Joint Assembly

TSG – VMSG – BGA

January 4th – 6th

University of Liverpool

TIMETABLE

Day 1 - Wednesday 4th January

TIME	ROOM A	ROOM B	ROOM C
10.00 - 10.10	Welcome address		
10.10 - 11.00	Keynote 1		
11.00 - 11.15	Break		
11.15 - 11.45	Gas, aerosols, ash and the atmosphere (s8)	The structure and mechanics of fault zones I (s6)	Earth's deep interior (s10)
12.45 - 14.15	Hot lunch and posters		
13.45 - 14.10			How to start writing!
14.15 - 15.30	Physical volcanology I (s11)	The structure and mechanics of fault zones II (s6)	Seismology, geodesy and remote sensing: Methodologies and applications I (s4)
15.30 - 16.00	Tea/coffee break and posters		
16.00 - 17.15	Physical volcanology II (s11)	The structure and mechanics of fault zones III (s6)	Seismology, geodesy and remote sensing: methodologies and applications II (s4)
17.15 - 19.00	BGA-sponsored Ice-breaker and poster session		

Day 2 - Thursday 5th January

TIME	ROOM A	ROOM B	ROOM C
09.00 - 10.12	The volatile Earth: The role of liquids and gases in the dynamic solid Earth (s2)		
10.12 - 10.45	Tea/coffee break and posters		
10.45 - 12.30	Heterogeneity in the Earth: From micro to macro scale - incl. Keynote 2 (s1)		
12.30 - 14.00	Cold buffet lunch and posters		
13.10 - 13.50	Student forum		
14.00 - 15.12	Tectonic and magmatic processes during continental extensional tectonics and rifted margin formation I - incl. Keynote 3 (s3)		
15.12 - 16.00	Tea/coffee break and posters		
16.00 - 17.24	Tectonic and magmatic processes during continental extensional tectonics and rifted margin formation II (s3)		
17.30 - 18.00	Prizes		
18.30	Meet to walk to dinner and party (approx. 30 min)		
19.00 - 02.00	Dinner and party at CAMP AND FURNACE		

Day 3 - Friday 6th January

TIME	ROOM A	ROOM B	ROOM C
09.00 - 10.30	Jon Davidson Memorial Session: Magma genesis, storage and transport I - incl. Keynote 4 (s5)	Microstructures and deformation I (s9)	New frontiers in experimentation, rock physics and magma rheology (s14)
10.30 - 11.00	Tea/coffee break and posters		
11.00 - 12.30	Jon Davidson Memorial Session: Magma genesis, storage and transport II (s5)	Microstructures and deformation II (s9)	Georesources and geohazards in an evolving planet I (s7)
12.30 - 14.00	Cold buffet lunch and posters		
13.15 - 14.00	VMSG AGM	TSG AGM	BGA AGM
14:00 - 15.30	Jon Davidson Memorial Session: Magma genesis, storage and transport III (s5)	Earthquakes, palaeoseismology, and rates of fault slip (s12)	Georesources and geohazards in an evolving planet II - incl. Keynote 5 (s7)
15.30 - 16.00	Prizes and close		
18.30	Pub crawl departing from venue		

Front cover by Sergio Leon Rios and Jackie E. Kendrick, images from delegates participating in the Joint Assembly Photo Competition

UNIVERSITY OF LIVERPOOL

Joint Assembly

Liverpool

4th – 6th January 2017

CONTENTS

Welcome to the Liverpool Joint Assembly 2017

Chair of the Local Organising Committee, Yan Lavallée, University of Liverpool

It is my great pleasure to welcome you all to Liverpool for the 2017 Joint Assembly of the VMSG, TSG and BGA – a first step, in what I hope will be the future of a closer geoscience community in the UK in years to come. While each of these study groups celebrates many years of vibrant activities, 2017 marks the centenary of the Department of Geology at the University of Liverpool. Over the course of its existence, the department has evolved to answer the need for integrating various disciplines in the curriculum of its geoscientific undertakings and this is what I wish to achieve by inviting the three study groups to align their activities. Geosciences represent a family of disciplines, linked by the nature of the problems addressed rather than even a basic commonality of methodology or approach. It has never been easy to bind these approaches together in a single conversation; yet this conversation is necessary to mount efforts to resolve the grand challenges of today. The interdisciplinary scientific program put together this year promises to be enriching and I hope it will establish new ties and open a dialogue between many of us who remain yet to meet one another!

Principal Organiser, Jackie Kendrick, University of Liverpool

The Local Organising Committee at the University of Liverpool are proud hosts of the Volcanic and Magmatic Studies Group (VMSG) 53rd Annual Conference, the Tectonic Studies Group (TSG) 47th Annual Conference and the British Geophysical Association's annual New Advances in Geophysics (NAG) meeting. Over 400 participants registered for the full conference, with more still taking advantage of our day-rates (new this year)! We also had a fantastic turnout for the scientific programme, and will have 123 talks and 204 posters over the 3 days, including 5 great Keynote speakers - making for a packed schedule along with our exciting social events, notably the conference dinner and party at Camp & Furnace which promises to be spectacular! Liverpool is a vibrant town with much more to do than possible in the time you're here for. On behalf all the organisers I do hope you'll enjoy your stay and will return again soon!

Local Organising Committee


Yan Lavallée


Jackie E. Kendrick


Sarah Henton De Angelis


Paul A. Wallace


Janine Kavanagh


Rebecca Coats


Felix W. von Aulock


Anthony Lamur


Sergio Leon Rios


Helen Kinvig


Oliver D. Lamb


Silvio De Angelis

Administration / on-site assistance / other help:
Jamie Hughes
Paula Houghton
Lindsay Davies
Gudjon H. Eggertsson
Amy Hughes
James Ashworth
Caroline Harkin

VOLCANOLOGY IN LIVERPOOL

Chair of the TSG, Clare Bond, University of Aberdeen

Welcome to the Joint Assembly of the TSG-VMSG-BGA. The Joint Assembly provides an exciting opportunity to bring together interleaved aspects of Earth Science for which tectonics and structural geology play a key role. The conference takes TSG's normal AGM format, of a student supportive community conference, and twists it into a bigger, broader event ripe for new collaborations and engagement. You will find TSG focused sessions mixed with wider cross-cutting themes on: the volatile Earth, integrating monitoring strategies, physical volcanology, and the Earth's deep interior, bringing together the specialist groups into one forum. The carefully crafted sessions should inspire you to look beyond the details of structural geology and tectonics into the interactions with other processes, and their impact on other disciplines. For example the TSG keynote by Othmar Müntener the "Key role of mantle rocks for rifted margin studies: observations, data and speculations" will investigate the link between the petrography of the mantle and crustal rifting. The technical sessions are run in combination with a full social programme, this and Liverpool's lively night scene should provide a great basis for networking and the building of new scientific partnerships.

TSG is pleased to support, for the second year, sponsored crèche places for those with caring responsibilities for the young. We also have a series of initiatives to support the development of early career researchers in the field of structural geology and tectonics, from field trips and conference travel grants to prizes and awards. Come along to our official AGM on Friday to find out about the exciting opportunities on offer in 2017 and how you can engage, support and help build the TSG community.

I hope the Joint Assembly provides an opportunity to expand your mind, build new interdisciplinary scientific collaborations and to enjoy the breadth and diversity of our Science.

Enjoy Liverpool 2017!

BGA President, Jenny Collier, Imperial College London

It is my great pleasure to welcome everyone to the first Joint Assembly on behalf of the British Geophysical Association (@britgeophysics). By bringing VMSG, TSG and the BGA together we hope to strengthen collaborative relationships across the UK Solid Earth Science sector. We would like to thank our local organising committee for putting together such an exceptional programme of talks, posters and workshops. The BGA are proud to be sponsoring one of our invited speakers, Freysteinn Sigmundsson from the Nordic Volcanological Center at the University of Iceland and also the Icebreaker reception on Wednesday 4th January, which we hope will set the scene for the exciting three days we have ahead of us!

Chair of the VMSG, Mike Widdowson, University of Hull

On the behalf of the VMSG Committee, it is a pleasure to welcome you to our Annual Conference in this, the 53rd year of our Special Interest Group (SIG). The SIGs exist under the auspices of the parent bodies of the Mineralogical Society of Great Britain and Ireland, and the Geological Society of London, and represent crucial components contributing to the visibility and vibrancy of our Geoscience communities within the UK, Ireland, and their influence further abroad.

This year, we are delighted to be hosted by University of Liverpool, and in particular we extend our gratitude to the organising team from the Department of Earth, Ocean and Ecological Sciences led by Yan Lavallée and Jackie Kendrick. The organisation and delivery of the annual VMSG meeting for c. 200 delegates has, over the last decade or so, become a truly major undertaking, requiring an efficient local organising committee. This year, Jackie, Yan and the team have taken this level of effort even a stage further and organised a Joint Assembly comprising scientifically rich symposia involving three key Special Interest Groups (SIGs; TSG, BGA and VMSG). This is a fantastic achievement!

Professor Yan Lavallée was last year's VMSG award winner, and the delegates of VMSG 2016 at Trinity College Dublin, were delighted and impressed to receive his acceptance speech via Skype link from his fieldwork area on the very flanks of the active Santiaguito volcano in Guatemala. This year the Committee is delighted to announce that the 2017 VMSG Award winner is Dr Sue Loughlin, Head of Volcanology at BGS in recognition of her considerable contribution to volcano science, hazards and risk, and to our own VMSG Committee. We are pleased to say that both the 2016 and 2017 winners will present keynote lectures during the conference.

Geoscience contains an ever widening range of related disciplines and expertise. A key factor in the continuing success of UK Geoscience has been the willingness of institutions, groups and individuals to work across these disciplines, often discovering that major advances are made at the interface between areas of expertise. In recent years both MinSoc and GSL have promoted and fostered cross-disciplinary dialogue within their families of SIGs. This encouragement continues through the current Chair and President of MinSoc and GSL, as well as previous forward-thinking leaders such as the late Prof. Jon Davidson (Durham University). Jon was Chair of VMSG (2006-2009), and then Chair of MinSoc (2012-2013) and actively encouraged cross-disciplinary SIG cooperation. It is a fitting tribute to Jon, and other recent Chairs, that the current Liverpool meeting represents a realisation of his vision toward more cross-disciplinary thinking in the Geosciences.

As with all good Geoscience practice, this VMSG-TSG-BGA symposium began with a key observation (that significant advances can be made at disciplinary interfaces), followed by the building of a collaborative project team to test its viability (the contributing SIGs); next, the design of a testable outcome (that SIG collaboration may develop new ideas and areas of investigation), and then the running of the 'experiment' (this Liverpool Joint Assembly). The 'outcome and result' of that experiment will, hopefully, be 'measurable' in terms new ideas for research collaboration, grant proposals and papers. So, having now joined us Liverpool, this latter stage of this 'project', the fate of its success and legacy is now your hands…

Finally, the VMSG Committee are looking forward to seeing old friends (yes, some of you have been making the annual pilgrimage to our meeting for decades - and have contributed as postgraduates, and as professors) – but especially to those of you for whom VMSG is still a novel experience – welcome to our 'scientific family'.

Especially, we are delighted to so many young geoscientists here. We sincerely hope this forum will play positive role at the start of your own scientific journey.

History

VMSG: The Volcanic and Magmatic Studies Group (VMSG) is a joint specialist group of both the Mineralogical Society of Great Britain & Ireland and the Geological Society of London. The group, started in 1963-4, provides a focus for UK study of magmatic processes and volcanology through organisation and sponsorship of scientific meetings and fieldtrips. In particular, we organise an annual thematic and research in progress meeting, hosted at a UK based university venue. The Volcanic Studies Group was initially formed at Birkbeck College, University of London, on December 4th 1963, at the instigation of Dr. A.T.J. Dollar and Dr. G.P.L. Walker. The Group became formally associated with the Society as a specialist group in January 1964, and a steering committee was formed under the chairmanship of Professor F.H. Stewart. The Group's first meeting in the Society's 'apartments', held on March 18th 1964, took the form of a one-day colloquium on pyroclastic rocks. A second one-day colloquium, on acid rocks in the North Atlantic Tertiary province, was held on November 11th 1964. The latter meeting was chaired by Professor Hawkes and included contributions from Sabine (Rockall), Dunham & Emeleus (the acid rocks of Rhum), Skelhorn (the acid rocks of Ardnamurchan and Mull), Moorbath & Bell (Sr isotope studies), Walker (the acid rocks of Iceland), Cann (Ascension Island) and Le Bas (Carlingford), among others. VSG continued to grow henceforth, with the meeting of 21-22 October 1966 on 'the Origin and Evolution of Basaltic Magmas' being unusual for two reasons; it was a 2-day symposium, and it was held in the Grant Institute at the University of Edinburgh – the first meeting of the VSG away from Burlington House. Following the Edinburgh meeting, the tradition of holding a meeting in a different Department each year seems to have developed, with the 1967 meeting in Sheffield and 1968 in Manchester. The first AGM of the Group was held on the 18th of January 1967 and the Group's first committee was elected, with Peter Sabine as Chair.

This information was taken and edited from the official VMSG website (www.vmsg.org.uk)

TSG: The Tectonic Studies Group (TSG) has existed since the early 1970s as a forum for discussion of research in structural geology and tectonics. It has the status of a specialist group affiliated to the Geological Society of London, but has no formal membership. All are welcome to attend meetings and to propose and organize events such as conferences, workshops and field excursions. The lack of formality of TSG meetings provides a suitable environment for the testing of new ideas and the discussion of research in progress. The group particularly encourages young researchers to present their results.

This information was taken from the official TSG website (www.tectonicstudiesgroup.org)

BGA: The British Geophysical Association is a Joint Association of the Geological Society of London and the Royal Astronomical Society. Its aims are to promote the subject of geophysics, and to strengthen the relationship between geophysics and the other natural sciences in the UK. Membership of the BGA is open to Fellows of either of the parent Societies.The Geological Society of London was founded in 1807, and is the UK national society for geoscience. The Royal Astronomical Society (RAS) was founded in 1820, and promotes the study of astronomy, solar-system science, geophysics and closely related branches of science. Both societies have a long history of sponsoring meetings and publishing research on topics such as earthquakes, and the Earth's gravity and magnetic fields. Despite the BGA's association with the oldest geological and astronomical societies in the world, it has had a relatively short history. The BGA was formed in 1980 but was originally called the Joint Association for Geophysics (JAG); the name British Geophysical Association was adopted in 1997 and the current BGA logo was designed in 2010.

This information was taken from the official BGA website (www.britgeophysics.org)

Conference Information

About

We are delighted to welcome you to the Joint Assembly 2017 meeting at the University of Liverpool. This is the first joint meeting of the Volcanic and Magmatic Study Group (VMSG), the Tectonic Study Group (TSG) and the British Geophysical Association (BGA).

A key aim of the conference is to celebrate the latest developments in volcanology, tectonics and geophysics and their research communities. We have put together an engaging scientific programme which presents the latest discoveries and advances in each discipline, exploring and discussing the plethora of cross-disciplinary research that is pushing the frontiers in Earth Sciences across the UK and overseas.

Liverpool is a great place to host this joint meeting, with its reputation as a fun-loving, culture-filled and vibrant city. As a European Capital of Culture winner, there is always something of interest going on in Liverpool. It also offers a fantastic range of cafes, pubs and restaurants where you will be able to continue your after-conference discussions.

Venue Information

The Joint Assembly will be held at the University of Liverpool's Central Teaching Hub (CTH); a state-of-the-art building and a unique, multi-disciplinary teaching facility. Set in the heart of Georgian-Victorian Liverpool, the University campus is an eclectic mix of old and new, punctuated by green spaces and flanked by not one but two monumental cathedrals. The venue is just a short walk from the bustling city centre, Lime Street Station and a number of other thriving areas with plenty to see and do on any budget.

The University has made a total investment of £28.6m in the new building and research equipment. The adjacent general teaching rooms and lecture theatres have been refurbished to provide a uniformly high quality student experience.

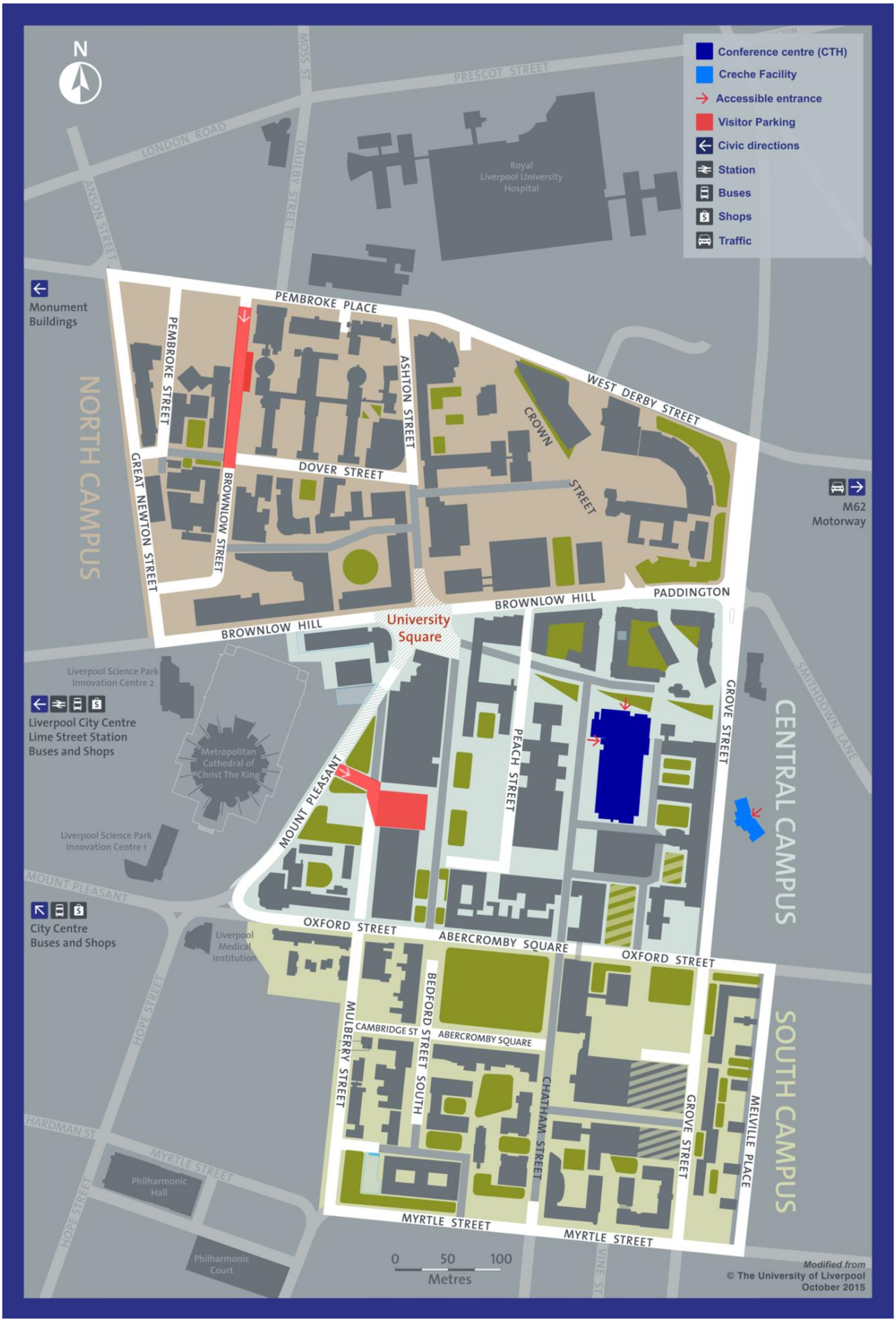
To provide an inclusive and integrated teaching experience the CTH is a fully DDA compliant building, exceeding current legislative requirements and demonstrating the University's commitment to maintaining the highest standards of building quality but also ensure it is accessible and useable by all.

