and Works Agency for Palestine Refugees in the Near East (UNRWA), which is a UN agency that supports the relief and human development of Palestinian refugees. As part of this, we identified a need for strengthening links between COMET and UK governmental representatives, for both event response and disaster preparedness.

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.

After our response to the Türkiye-Syria earthquake, new lines of communication between COMET and the FCDO were created. We are continuing to develop this relationship, and our methods of communicating to different audiences, to ensure long-term, impactful engagement. Through our partnership with BGS, we also provide emergency advice for the Scientific Advisory Group in Emergencies (SAGE) and Cabinet Office Briefing Room (COBR) and further scientific expertise on volcanic hazards and impacts as requested to UK government departments and the European Emergency Response and Coordination Centre.

Through the NATO Science for Peace and Security (SPS) program 'Geoenvironmental Security of the Kazakh and Kyrgyz republics', COMET researchers are building detailed earthquake records across the Tien Shan region, and incorporating these data into national hazard maps and assessments in collaboration with our partners. We are also having significant impact through our continued training activities and through the strengthening of research capacity and equipment within our partner institutes.

We have 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. A new EPSRC Innovation Accelerator Account project, joint between GEM and COMET researchers in Oxford, aims to develop 'mid-scale' hazard models for the south Caucasus region, fusing detailed active fault mapping with remote-sensing derived estimates of landslide susceptibility and liquefaction potential.

We also sit on the Committee on Earth Observation Satellites (CEOS) Working Group on Disasters (leading the Pilot and Demonstrator projects) and Deep Carbon Observatory, and make our data available via the European Plate Observing System (EPOS). Finally, we work with the space agencies, advising ESA on Sentinel-1's acquisition strategy and helping to develop new EO missions, with COMET scientists sitting on the Mission Advisory Groups for Earth Explorer 10 mission Harmony, and Sentinel-1-NG.

INNOVATION

COMET actively contributes to codesigned and innovative research seeking to increase the use and benefits of data and development of tools and applications:

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

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

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

INFLUENCE

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

Samantha Engwell (COMET Scientist, BGS) is a member of the WMO/ICAO Volcanic Science for Aviation Advisory Group to provide advice on current state of knowledge with regards

40. GOTW - Grants on the Web (nerc.ac.uk)

to volcanic emissions and their transport, and their impact on aviation.

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

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

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

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

KNOWLEDGE TRANSFER

Embedding geoscience innovation into hazard, risk, and resilience workshop

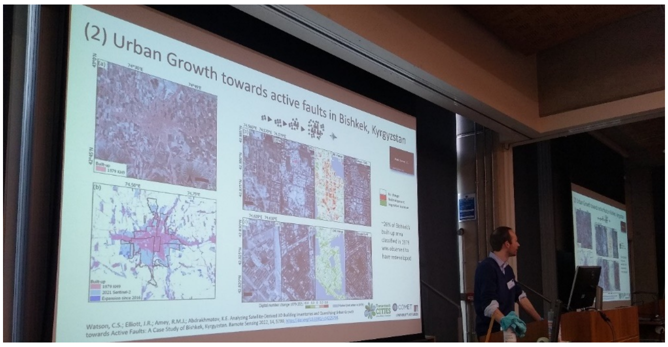
Richard Walker, COMET Scientist, University of Oxford

The workshop was held on the 21st and 22nd March, and was supported through a UKRI program ‘Cross-Disciplinary Research for Discovery Science at Oxford’ with contributions also from Reuben College, Oxford, from the NATO Science for Peace and Security program, and from the UKRI COMET (Centre for the Observation and Modelling of Earthquakes, Volcanoes, and Tectonics). The workshop had three main aims:

1. **To showcase research relevant to geohazards across the various departments in Oxford**, for the benefit of those from outside, and also to identify links and shared research interests within the University.
2. **To learn about how geoscience research outputs are applied in sectors ranging from reinsurance, civil engineering, nuclear safety, and development**, in order to assess how links can be made to strengthen the transfer of knowledge between academic and end-users, and to increase impact of research outputs.
3. **To build better integration of research efforts within the University, and closer collaborations outside the University**, drawing in particular on experiences from academic consortia elsewhere in the UK and overseas, and in identifying priority areas in applied sectors.

Oxford-based research was presented from the departments of Earth Sciences, Geography (Human, Physical, Smith School), Engineering, and Archaeology/Oriental Studies, including many of the Oxford COMET community. We also heard from Scott Watson, COMET scientist from Leeds, representatives from UCL Disaster Engineering for ResIlient SoCieties (DERISC) laboratory, and the Earth Observatory of Singapore describing the new interdisciplinary program ‘Integrating Volcano and Earthquake Science and Technology (InVEST) in Southeast Asia’). We had wide representation outside the University sector, including civil engineering, re-insurance, the international community, and from development NGOs.