The CTH was designed to meet the BREEAM "Excellent" criteria, which is extremely demanding for laboratory buildings due to the large amounts of energy consumed and the difficulty in minimising losses. To compensate for this CTH was constructed as a long span steel frame with precast concrete floors units, clad in Corten steel and limestone veneer. Exposed concrete surfaces provide thermal mass to improve energy efficiency, which has been paramount in the building's design with passive ventilation where possible, solar shading, low velocity air distribution, chilled beams, high ceilings to maximise day lighting, use of heat and power from a campus Energy Centre, and solar heating.

Registration Desk

Upon arrival to the conference venue please collect your registration welcome pack. The registration desk will be based at the entrance of the CTH throughout the conference.

Campus Map


N
Conference centre (CTH)
Creche Facility
Accessible entrance
Visitor Parking
Civic directions
Station
Buses
Shops
Traffic
PRESCOT STREET
LONDON ROAD
MOSS ST
DAULBY STREET
ANSON STREET
Royal Liverpool University Hospital
Monument Buildings
NORTH CAMPUS
PEMBROKE PLACE
PEMBROKE STREET
ASHTON STREET
WEST DERBY STREET
CROWN STREET
DOVER STREET
GREAT NEWTON STREET
BROWNLOW STREET
BROWNLOW HILL
PADDINGTON
M62 Motorway
University Square
Liverpool Science Park Innovation Centre 2
Liverpool City Centre
Lime Street Station
Buses and Shops
Metropolitan Cathedral of Christ The King
Liverpool Science Park Innovation Centre 1
MOUNT PLEASANT
PEACH STREET
GROVE STREET
SMITHDOWN LANE
CENTRAL CAMPUS
City Centre
Buses and Shops
Liverpool Medical Institution
OXFORD STREET
ABERCROMBY SQUARE
HOPE STREET
BEDFORD STREET SOUTH
MULBERRY STREET
CAMBRIDGE ST
CHATHAM STREET
MELVILLE PLACE
SOUTH CAMPUS
HARDMAN ST
MYRTLE STREET
Philharmonic Hall
Philharmonic Court
VINE ST
0 50 100
Metres
Modified from
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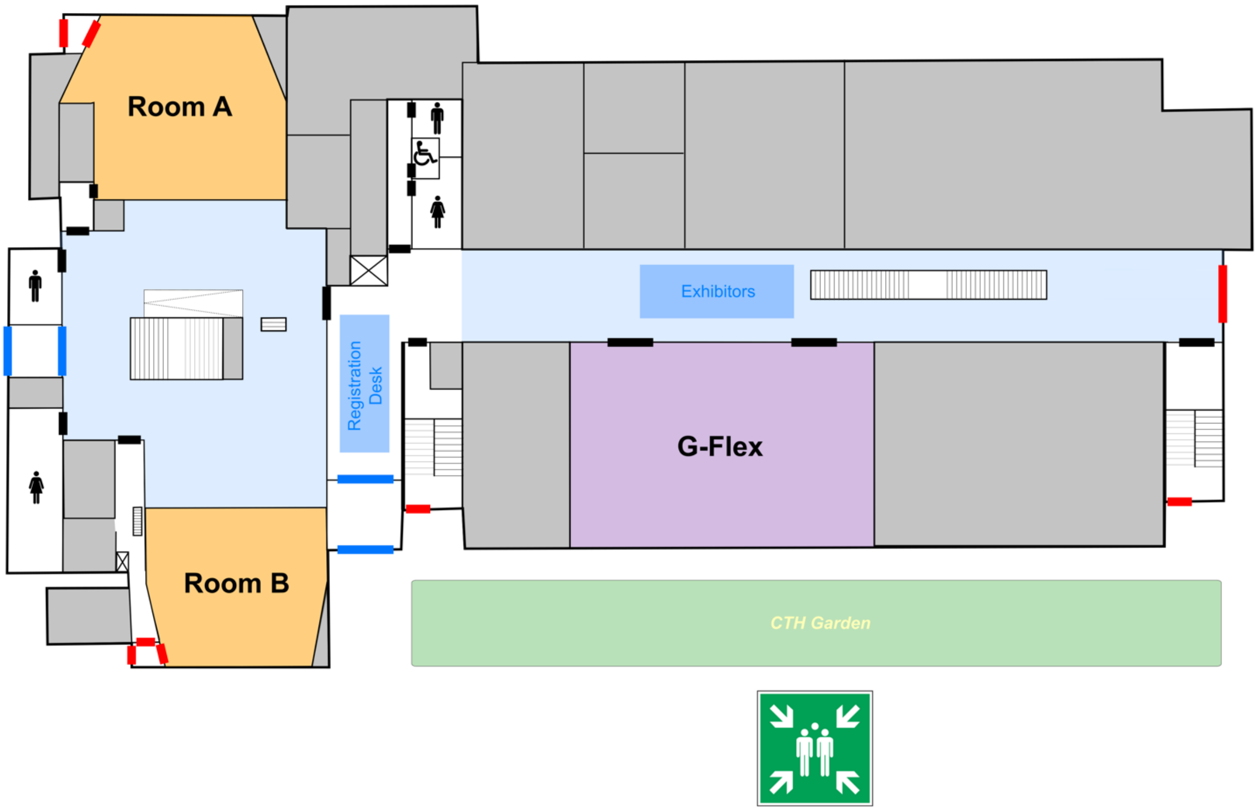
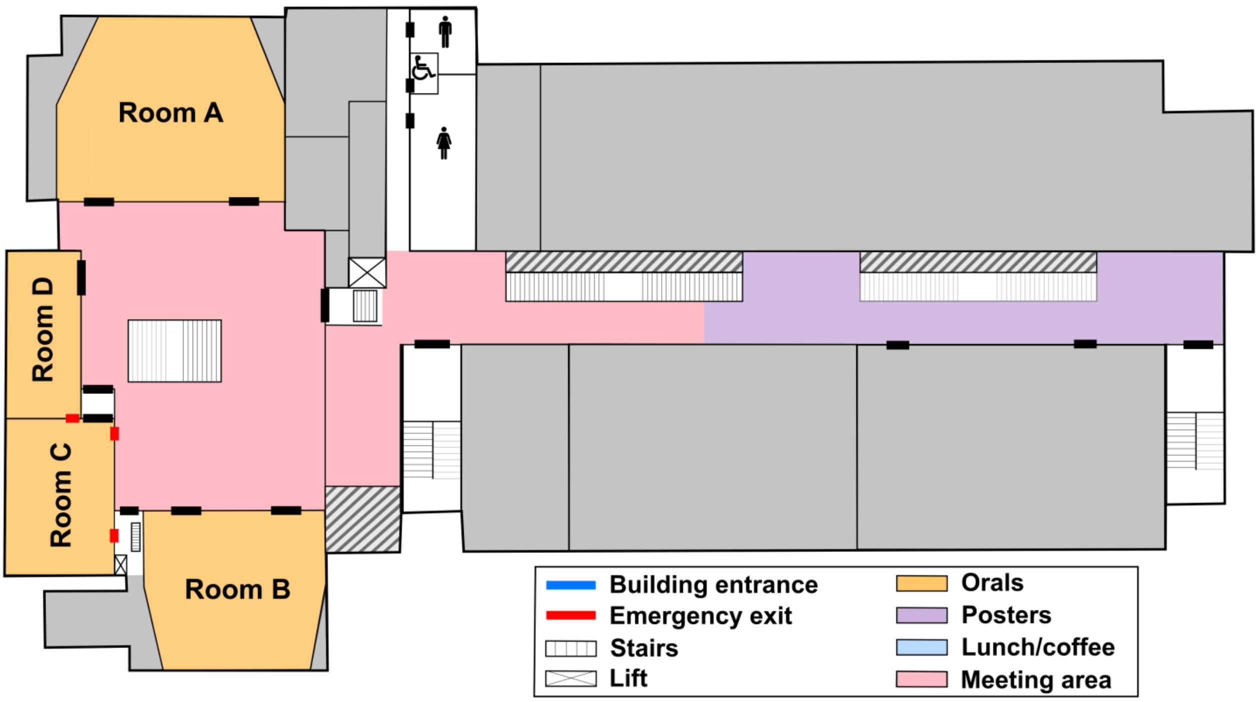
October 2015

VENUE FLOOR PLAN

Ground Floor



First Floor



Internet/Wifi Facilities

As our conference venue is held on the University of Liverpool campus, delegates will have full access to Eduroam (World Wide Education Roaming) facilities. If you do not have access to Eduroam, guest Wifi login details will be provided in your welcome packs at registration.

Social Media Policy

The Joint Assembly encourages and supports open science and welcomes discussion around the meeting on social media. All presenters have been asked to add a 'no Tweet' logo if they do not wish information to be shared on social media. Please respect this and tweet responsibly at all times, for example, do not Tweet photographs of talks or posters without permission. Our twitter page is @GeoLiv2017 and the official hashtag is #cometogether2017.

Presentation Guidelines

Oral presenters

- Please upload your talk in the correct room in the break preceeding your session.
- Talks have been allocated either 12 or 15 minutes including >2 minutes for questions.
- Ensure your presentation is kept to the allocated time in order that the conference runs on schedule.
- Presentations should be in one of the following formats: *ppt*, *pptx*, *pdf*.
- Microphones will be available.

Poster presenters

- All poster will be displayed throughout the duration of the conference in the Central Teaching Hub (CTH). Please ensure your poster is set up at your allocated poster board number.
- Poster boards are in portrait orientation.
- Velcro attachments for posters will be provided at the registration desk.

All presentation enquiries should be sent to geoconf2017@liverpool.ac.uk

Prizes

There are two prize ceremonies at which all prizes will be announced and presented:

- Thursday 5th January 17:30-18:00
- Friday 6th January 15:30-16:00

Meals and Refreshments

Lunches

Wednesday 4th January 12:45-14:15: A selection of hot meals will be served*

Thursday 5th January 12:30-14:00: Cold buffet will be served*

Friday 6thJanuary 12:30-14:00: Cold buffet will be served*

Tea/Coffee Breaks

Wednesday 4th January 09:00-10:00 & 15:30-16:00

Thursday 5th January 10:12-10:45 & 15:12-16:00

Friday 6thJanuary 10:30-11:00

***Catering has been arranged according to the dietary requirements provided at the time of registration. Information will be available onsite.

Social Programme

The conference will have a packed social calendar to keep everyone entertained throughout! This includes:

- Meet-and-Greet event at McCooley's (www.mccooleys.co.uk/) on Tuesday 3rd January from 18:00
- BGA-sponsored Ice-breaker with poster session in the Central Teaching Hub on Wednesday 4th January from 17:15-19:00
- Conference dinner & party at the fantastic Camp and Furnace (see details below; www.campandfurnace.com/) on Thursday 5th January from 19:00-02:00
- An authentic Liverpool pub crawl on Friday 6th January departing CTH at 18:30

Conference Dinner & Party

Set in the heart of Liverpool's Industrial docklands, the Camp and Furnace is part of Liverpool's now iconic Baltic Triangle - a hub of cultural activity thriving with bars, bakeries and bike-shops. The conference dinner and party will take place from 7pm on Thursday 5th January and is sure to be a night to remember!

Address: Camp and Furnace, 67 Greenland Street, Liverpool, L1 0BY

This event will include drinks and dinner (see menu on next page).

Dinner Menu

TACO TACO

PORK PIL BIL

SLOW ROAST PORK, TEQUILA & LIME, PICKLED RED CABBAGE, APPLE RELISH, WRAP

AZZOR CON POLLO

MARINATED CHICKEN THIGHS, RICE, OLIVES, JALAPENO SALSA

NARANJARDA TACOS / V

SQUASH, BLACK EYED BEANS, TACO, GUACAMOLE, CORN SALSA, SOUR CREAM

CHIPPY TEA

“FISH, PEAS & CURRY”

WHITE BEER BATTERED COD CHEEK, CRUSHED PEAS, LANCASHIRE SAUCE KETCHUP

“SAUSAGE DINNER”

GLAZED CHORIZO, CARAMELISED RED ONIONS GRAVY, POTATO SCALLOP, AIOLI

BURGERS

ALL OF OUR BURGERS ARE MADE WITH 80/20 BRITISH BEEF MINCE & BONE MARROW

CLASSIC / SMOKED BACON AND MONTEREY JACK CHEESE, ICEBERG LETTUCE

DIRTY / PULLED PORK CHEEK, CHILLI JAM, SMOKED CHEESE, ONION RINGS

GARDEN / SWEETCORN FRITTER, GREEN SAUCE, SWEET TOMATO CHUTNEY (V)

THE GARDEN

POTTED PEAS, GOAT’S CURD, FLOWERS, SHALLOTS, DILL, ONION TEXTURES

HOT ROAST POTATO CRUMBLE SOUP WITH FRESH HERBS

FATTOUSH SALAD WITH ZA’TAR & LABNEH WITH BRAZIL NUTS

ROAST SALMON CAESAR SALAD WITH BUTTERHEAD LETTUCE & CHALLAH CROUTONS

(A choice of 2 plates per person, selected drinks included, plus midnight snacks and a taster of the cake competition entries)

ADDITIONAL EVENTS

Photo Competition

The photo competition entries have been used for our front cover. Photos will be displayed throughout the conference and you can vote for your favourite until Friday morning. The winner will be announced at the prize ceremony on Friday.

Geo-Cake Competition

The winner of the cake competition will be decided at the conference dinner & party at Camp and Furnace on Thursday. So will it be a stratigraphically layered Mille-feuille, a jam-packed igneous intrusion sponge-cake or a dip-slip faulted tiramisu that takes the prize?

Lunch-time Seminar

Wednesday 4th January 13:45-14:10

Room C: How to start writing! By Olga Degtyareva, PhD

Do you need to write up your thesis or your research paper but feeling stuck with it?Even when we know we should be writing we find it difficult to actually sit down to write but instead get ourselves busy with all other things we have on our plate. When we finally find time to sit down and write, we struggle to make a start. We don't know where to start, we worry that we have not read enough yet, that the supervisor won't like it, that it will take too long and that we won't manage it on time at such a slow speed. And then we don't write. Week after week goes by (and sometimes months and years) and that paper is still not written. Sounds familiar? Well, here is the lecture that is going to talk exactly about these challenges and give you the strategies to overcome procrastination and start writing. You'll get the exact step-by-step guide so that you too can start writing, grow content fast and stay on track with your paper or thesis until completion.

Student Forum

Thursday 5th January 13:10-13:50

Room A

This is an opportunity to air your views (positive or negative), give suggestions or ask general questions.

Annual General Meetings (AGM)

Friday 6th January 13:15-14:00

Room A - VMSG

Room B - TSG

Room C - BGA

CONFERENCE EXHIBITORS AND SUPPORTERS

We would like to thank the following, whose contributions have aided the preparation of the Joint Assembly 2017:

frontiers

UNIVERSITY OF LIVERPOOL

severn thermal solutions

INSTRON®

TVR Thermalvisionresearch
Beyond light we see heat...

midland valley

nature COMMUNICATIONS

güralp

NETZSCH

ThermoFisher SCIENTIFIC

LEO LIVERPOOL EARTH OBSERVATORY

TSG Tectonic Studies Group

VMSG

BGA British Geophysical Association

Mineralogical Society

The Geological Society
serving science & profession

Royal Astronomical Society 1820
Advancing Astronomy and Geophysics

erc European Research Council

VOLCANOLOGY IN LIVERPOOL

NERC SCIENCE OF THE ENVIRONMENT

Liverpool Information

Liverpool Area Guide

Liverpool is known for its industrial past, and the footprint of industry is still evident in its architecture; this harbour town, infamous the World-over for the Beatles, the Titanic and its footballing is a cultural hub in the North of England, a locale not to be missed! We've put together a short guide to familiarise yourself with the different areas in Liverpool, and a list of the bars and eateries not to be missed.

Albert Dock: On the edge of the city centre, the Albert dock is one of the most iconic places to visit in Liverpool. A huge warehouse converted into luxury apartments, shops, restaurants, museums, and hotels, Albert dock is the place not to miss in Liverpool!

The Baltic Triangle: Used as storage when 40% of the world's trade was passing through Liverpool, the Baltic Triangle's warehouses have nowadays been converted and renovated into restaurants, pubs and nightclubs or even ephemeral art galleries. About 15 minutes' walk away from the city centre, you will be able to enjoy the Baltic Triangle's delights during our social dinner.

The Cathedrals: Because one cathedral is too normal, Liverpool has two! At either end of the aptly named Hope Street you can clamber to the top of the impressive tower of the Anglican Cathedral for an unparalleled view over Liverpool and across the estuary to Wales, or enjoy the beauty of the glass work inside the circular Metropolitan Cathedral.

Liverpool One: Newly built, Liverpool One is the city centre shopping area. Counting numerous shops, Liverpool One also offers all the usual chain restaurants and bars, cinema and a number of other attractions such as mini-golf, seasonal markets and ice skating.

Bold Street: In between Liverpool Central and Concert Square, Bold Street offers the most cosmopolitan experience in Liverpool. Whether you want to drink coffee surrounded by arts and crafts, pick up an authentic Lebanese meal or grab some hand-made leather shoes, Bold Street has it all!

Concert Square: Located a few minutes away from the city centre by foot, Concert Square is considered to be the heart of Liverpool's nightlife. It offers a wide variety of pubs and nightclubs, from flashy in-your-face nightclubs to discrete cocktail bars; here you will find the atmosphere you're looking for. Our Ice-breaker will bring you in the centre of Concert Square for a preview.

Mathew Street: Right in the city centre, Mathew Street saw the Beatles rise to fame at The Cavern Club. Riding on the fabulous-four fame, Mathew Street has become one of the most famous places in Liverpool. It will provide you with the ultimate "Scouse experience" with its numerous pubs and clubs that almost never sleep.

Radio Tower: In close proximity to Lime street station, the Radio Tower offers a panoramic view over Liverpool, the Mersey/ the Irish Sea as well as onto the Wirral and the Ordovician mountains of Snowdonia in North Wales.

Lark Lane: Leading to Sefton Park, Lark lane has become famous thanks to its bohemian style. Packed with numerous craft stores, antique and vintage shops, and independent cafes, bars and restaurants this is the ultimate spot for brunch or a chilled night out!

TAXI SERVICES

Taxis are a cheap and convenient way of getting around in Liverpool, cheaper-still than hailing a black cab, a number of private hire options are available by phone or with Apps for apple and android:

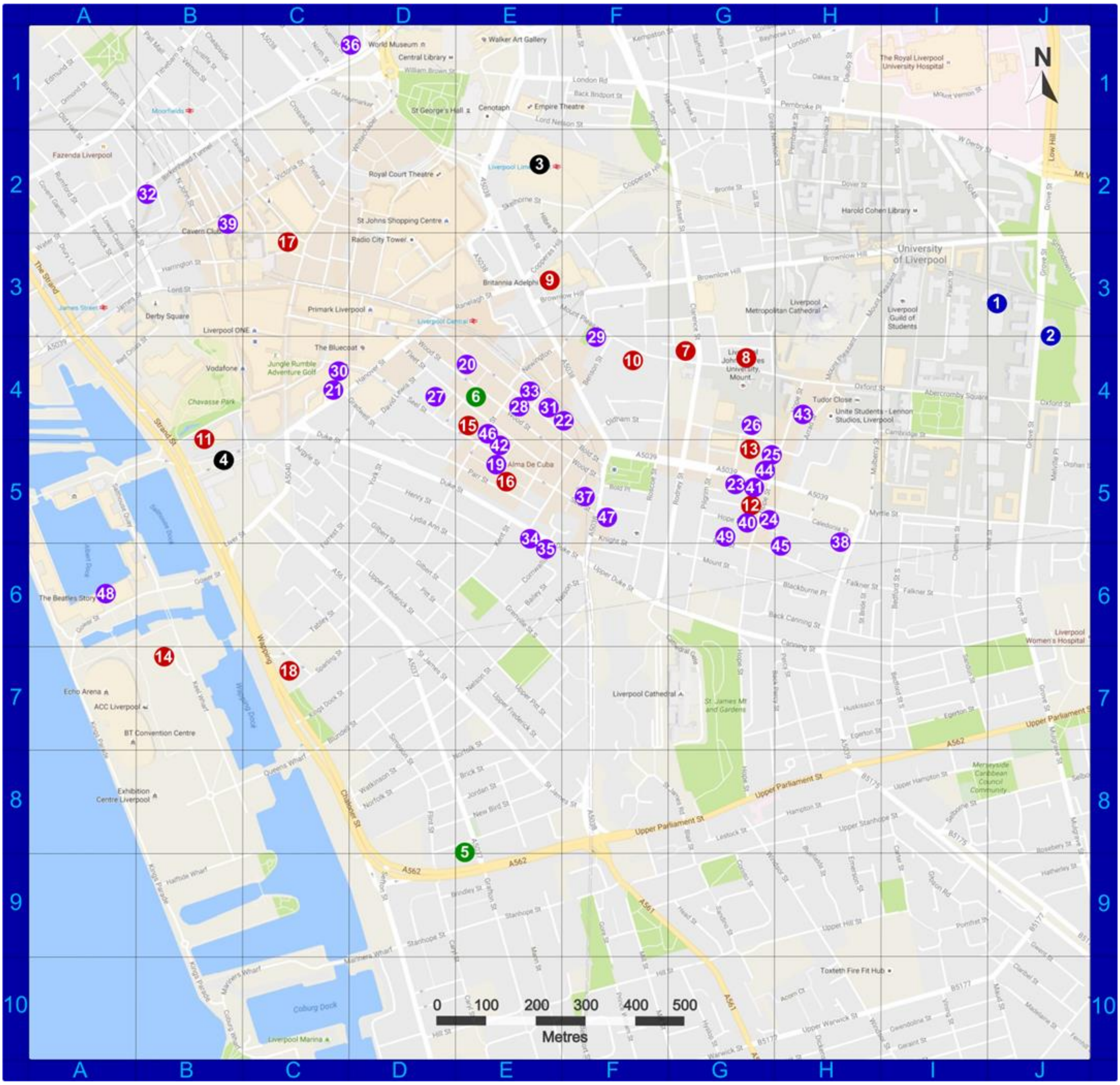
Delta - 0151 922 7373

ComCab - 0151 298 2222 (5 passenger seats as standard)

Alpha - 0151 722 8888

Village - 0151 427 7909

Bars and Eateries



Conference interest points

1. **Conference Venue (CTH)** *J3*
2. **Crèche Facility** *J3-J4*

Transports

3. **Lime Street Station** *E2*
4. **Liverpool One Bus Station** *B5*

Conference Events

5. **Conference Dinner (Camp and Furnace)** *E8-E9*
6. **Meet and Greet (McCooley's)** *E4*

Hotels

7. **Aachen Hotel** *G4*
8. **Best Western Hallmark** *G4*
9. **Brittania Adelphi** *E3*
10. **Hatters Hostel** *F4*
11. **Hilton Liverpool** *B4-B5*
12. **Hope Street Hotel** *G5*
13. **International Inn** *G5*
14. **Jurys Inn** *B7*
15. **The Nadler** *E4*
16. **Parr Street Hotel** *E5*
17. **Signature Living** *C3*
18. **YHA Liverpool** *C7*

Bars and restaurants

19. Alma de Cuba *E5*
A Cuban-fusion restaurant in a converted church complete with palm trees and the best cocktails in town, book for dinner in advance not to be disappointed, or stop by to visit the ground-floor bar.

20. Bakchich *E4*
Specialises in Lebanese street food, something you may never have known you wanted until you tried it!

21. Bem Brazil *C4*
An award-winning Brazilian Restaurant where you can enjoy a Rodizio style barbecue and plentiful buffet!

22. Bold Street Coffee *E4-F4*
Undoubtedly the most potent coffee in town, with great little snacks too.

23. Buyers Club *G5*
Newly opened bar with an ever-evolving beer and wine list, cool ambiance and good music, also offering small plates and snacks.

24. Ego *G5*
Serves rich Italian / Mediterranean style food. Ideal for a nice, affordable sit-down dinner in a handy location near the conference.

25. Fredericks *G5-H5*
Serves stone-baked pizzas and hearty burgers at an affordable price, as well as being a brewery.

26. Free State Kitchen *G4*
A burger restaurant with plenty of choice, just off Hope Street, ideal to get warm during winter!

27. Grove *D4*
A small hidden bar with inventive tapas dishes and chilled atmosphere just off Concert Square.

28. Kasbah *E4*
Serves balanced, authentic and healthy Moroccan cuisine in a relaxed setting on Bold Street.

29. Kimos *F3-F4*
A Mediterranean style restaurant serving high quality kebabs and koftas right next to Hatters Hostel.

30. Lunya *C4*
A Catalan deli and tapas bar, serves the best selection of wine around; located down a pedestrian side-street out of the hustle and bustle of the city centre, this place is a gem.

31. Leaf *E4*
A tea shop, artisan café, independent bar and all round hub of social activity, made all the more enticing by a delicious range of plates and platters.

32. Moose Coffee *B2*
Provides big, hearty North American breakfasts, just what you need after a night out.

33. Raggas *E4*
A Liverpool institution, offering Caribbean flavour in the heart of the city; the jerk chicken is not to be missed!

34. Sapporo Teppanyaki *E5*
A Japanese restaurant like no other; your own personal chef will give a real show!

35. Savina *E6*
A Mexican restaurant with great authentic food and potent margaritas at a mid-range budget.

36. Ship and Mitre *C1-D1*
An old-fashioned pub, serving a wide range of European beers. Ideal if you're looking for Belgian and German beers.

37. Slims Pork Chop Express *F5*
The perfect pit-stop for everything you shouldn't be craving but are!

38. The Caledonia *H5-H6*
A favourite amongst the alternative scene in Liverpool, serving a range of ales and beers and good home-cooked meals at a steal.

39. The Cavern Club *B2*
An iconic venue originally opened in 1957 as a jazz club, it later became an infamous venue thanks to the Beatles – you can stop by any time of day or night for all kinds of entertainment!

40. The London Carriage Works *G5*
A top-notch restaurant offering a small but carefully selected lunch and dinner menu, and exceedingly good afternoon teas!

41. The Old Blind School *G5*
Recently refurbished and now a classic gastro-pub / restaurant with a varied menu and a good drink selection just 10 minutes from the conference venue.

42. The Peacock *E4-E5*
Serves great stone-baked pizza in a trendy location just off Concert Square; this converted townhouse is great for an easy dinner-to-drink transition.

43. The Pen Factory *H4*
A pub-restaurant that serves a range of UK and European beers, along with rich and fancy tapas and bistro-style food.

44. The Philharmonic *G5*
A landmark pub on Hope Street, hosting a great selection of ales and the World's only grade II listed urinal; that in itself is a must-see!

45. The Quarter *H5-H6*
A staple pasta and pizza restaurant just up the street from Hope Street Hotel.

46. The Shipping Forecast *E4*
A converted warehouse-turned pub with good food in big portions served along to a great soundtrack, a Liverpool staple.

47. TriBeCa *F5*
A pizza place / nightclub. This is a great place to line your stomach for a night out.

48. Vinea *A6*
A small wine bar right on Albert Dock, an ideal spot for a quiet drink and a cheese platter.

49. Ye Cracke *G5*
Best known for being John Lennon's hideout during college, this quirky place has low beams, crooked floors and real ale!

SCIENTIFIC PROGRAMME

MEET YOUR KEYNOTES

Keynote Speaker 1: **Professor Freysteinn Sigmundsson** (Wednesday 4th, 10:10-11:00, room A)

Freysteinn Sigmundsson finished a Ph.D. degree in Geophysics at University of Colorado, Boulder in 1992, after completing undergraduate and MS degree at University of Iceland. He is a research professor at the Nordic Volcanological Centre, Institute of Earth Sciences at University of Iceland. Together with a wide network of collaborators he has applied Global Positioning System (GPS) geodesy and interferometric analysis of synthetic aperture radar images (InSAR) to map deformation and study geological processes, with focus on volcanism, magmatic and tectonic processes, plate spreading, earthquakes, and glacio-isostasy. He was the coordinator of FUTUREVOLC, an EC funded volcanological supersite project 2012-2016 and is a point of contact for the Icelandic volcanoes permanent geohazard supersite. He has responded to, provided advice to the Iceland Civil Protection, and published on all recent eruptions in Iceland.

The 2014-2015 caldera collapse, lateral dike formation, and major effusive eruption in the Bardarbunga volcanic system, Iceland

FREYSTEINN SIGMUNDSSON*[1], MAGNÚS T GUDMUNDSSON[1] KRISTÍN JÓNSDÓTTIR[2], ANDREW HOOPER[3],SÆMUNDUR A. HALLDÓRSSON[1], EOGHAN P. HOLOHAN[4,5], BENEDIKT G. ÓFEIGSSON[2], SIMONE CESCA[4], KRISTÍN S. VOGFJÖRD[2], PÁLL EINARSSON[1], OLGEIR SIGMARSSON[1,6], ALEXANDER H. JAROSCH[1], SIGRÚN HREINSDÓTTIR[7], ELÍAS RAFN HEIMISSON[1,8], MICHELLE PARKS[1], STÉPHANIE DUMONT[1] AND OTHER COAUTHORS ON BARDARBUNGA PAPERS

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[5]UCD School of Earth Sciences, University College Dublin, Ireland.
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[8]Now at Stanford University, California, USA.

The plate boundary in Iceland offers outstanding prospects for multidisciplinary studies of volcanic eruptions and magma plumbing systems. For example, recent events within the partly subglacial Bardarbunga volcanic system provide opportunities to understand links between the formation of a 48-km long dyke, a 65 m caldera collapse at one end of the dyke, over a period of 180 days, and a 1.5 ± 0.2 km^3 effusive eruption at the other end of the dyke. Data sets used to model the activity include seismic observations (location and rate of seismicity, fault plane solutions, moment tensor solutions), geodetic measurements (GPS, InSAR, radar altimetry), radio-echo soundings of ice thickness, geochemistry and petrology of eruptive products and sub-aerial gas measurements. The temporal relation of seismicity and deformation, coupled with constraints from topography and ice surface on dike propagation, 3D ice flow modelling in the Bardarbunga caldera and distinct element method (DEM) numerical modeling for the Bardarbunga collapse were also utilized to model the evolution of this major caldera collapse and rifting event. The data are consistent with a caldera collapse initiated through withdrawal of magma, and lateral migration through a 48-kilometers-long dike, from a deep reservoir, approximately 12-kilometers under the caldera. Interaction between the pressure exerted by the subsiding reservoir roof and the physical properties of the subsurface flow path explain the gradual, near-exponential decline of both collapse rate and the intensity of the 180-day-long eruption.

Keynote Speaker 2: **Professor Yan Lavallée** – 2016 winner of the VMSG Award (Thursday 5th, 11:57-12:30, room A)

Chair of Volcanology and Magmatic Processes at the University of Liverpool, Yan Lavallée received his B.Sc. (2001) in Earth and Planetary Sciences from McGill University, Canada, his M.Sc. (2003) in Space Studies from the University of North Dakota, USA, and his PhD (2008) in Mineralogy from the Ludwig Maximilian University, LMU-Munich, Germany. Between 2008 and 2012 he held the position of Assistant Professor in Volcanology at the LMU-Munich until he was appointed at the University of Liverpool, where he built an experimental volcanology and geothermal research facility, partially funded by the European Research Council. Professor Lavallée's principal research interest is in understanding the mechanics of magma and rocks, and their impact on volcanic, hydrothermal and geothermal systems via interdisciplinary scientific collaborations. He has been involved in a number of international projects (VUELCO, MED-SUV, HOTSPOT) and partakes in the ongoing ICDP-funded Krafla Magma Drilling Project. He is a member of the Institute for Risk and Uncertainty at the University of Liverpool and Chair of Physical Sciences and Engineering in the Young Academy of Europe, *Academia Europaea*.

Strain Localisation in Magma: a multidisciplinary collaboration

YAN LAVALLÉE *[1], JACKIE E. KENDRICK[1], FELIX W. VON AULOCK[1], ANTHONY LAMUR[1], ADRIAN HORNBY[1], OLIVER LAMB[1], PAUL WALLACE[1], REBECCA COATS[1], JAMES ASHWORTH[1], GUÐJÓN HELGI EGGERTSSON[1], AMY HUGHES[1], SILVIO DE ANGELIS[1], SARAH HENTON DE ANGELIS[1], RICHARD WALL[1], FABIAN B. WADSWORTH[2], JEREMIE VASSEUR[2], WENJIA SONG[2], DONALD B. DINGWELL[2]

[1]Department of Earth, Ocean and Ecological Sciences, University of Liverpool, 4 Brownlow Street, Liverpool, U.K. (ylava@liv.ac.uk)
[2]Department of Earth and Environmental Sciences, Ludwig Maximilian University of Munich, Germany.

The heterogeneous distribution of structures in the Earth enhances strain localisation. Just as magmatism is a manifestation of strain localisation in the lithosphere, volcanism reflects the degree of strain localisation in magma (SLiM). Amongst the many volcanic processes that threaten our environment, the spectacular switch from low-risk effusive to high-risk explosive eruptive behaviour is a direct consequence of SLiM during transport in volcanic conduits.

Our understanding of volcanic eruptions has increased manifolds in recent decades as a result of growing interdisciplinary research strategies worldwide. In particular quantification of the physico-chemical processes underlying eruptive activity is advancing, thanks in part to controlled laboratory experimentation, which provides an opportunity to access the fundamentals of materials behaviour and gauge eruption simulations. Here, we review how laboratory studies on strain localisation in magma have contributed to answer some of the questions raised by geological, geophysical and geochemical studies, discussing processes ranging from volatile exsolution and outgassing to deformation and seismogenic faulting processes associated with volcanic unrest.

Keynote Speaker 3: **Professor Othmar Müntener** (Thursday 5^{th}, 14:00-14:30, room A)

Othmar Müntener is a professor for igneous petrology at the University of Lausanne, Switzerland. After graduating from ETH, post-docs at WHOI, MIT and ETH, and a research fellow position in Neuchatel, he was awarded a prestigious Swiss National Science foundation professorship before moving to Lausanne in 2006. He is a petrologist by training combining field studies, geochemistry, and experiments and working on the formation and evolution of continental and oceanic crust, subduction zone processes, and the formation of ocean-continent transition zones. His research group is using and developing LA-ICP-MS methods to study Earth material processes.

Key role of mantle rocks for rifted margin studies: observations, data and speculations

OTHMAR MÜNTENER*[1]

[1]Institute of Earth Science, University of Lausanne, Géopolis, CH-1015 Lausanne Switzerland (othmar.muntener@unil.ch)

Mantle peridotites and their serpentinized counterparts from ocean-continent transition zones (OCT's) and (ultra-) slow spreading ridges question a series of 'common beliefs' that have been applied to understand Alpine-type orogens in the framework of the ophiolite concept. Among these are: (i) the assumption of a simple genetic link between mantle melting and mafic (MORB-type) magmatism, (ii) that pre-collisional continental crust and oceanic crust can be reconstructed and used to estimate the size of small subducted oceanic basins. Here I provide a synopsis of mantle rocks from the European realm and the Iberia-Newfoundland rifted margins to show that inherited mantle signatures from previous orogenies play a key role for the interpretation of ophiolites, and that peridotites from present-day passive margins show striking similarities to the metamorphic equivalents in Alpine type orogens. Field data and petrology shows that ancient, thermally undisturbed, pyroxenite-veined subcontinental mantle formed parts of the ocean floor next to thinned continental crust. These heterogeneities might comprise an ancient subduction component. Mantle upwelling and decompression melting during rifting forms partial melts that enter a thick conductive lithospheric mantle and inevitably leads to freezing and refertilization of the lithospheric mantle. Such a 'lithospheric mantle sponge' may explain the difference between magma-poor and volcanic margins, and anomalous isostatic response in the sedimentary record. Mafic bodies are small and discontinuous. Plagioclase peridotites in Alpine ophiolites are interpreted as recorders of refertilization processes related to thinning and exhumation of mantle lithosphere. Another important result is the discovery of extremely refractory Nd-isotopic compositions with highly radiogenic $^{147}Sm/^{144}Nd$ indicating that partial melting processes in the mantle and Jurassic magmatism in the Western Tethys are decoupled. Although the isotopic variability might be explained by mantle heterogeneities, an alternative is that depleted domains represent snapshots of melting processes that are related to previous crust forming processes. The findings of refractory mantle rocks in the Western Alpine arc and the similar model ages of depletion suggests a connection to Early Permian magmatism. If the dimensions of mantle exhumation and the formation of proto-oceanic crust can be compared to the Iberia-Newfoundland or the Australian - Antartic margins, then there is little room for true oceanic crust in the Ligurian Tethys. Possible consequences will be discussed.