The workshop was a really valuable opportunity to hear directly about how geoscience research is applied within a range of sectors. By interacting directly within the workshop we were also able to identify some of the barriers and gaps between the physical sciences research and the needs of industry. We are now looking for ways to better integrate, and to ensure that COMET-related research is impactful outside research institutes.



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 COMET InSAR Training Workshop 2022 (16-18 November 2022) was hosted both in-person and online with over 300 participants from 51 countries. Lectures and practical exercise included: InSAR backgrounds and basics, InSAR time series analysis, atmospheric effects and corrections, earthquake deformation and modelling, and InSAR volcanic applications and modelling. The practical sessions used Jupyter notebooks to allow participants to interactively analyse data. User feedback was overwhelmingly positive, with 91% of respondents (n=97) rating the workshop positively and 96% stating they would recommend the workshop to colleagues.

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.

A number of flagship training activities have occurred within the NATO SPS program ‘Geoenvironmental Security of the Kazakh and Kyrgyz republics’, including an in person workshop on quaternary dating and earthquake hazard assessment in Centre Européen de Recherche et d’Enseignement des Géosciences de l’Environnement (CEREGE), France, and an intensive field-based workshop on paleoseismic trenching in Kyrgyzstan (with the training activities contributing to real research outcomes).

COMET’s Postdoctoral Researcher, Ian Pierce (University of Oxford) wrote a new tutorial on how to combine iOS lidar with Structure-from-Motion photogrammetry to make accurately scaled paleoseismic trench logs.

COMET Scientist, Samantha Engwell (BGS), features in the eVolcano teaching videos. The first video presented by Julia Eychenne (Laboratoire Magmas et Volcans, France) and Samantha Engwell on pyroclastic fall deposits is now available to watch [41].

References
41. https://evolcano.iavceivolcano.org/pyroclastic-fall-deposits-2/

Folds cut by rivers, above Pakistan (Jan. 2023)
Credit: Chia-Hsin Tsai, University of Oxford

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. We also aim to improve access to and diversity in Environmental and Earth Sciences through effective outreach activities.

WEBINARS

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

The COMET webinars[42] have covered a number of topics, including: Satellite imagery in disaster response, the UK's Space Geodesy Facility, large-scale strain mapping over the northeast Tibetan Plateau, drivers of explosive volcanic eruptions and their impacts, seismotectonics of the Himalayas, probing the upper end of intra-continental earthquake magnitude, insights from neotectonics, potential of SAR backscatter for monitoring volcanic eruptions, the COMET fieldwork guidelines, calculating the petrological behaviour of Earth's melting mantle, using deep learning to search for induced small earthquakes, and large-scale interseismic strain accumulation along the Altyn Tagh Fault determined from InSAR.

In total we have offered 9 COMET webinars within our normal programme of talks, 1 COMET Women's Network Webinar that featured three COMET speakers to mark International Day of Women and Girls in Science, 4 COMET Podcast episodes and 1 COMET+ webinar. The COMET+ webinar series showcases work across a diverse range of backgrounds and topics, and are usually presented by international colleagues or partners of COMET.

Over the last year, we have had between 100-150 registrations per webinar, on average. The webinars and podcasts we uploaded to YouTube in this reporting period have reached a large audience, with over 2200 views.

WEBSITE AND SOCIAL MEDIA

The COMET website received 64,967 views and 28,055 visitors 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[43]. We are currently updating the look and content of the website to ensure that it is user-friendly and up-to-date.

COMET continues to promote our research and the achievements of our members to a public audience through social media. We gained an incredible 753 Twitter followers over the last year – we now have 3,739 followers[44]. Our Instagram followers have also risen to 132[45].

MEDIA

Our work is widely accessible online and in print and COMET experts are contacted by the media to provide expert information about a range of topics[46]. COMET members have commented on a wide range of topics and shared their research in the media over the last year including on: the transition to net zero and the role for volcanoes as a novel route to a more sustainable future, moving the Everest base camp due to glacier instability, the 2022 volcanic eruption in Iceland, Afghanistan's long-standing vulnerabilities when an earthquake strikes, activity detected under a dormant volcano near Sitka, Alaska, the Mauna Loa volcanic eruption in 2022, Indonesia's Mount Semeru volcano eruption in 2022, weak seismic ground shaking triggering landslide acceleration, and expert commentaries on the devastating Turkey-Syria earthquake.

PUBLIC ENGAGEMENT AND OUTREACH

COMET members have given 4 talks to schools groups. COMET members at the University of Oxford have created a set of engaging and hands-on activities around volcanoes and volcanic activity which we use regularly to engage with primary-school groups, and as demonstrations at science fairs and open days. In 2023, a version of this was run at the 'Volcano Day' in the Natural History Museum, London as a part of an ongoing collaboration with colleagues at the University of East Anglia.

Ekbal Hussain (BGS) also gave a presentation on the why hazards turn into disasters at the London International Model United Nations annual conference. After his talk, the audience reported a change in views and opinions.

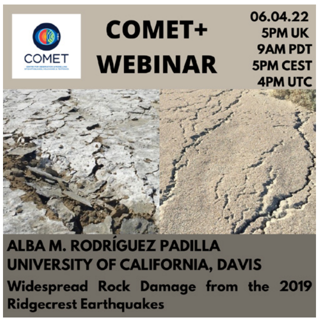
In April 2022, COMET Director, Tim Wright, and COMET Manager, Charlotte Royle, co-wrote an article for the A-level magazine, Geography Review, which reaches a large number of schools around the UK.

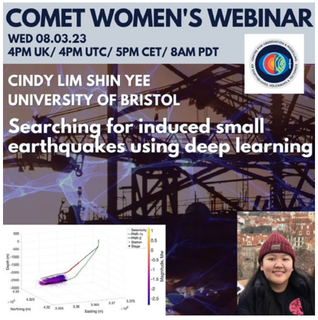
Tamsin Mather and David Pyle (University of Oxford) appear in a new book about volcanoes from COPE Champions, aimed to increase the disaster resilience of children globally[47].

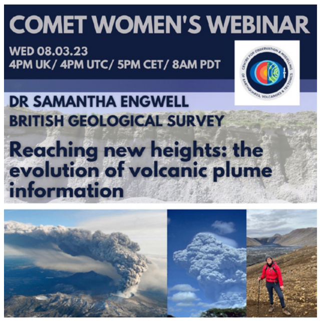
42. comet.nerc.ac.uk/comet-webinar-series/
43. comet.nerc.ac.uk/volcanoes/
44. @nerc_comet
45. https://www.instagram.com/comet_nerc/
46. https://comet.nerc.ac.uk/in-the-news/
47. COPE_Volcanoes.pdf (cope-disaster-champions.com)

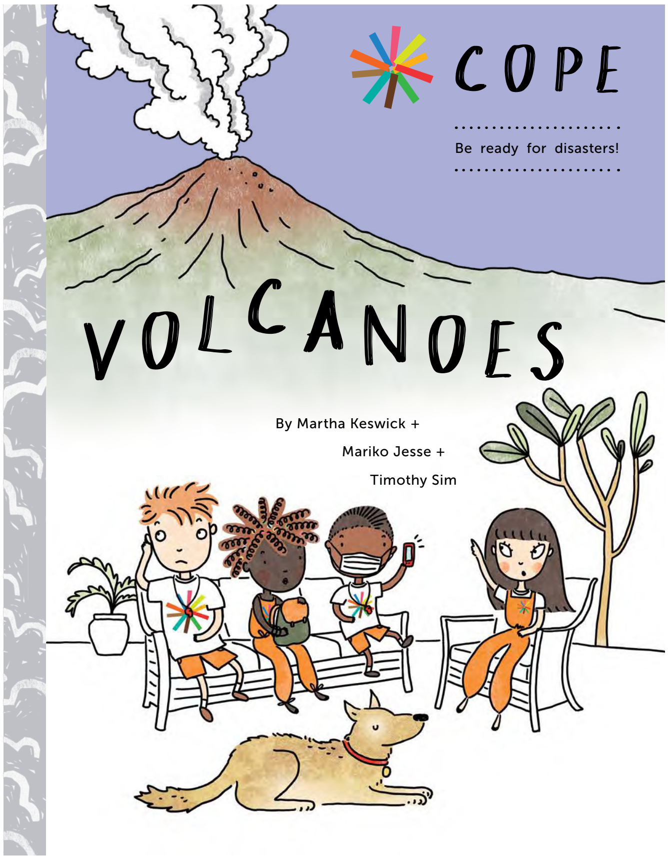
COMET researchers attended public events to promote their research. Cat Hayer and Ben Esse (University of Manchester), attended Bluedot Science Festival in August 2022. David Pyle (University of Oxford) also attended Norwich Science Festival 2023 to present creative and engaging hands-on activities and demonstrations around volcanoes, volcanic activity and uncertainty. These activities were developed by a multi-institution team led by Professor Jenni Barclay. Ekbal Hussain (BGS) gave informative presentations on why hazards turn into disasters to a number of geological societies around the UK.