Keynote Speaker 4: **Doctor Sue Loughlin** - 2017 winner of the VMSG Award (Friday 6th, 11:00-11:30, room A)

Dr Sue Loughlin has been Head of Volcanology at the British Geological Survey since 2008. She leads a multidisciplinary team of scientists studying topics from volcanic processes, volcano monitoring and volcanic hazards to volcanic risk. Dr Loughlin worked at the Montserrat Volcano Observatory as Deputy Chief Scientist between 1997 and 1999 and then as Director from 2004 to 2006. She has continued to work in volcanic hazards and risk since then and was instrumental in integrating volcanic risk into the UK National Risk Register from 2010. She has worked in Ethiopia, Tanzania, Iceland, Ecuador, Colombia, Mexico, St Vincent and Montserrat in a variety of projects. She co-leads the Global Volcano Model network, with Professor Sparks at Bristol University. This growing collaboration of volcano scientists worldwide compiled the first global assessment of hazard and risk for UNISDR in 2015 and is continuing to raise the profile of volcano science worldwide.

Global monitoring, reporting and anticipation of volcanic activity: can we do it?

SUE LOUGHLIN*[1]

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Our efforts to understand how volcanoes work, from the generation of magma through magmatic and eruptive processes to the transport of eruptive products, have never been more important. This knowledge underpins interpretation of observations and monitoring signals, it underpins activities such as ‘expert elicitations’ that are increasingly needed to deal with uncertainties when addressing hazards and risk, it underpins the way we talk about volcanoes and communicate with the public and other decision-makers. There is also an increasing demand for information about volcanoes from communities, governments, the private sector, NGOs, the media and others, sometimes these demands are immediate and sometimes more long term but this information must be backed by robust scientific evidence. In this talk I will discuss how robust scientific studies and the collation and availability of sound data are essential as we tentatively step into a world of global monitoring and reporting.

Keynote Speaker 5: **Professor John Ludden CBE** (Thursday 5th, 14:15-14:45, room C)

Executive Director at the BGS since 2006, John Ludden has held numerous science direction and management posts. He was Director of the Earth Sciences Division at the French National Centre for Scientific Research (CNRS) and also served as Director of Research for the CNRS in Nancy, France, where he also taught at the French National School of Geology (ENSG-Nancy). Prior to this, Professor Ludden worked at the University of Montreal, Columbia University and with Woods Hole Oceanographic Institution in the USA. He holds a doctorate in Igneous Petrology from the University of Manchester, UK. Professor Ludden is a visiting professor at Oxford and Leicester universities and a Foreign member of the Russian Academy of Sciences. He is a past president of the European Geosciences Union and also EuroGeosurveys.

The Energy Security and Innovation Observing System for the sub-surface (ESIOS)

JOHN LUDDEN *[1], MIKE STEPHENSON[1], GEOFF BAXTER[1]

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New and emerging subsurface energy technologies could make a major contribution to the energy security of the UK, the UK economy and to jobs. However, the complexity of geological conditions in the UK means that there is a need to better understand the impacts of energy technologies on the subsurface environment. Our vision is that the Energy Security and Innovation Observing System for the sub-surface (ESIOS) research facilities will allow us to carry out ground-breaking scientific monitoring, observation and experimentation to gather critical evidence on the impact on the environment of a range of geoenergy technologies. The Natural Environment Research Council (NERC) through the British Geological Survey, the UK environmental science base and in collaboration with industry, will deliver the ESIOS project comprised of two new world-class subsurface research facilities. These facilities will enable rigorous, transparent and replicable observations of subsurface processes, framed by the ESIOS Science Plan. They will form the heart of a wider distributed network of sensors and instrumented boreholes for monitoring the subsurface across the UK. Scientific research will generate knowledge applicable to a wide range of energy technologies including: shallow geothermal energy, shale gas, underground gas storage, coal bed methane, underground coal gasification, and carbon capture and storage.

SESSION DESCRIPTIONS

Heterogeneity in the Earth: From micro to macro scale (session 1)

Jackie E. Kendrick, University of Liverpool, Jackie.kendrick@liverpool.ac.uk
Anthony Lamur, University of Liverpool, Anlamur@liverpool.ac.uk

This session aims at bringing together all fields of geology and geophysics to challenge the common assumption of homogeneity and isotropic processes in geological settings. The session provides a platform to discuss the impact of heterogeneity across all scales, from micro-scale features (e.g. crystals, micro-cracks, pores) to outcrop scale (e.g. faults, shear zones) to Earth-system scale (e.g. mantle segregation). This session will welcome studies from any discipline, and studies which incorporate a multi-parametric approach. Ultimately, we aim to highlight and examine how complexity arises in geological settings, dependent upon the length-scale of observation and how we can incorporate this intricacy into our current models and understanding of the Earth.

The volatile Earth: The role of liquids and gases in the dynamic solid Earth (session 2)

Tom Garth, University of Liverpool, Tomgarth@liverpool.ac.uk
Felix von Aulock, University of Liverpool, F.Von-Aulock@liverpool.ac.uk

In recent decades, understanding the role of volatiles in Earth systems has become a major research theme across numerous solid Earth disciplines. Volatiles are thought to impact processes as significant and diverse as mantle convection, the deformation of subducted slabs, and styles of volcanic activity. We invite researchers from across the geoscience disciplines to show the role that volatiles play in the Earth system that they study; including the delivery of volatiles to the deep Earth, the effect of volatiles in the Earth's mantle and crust, the role of volatiles in subduction and subduction-related volcanism, and the impact of magmatic volatiles on volcanic activity.

Tectonic and magmatic processes during continental extensional tectonics and rifted margin formation (session 3)

Nick Kusznir, University of Liverpool, SR11@liverpool.ac.uk
Caroline Harkin, University of Liverpool, Sgcharki@student.liverpool.ac.uk
Julia Gómez Romeu, University of Liverpool, Juliagr@liverpool.ac.uk

This session focuses on advances in our knowledge and understanding of magmatic and tectonic processes during continental extensional tectonics, including basin development and the formation and subsequent evolution of continental rifted margins. The timing, composition and quantity of magmatism and their relationship to the evolution of extensional processes (whether cause or effect?) remain important questions, as are the linkages between melt extraction and emplacement processes and tectonics. We welcome abstracts from both geological and geophysical studies based on field, laboratory or seismic observations, or from modelling.

Seismology, geodesy and remote sensing: Methodologies and applications (session 4)

Pablo J. Gonzales Mendez, University of Liverpool, Pjgonzal@liverpool.ac.uk
Ryan Lloyd, University of Bristol, Ryan.lloyd@bristol.ac.uk
Oliver Lamb, University of Liverpool, Olamb245@liverpool.ac.uk
Jessica Johnson, University of East Anglia, Jessica.johnson@uea.ac.uk
Susanna Ebmeier, University of Leeds, S.K.Ebmeier@leeds.ac.uk
Silvio De Angelis, University of Liverpool, Silvioda@liverpool.ac.uk

In recent years, the extensive use of seismic and ground deformation networks and satellite remote sensing have significantly improved our capability of monitoring volcanic and tectonic activity. In addition, new models and processing techniques have led to innovative contributions in the interpretation and inversion of observational data. Each discipline are also priorities for training the next-generation of scientists to monitor and report on geohazards. Within this context, this session aims to bring together the latest in observations, methods and models that improve our understanding within the fields of seismology, geodesy and remote sensing.

Jon Davidson Memorial Session: Magma genesis, storage and transport (session 5)

Sarah Henton De Angelis, University of Liverpool, Shdeange@liverpool.ac.uk
Janine Kavanagh, University of Liverpool, Janinek@liverpool.ac.uk
Paul Wallace, University of Liverpool, Paul.wallace@liverpool.ac.uk

This special session will be held in honour of Professor Jon Davidson and provides an opportunity to reflect on the legacy of his research and to celebrate his many contributions to our community. Jon's research was focused on magmatic processes in subduction zones, and in particular how geochemistry and petrology can be used to unlock the mysteries of volcanic activity. In this session, we will focus on how styles of volcanic activity are controlled by the physical and chemical parameters of the magma. In turn, these attributes reflect the history of the magma, from genesis to subsequent evolution during storage and transport. The defining features of a magma, including its physio-chemical properties and the processes that contributed to its development, are recorded in melt and mineral phases, and in the nature of interactions with other materials (e.g., other magma bodies, host rocks). We invite contributions from researchers investigating magma genesis, storage, and transport using experimental and analytical methods in mineralogy, petrology, physical volcanology, and/or field volcanology.

The structure and mechanics of fault zones (session 6)

Stefano Aretusini, The University of Manchester, stefano.aretusini@postgrad.manchester.ac.uk
Matteo Demurtas, Università degli Studi di Padova, matteo.demurtas@phd.unipd.it
Giulio Di Toro, The University of Manchester, giulio.ditoro@manchester.ac.uk
Michele Fondriest, The University of Manchester, michele.fondriest@manchester.ac.uk

Fault zones are one of the most common geological features in the Earth and they impact human activity on a daily basis (from seismic hazards, to mining activities, to exploitation of hydrocarbon and water reservoirs, etc.). In this broad-targeted session, we welcome contributions aimed at constraining the structure and mechanics of fault zones by means of (1) geological and geophysical (e.g., geodetic, seismological, magnetotelluric) investigations, (2) experimental studies (e.g., rheology of brittle faults and ductile shear zones), (3) microstructural/ mineralogical/ geochemical investigations of natural and experimental products (e.g., fault-related processes and fluid-rock interaction) and, (4) modelling (e.g., evolution of fault zones with time).

Georesources and geohazards in an evolving planet (session 7)

Yan Lavallée, University of Liverpool, Yan.lavallee@liverpool.ac.uk
Guðjón Helgi Eggertsson, University of Liverpool, G.Eggertsson@liverpool.ac.uk
Sergio Leon Rios, University of Liverpool, Leonrios@liverpool.ac.uk
James Holt, University of Liverpool, Sgjholt@student.liverpool.ac.uk

With a growing population and a politico-economic system demanding preparedness and resilience to natural hazards as well as cheap, clean, sustainable and renewable resources, all eyes turn to geoscientists to answer the need. Yet, many scientific questions remain unanswered as our models still struggle to understand the signals and predict patterns that lead to geological catastrophes, and determine the detection (location and extent) and optimal exploitation/ extraction of resources. This session aims to present advances in our understanding of geohazards as well as in our search for new energy resources, including geothermic and hydrocarbons. We welcome contributions from geologists, geophysicists, geochemists, experimentalists, geo-engineers and numerical modellers, addressing key aspects of hazard assessment and risk mitigation, and of our pursuit for new energy frontiers.

Gas, aerosols, ash and the atmosphere (session 8)

Mike Burton, University of Manchester, Mike.burton@manchester.ac.uk
Amy Donovan, Kings College London, Amy.donovan@kcl.ac.uk
Evgenia Ilyinskaya, University of Leeds, E.Ilyinskaya@leeds.ac.uk

Volcanic activity produces gas, aerosols and ash, reflecting a multitude of processes, encompassing magma chemistry and dynamics, eruption processes and climate impacts. The purpose of this session is to provide a forum for examining the state of the art in observations, experiments and modelling of the processes which produce gas, aerosol and ash emissions, and their climatic effects. We envisage contributions from satellite and ground-based remote sensing, in-situ quantification of gas and aerosol compositions, experiments on magma flow and crystallisation, modelling of magma ascent dynamics, eruption columns, plume dispersion, plume chemistry and climatic impacts. Multidisciplinary approaches which draw on combinations of observations, experiments and models are particularly encouraged.

Microstructures and deformation (session 9)

Joe Gardner, University of Liverpool, Jgardner@liverpool.ac.uk
Elisabetta Mariani, University of Liverpool, Mariani@liverpool.ac.uk

The way rocks and minerals deform in response to stress by the rearrangement of material on the grain-scale dictates the overall deformation response, from outcrop- to tectonic-scale. Resultant microstructures record the physical mechanisms that dominate strain accommodation, so can give insight into the kinematics and mechanical conditions of deformation. Temporal evolution of microstructures associated with metamorphism, including changes in grain size and dominant deformation mechanism, the development or destruction of textures, and other modifications to material parameters can induce strain localisation and changes in rheology, and thus influence the geodynamic response. We invite contributions that target the analysis of microstructures derived from nature, theory and experiment. Topics may include viscous deformation mechanisms and texture development, the brittle-ductile transition, strain localisation and the development of shear zones, effect of fluids on deformation, and associated studies addressing microstructurally-derived insights into the deformation of Earth materials.

Earth's deep interior (session 10)

Andreas Rietbrock, University of Liverpool, Ariet@liverpool.ac.uk
Andy Nowacki, University of Leeds A.Nowacki@leeds.ac.uk

The Earth's core and mantle reflect and control the long-term evolution and structure of the planet, from the creation of the magnetic field, through the subduction of the lithosphere at the surface, to the convection of material in the deep mantle. These processes bring long-term and broad-scale global dynamics to bear on the shallow surface when solar material interacts with the magnetic field, at convergent and divergent margins, in regions of isolated volcanism, where dynamic topography is significant, and in countless other ways. This session is focussed on observations, models and experiments that bring to light the properties and behaviours of the deep Earth. We invite contributions in the fields of seismology, mineral physics, palaeomagnetics, cosmo- and geochemistry, geodynamics, geoelectrics, and all relevant fields. We especially encourage integrated studies of the deep Earth and the insight gained therefrom.

Physical volcanology (session 11)

Hugh Tuffen, Lancaster University, H.tuffen@lancaster.ac.uk
Rebecca Coats, University of Liverpool, R.coats@liverpool.ac.uk
Helen Kinvig, University of Liverpool, Kinvigh@edgehill.ac.uk
Sue Loughlin, British Geological Survey, sclou@bgs.ac.uk

Physical volcanology underpins all studies of volcanism and magmatism; from chamber to crater, effusive to explosive, observations to experiments, this session will delve into the physics behind volcanism, starting at the source and moving our way up to the atmosphere. Contributions investigating the physical processes which constrain the evolution of magma, including formation, movement and eruption are encouraged, as well as studies which aim to constrain when, how and why volcanoes erupt and those which study the deposition and preservation of volcanic materials at the Earth’s surface.

Earthquakes, palaeoseismology, and rates of fault slip: from milliseconds to millions of years (session 12)

Laura Gregory, University of Leeds. L.c.gregory@leeds.ac.uk
Edmund Garrett, Geological Survey of Belgium, Egarrett@naturalsciences.be
Luke Wedmore, University College London, L.wedmore.11@ucl.ac.uk

It is possible to measure fault slip rates and the patterns of earthquakes on a huge variety of temporal and spatial scales. This session aims to bring together observations and models of fault slip across all scales, in order to better understand the complexities of earthquake recurrence, the development of fault systems, and the relationship between large scale strain accumulation and seismic energy release. We welcome contributions addressing fault slip rates and states from the fields of paleoseismology, active faulting utilising Quaternary dating techniques and/or high resolution topography, geodesy, seismology, and thermochronology. We particularly encourage contributions that address the transient nature of earthquake recurrence and fault behaviour from subduction megathrusts to continental fault networks.

New frontiers in experimentation, rock physics and magma rheology (session 14)

Michael J. Heap, Institut de Physique de Globe de Strasbourg, Heap@unistra.fr
Yan Lavallée, University of Liverpool, Yan.lavallee@liverpool.ac.uk
Claire Harnett, University of Leeds, eeceh@leeds.ac.uk
Simon Martin, University of Liverpool, Smartin@liverpool.ac.uk

Technological advances are rapidly pushing our ability to experimentally test Earth's materials under pressure, temperature and strain conditions applicable to many geological processes. With increasing depth and/or temperature, geological materials can undergo a transition in failure mode from localised brittle deformation to distributed ductile flow. The transition typically involves a change in micromechanical deformation mechanism from microcracking to a plethora of micromechanisms (cataclastic pore collapse, viscous flow, granular flow, pressure solution, intracrystalline plasticity, diffusive mass transfer, amongst others), and has important implications for fluid flow and pore pressure distribution - factors known to influence landslide, faulting processes, hydrothermal activity and volcanic eruption recurrence. Understanding material behaviour and evaluating the brittle-ductile transition for a range of geomaterials (sedimentary, metamorphic, igneous, and volcanic materials), material attributes (low- and high-porosity rocks, grain/pore size and shape, mineralogical assemblage and crystal attributes), and environmental conditions (pressure, temperature, pore fluids) therefore represents an important challenge. This session provides the opportunity for contributions that discuss the brittle-ductile transition in geological materials under geological conditions. We welcome contributions on theory and simulations, instrumentation, laboratory experiments and field measurements, data analysis and interpretation, as well as inversion and modelling techniques, tackling a range of mechanical, rheological, petrological and volcanological problems.

ORAL SCHEDULE

Day 1 - Wednesday 4th January

9:00 – 10:00 Registration opens and tea/coffee served

Student	Non-student

10:00 - 10:10

ROOM A: Welcome address: Joint Assembly Chair Yan Lavallée

10:10 - 11:00

ROOM A: Keynote 1

10:10 (Keynote 1)	**Freysteinn Sigmundsson*, Magnús T. Gudmundsson, Kristín Jónsdóttir, Andrew Hooper, Sæmundur A. Halldórsson et al.**	**The 2014-2015 caldera collapse, lateral dike formation, and major effusive eruption in the Bardarbunga volcanic system, Iceland**

11:00 - 11:15 Break

11:15 - 12:45

ROOM A: Gas, aerosols, ash and the atmosphere I (session 8)

11:15	Brendan McCormick Kilbride*, Lois Salem, Roberto D'Aleo, Peter Barry, Santiago Arellano et al.	Multi-sensor measurements of gas emissions from the volcanoes of Papua New Guinea
11:30	Thomas C. Wilkes*, Tom D. Pering, Andrew J. S. McGonigle, Angus J. Taggart, Giancarlo Tamburello et al.	The development of a low-cost UV camera and its application to the quantification of volcanic SO2 fluxes
11:45	Kerry A Reid*, Hazel Rymer, Stephen Blake, John Murray	Lava lakes and persistent degassing at Masaya volcano, Nicaragua
12:00	Giuseppe La Spina*, Mike Burton, Mattia de' Michieli Vitturi, Fabio Arzilli	Key role for syn-eruptive plagioclase disequilibrium crystallisation in basaltic magma ascent dynamics
12:15	Celine M. Vidal*, Nicole Metrich, Jean-Christophe Komorowski, Indyo Pratomo, Agnes Michel et al.	The 1257 Samalas eruption: the single greatest gas release of the Common Era
12:30	Matthew J. Genge*	The injection of volcanic dust into the mesosphere by electrostatic levitation

ROOM B: The structure and mechanics of fault zones I (session 6)

11:15	Åke Fagereng* Sabine A.M. den Hartog	Subduction megathrust creep governed by pressure solution and frictional-viscous flow
11:30	Efstratios Delogkos*, Conrad Childs, Tom Manzocchi, John J. Walsh, Spyros Pavlides	From an initially unsegmented normal fault to a complex fault zone: The role of bed-parallel slip
11:45	Michael J. Allen*, Elisabetta Mariani, Carolyn Boulton, Daniel Faulkner	Evidence for cyclical fault zone sealing and strengthening, Alpine Fault, New Zealand
12:00	Mark B. Allen*, Richard J. Walters, Shuguang Song, Christopher Saville, Nicola De Paola et al.	Partitioning of oblique convergence coupled to the fault locking behaviour of fold-and-thrust belts: evidence from the Qilian Shan, northeastern Tibetan Plateau

12:15	Daniel Possee*, Derek keir, Nick harmon, Catherine Rychert, Caroline Eakin, et al.	Crustal Imaging of Haiti’s Transpressional Fault System through Seismicity and Tomography
12:30	Alexander P. Clarke*, Paola Vannucchi, Jason Morgan	Seamount – Subduction Zone Interactions: Impact of ocean floor relief on subduction accretion/erosion & subduction channel heterogeneity

ROOM C: Earth's deep interior (session 10)

11:15	Jon Mound*, Chris Davies	The influence of mantle heterogeneity on core convection
11:30	Jessica C. E. Irving*, Sanne Cottaar Vedran Lekić	Earth’s outer core properties estimated using bayesian inversion of normal mode eigenfrequencies.
11:45	Patrick Ball*, Nicholas White, John Maclennan, Finlay Stuart	Quantifying the Relationship Between Intra-Continental Magmatism and Dynamic Topography: North Africa
12:00	Jennifer Jenkins*, Arwen Deuss, Sanne Cottaar	Searching for structure in the mid-mantle: Observations of converted phases beneath Iceland and Europe
12:15	Emmanuel C. David*, Nicolas Brantut, Lars N. Hansen, Thomas M. Mitchell	Mechanics and seismic signature of semi-brittle deformation in antigorite
12:30	Tom Garth*, Sophie Coulson, Andreas Rietbrock	Constraints on subduction zone hydration from guided wave observations from three Pacific subduction zones

12:45 – 14:15 Hot Lunch and posters incl.:

13:45 – 14:10	ROOM C - Dr. Olga Degtyareva	How to start writing!

14:15 – 15:30

ROOM A: Physical volcanology I (session 11)

14:15	Thomas J. Jones*, Edward W. Llewellin, Laura Höltgen	Exchange flow within a dyke: an analogue experimental study
14:30	Margherita Polacci*, Fabio Arzilli, Mike Burton	Conduit processes in basaltic systems by quantitative analysis of X-ray microtomographic images of volcanic rocks
14:45	Amelia A. Bain*, Eliza S. Calder, Joaquín A. Cortés, Gloria Patricia J. Cortés, Susan C. Loughlin	Shallow conduit architecture associated with cyclic vulcanian explosions at Galeras volcano, Colombia
15:00	Wim Degruyter*, Christian Huber, Olivier Bachmann	The role of pre-eruptive exsolved volatiles in changing the eruptive style at Quizapu volcano (Chile)
15:15	Robert J. Gooday*, David J. Brown, Kathryn M. Goodenough, Andrew C. Kerr.	The Arran Volcanic Formation: eruption and collapse of a well-preserved Scottish caldera

ROOM B: The structure and mechanics of fault zones II (session 6)

14:15	Conrad Childs*, Tom Manzocchi, Efstratios Delogkos, Martin Schöpfer, John Walsh et al.	A quantitative description of fault zone internal structure

14:30	Hannah Watkins*, Rob Butler, Clare Bond	Using laterally compatible cross sections to infer fault growth and linkage models in foreland thrust belts
14:45	Koen Torremans*, Roisin Kyne, Robert Doyle, John Güven and John Walsh	Fluid flow, feeders and fault zone structure – controls on metal distributions in Irish-type deposits
15:00	Christina M. Kelly*, Daniel R. Faulkner, Andreas Rietbrock	Imaging faults in anisotropic rocks
15:15	Ernie Rutter*, Julian Mecklenburgh	Hydraulic conductivity of thin, planar cracks in shale and sandstone as a function of shear and normal stress

ROOM C: Seismology, geodesy and remote Sensing: Methodologies and applications I (session 4)

14:15	Rodrigo Contreras-Arratia*, Jürgen Neuberg	Curved Seismic Source for LP Events: Model and Radiation Patterns
14:30	Oliver Lamb*, Silvio De Angelis, Yan Lavallée, Anthony Lamur, Adrian Hornby, et al.	Changes in long-term eruption dynamics at Santiaguito, Guatemala: Observations from seismic data
14:45	Tim Greenfield*, Derek Keir, Atalay Ayele, Aude Lavayssiere, J-Michael Kendall	Seismic velocity structure of Corbetti, Ethiopia
15:00	James Hickey*, Joachim Gottsmann, Haruhisa Nakamichi, Masato Iguchi	Mechanical and thermal controls on volcano deformation and magma supply
15:15	Adam J. Cawood*, Clare E. Bond, Yukitsugu Totake, John A. Howell, Robert W.H. Butler	Stackpole Quay: A case study on the applicability of virtual outcrops in structural model building

15:30 – 16:00 – Tea/ coffee break and posters

16:00 – 17:15

ROOM A: Physical volcanology II (session 11)

16:00	Ben S. Ellis*, Dawid Szymanowski, Tomas Magna, Olivier Bachmann, Marcel Guillong	The effect of cooling rates on lithium in rhyolites
16:15	Nathan Magnall*, Mike R James, Hugh Tuffen, Charlotte Vye-Brown	Emplacing a cooling limited rhyolite flow
16:30	Clarke, B*, Calder, E. S., Butler, I., Cortes, J. A., Dessalegn, F., Yirgu, G.	Peralkaline Rhyolite Achneliths with Evidence of Post-Emplacement Vesiculation at Aluto Volcano, Main Ethiopian Rift: What can these unusual pyroclasts tell us?
16:45	Jonathan Moles*, Dave McGarvie, Sarah Sherlock, John Stevenson, Peter Abbott	In search of the source of North Atlantic Ash Zone II and the Thórsmörk Ignimbrite
17:00	Kathrin Laeger*, Maurizio Petrelli, Daniele Andronico, Valeria Misiti, Corrado Cimarelli et al.	High-resolution geochemistry of volcanic ash highlights complex magma dynamics during the Eyjafjallajökull 2010 eruption

ROOM B: The structure and mechanics of fault zones III (session 6)

16:00	Tom M. Mitchell*, Blaise R. Winnard, John Browning, Philip. G. Meredith	Controls on Fracture Healing in Fault Damage Zones

16:15	Christopher Harbord*, Stefan Nielsen, Daniel Faulkner, Nicola De Paola	An experimental investigation of earthquake rupture in granite at hydrothermal temperatures (20-160oC)
16:30	Karen Mair*, Steffen Abe	3D modelling of roughness evolution and gouge production in faults
16:45	Giacomo Pozzi*, Nicola de Paola, Stefan B. Nielsen, Robert E. Holdsworth	Viscous Flow Causes Weakening in Calcite Gouges Sheared at Seismic Velocity
17:00	Sabine A.M. den Hartog*, Daniel R. Faulkner, Christopher J. Spiers	What really controls friction in phyllosilicate fault gouges?

ROOM C: Seismology, geodesy and remote sensing: Methodologies and applications II (session 4)

16:00	Andrew Hooper*, Magnús T Gudmundsson, Marco Bagnardi, Karsten Spaans, Freysteinn Sigmundsson et al.	Forecasting of flood basalt eruptions: lessons from Holuhraun
16:15	Thorbjörg Ágústsdóttir*, Jennifer Woods, Tim Greenfield, Robert G. Green, Robert S. White	Seismicity accompanying the 2014 Bárðarbunga-Holuhraun intrusion and the co- and post-eruptive activity
16:30	Tom S. Hudson*, Robert S. White, Alex Brisbourne	Exploring deep melt migration before and after an Icelandic eruption
16:45	Robert G Green*, Keith F Priestley, Robert S White	Seismic velocity structure of volcanic rift zones in Iceland
17:00	Olivier Galland*, Håvard S. Bertelsen, Frank Guldstrand, Tobias Schmiedel, Benjamin Rogers,	Dyke tip processes and large-scale deformation: implications for geodetic modelling

17:15 – 19:00

BGA-sponsored Ice-breaker and Poster session

Day 2 - Thursday 5th January

9:00 – 10:12

ROOM A (relayed on-screen in ROOM B): The volatile Earth: The role of liquids and gases in the dynamic solid Earth (session 2)

09:00	Elliot Carter*, Brian O'Driscoll, Ray Burgess, Patricia Clay	Ophiolite halogens and noble gases: quantifying subducted volatiles
09:12	Jacob Tielke*, Julian Mecklenburgh, Elisabetta Mariani, John Wheeler	Influence of water on the strength of olivine dislocation slip systems
09:24	Fabio Arzilli*, Mike Burton, Giuseppe La Spina*, Colin G. Macpherson	Extensive sub-arc decarbonation of subducting slabs
9:36	Brendan C. Hoare*, Emma L. Tomlinson, Jaime D. Barnes, John Caulfield	Long term residence of subduction-derived halogens in the Earth's ancient lithospheric mantle
9:48	Lois C Salem*, Marie Edmonds, John Maclennan, Bruce Houghton, Mike Poland	Aligning petrology with geophysics: the Father's Day intrusion and eruption, Kīlauea Volcano, Hawaiʻi
10:00	Samuel J. Mitchell*, Iona M. McIntosh, Bruce F. Houghton, Rebecca J. Carey	Syn-eruptive hydration of a deep-submarine explosive eruption: Water speciation analysis of volatiles in rhyolitic glass

10:00 - 10:45 – Poster session and tea/coffee served

10:45 - 12:30

ROOM A (relayed on-screen in ROOM B): Heterogeneity in the Earth: From micro to macro scale (session 1) incl. Keynote 2

10:45	James O. S. Hammond*, J-Michael Kendall	Seismically Imaging Melt
10:57	Simon Matthews*, Oliver Shorttle, John Maclennan, Jonathan Dawe	Olivine crystallisation temperatures as a proxy for mantle temperature
11:09	Clare E. Bond*, Robert A. Cliff, Robert W. H. Butler, John E. Dixon	Heterogeneity in tectonometamorphic systems; insights from Rb–Sr mica ages from the Cycladic Blueschist Belt, Syros (Greece)
11:21	Roberto Emanuele Rizzo*, David Healy, Natalie Jane Farrell	Riding the right wavelet: Detecting scale transitions in fracture and fault orientations using Morlet wavelets
11:33	Lars Hansen*, Kathryn Kumamoto, Christopher Thom, David Wallis, David Armstrong, et al.	Size effects in olivine: Reconciling 40 years of study into plasticity near the brittle-ductile transition
11:45	Timothy J. Davis*, David. Healy, Alodie Bubeck, Richard Walker	Exploring vesicle (pore) geometry and orientation on basalt strength
11:57 (Keynote 2)	**Yan Lavallée*, Jackie Kendrick, Felix W. von Aulock, Anthony Lamur, Adrian Hornby et al.**	**Strain Localisation in Magma: A multidisciplinary collaboration**

12:30 – 14:00 – Cold Buffet Lunch and posters incl.:

13:10 – 13:50	ROOM A - Student Forum

14:00 – 15:12

ROOM A (relayed on-screen in ROOM B): Tectonic and magmatic processes during continental extensional tectonics and rifted margin formation I (session 3) incl. Keynote 3

14:00 (Keynote 3)	**Othmar Müntener***	**Key role of mantle rocks for rifted margin studies: observations, data and speculations**
14:30	Chen Chen*, Louise Watremez, Tim Minshull, Rose Edwards, Manel Prada et al.	From continental hyper-extension to seafloor spreading: new insights from South porcupine basin
14:42	Carl McDermott*, Jenny S. Collier, Lidia Lonergan, Kenneth McDermott	Using SDRs to identify the mode of breakup along South America’s magma-rich margin
14:54	James R. Norcliffe*, Douglas A. Paton, Andrew M. McCaig, Estelle J. Mortimer	Spatio-temporal variations in magmatism during continental breakup – insights from the 3D structure of Seaward Dipping Reflectors
15:06	Kamaldeen O. Omosanya*, Ståle E. Johansen, Ovie E. Eruteya, Nicolas D. Waldmann, et al.	Basal configuration of a mass-transport deposit influenced by subsurface magmatic plumbing: A 3D seismic case study from the Vøring Basin, offshore Norway

15:12 – 16:00 – Tea/coffee break and posters

16:00 – 17:24

ROOM A (relayed on-screen in ROOM B): Tectonic and magmatic processes during continental extensional tectonics and rifted margin formation II (session 3)

16:00	Robert (Bob) White*, iSIMM team and Cambridge Volcano Seismology team	Caught in the Act: Rifting and Melt Injection from the Faroes Margin to the Icelandic Rift Zones
16:12	Jeanne m. Giniaux*, Andy Hooper, Marco Bagnardi	The enigmatic magma plumbing system of Askja volcano (Iceland)
16:24	Stewart Fishwick*	Lithospheric structure of the East African Rift System: mantle controls on rifting, volcanism & plate boundaries
16:36	Aude Lavayssiere*, Catherine Rychert Nicholas Harmon, Derek Keir, James Hammond, et al.	Imaging lithospheric discontinuities beneath the Afar Rift using S-to-P receiver functions
16:48	Melanie Siegburg*, Thomas Gernon, Jon Bull, Derek Keir, Rex Taylor, et al.	Tectono-magmatic evolution of the Boset-Bericha Volcanic Complex in the Main Ethiopian Rift
17:00	Fiona Iddon*, Marie Edmonds, Charlotte Jackson, William Hutchinson, Tamsin Mather et al.	Reservoir architecture beneath peralkaline volcanoes, Main Ethiopian Rift
17:12	Juliane Hüebert*, Kathy Whaler, Shimeles Fisseha	Evidence for off-axis magma pathways in the Central Main Ethiopian Rift as imaged by Magnetotellurics

17:30 – 18:00

ROOM A: Prizes

18:30 – Meet to walk to dinner and party (approx. 30 min)

19:00 – 02:00 – Dinner and Party at CAMP AND FURNACE

Day 3 – Friday 6th January

9:00 – 10:30

ROOM A: Jon Davidson Memorial Session: Magma genesis, storage and transport I (session 5)

09:00	Adam Jeffery*, R. Gertisser, S. Self, A. Pimentel, B. O'Driscoll, et al.	Petrogenesis of the peralkaline ignimbrites of Terceira, Azores
09:15	Juliana Troch*, Ben S. Ellis, Chris Harris, Peter Ulmer, Olivier Bachmann	Bulk melting not an option: Assimilation and remelting in the Yellowstone volcanic field
09:30	Benjamin M. Jost*, Lloyd White, Max Webb	Pulses of Phanerozoic magmatism and associated high-T/low-P metamorphism in the Bird's Head, New Guinea
09:45	Victoria C. Honour*, Marian B. Holness, Bernard Charlier	The behaviour of immiscible silicate liquids in a crystal mush
10:00	Fiona. K. Couperthwaite*, Daniel. J. Morgan, Thor Thordarson, Jason Harvey	Petrological Journey Through an Icelandic Magma Plumbing System in Simulated Real Eruption Time
10:15	Brendan Murphy*	The role of the ancestral Yellowstone plume in the tectonic evolution of the western United States

ROOM B: Microstructures and deformation I (session 9)

09:00	Luca Menegon*, Giorgio Pennacchioni, Nadia Malaspina	Strain localization in pseudotachylyte veins at lower crustal conditions
09:15	Melanie A. Finch*, Roberto F. Weinberg, Nicholas J.R. Hunter	Water loss and the origin of thick ultramylonites
09:30	Aretusini Stefano*, Oliver Plümper, Elena Spagnuolo, Giulio Di Toro	Seismic slip on clay nanofoliation
09:45	Joe Aslin*, Elisabetta Mariani, John Wheeler, Daniel Faulkner	The role of micas in deformation and strain partitioning within mid-crustal shear zones
10:00	Giulia Degli Alessandrini*, Luca Menegon, Francesco Giuntoli	Protracted weakening during lower crustal shearing along an extensional shear zone
10:15	Amicia L. Lee*, Taija Torvela, Geoffrey E. Lloyd, Andrew M. Walker	Crustal deformation mechanisms of migmatites and mylonites from the Western Gneiss Region, Norway

ROOM C: New frontiers in experimentation, rock physics and magma rheology (session 14)

09:00	John D. Bedford*, Daniel R. Faulkner, Henri Leclère, John Wheeler	Deforming porous rock: yield curve evolution and the implications for compaction, dilatation and localisation
09:15	Paul K. Byrne*, Michael J. Heap, Sami Mikhail	The role of gravity on Martian volcanism and tectonism from rock deformation studies
09:30	Thomas Breithaupt*, Lars Hansen, David Wallis, David Armstrong	Low temperature plasticity of plagioclase from nanoindentation
09:45	Katherine J Dobson,*, Donald B Dingwell, Danilo Di Genova, Fabian B Wadsworth, Stephan Kolzenburg,	Magmas on the Move: in situ 4D Rheology of Three-Phase Magmas Using Ultra Fast X-ray Tomography
10:00	Anthony L.H. Lamur*, Gudjon H. Eggertson, Jackie E. Kendrick, Fabian B. Wadsworth, Yan Lavallée, et al.	Tensile fractures impact on fluid flow in dynamic geological settings
10:15	Emily J. Butcher*, Andrew Gibson, Philip Benson	Initial Development of an NIR strain measurement technique in brittle geo-materials