Podcasts are an engaging and effective way of communicating research information to a public audience. At the COMET Student Meeting 2022, COMET PhD researchers started a COMET Podcast for public and academic audiences. The first four episodes can be found on the COMET webinars YouTube channel. COMET Scientist Marie Edmonds (University of Cambridge) was also interviewed for The Naked Scientists podcast about her research: Listening to the sounds inside a volcano can tell us more about its future activity.









COLLABORATIONS AND PARTNERSHIPS

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

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

EUROPEAN CATALOGUE OF VOLCANOES

EUROVOLC[48] is a European Commission Horizon2020 Infrastructure project established to support interconnection and collaboration within the European volcanological community and enable access to the community's research infrastructure and data. The project builds upon experiences of FUTUREVOLC, with partners from 9 European countries representing volcano research and monitoring institutions, civil protection agencies, a volcanic ash advisory centre and companies from R&D, IT and geothermal industries.

EPOS EUROPEANPLATEOBSERVINGSYSTEM

The European Plate Observing System (EPOS)[49] 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.

GEM Global Earthquake Model (GEM)[50] COMET has extended collaboration with GEM through a project aimed at improving probabilistic seismic hazard and risk assessment in Central Asia.

LiCS LOOKING INSIDE THE CONTINENTS FROM SPACE

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

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

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

48. eurovolc.eu
49. www.epos-eu.org/
50. www.globalquakemodel.org/gem

RiftVolc[51], 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.[52]

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.

MAST: Imaging Magmatic Architecture using Strain Tomography Volcanologists watch for changes in magma that cause other phenomena. For instance, magma moving toward the surface usually causes swarms of earthquakes. With the aim of improving forecasting skills, the ERC-funded MAST project will draw on the improved observations of magmatic systems. It will consider the geophysical and petrological evidence that a fluid-dominated ‘magma chamber’ is only one component of a much larger system with a heterogeneous distribution of melts, crystals and gases. The project will also use data collected by satellite images (dense time-series of high-resolution images), showing the complexity and diversity that was not apparent when only infrequent point measurements were available.[53]

51. riftvolc.wordpress.com/
52. www.tomorrowscities.org/
53. https://cordis.europa.eu/project/id/101003173

AWARDS AND RECOGNITION

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

Susanna Ebmeier (COMET Scientist, University of Leeds) was named as a recipient of the 2022 AGU John Wahr Early Career Award in the Geodesy section. The John Wahr Early Career Award is presented annually and recognises significant advances in geodetic science, technology, applications, observations, or theory. Susi was also awarded the ESA-EGU 2023 Earth Observation Excellence Award, honouring individual scientists and teams of scientists that have contributed to the innovative use of Earth observation data.

Tamarah King (COMET Research Staff,, University of Oxford) Oxford University MPLS (Maths, Physical, Life Sciences) Division - Teaching Award.

Zoe Mildon (COMET Associate, University of Plymouth) was awarded the 2023 Bullerwell Lecturer. The Bullerwell Lecture is an annual award from the British Geophysical Association (BGA) bestowed on an individual for significant contribution to the field of geophysics. Scientists of any nationality but working in an academic institution in the United Kingdom qualify for the award.

Cindy Lim (PhD Researcher, University of Bristol) was awarded a place onto the Alan Turing Institute's 2022 Enrichment Community Scheme. The award, of which there are only 50 across all disciplines in the UK, provides students with opportunities and funds to engage with the UK's premier artificial intelligence research institute and community.

Tamsin Mather (COMET Scientist, University of Oxford) was honoured with Geochemistry Fellow from the Geochemical Society and the European Association of Geochemistry. Awarded by the US-based and European societies upon outstanding scientists who have made a major contribution to the field. Tamsin was also named as the Co-chair of the Science Committee Goldschmidt meeting Chicago 2024, shaping the science programme of the premier geochemistry international meeting.

Jessica Payne (PhD Researcher, University of Leeds) was awarded an Outstanding Student Presentation Award (OSPA) for the AGU presentation: "Characterising Iran's Subsiding Regions using Earth Observation Data".

Richard Walker (COMET Scientist, University of Oxford) Oxford University MPLS (Maths, Physical, Life Sciences) Division - Societal Impact Award.