10:30 - 11:00 – Tea/ coffee and posters

11:00 - 12:30

ROOM A: Jon Davidson Memorial Session: Magma genesis, storage and transport II (session 5) incl. Keynote 4

11:00 (Keynote 4)	**Sue Loughlin***	**Global monitoring, reporting and anticipation of volcanic activity: can we do it?**
11:30	Michael J. Stock*, Madeleine C.S. Humphreys, Victoria C. Smith, Roberto Isaia, David M. Pyle	Interpreting apatite volatile compositions using thermodynamic models: new insights into pre-eruptive processes at Campi Flegrei
11:45	Rebecca L. Astbury*, Maurizio Petrelli, Ilenia Arienzo, Massimo D'Antonio, Daniele Morgavi, et al.	Using trace element mapping to identify discrete magma mixing events from the Astroni 6 eruption
12:00	Euan J.F. Mutch*, John Maclennan, David A. Neave, Marie Edmonds	Constraining the timescale of magmatic ascent prior to the Skuggafjöll eruption, Iceland
12:15	Martin Mangler*, Chiara Maria Petrone, Julie Prytulak, Hugo Delgado-Granados	A pyroxenic view on major effusive and explosive eruptions at Popocatépetl volcano, Mexico, in the last 2000 years

ROOM B: Microstructures and deformation II (session 9)

11:00	Geoffrey E. Lloyd*, David Wallis	Analysis of crystal plasticity from EBSD datasets based on Schmid factor and critical resolved shear stress: possibilities and caveats
11:15	John Wheeler*	Things you didn't know you didn't know about diffusion creep
11:30	David Wallis*, Lars Hansen, Miki Tasaka, Kathryn Kumamoto, Geoffrey Lloyd, et al.	The impact of water on dislocation content and slip system activity in olivine constrained by HR-EBSD maps and VPSC simulations
11:45	Katy Willis*, Greg Houseman, Tim Wright, Andy Hooper	The strong influence of weak heterogeneities on strain distribution
12:00	Tyler Ambrose*, David Wallis, Lars Hansen, Dave Waters, Mike Searle	Controls on the rheology and mineralogy of peridotite in a palaeosubduction zone: a transect through the base of the Oman-UAE ophiolite
12:15	Alberto Ceccato*, Giorgio Pennacchioni, Luca Menegon, Michel Bestmann	Crystallographic control on microstructural evolution of coarse grained quartz veins

ROOM C: Georesources and geohazards in an evolving planet I (session 7)

11:00	Stephan Gehne*, Phillip Benson, Nick Koor, Mark Enfield	Fluid driven fracture mechanics in highly anisotropic shale: a laboratory study with application to hydraulic fracturing
11:15	Jonathan D. Smith*, Robert S. White	Hypocentral Event Location within the Groningen Gas Reservoir, NE Netherlands.
11:30	Helen Robinson*, Nemesio Perez, Paul Younger	Using surface geochemistry to identify and map fluid and gas conduits in high enthalpy geothermal systems in East Africa
11:45	Guðjón H. Eggertsson*, Yan Lavallée, Jackie E. Kendrick, Sigurður H. Markússon	How mechanical properties effect permeability within the Krafla reservoir, North-East Iceland
12:00	Thomas A.G. Utley, Robert E. Holdsworth, Ken J.W. McCaffrey, Edward D. Dempsey, Robert A. Strachan, et al.	The structural geology of Foula, Shetland: an onshore analogue for the top of the Clair Ridge, west of Shetland
12:15	Jonathan Dietz*, David Brown	Hydrocarbon exploration in volcanic rifted margins: an analogue from the Hreppar Formation, Iceland

12:30 – 14:00 – Cold Buffet Lunch and posters incl.:

13:15 – 14:00	ROOM A - VMSG Annual General meeting ROOM B - TSG Annual General meeting ROOM C - BGA Annual General meeting

14:15 – 15:30

ROOM A: Jon Davidson Memorial Session: Magma genesis, storage and transport III (session 5)

14:15	William Hutchison*, Adrian A. Finch, Adrian J. Boyce, Henrik Friis, Anouk M. Borst, et al.	New insights into magma ascent and emplacement from alkaline roof zones of Southern Greenland
14:30	Steffi Burchardt*, Tobias Mattsson, Octavio Palma, Olivier Galland, Karen Mair	Syn-emplacement fracturing of laccoliths

14:45	Margaret E. Hartley*, Enikö Bali, Sæmundur A. Halldórsson, John Maclennan,	Holuhraun 2014-2015: Geochemical constraints on magma storage and transport during a major volcano-tectonic episode
15:00	Tara Stephens*, Richard J. Walker, David. Healy, Richard W England, Ken J.W. McCaffrey, et al.	Remote stress state control on igneous sill geometry
15:15	John Browning*, Kyriaki Drymoni, Agust Gudmundsson	A model to forecast magma chamber rupture

ROOM B: Earthquakes, palaeoseismology, and rates of fault slip: From milliseconds to millions of years (session 12)

14:15	Jennifer Weston*, Bob Engdahl, James Harris, Dmitry Storchak, Domenico Di Giacomo	ISC-EHB: Reinventing the EHB Earthquake Database
14:30	Ken J.W. McCaffrey*, Laura Gregory, Luke Wedmore, Maxwell W. Wilkinson, Gerald Roberts, et al.	Near-field monitoring of fault slip during the 2016 Central Italy seismic sequence
14:45	Austin J. Elliott*, John R. Elliott, James Hollingsworth, Barry E. Parsons	Rupture of the Karakul-Sarez fault in the 7 Dec, 2015 M72 Murghob, Tajikistan earthquake: implications for secondary hazards and the enigmatic 1911 event in the Pamirs
15:00	Richard Walters*, Laura Gregory, Luke Wedmore, Tim Craig, John Elliott, et al.	The evolution of the 2016 Central Italy seismic sequence from geodesy, seismology and field investigation
15:15	Ed J. Rhodes*, James F. Dolan, Sally F. McGill	Determining the chronology of Holocene earthquake clustering on the Garlock fault, California

ROOM C: Georesources and geohazards in an evolving planet II (session 7) incl. Keynote 5

14:15 (Keynote 5)	**John Ludden*, Mike Stephenson, Geoff Baxter**	**The Energy Security and Innovation Observing System for the sub-surface (ESIOS)**
14:45	John M. MacDonald*	Carbonate Clumped Isotopes: An Innovative Technique for Geo-Resource Characterisation
15:00	John M. Millett*, Eric Haskins, Donald Thomas, Dougal, A. Jerram, Sverre Planke, et al.	Lava flow reservoirs during burial: laboratory petrophysical and wireline geophysical results from two fully cored boreholes, Big Island, Hawai'i
15:15	James .P. Verdon*, J-M. Kendall, J.H. Johnson, R. Luckett, B.J. Baptie	Geomechanical Modelling of Seismicity Induced by Coal Mining

15:30 – 16:00

Room A: Prizes and close

18:30 – Pub crawl departing from venue

POSTERS

By poster number:

Student	Non-student

The volatile Earth: The role of liquids and gases in the dynamic solid Earth (session 2)

001	Rebecca Paisley*, Kim Berlo, Hugh Tuffen, Bassam Ghaleb	Using trace elements to constrain gas pathways at Cordón Caulle, Chile
002	Anna K. Bidgood*, Mike Searle, Dave Waters, Talat Ahmad, et al.	The Role of Water in Subduction Zone Dynamics
003	Patrick J. Sugden*, Ivan P. Savov, Marjorie Wilson, Gevorg K. Navasardyan, Khachatur Meliksetian	The role of fluids in the subduction-intraplate geochemical transition
004	Sophie Coulson*, Tom Garth, Andreas Rietbrock	Constraining the velocity structure of the Alaskan-Aleutian subduction zone using guided wave
005	Emma J. Liu*, Marie Edmonds, Margaret E. Hartley	Sulfide saturation and breakdown during the 2014-2015 Holuhraun eruption, Iceland
006	Daniel Cox*, Sebastian Watt, Alan Hastie, Frances Jenner	Magma storage and evolution beneath Antuco volcano, Chile
007	Amber L. Madden-Nadeau*, Matthew J. Genge, Julie Prytulak	Volatile loss from ignimbrites: Evidence for fiamme-vesicle interactions
008	Charlotte G. Jackson*, Sally A. Gibson	New insights into volatile-rich mantle metasomatism at the Bultfontein diamond mine, Kimberley, South Africa
009	Dónal J. O'Farrell*, Emma L. Tomlinson, John T. Caulfield	Volatiles in the Proto-Iceland Plume Source Mantle
010	Emily Mason*, Marie Edmonds, Alexandra V. Turchyn	Earth's exhaust pipe: carbon isotope systematics in volcanic arc gases
011	Sophie Gill*, M. Edmonds, A.V.Turchyn	Global trends in volcanic arc sulfur outgassing
012	Jane L. MacArthur*, J.C. Bridges, M.J. Branney	Clastic meteorite from Mars: petrological & textural insights
013	Amy P. Kelly*, Brian O'Driscoll, Patricia L. Clay, Luke N. Hepworth, Ray Burgess	Cycling of halogen-bearing fluids in the Rum Layered Suite, NW Scotland
014	Felix W. von Aulock*, Yan Lavallée, Fabian B. Wadsworth	Hydration of Silicate Glasses below the Glass Transition Temperature

Tectonic and magmatic processes during continental extensional tectonics and rifted margin formation (session 3)

015	Jonathan A. Hunt*, Tamsin A. Mather, David M. Pyle	The structure and past behaviour of peralkaline volcanoes in the Main
016	Matthew L.M. Gleeson*, William Hutchison, Michael J. Stock, Tamsin A. Mather, David M. Pyle	Magma genesis and storage conditions in the Ethiopian Rift: new constraints from oxygen isotopes and phase equilibria models
017	Berhe Goitom*, J-Michael Kendall, James O.S. Hammond, Ghebrebrhan Ogubazghi, Derek Keir, et al.	Characteristics of seismicity in Eritrea (2011-2012): Implications for rifting dynamics
018	Delphine Smittarello*, Raphael Grandin, Jean-Bernard De Chabalier, Cecile Doubre, Aline Deprez, et al.	Transient deformation in the Asal-Ghoubbet Rift (Djibouti) since the 1978 diking event: Is deformation controlled by magma supply rates?

019	Martyn P. Steel *, Stewart Fishwick	Seismic Tomography to illuminate crust and mantle structure beneath the East African Rift System
020	Thomas B. Phillips, Craig Magee*, Christopher A-L. Jackson, Rebecca E. Bell	Seismic imaging of a Permian-Carboniferous dyke swarm offshore southern Norway
021	André R. Guimaraes*, Godfrey Fitton, Linda Kirstein	Synchronous intraplate volcanism on the African and South American conjugate margins: coincidence?
022	Caroline Harkin*, Nick Kusznir, Alan Roberts, Gianreto Manatschal	Ocean-Continent Transition Structure of the Pelotas Magma-Rich Continental Margin, South Atlantic
023	Oliver G. Sanford*, Richard W. Hobbs, Richard J. Brown, Nick Schofield, Richard J. Walker	Challenges with Seismic Imaging in Volcanic Margins
024	Dougal A. Jerram*, Peter Reynolds, Sverre Planke, John M. Millett, Henrik Svensen, et al.	Assessing the volcanic styles and types of the North Atlantic igneous province: new insights from the Greenland margin
025	Nick Kusznir*, Caroline Harkin, Alan Roberts, Gianreto Manatschal, Ken McDermott	Deep seismic reflections at volcanic margins: The petrological Moho or from within the mantle?
026	Lorenzo Valetti, Alicia McCabe, Ernie Rutter*, Julian Mecklenburgh	The structure of the Sorbas Basin (S.E. Spain) from geological mapping and regional gravity surveying
027	Murray Hoggett*	Reinterpretation of the tectonics and evolution of the Pernambuco Plateau, Brazil
028	Gaël Lymer*, Derren J.F. Cresswell, Tim J. Reston, Carl T.E Stevenson, Jon M. Bull, et al.	Corrugations on the S reflector west of Spain: kinematic implications
029	Júlia Gómez-Romeu*, Nick Kusznir, Gianreto Manatschal, Alan Roberts, Marie-Eva Epin	Evolution of extensional faulting and its flexural isostatic response during ocean-continent transition formation at rifted margins
030	Jonathan M. Pownall*, Robert Hall, Gordon S. Lister	Extension along a 60,000 km^2 detachment fault opened the 7 km Weber Deep in eastern Indonesia
031	Finnigan Illsley-Kemp*, Jonathan M. Bull, Derek Keir, Taras Gerya, Carolina Pagli, et al.	Formation of an oceanic transform fault during continental rifting
032	Thomas B. Phillips*, Christopher A-L. Jackson, Rebecca E. Bell, Oliver B. Duffy	Oblique rifting above a lower crustal lineament: What can upper crustal faults tell us about deeper structures?
033	Michael Hodge*, Åke Fagereng, Juliet Biggs, Hassan Mdala	Segmentation, growth and linkage of large, normal faults
034	Derren J.F. Cresswell*, Gaël Lymer, Tim J. Reston Carl T. Stevenson, Jon M. Bull, et al.	Hyperextension and Fault Linkage
035	Alexander J. Coleman*, Christopher A.-L. Jackson, Oliver B. Duffy	The Relationship between Sub- and Supra-salt Deformation in Salt-Influenced Rifts: Observations from the Halten Terrace, offshore Norway
036	Richard J. Walker*, Tara Stephens, David Healy, Alodie Bubeck, Ken McCaffrey	Conjugate dykes and sills: a record of differential stress?

037	Thomas Lamont*, Mike Searle, Dave Waters, Nick Roberts, Andrew Smye	Compression to extension: Evidence for a complete orogenic cycle from Naxos, Greece
038	Awara Amin*, Roderick Brown	Using an innovative approach to apatite (U-Th)/He thermochronometry to study the tectonic-geomorphic history of Grampian Highland area-Scotland
039	Sarah R. Eriksson*, Abigail K. Barker, Valentin R. Troll, Fiona C. Meade, Andrew Morton, et al.	Provenance of Metasedimentary Rocks in the North Atlantic
040	Philip G. Smith*, Richard England, Jan Zalasiewicz	The onshore Cenozoic basin development of the UK and its relation to present-day vertical surface motions
041	Zachary Killingback*, Bob Holdsworth, Eddie Dempsey, Richard Walker, Ken McCaffrey, et al.	A bigger splat: rock fall impact processes in wet sediment
042	Ahmed K. Obaid*, Mark B. Allen	Distributed deformation in the Zagros fold-and-thrust belt: insights from geomorphology
043	Adamu A. Suleiman*, Christopher A-L. Jackson, Alastair J. Fraser, Craig Magee	Outcrop analysis of the Upper Benue Trough, NE Nigeria; Insights into the Tectono-Stratigraphic Development of the Subsurface Bornu Basin
044	Wen Shi*, Neil Mitchell, Lara Kalnins	Nature of crust in the central Red Sea

Heterogeneity in the Earth: From micro to macro scale (session 1)

045	Thilo Wrona*, Christopher A-L. Jackson, Craig Magee, Mads Huuse, Kevin G. Taylor	Kinematics of polygonal faulting in the northern North Sea
046	Abdulaziz Samkari*, David Farris Richard Walker, Marc Reichow, Chris MacLeod	The role of the Ad Damm Shear Zone during Red Sea rifting: western Saudi Arabian Margin
047	Eleni M. Wood*, Clare J. Warren, Tom Argles, Nick M. W. Roberts	The microtextural and petrochronological record for the rapid tectonic exhumation of Himalayan lower crust
048	Jacob Forshaw*, David J. Waters	Thermodynamic modelling of mafic minerals and melt can illuminate lower crustal heterogeneity
049	Stephanie G. Zihms*, T. Miranda, H. Lewis, S. Hall	Comparison of fracture features at different scales for laminites
050	Rachael Ellen*, Stephanie Zihms, Susana Garcia Nazia, Mubeen Farooqui, M. Mercedes Maroto-Valer, et al.	Exploring the micro-scale controls on fracturing in a Carboniferous limestone, and their implications for carbon capture and storage
051	Philip Meredith*, John Browning, Chris Stuart, David Healy, Sophie Harland, et al.	Acoustic characterization of crack damage evolution in rocks deformed under true triaxial loading
052	Alodie Bubeck*, Richard Walker, David Healy, Marcus Dobbs, David Holwell	Pore geometry controls rock strength
053	James D. Ashworth*, Yan Lavallée, Paul A. Wallace, Jackie E. Kendrick, Rebecca Coats, et al.	Shear regime controls on permeability during magma extrusion at Unzen volcano, Japan
054	Kyriaki Drymoni*, John Browning, Agust Gudmundsson	How damaging is caldera collapse for a volcanic edifice?
055	Julia Woitischek*, Marie Edmonds, Andrew W. Woods	Persistent outgassing of open vent basaltic volcanoes

056	Abigail K. Barker*, E. Magnusson, V.R. Troll, C. Harris, F. Pérez-Torrado, et al.	Temporal variations in the mantle source beneath Fogo, Cape Verde
057	Matthew L.M. Gleeson*, Sally A. Gibson	Plume-ridge interactions and the transfer of volatiles at the Galápagos Spreading Centre
058	Ella Young*, Chris MacLeod	Accretion of the upper crust of the Troodos ophiolite (Cyprus)
059	Grace F. Manley*, Richard F. Katz, Tobias Keller	Melt & Trace Element Transport in a Heterogeneous Mantle
060	Samantha K. Bell*, A. Alexander G. Webb	Does the geological record support the heat-pipe Earth model?