A commemorative street sign placed in the 2021 lava flow field in La Palma by members of the same street, remembering the community lost beneath the thick flows.
Credit: Ben Ireland, University of Bristol

EQUITY, DIVERSITY AND INCLUSION

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

During 2022-2023 the COMET EDI Action Group has:

- Developed a summer internship programme, aimed at increasing access to COMET research areas. Based on underrepresented groups within COMET, we strongly encouraged applicants from minority backgrounds, and from students who are the first generation in their family to attend University. The first two students under this scheme were appointed in summer 2022.

- Arranged for COMET to attend the Girls into Geoscience event in July 2023.

- Created an outreach repository for COMET members.

- Developed the COMET fieldwork guidelines to encourage safe, equitable and inclusive fieldwork practice, both in COMET and the wider community. COMET EDI Group Chair, Sam Wimpenny (Leeds), presented a webinar to share the guidelines with a wide audience.

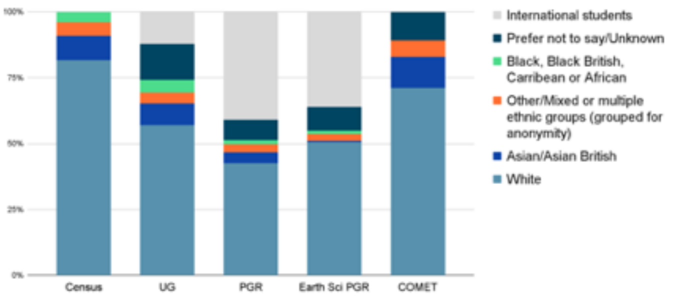
- Continued the COMET+ webinar series. The COMET+ webinar series aims to promote research being undertaken by collaborators of COMET scientists. Particularly in-country collaborators, early career researchers, and scientists from minority backgrounds.

- Requested the optional collection of COMET diversity data, with the aim of identifying and addressing any inequalities, and allowing us to make specific adjustments or interventions to attendance at and participation in COMET events. 108 COMET members participated in an EDI survey in advance of the COMET Annual Meeting 2022. This data was analysed and presented anonymously to the EDI Action Group. Some of our findings are outlined below. We will continue to analyse these data over the years and adjust our activities accordingly.

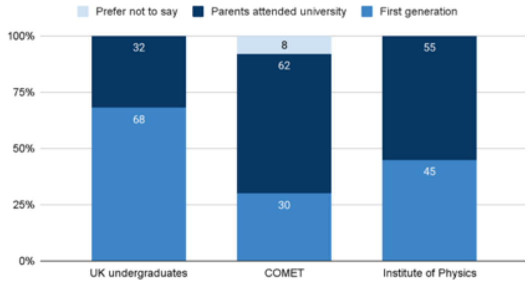
EQUITY, DIVERSITY AND INCLUSION

WHO COMES INTO COMET?

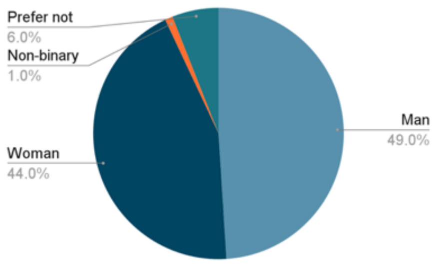
Ethnicity



Parental Education



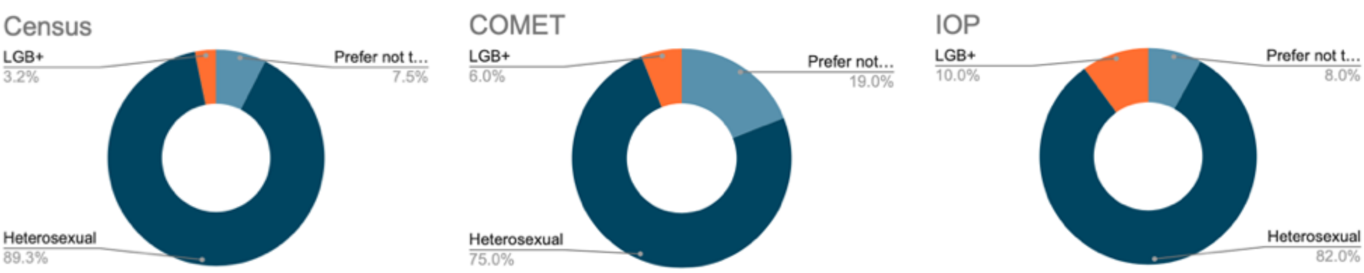
Who is COMET losing?



Gender diversity data across COMET membership

Dividing gender diversity by age category leads to a lower proportion of women in the 30-40 age category than below 30 or between 40-50.

Who feels comfortable in COMET?



Compared to the Institute of Physics (IOP) and UK Census, we have a much higher ‘Prefer not to say’ rate, especially for sexual orientation.

OUR MEMBERS, 1 APRIL 2022 - 31 MARCH 2023

COMET Directorate

Professor Tim Wright (Leeds) COMET Director

Professor Juliet Biggs (Bristol) Deputy Director (Volcanoes)

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

Professor Don Grainger (Oxford) Deputy Director (Earth Observation)

Luke Bateson (BGS) BGS Representative

Dr Susan Loughlin (BGS) BGS Representative

Suzanne Banks (Leeds) COMET Finance Administrator

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

Charlotte Royle (Leeds) COMET Manager

Lucy Sharpson (Leeds) COMET Research Administrator

COMET Scientists

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

Dr Brian Baptie (BGS)

Professor Mike Burton (Manchester)

Dr Timothy Craig (Leeds)

Dr Melanie Jane Duncan (BGS)

Dr Susanna Ebmeier (Leeds)

Professor Marie Edmonds (Cambridge)

Dr John Elliott (Leeds)

Dr Samantha Engwell (BGS)

Dr Pablo Gonzalez (Liverpool)

Dr Laura Gregory (Leeds)

Dr Jessica Hawthorne (Oxford)

Professor Andy Hooper (Leeds)

Dr Ekbal Hussain (BGS)

Professor James Jackson (Cambridge)

Dr David Kerridge (BGS)

Professor Tamsin Mather (Oxford)

Dr Ilaria Mosca (BGS)

Professor Jurgen (Locko) Neuberg (Leeds)

Dr Alessandro Novellino (BGS)

Professor David Pyle (Oxford)

Dr Susanne Sargeant (BGS)

Professor Richard Walker (Oxford)

Professor Matthew Watson (Bristol)

Dr Max Werner (Bristol)

Professor Marek Ziebart (UCL)

COMET EMERITUS

Professor Philip England (Oxford)

Professor Gregory Houseman (Leeds)

Professor Barry Parsons (Oxford)

Professor Geoff Wadge (Reading)

COMET RESEARCH STAFF

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

Dr Edna Dualeh (Bristol)

Dr Matthew Gaddes (Leeds)

Dr Tamarah King (Oxford)

Dr Milan Lazecky (Leeds)

Dr Yasser Maghsoudi (Leeds)

Dr Qi Ou (Leeds)

Dr Isabelle Taylor (Oxford)

Dr C. Scott Watson (Leeds)

COMET POSTDOCTORAL RESEARCHERS

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

Dr Jose Bayona (Bristol)

Dr Yannick Canniven (Oxford)

Dr Ben Esse (Manchester)

Dr Cat Hayer (Manchester)

Dr Hui Huang (Oxford)

Dr Camila Novoa Lizama (Leeds)

Dr Odysseas Pappas (Bristol)

Dr Ian Pierce (Oxford)

Dr Lin Shen (Leeds)

Dr Gregor Weber (Bristol)

Dr Luke Wedmore (Bristol)

Dr Sam Wimpenny (Leeds)

OUR MEMBERS, APRIL 2022 - MARCH 2023

COMET ASSOCIATES

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

Dr Pui Anantrasirichai (Bristol)

Dr Philip Benson (Portsmouth)

Dr Lidong Bie (UEA)

Dr Sarah Boulton (Plymouth)

Professor Peter Clarke (Newcastle)

Professor Ake Fagereng (Cardiff)

Dr David Ferguson (Leeds)

Dr Matt Fox (UCL)

Dr James Hickey (Exeter)

Dr Anna Hicks (BGS)

Dr Evgenia Ilyinskaya (Leeds)

Professor Chris Jackson (Imperial)

Professor Mike Kendall (Oxford)

Professor Zhenhong Li (Newcastle)

Dr Brendan McCormick Kilbride (Manchester)

Dr Craig Magee (Leeds)

Dr Zoe Mildon (Plymouth)

Dr Andy Nowacki (Leeds)

Dr Camilla Penney (Cambridge)

Dr Tom Pering (Sheffield)

Dr Margherita Polacci (Manchester)

Professor Ed Rhodes (Sheffield)

Dr Chris Rollins (Leeds/GNS)

Dr Dylan Rood (Imperial)

Dr Peter Rowley (Bristol)

Dr Anja Schmidt (Cambridge/ DLR & LMU Munich)

Dr Margarita Segou (BGS)

Dr Victoria Smith (BGS)

Dr Charlotte Vye-Brown (BGS)

Dr Tom Wilkes (Sheffield)

Dr Annie Winson (BGS)

Dr Gang Zheng (Leeds)