Seismology, geodesy and remote sensing: Methodologies and applications (session 4)

061	Alex J. Clark*	Post-eruptive dike seismicity following the 2014-15 Bárðarbunga-Holuhraun fissure eruption, central Iceland
062	Tom Winder*, Jennifer Woods, Robert S. White, Thorbjörg Ágústsdóttir, Tim Greenfield, et al.	Small-scale en-echelon dyke segmentation beneath the 2014-15 Holuhraun eruption fissure recorded by microseismicity
063	Benjamin G. Stokell*, Mel Rodgers, David A. Clifton, Tamsin A. Mather, Marco A. F. Pimentel, et al.	Dante's Maximum Likelihood: Exploring a machine-learning approach to detecting changes in volcanic activity
064	Luke Marsden*, Jurgen Neuberg, Mark Thomas	Using seismic and tilt measurements to forecast eruptions of silicic volcanoes – an introduction
065	Nikola Rogic*	The deformation-fracturing during the intermittent dome growth at SHV
066	Jessica L. Williamson*, Juliet Biggs[1], Cyril Muller[2]	Understanding conduit processes with InSAR at Turrialba, Costa Rica
067	Pablo J. Gonzalez*, Richard Walters, Emma Hutton, Karsten Spaans, Andrew J. Hooper, et al.	Global surface ground deformation monitoring using Sentinel-1 mission
068	Tesfaye T. Tessema*, Juliet Biggs, Elias Lew	Sustained Deformation at the Tendaho Geothermal Prospect, Ethiopia
069	John R. Elliott*, R. Jolivet, P.J. González, J.-P. Avouac, J. Hollingsworth, et al.	Geodetically constrained slip on the Main Himalayan Thrust fault from the 2015 Gorkha earthquake
070	Ryan Lloyd*, Juliet Biggs, Yelebe Birhanu	Storage and Transportation of Magma at a continental rift caldera
071	Frances Boreham*, Kathy Cashman, Alison Rust	High Resolution Mapping of Icelandic Rootless Cones using UAVs
072	Hannah Moss-Davies*	Volcanoes: Hot or Not? A neural network perspective
073	Susanna K. Ebmeier*	Application of Independent Component Analysis to multi-temporal InSAR with volcanic case studies

Jon Davidson Memorial Session: Magma genesis, storage and transport (session 5)

074	George F. Cooper*, Jon D. Blundy, Jon P. Davidson, Jing Zhang	Plutonic xenoliths from Martinique and Statia: A window into Lesser Antilles crust
075	William Hutchison*, Adrian A. Finch, Adrian J. Boyce, Henrik Friis, Anouk M. Borst, et al.	New insights into magma ascent and emplacement from alkaline roof zones of Southern Greenland

076	Alexandra Gutai*, John Maclennan, Euan J.F. Mutch, David A. Neave	Timescales of Magma Storage and Transport in the Krafla Volcanic System
077	Andrew J. Gilbert*, Jerome. A. Neufeld, Robert. S. Farr, Felix. K. Oppong, et al.	Assessing the mobility of crystals and mush cohesion in magma chambers
078	Anikó Batki*, Elemér Pál-Molnár, Andrew Kerr, M. Éva Jankovics	Magma recharge and mingling events recorded by clinopyroxene in the Ditrău Alkaline Massif, Romania
079	Ben M. Manton*	Multi-bowl sills – interpreting their mode of emplacement
080	Ben Rogers*, Håvard S. Bertelsen, Olivier Galland	Magma intrusion in viscoelastic media: laboratory model of coeval brittle and ductile deformation
081	Cathy Lucas*, Amel Benhallou, Bernard Bonin, Faten Bechiri-Benmerzoug	Megacrysts in tephra of the Manzaz Volcanic District (Central Hoggar, Algerian Sahara)
082	Chiara Maria Petrone*	Timescale of effusive to Plinian eruptions at Popocatépetl (Mexico)
083	David E. Cavell*, Alan R. Hastie, Sebastian F.L. Watt, Carl T. Stevenson, Andrew C. Kerr, et al.	Investigating the role of oceanic plateaus in early continental growth
084	Emma N. Bennett*, Johan Lissenberg, Katherine Cashman	Complex plagioclase crystal cargo: Insights into magmatic processes
085	Eva Hartung*, Luca Caricchi	Physical properties of felsic melts in the upper crust: implications for the built-up of large explosive eruptions
086	Frey S. Fyfe*, David M. Pyle, Chiara M. Petrone, Tamsin A. Mather	Long-term mass balance at andesitic volcanoes
087	Hugo Moreira*, Craig Storey, Mike Fowler, Guilherme O. Gonçalves, Luís A.R. Seixas	Unravelling subduction and collision stages of the Mineiro Belt: the tectonic framework of a Paleoproterozoic orogeny
088	Janine L. Kavanagh*, Ben Rogers, David Boutelier, Sandy Cruden	Fracture toughness controls on the propagation of magma-filled fractures: Insights from analogue experiments
089	John Maclennan*, David A. Neave, Thor Thordarson	Magma storage depths under Icelandic volcanoes from refreshed petrological barometry
090	Jonathan Dawe*, Simon Mathews, Oliver Shorttle, John Maclennan	Constraints on the thermal structure of the Iceland plume from olivine crystallisation temperatures
091	Kate Laxton*, Ivan Savov, Jason Harvey	Petrological and geochemical evolution of the Kyushu-Palau (proto-IBM) volcanic arc, Western Pacific
092	Kate Saunders*, Ester Jolis, Duncan Muir, Valentin R. Troll, David A. Budd, et al.	Differentiation processes of Sumatran Andesites
093	Kirsten Spry*, Marie Edmonds, John Maclennan	Crystal cargoes of Kilauean eruptions
094	Krzysztof Sokol*, Ralf Halama, Khachatur Meliksetian, Ivan Savov	Petrogenesis of the volcano-plutonic Tezhsar Alkaline Complex in a collision zone setting (Armenia)
095	M. Éva Jankovics*, Balázs Kiss, Szabolcs Harangi, Theodoros Ntaflos	Complex evolution of the magmatic system beneath a monogenetic volcano: evidence from olivine crystals and their spinel inclusions

096	Julien Scheibert, Olivier Galland*, Andreas Hafver	Inelastic deformation during sill and laccolith emplacement: insights from an analytic elasto-plastic model
097	Martijn Klaver*, Pieter Vroon	The anatomy of the plumbing system of Nisyros volcano, Aegean arc
098	Max Webb*, Lloyd T. White, Benjamin Jost	Young arc magmas are found along the length of New Guinea
099	Melanie Ray*, Teresa Ubide, Hilary Downes, Simon Day*	Preliminary investigation of a complex plumbing system at Ritter Island volcano (PNG) using LA-ICP-MS mapping
100	Mike Cassidy*, Jonathan Castro, Christoph Helo, Sebastian Watt	Experimental petrology constraints on magma storage conditions for explosive and effusive eruptions at Kelud volcano, Indonesia
101	Nicola J. Horsburgh*, Adrian A. Finch,	Insights into rare earth petrogenesis using luminescence
102	Olle Risby*, Abigail K. Barker, Steffi Burchardt, Björn Sandback, Jaime Almeida	Magma storage of the Monte Amarelo dikes, Fogo, Cape Verde
103	Othmar Müntener*, Peter Ulmer	The ‘amphibole sponge’ legacy: field and experimental data related to island arcs
104	Penny Wieser*, Stephen Turner, David M. Pyle, Tamsin A. Mather	Whole-rock and olivine chemistry of Don Casimiro and associated rear-arc volcanism: An insight into geochemical variations along the Andean Southern Volcanic Zone
105	Richard Junokas*, Sebastian Watt, Mike Cassidy	Investigating changes to pre-eruptive storage conditions of Kelud volcano prior to the 1990, 2007 and 2014 eruptions
106	Ruth Farley*, Rex N. Taylor, Thomas M. Gernon	A single eruption "snapshot" through a complete magma reservoir
107	Samuel J.P. Hill*, Martin F. Mangler, Julie Prytulak, Chiara M. Petrone	Magma mixing in effusive flank eruptions at Popocatépetl volcano (Mexico): A textural and chemical study of pyroxenes
108	Simon Martin*, Janine Kavanagh, Andy Biggin	Recording magma flow variation across sill thickness: insights from magnetic anisotropy studies
109	Suraya H. Hazim*, Janine L. Kavanagh	A systematic study of the rheology and viscoelastic range of gelatine for modelling magma chamber growth
110	Tobias Mattsson*, Steffi Burchardt, Karen Mair	Fracturing related to granite emplacement in the Mourne Mountains
111	Zoltán Taracsák*, Szabolcs Harangi, Gábor Molnár	Melt generation in a dynamic melting column and its application to the genesis of intracontinental basalts

The structure and mechanics of fault zones (session 6)

112	Yukitsugu Totake*, Robert W.H. Butler, Clare E. Bond	Linkage and imbrication of fold-thrust structures, offshore Northwest Borneo
113	Ricardo Tomás*, Philip M. Benson	Experimental approach to Gypsum’s Dehydration reaction and associated acoustic emission
114	Matteo Demurtas*, Steven Smith, Elena Spagnuolo, Michele Fondriest, Giulio Di Toro	Coseismic origin of foliated cataclasites and their preservation potential during the seismic cycle

115	Nick M.W. Roberts*, Richard J. Walker	Constraining the timing of fault-zone evolution using LA-ICP-MS U-Pb geochronology of calcite
116	Gabriel Meyer*, Nicolas Brantut	Damage Recovery in Carrara Marble
117	Graham Leslie*, Rachael Ellen, Mike Browne, Tom Cain	SCARP: a Scottish Carboniferous Research Park
118	Ekbal Hussain, Tim J. Wright *¸Richard J. Walters, David P. Bekaert, Ryan Lloyd	InSAR observations of focused interseismic strain along the entire North Anatolian Fault: implications for seismic hazard assessment and the rheology of the lower crust
119	Joshua R. Williams*, Jessica C. Hawthorne, Sebastian Rost, Tim J. Wright	Stress drop for earthquakes M ≥4.0 across the Blanco Oceanic Transform Fault
120	Tomas Cain*, Stuart M. Clarke, Graham A. Leslie	Architecture and growth of oblique slip fault zones in heterogeneous multilayer sequences
121	Angela Castagna*, Audrey Ougier-Simonin, Philip M. Benson, John Browning, Marco Fazio	The effects of Water and Temperature on Etnean Limestone
122	Cathal Reilly*, Hugh Anderson, Steve Mücklisch	Fault displacement and seal analysis in space and time
123	Natalie J.C. Farrell*, David Healy, Michael J. Heap, Roberto E. Rizzo, Michael Smith	Variations in pore and crack fabrics with stress in triaxially deformed sandstone
124	Jackie Kendrick*, Yan Lavallée	Shear zone development in high-viscosity magmatic systems
125	Tom Blenkinsop*, Gerard Tripp	Faulting and fluid flow controlled by cleavage, shear zones and crenulations at Kainantu gold-copper mine, Papua New Guinea
126	Ahmad Shmela*, Douglas Paton, Richard Collier	Investigation of Rift Evolution through Examining Scaling Properties of Fault Populations within the Central Kenya Rift
127	Roisin Kyne*, Koen Torremans, Robert Doyle, John Güven, John Walsh	The role of fault segmentation and relay ramp geometries on the formation of Irish-type deposits
128	Dave McCarthy*	The North Scotia Ridge; A Plate Boundary?
129	Withdrawn	
130	David G. Cornwell*, Elvira Papaleo, David A. Thompson, Sebastian Rost, Gregory A. Houseman, et al.	Crust and upper mantle structure of the North Anatolian Fault, Turkey
131	David Healy*, Roberto Rizzo, David Cornwell, Natalie Farrell, Hannah Watkins, et al.	FracPaQ: a MATLAB™ toolbox for the quantification of fracture patterns
132	Michele Fondriest *, Tom Mitchell, Maurizio Vassallo, Giuseppe Di Giulio, Fabrizio Balsamo, et al.	Multi-scale velocity structure of an active seismogenic normal fault zone
133	Samuel Melia*	The Sorong Fault Zone, Indonesia: A Fresh Perspective
134	Lisa A. Millar*, Z.K. Shipton, A. Hamilton	2D and 3D analysis of cataclastic deformation bands in poorly consolidated sandstones
135	Andrew Cooke*, Quentin Fisher, Emma Michie, Graham Yielding	Advances in the understanding of the key parameters determining carbonate fault rock permeability

136	Giles A. Ostermeijer*, Tom M. Mitchell, John Browning, Nicolas Brantut, Tom Rockwell et al.	Detailed fault damage zone characterisation and analysis of seismically active faults for improving estimations of the earthquake energy budget
137	Elliot P. Wood*, Janine L. Kavanagh, Daniel R. Faulkner	The Fault Damage Zone; Implications of slip displacement on damage zone width
138	Rosanne Mckernan, Julian Mecklenburgh* Ernie Rutter	Microstructural controls on the pressure-dependent permeability of Whitby Mudstone

Georesources and geohazards in an evolving planet (session 7)

139	Michael R. Chandler*, Nicolas Brantut, Philip G. Meredith	Simulated crack propagation trajectories in transversely anisotropic media
140	Alistair T. McCay*, Helen Robinson, Neil Burnside, Paul Younger, Rob Westaway	Geothermal Energy. The nexus between magmatics, tectonics, and geophysics
141	Jazmin P. Scarlett*, Rebecca Williams, Briony McDonagh	Volcanic risk through the ages: social factors influencing volcanic risk on St Vincent, Lesser Antilles from a historical perspective
142	Helen Kinvig*, Yan Lavallée, Tom Garth, Silvio De Angelis, Jackie Kendrick, et al.	Investigating the source and structural controls of volcano-seismic unrest at Nisyros Volcano (Greece)
143	Nils R. Backeberg*, Francesco Lacoviello, Tom M. Mitchell, Adrian P. Jones, Joshua J. Bailey, et al.	Anisotropic permeability in shale rocks: Evidence from acoustic, pressure, chemical and X-ray nano-CT analyses
144	Withdrawn	
145	Simon J. Oldfield*, Douglas A. Paton, Emma K. Bramham	Elucidating structural uncertainty using seismic forward modelling

Gas, aerosols, ash and the atmosphere (session 8)

146	Martin W. Airey*, R. Giles Harrison, Keri A. Nicoll, Paul D. Williams, Graeme J. Marlton	VolcLab: A balloon-borne instrument package to measure ash, gas, electrical, and turbulence properties of volcanic plumes
147	Ben D. Esse*, Mike Burton	Mitigating volcanic ash risks with ultraviolet spectroscopy
148	Jennifer Saxby*, Katharine Cashman, Alison Rust, Frances Beckett	Morphology of the Katla SILK tephra and implications for volcanic ash dispersion modelling
149	Simone Cogliati*, Sarah Sherlock, Alison Halton, Tiffany Barry, Mike Branney, et al.	Understanding the degassing of young volcanic systems using noble gases
150	Federica Pardini*, Mike Burton, Stefano Corradini, Luca Merucci, Giuseppe Salerno, et al.	Retrieval and validation of volcanic SO_2 injection height and eruption time from satellite maps
151	Matthew R.J. Varnam*, Mike Burton	Continuous volcanic monitoring using the SO_2 camera
152	Evgenia Ilyinskaya*, Anja Schmidt, Tamsin Mather, Francis Pope, Peter Baxter, et al.	Aerosol and gas emissions from Holuhraun eruption 2014-2015: size-resolved chemistry at source and in exposed communities
153	Tom D. Pering*, Andrew J.S. McGonigle	A model based characterisation of passive degassing in basaltic magmas
154	Elisa Carboni*, R.G. Grainger, T.A. Mather, A. Schmidt, I. Ialongo	Bárðarbunga sulfur dioxide (SO_2) emission estimate from IASI

Microstructures and deformation (session 9)

155	Billy Andrews*, Geoffrey E. Lloyd, Andrew J. Parsons	Critical evaluation of Electron Backscatter Diffraction (EBSD) derived grain-size analysis and its impact on paleo-piezometry and flow law studies
156	Anne-Laure Fauchille*, Stephen Hedan, Valery Valle, Dimitri Pret, Philippe Cosenza	Overestimation of strains due to multiscale cracking in clayrock
157	Ieva Kaminskaite*, Quentin Fisher, Emma Michie, Graham Yielding	Microstructure of deformation bands in carbonates
158	Mark Jefferd*, Nicolas Brantut	The Permeability evolution of Etna Basalt during Brittle Creep
159	Blaise R. Winnard*, Rob J. Cuss, Tom M. Mitchell, John Browning, Simon Norris, et al.	Freeze-thaw effects on the mechanical and microstructural properties of bentonite
160	Jack C. Richardson*, G.I. Alsop, C. Magee, P. Anderson, C.T.E. Stevenson	Revealing the internal flow of salt structures using anisotropy of magnetic susceptibility
161	Benjamin Fernando*, David Wallis, Lars Hansen	Deformation mechanisms in plagioclase investigated by HR-EBSD
162	Diana Avadanii*, David Wallis, Lars Hansen, David Waters	A new barometer from stress fields around inclusions
163	Josh Vaughan-Hammon, Elisabetta Mariani*	Emplacement mechanisms of the Alpe Morello peridotite, Ivrea-Verbano Zone, NW Italy: insights from microstructural analyses
164	Joe Gardner*, John Wheeler, Betty Mariani	Quantifying grain boundary sliding during pressure solution

Earth's deep interior (session 10)

165	Andy Nowacki*, Jack Walpole, D. Rhodri Davies, Hein Van Heck, J. Huw Davies, et al.	The signature of ‘sharp sides’ to the seismically slow regions at the base of the Earth’s mantle
166	Marthe Klöcking*, Nicky White, John Maclennan, Godfrey Fitton	Using magmatism to link mantle temperature and dynamic topography beneath western North America
167	David A. Thompson*, George Taylor, Sebastian Rost, David G. Cornwell	A detailed snapshot of Cyprus Slab Interaction with the Mantle Transition Zone Beneath Turkey
168	William Brown*, Ciarán Beggan, Susan Macmillan	Rapid geomagnetic secular variation during the Swarm era and its impact on global field models
169	Imogen E.P. Kempton*, David Wallis, Lars N. Hansen	Transient creep of single crystals of San Carlos olivine
170	Grace A. Cox*, Phil W. Livermore, Jon E. Mound	The observational signature of modelled torsional waves and comparison to geomagnetic jerks
171	Lauren Waszek*, Nicholas Schmerr, Maxim Ballmer	Seismic observations of mid-mantle reflectors linked to significant compositional heterogeneity in the deep Earth
172	Louise M.A. Hawkins*, Richard T. Holme, Taslima Anwar, Valentina V. Shcherbakova, Andrew J. Biggin, et al.	Implications of a weak geomagnetic field ~370 million years ago for the effects of whole-mantle convection on long-term geomagnetic variation

Physical volcanology (session 11)