COMET STUDENTS

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

Rami Alshembari (Exeter)
Josefa Sepulveda Araya (Leeds)
Nick Barber (Cambridge)
Pedro Espin Bedon (Leeds)
Mark Bemelmans (Bristol)
Rachel Bilsland (Leeds)
Alice Blackwell (Leeds)
Reza Bordbari (Leeds)
Felix Boschetty (Leeds)
Manon Carpenter (Leeds)
Jennifer Castelino (Leeds)
Robbie Churchill (Bristol)
Anna Pardo Cofrades (Manchester)
Rebecca Colquhoun (Oxford)
John Condon (Leeds)
Jacob Connolly (Leeds)
James Dalziel (Bristol)
Juliette Delbrel (Manchester)
Manuel-Lukas Diercks (Plymouth)
Edna Dualeh (Leeds)
Bob Elliott (Durham)
Jin Fang (Leeds)
Natalie Forrest (Leeds)
Yuan Gao (Leeds)
Dan Gittins (Oxford)
Olivia Hogg (Cambridge)
Alice Hopkins (Leeds)
Ben Ireland (Bristol)
Alex Jenkins (Bristol)
Yu Jiang (Liverpool)
Benedict Johnson (Oxford)
Russell Khan (Bristol)
Lizzie Knight (Cambridge)
Rosie Lewis (Leeds)
Fei Liu (Leeds)
Ahmed Mahmoud (Nottingham)
Neill Marshall (Oxford)
Jack McGrath (Leeds)
Gauhar Meldebekova (Newcastle)
Sophie Miocevich (Cambridge)
Adam Morley (Cambridge)
Matthew Morris (Cambridge)
Muhammet Nergizci (Leeds)
Elish O'Grady (Leeds)
Aisling O'Kane (Cambridge)
Simon Orrego Astudillo (Bristol)
Alice Paine (Oxford)
Jessica Payne (Leeds)
Robert Popescu (Bristol)
Victoria Purcell (Leeds)
Maddie Reader (Bristol)
Eoin Reddin (Leeds)
Michelle Rygus (Pavia, BGS)
Daniel Sefton (Leeds)
Anza Shakeel (Durham)
Chuang Song (Newcastle)
Richard Strange (Oxford)
Chia-Hsin (Wendy) Tsai (Oxford)
Alice Turner (Oxford)
Megan Udy (Leeds)
Laura Wainman (Leeds)
Dehua Wang (Leeds)
Andrew Watson (Leeds)
Nemi Welding (Hull)
Rachel Whitty (Leeds)
Andrew Whyte (Cambridge)
Roberta Wilkinson (Oxford)
Kevin Wong (Leeds)
Mia Wroe (Cambridge)
Cindy Lim Shin Yee (Bristol)
Stanley Yip (Bristol)
Eva Zand (Leeds)
Tianyuan Zhu (Bristol)

ALL COMET PUBLICATIONS, APRIL 2022 - MARCH 2023

COMET has a strong publication record: since 2014, COMET has published 700 papers in international scientific journals, including 63 in Science or Nature Research journals.

82 were published between 1st April 2022 and 31st March 2023, and, of these, 19 had student first authors.

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A fold in Dorset, UK. (Aug. 2021)
Credit: Chia-Hsin Tsai, University of Oxford

GLOSSARY

ABI	Advanced Baseline Imager
AGL	Absolute Gravity Laboratory
AGU	American Geophysical Union
AHB	Alpine-Himalayan Belt
ALOS	Advanced Land Observing Satellite-2
ATLAS	Advanced Topographic Laser Altimeter System
BGA	British Geophysical Association
BGS	British Geological Survey
BIRA	Belgium Institute for Space Aeronomy
CEMAC	The Centre for Environmental Modelling And Computation
CEOS	Committee on Earth Observation Satellites
CEREGE	Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement
COBR	Civil Contingencies Committee
COMET	Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics
COPE	Candy, Ollie, Ping and Eddy - illustrated not-for-profit books, aimed to increase the disaster resilience of children
COSI-Corr	Measuring Ground Deformation Using Optical Satellite and Aerial Images
COSMO-SkyMED	SAR Sensor
CrIS	Cross-track Infrared Sounder
CSK	SAR Sensor
DEEPVOLC	Forecasting Volcanic Activity Using Deep Learning
DEM	Digital Elevation Model
DERISC	UCL Disaster Engineering for ResIlient SoCieties Laboratory
DTMs	Digital Terrain Models
ECMWF	European Centre for Medium-Range Weather Forecasts
EDI	Equity, Diversity and Inclusion EGMS European Ground Motion Service
EIDP	Earthquake InSAR Data Provider
ENVISAT	European Earth Observation Satellite
EO	Earth Observation EPOS European Plate Observing System
EPSRC	Engineering and Physical Sciences Research Council
ERC	European Research Council
ERDAS	Geospatial Data Authoring System
ESA	European Space Agency
ETAD	Sentinel-1 Extended Timing Annotation Dataset
EUMETSAT	European Operational Satellite Agency for Monitoring Weather, Climate and the Environment from Space
EUROVOLC	European Network of Observatories and Research Infrastructures for Volcanology
FCDO	Foreign, Commonwealth & Development Office
FUTUREVOLC	European Volcanological Supersite in Iceland: A Monitoring System and Network for the Future
GACOS	Generic Atmospheric Correction Online Service for InSAR
GCRF	Global Challenges Research Fund

GEM	Global Earthquake Model
GNS	Institute of Geological and Nuclear Sciences Limited
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GVM	Global Volcano Model
IASI	Infrared Atmospheric Sounding Interferometer
IASI-NG	Infrared Atomospheric Sounding Interferometer-Next Generation
ICAO	International Civil Aviation Organization
ICESat-2	Ice, Cloud, and Land Elevation Satellite 2
INGV	National Institute of Geophysics and Volcanology
InSAR	Synthetic Aperture Radar Interferometry
InVEST	Integrating Volcano and Earthquake Science and Technology
iOS	Mobile Operating System
IRS	InfraRed Sounder
ISCE	InSAR Scientific Computing Environment
JASMIN	Globally-Unique Data Analysis Facility
JVGR	Journal of Volcanology and Geothermal Research
LiCS	Looking inside the Continents from Space
LICSAR	COMET-LICS InSAR processing suite, built on top of Gamma Remote Sensing InSAR software
LICSBAS	An open-source package in Python and bash to carry out InSAR time series analysis using LiCSAR products
LoS	Line-of-Sight
MAST	Imaging Magmatic Architecture using Strain Tomography
MIROVA	Middle Infrared Observation of Volcanic Activity
MODIS	Moderate Resolution Imaging Spectroradiometer
MORSE	MIPAS Orbital Retrieval Using Sequential Estimation
MPLS	Oxford University Maths, Physical, Life Sciences
MVO	Montserrat Volcano Observatory
NASA	US Space Agency (National Aeronautics and Space Administration)
NASA-JPL	National Aeronautics and Space Administration-Jet Propulsion Laboratory
NATO	North Atlantic Treaty Organisation
NCEO	National Centre for Earth Observation
NEMO	National Emergency Management Organisation
NERC	Natural Environment Research Council
NGO	Non-Governmental Organisation
NISAR	NASA-ISRO SAR Mission
NOAA	National Oceanic and Atmospheric Administration
ODA	Official Development Assistance
OSPA	Outstanding Student Presentation Award

GLOSSARY

PDC	Pyroclastic Density Currents
PSHA	Probabilistic Seismic Hazard Analysis
R4Ash	Radar-Supported Next-Generation Forecasting of Volcanic Ash Hazard
RAL	Rutherford Appleton Laboratory
RAS	Royal Astronomical Society
RGT	Reference Ground Tracks
RiftVolc	Volcanoes and Volcanic Plumbing Systems in the East African Rift Valley
RISE	Real-Time Earthquake Risk Reduction for a Resilient Europe
RVO	Rabaul Volcanological Observatory
S1	SAR Sensor
SAGE	Scientific Advisory Group in Emergencies
Sentinel-1	Constellation of Two Satellites
SGF	Space Geodesy Facility
SPS	NATO Science for Peace and Security Program
TerraSAR-X	Imaging Radar Earth Observation Satellite
tICA	Temporal Independent Component Analysis
TROPOMI	The TROPOspheric Monitoring Instrument
TSX	SAR Sensor
UAVS	Unmanned Aerial Vehicle
UCL	University College London
UKRI	UK Research and Innovation
UNRWA	United Nations Relief and Works Agency for Palestine Refugees in the Near East
USGS	US Geological Survey
UTC	Coordinated Universal Time
UWI-SRC	Seismic Research Centre of the University of the West Indies
VCI	Volcano Climate Index
V-Plus	Volcanic Plume Understanding and Forecasting: Integrating Remote-Sensing, In-situ Observations and Models
WMO	Word Meteorological Organisation

Sophie Miocevich and Owen Weller examining a deformed and exhumed section of the mid-crust. The rocks record a protracted period of intrusion, metamorphism, and deformation, spanning over a billion years, and formed within a series of Precambrian mountain belts.
Credit: Alex Copley, University of Cambridge

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