173	Peter E. Marshall*, Mike Widdowson, David T. Murphy, Simon P. Kelley	Unmasking the Kalkarindji: the effects of long term weathering on the primary magmatic signature
174	Alexander Steele*, Danielle Charlton, Lara Smale, Christopher Kilburn, Agust Gudmundsson, et al.	Pre-eruptive unrest at Campi Flegrei Caldera, Southern Italy
175	Pete J. Rowley*, Brittany D. Brand, Nick Pollock	Capture of shear mixing in pyroclastic density currents at Mount St. Helens
176	Katie Preece*, J. Barclay, R. Brown, D. Mark, K. Chamberlain, et al.	A 1 million year eruption history of Ascension Island
177	Claire Harnett*, Mark Thomas, Adam Stinton, Jackie Kendrick, Yan Lavallée, et al.	Evolution of mechanical properties of dome rock across eruptive periods
178	Peter Reynolds*, Simon Holford, Nick Schofield	3D Seismic Constraints on the Morphology and Emplacement of Mafic Laccoliths: Implications for Surface Folding and Shallow Magma Transport
179	Abdelsalam Elshaafi*, Agust Gudmundsson	Emplacement and inflation of the Al-Halaq al Kabir lava flow-field, central part of the Al Haruj Volcanic Province, Central Libya
180	Zoë Matthews*, Christina J Manning	Textural analysis of obsidian: An insight into collision related magmatism
181	Hannah M. Buckland*, Julia Eychenne, Katharine V. Cashman, Alison C. Rust	Relating the physical properties of volcanic rocks to the characteristics of ash generated by experimental abrasion
182	Nina Jordan*	Mixed populations of distal tephras – friend or foe?
183	Pamela Rattigan*, David Brown	The stratigraphy and emplacement of lava-like and welded ignimbrites on the southern flank of Las Cañadas Caldera, Tenerife, Canary Islands
184	Keri McNamara*, Karen Fontijn, Katharine V. Cashman, Alison C. Rust, Amdemichael Z. Tadesse, et al.	Using lake cores for tephrochronology in Ethiopia: an investigation into ash settling processes in lakes
185	Mark E. Thomas*, Jurgen W. Neuberg, Claire Harnett	The role of lava domes in controlling volcanic eruptions
186	Hannah C. Moore*, Jonathan D. Dietz, David J. Brown	The nature and emplacement of the rhyolitic lava-like Hruni Ignimbrite in the Hreppar Formation of southern Iceland
187	Harisma Andikagumi*, Colin Macpherson, Ken McCaffrey	Upper Plate Controls on Volcano Distribution in Magmatic Arcs
188	Amy L. Chadderton*, Peter Sammonds, Philip Meredith, Rosanna Smith, Hugh Tuffen	The influence of temperature on permeability evolution in Volcán Chaitén rhyolite: An experimental approach
189	Jason P. Coumans*, John Stix	Caldera collapse at near-ridge seamounts: an experimental investigation
190	Sean Whitley*, Ralf Halama, Ralf Gertisser	Skarn-Forming Processes in Calc-Silicate Xenoliths from Merapi Volcano, Indonesia
191	Jacqueline Owen*, Thomas Shea, Hugh Tuffen	The role of bubbles during the 1918 subglacial basalt eruption of Katla, south Iceland
192	David J, Ferguson*, Helge Gonnermann, Philipp Ruprecht, Terry Plank, Erik Hauri, et al.	Measuring magma decompression rates for explosive basaltic eruptions of Kilauea using melt embayments

193	Amy Hughes*, Jackie Kendrick, Giulio Di Toro, Yan Lavallée	Understanding the role of friction in volcanic environments
194	Gregory M. Smith*, Rebecca Williams, Peter Rowley, Daniel R. Parsons	Quantifying the sedimentation of ignimbrites: understanding pyroclastic density currents through experimental modelling

Earthquakes, palaeoseismology, and rates of fault slip: From milliseconds to millions of years (session 12)

195	Sarah A. Weihmann*, Dave Healy	Prediction of slip tendency with uncertain stress data
196	Laura Gregory*, Luke Wedmore, Richard Walters, Ken McCaffrey, Max Wilkinson, et al.	The 2016 Amatrice-Vettore Earthquakes: linked faults, multiple earthquakes, and repeated rupture
197	Luke N.J. Wedmore*, Laura Gregory, Gerald Roberts, Richard Walters, Ken McCaffrey, et al.	Stress triggering and field observations of the 2016 central Italy earthquake sequence

New frontiers in experimentation, rock physics and magma rheology (session 14)

198	Rebecca Coats*, Jackie Kendrick, Jose Godinho, Biao Cai, Felix Von Aulock, et al.	An investigation of the effect of crystals on magma flow and failure
199	Sami Mikhail*, Michael J. Heap	Estimating the brittle-ductile transition on Venus and exploring the disparate volcanic history of Earth's sibling (with a little help from Argon isotopes)
200	Michael J. Heap*, Marie Violay, Fabian B. Wadsworth, Jérémie Vasseur	Micromechanisms of ductile deformation in volcanic materials
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ALL ABSTRACTS TO FOLLOW ALPHABETICALLY

Seismicity accompanying the 2014 Bárðarbunga-Holuhraun intrusion and the co- and post-eruptive activity.

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An intense swarm of seismicity on 16 August 2014 marked the beginning of intrusion of a large dyke from the subglacial Bárðarbunga volcano, central Iceland. Melt propagated laterally NE from the volcano at the brittle-ductile boundary ~6 km b.s.l. and created over 30,000 earthquakes along a 48 km path. On 31 August a fissure eruption began at Holuhraun and the seismicity rate within the dyke immediately dropped to a much lower level, suggesting that once a pathway to the surface had formed magma was able to flow freely and largely aseismically. Melt was fed from the subsiding Bárðarbunga volcano to the eruption site at Holuhraun for 6 months. The volcano experienced over 70 earthquakes greater than M5 during the eruption and subsided 66 m in total. We discuss the relationship between bursts of seismicity in the volcano and periods of rapid dyke propagation, and the link between the volcano and the eruption site during the co- and post-eruptive periods. Full moment tensor solutions show distinct differences in failure mechanism between earthquakes occurring in the dyke and those occurring in the subsiding caldera. The dominant earthquake source in the dyke is left-lateral strike slip faulting in the advancing tip, orientated sub-parallel to the dyke, whereas in the caldera earthquakes arise from a chaotic trapdoor-piecemeal caldera collapse.

VolcLab: A balloon-borne instrument package to measure ash, gas, electrical, and turbulence properties of volcanic plumes

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Release of volcanic ash into the atmosphere poses a significant hazard to air traffic. Exposure to appreciable concentrations ($\geq$4 mg m^{-3}) of ash can result in engine shutdown, air data system loss, and airframe damage, with sustained lower concentrations potentially causing other long-term detrimental effects [1]. Disruption to flights also has a societal impact. For example, the closure of European airspace following the 2010 eruption of Eyjafjallajökull resulted in global airline industry losses of order £100 million daily and disruption to 10 million passengers. Accurate and effective measurement of the mass of ash in a volcanic plume can be used in combination with plume dispersion modelling, remote sensing, and more sophisticated flight ban thresholds to mitigate the impact of future events.

VolcLab is a disposable instrument package, attached to a standard commercial radiosonde, for rapid emergency deployment on a weather balloon platform. The payload includes a newly developed gravimetric sensor using the oscillating microbalance principle to measure mass directly without assumptions about particles' optical properties. The package also includes an SO_2 gas detector, an optical sensor to detect ash and cloud backscatter from an LED source [2], a charge sensor to characterise electrical properties of the plume [3], and an accelerometer to measure in-plume turbulence [4]. VolcLab uses the established PANDORA interface [5], to provide data exchange and power from the radiosonde. In addition to the VolcLab measurements, the radiosonde provides standard meteorological data of temperature, pressure, and relative humidity, and GPS location. Simultaneous collection of these datasets in multiple locations, and in real time, will provide in situ plume characteristics for airspace risk management planning as well as providing valuable scientific information on plume dynamics.

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Partitioning of oblique convergence coupled to the fault locking behaviour of fold-and-thrust belts: evidence from the Qilian Shan, northeastern Tibetan Plateau

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Oblique plate convergence is common, but it is not clear how the obliquity is achieved by continental fault systems. We address this problem in the Qilian Shan, northeastern Tibetan Plateau, using new fieldwork observations, geomorphic analysis and elastic dislocation modeling of published geodetic data.

A thrust dipping SSW from the northern range front underlies steeper, bivergent, thrusts in the interior ranges. Cenozoic thrust-related shortening is estimated to be ~140-160 km, based on two transects. Elastic dislocation modeling indicates that strain in the interseismic period is consistent with a low angle detachment thrust locked at ~20 km, dipping SSW at ~13^{o}. We suggest that this detachment is located above crust of the North China Block, which was originally underthrust during Paleozoic orogeny.

Dislocation models place the strike-slip displacement at the down-dip limit of the locked portion of the detachment, along the left-lateral Haiyuan Fault. This configuration is consistent with the strain partitioning described for oceanic subduction zones, but not has previously been shown by dislocation models of continental interiors.

The marginal, strike-slip, Altyn Tagh Fault influences thrusting within the Qilian Shan for 100-200 km from the fault, but, contrary to previous models, does not control the more regional structure of the range, where basement structures have been reactivated along an ~800 km long Paleozoic orogenic belt.

Overall, the Qilian Shan has elements of the main Tibetan Plateau in nascent form: active thrusts are marginal to an interior that is developing plateau characteristics, involving low relief, and low seismicity apart from along strike-slip faults.

Evidence for cyclical fault zone sealing and strengthening, Alpine Fault, New Zealand

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The Alpine Fault, a transpressional plate boundary fault between the Australia-Pacific plates, ruptures periodically (~300yr) with large magnitude earthquakes (Mw~8), is currently locked and nearing the end of its interseismic period. Using temporal and fine-scale spatial variations in carbonate deformation microstructures and geochemistry, this study investigates the influential role of calcite in sealing and restrengthening the Alpine Fault.

Phase 1 of the Deep Fault Drilling Project (DFDP-1) at Gaunt Creek revealed a fault zone structure with ~1m fault core with associated damage zone, overprinted by a zone of alteration in the hanging wall, formed through enhanced fluid-rock interaction on a fault which currently has very low permeability. Carbonate is one of the primary authigenic minerals in this alteration zone, with mineralisation concentrated within fault core fractures. Through Electron Backscatter Diffraction, Cathodoluminescence (CL) and Secondary Ion Mass Spectrometry multiple episodes of fracture generation and mineralisation have been recognised.

Early carbonate veins exhibit dull CL and high Fe concentrations; these generations have accommodated extensive deformation including intense mechanical e-twinning and dynamic recrystallization, indicating formation at temperatures of >250°C. Younger generations, attributed to more recent seismicity exhibit bright CL and greater Mn concentrations and lack deformation microstructures, supporting the absence of stable creep between rupture events on the central Alpine Fault. Variations in trace elements highlight fluctuations in ambient conditions/fluid source between generations of calcite veining, variation within a single generation indicates multiple pulses of fluid were required to fully seal some voids. Older calcite generations and those closer to the principal slip zone contain greater amounts of Fe and Mg, while younger generations and recrystallized regions contain more Mn.

The precipitation of secondary minerals appears to play an important role in fault sealing through the brittle seismogenic crust. Calcite appears to dominate within the Alpine Fault core to depths of <4km, below which calcite and quartz are likely to co-precipitate in the fault core; however evidence of this has been wiped out by successive cataclasis.

Controls on the rheology and mineralogy of peridotite in a palaeosubduction zone: a transect through the base of the Oman-UAE ophiolite

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The Semail thrust is a well exposed ductile shear zone that juxtaposed the Oman-UAE ophiolite over the metamorphic rocks of the subducted slab. Although much work has been done on the deformation and pressure-temperature history of the metamorphic rocks of the footwall sole, relatively few studies have investigated the peridotite in the base of the ophiolite. Studies of the basal peridotite provide unique insight into processes such as strain localisation, subduction initiation, and chemical interaction between the subducting slab and mantle wedge.

To elucidate controls on the mechanical properties of mantle lithosphere during initiation and early stages of a subduction zone, we used electron backscatter diffraction (EBSD) to analyse samples collected along a transect from the base of the ophiolite to ~500 m up the structural section. This analysis quantifies trends and relationships between grain size, modal mineral abundance, and crystal preferred orientation (CPO), allowing interpretation of their implications for deformation processes across the grain to tectonic scales.

Our results demonstrate that olivine grain size is inversely proportional to the modal abundance of secondary phases, primarily pyroxenes, consistent with grain size reduction through grain boundary pinning[1]. Experimentally-derived flow laws imply that under the inferred deformation conditions the viscosity of olivine is grain-size sensitive[2]. Our results also reveal that olivine grain-size is proportional to CPO strength, which can potentially be explained by changes in the relative contribution of deformation mechanisms to the total strain rate. As such, this indicates that grain size, and hence the abundance of secondary phases exerted a control on the viscosity during subduction-related deformation of the basal peridotite. However, in addition to the typical mineral assemblages of harzburgite, dunite, and lherzolite, the basal section of the ophiolite contains as much as 20% hornblende. The presence of hornblende has two important rheological implications. First, like pyroxene, it is a secondary phase that can pin olivine grain boundaries, limiting grain-size. Second, it is evidence for hydration of the mantle wedge. As the likely source for the water is fluids released during granulitisation of the sole, this implies that the weakening of the basal peridotite is concomitant with the strengthening of the metamorphic sole.

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2. Hansen et al., 2011, JGR 116.

Using an innovative approach to apatite (U-Th)/He thermochronometry to study the tectonic-geomorphic history of Grampian Highland area-Scotland.

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There is considerable evidence that the present-day topography of Scotland has been affected by tectonic uplift that started during Late Mesozoic to Early Cenozoic, although it remains unclear to what degree the present topography of Scottish Highlands has retained remnant features of the topography from Caledonian Orogeny c. 420 Ma. Generally, the juxtaposition of rocks of different ages across north western Scotland and particularly across the main faults suggests several episodes of uplift and denudation. Despite the substantial evidence of Late Cretaceous or Early Palaeocene activity on Scotland's landscape, it has been currently proposed that the mountains that formed during the Caledonian orogeny have survived and largely preserved their original topography (Nielsen et al. 2009). Over the last decade or so low temperature thermochronology methods including fission track and (U-Th)/He analysis have been utilized to quantify the surface uplift and denudation of rocks, as well as history of re-deposition across parts of Scotland (Hurford 1977, Lewis et al. 1992, Thomson et al. 1999, Persano et al. 2007, Holford et al. 2010). Low temperature thermochronology provides meaningful estimates of the thermal history, rate of exhumation and denudation on a time scale of millions of years to better understand landscape evolution, as well as modelling of sedimentary basins. The NW of Scotland, in particular the Early Cenozoic magmatic activity and its effects on the surrounding rocks has been broadly concentrated on over last three decades. However, not only in the NW of Scotland but also in many regions, the (U-Th-Sm)/He technique has been questioned because different apatite grains from the same rock have yielded very different AHe ages. More recent study by Brown et al. (2013) has shown that this dispersion contains useful information about the thermal history, particularly when it is combined with apatite fission track data of a sample. The thermochronometric study in this project has focused on Grampian Highland area, including key vertical profile sections where feasible (e.g. Cairngorms, Lochnagar, Ben Starav) to quantify the rate of denudation of syn/post Caledonian Orogeny, and showing the thermal modelling and their correlation with regional geological events. Also this study will utilize a novel new approach to deriving thermal histories from very dispersed AHe ages in combination with AFT data from the same sample.

Upper Plate Controls on Volcano Distribution in Magmatic Arcs

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New methods have been applied to describe the distribution of volcanoes within magmatic arcs. Previous approaches assumed that alignment of Mariana Arc volcanoes was best described by a small circle distribution and concluded that this pattern resulted from mantle wedge melting processes in a curved subduction zone. We reassessed the RMS misfit to a small circle for the dataset used in that study (12, mainly subaerial, volcanoes from Smithsonian Institute Global Volcanism Program) to be a 2.5 km. A more complete dataset including all 37 subaerial and submarine volcanoes, yields an 8.4 km RMS misfit for a small circle.

In contrast, applying the Hough Transform method to the larger dataset, achieved lower misfits, of 3.1 and 3.0 km, for great circle segments for two possible segments combinations. This indicates that Mariana Arc volcano distribution is better described by a great circle alignment, instead of small circle, and suggests that upper plate structure is most likely to control magma transport. Variogram analysis of volcano spacing and volume shows spatial correlation between 420 and 500 km distance which is similar to the maximum segment length (320 km).

To understand the magma transport within each segments, we determined the coefficient of variation (Cv) of volcano spacing. Cv values tend toward zero for non-random distributions. Monte Carlo simulation confirmed the regularity of spacing in the southernmost segment by rejecting the null hypothesis that volcano spacing are randomly generated, by 0.007 estimated probability at 95% confidence level. This distribution may be associated with the development of normal faults at the back arc as their Cv values also tend towards zero.

This study shows that volcano alignment might reflect lithospheric structures. Like Sunda Arc, which we have shown to have an *en echelon* segmentation pattern that differs from the upper crustal structure, the Mariana distribution indicates the need for further studies to understand the detail of upper plate influence upon arc volcano distributions.

Critical evaluation of Electron Backscatter Diffraction (EBSD) derived grain-size analysis and its impact on paleo-piezometry and flow law studies.

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Paleo-piezometers and flow laws are available for many common minerals and represent a key tool to understand deformation in the mid to lower crust. In many cases the use of grain size statistics, primarily mean grain size, is required to gain differential stress and strain-rate information. This work investigates the way grain size determination impacts such interpretations by analysing a suite of rocks from the Kali Gandaki Valley, central Nepal.

The two main techniques to obtain grain size statistics are the linear intercept (LI) and equivalent circle diameter (ECD) methods, which when undertaken optically are considered equivalent. In this study a strong correlation between methods was observed, however, LI consistently gave a smaller mean grain size estimate, with a greater disparity at larger grain sizes.

The factors controlling this disparity were; post-acquisition data processing, step size, minimum pixel size for ECD, and the spacing of the lines for the LI method. Mean grain size estimations are heavily affected by data processing, particularly the extrapolation of data into zero solutions, with the removal of wild spikes having a minor effect. Data processing effected ECD more than LI. The minimum number of pixels for ECD grain size has the greatest effect on mean grain size.

The step size and the spacing of intercept lines are important and a decrease in the spacing of both can cause LI method to give grain sizes up to 51% below ECD. This substantially increases differential stress and strain rate estimates. Twins need to be removed from the dataset; however, this is not always undertaken, or reported, leading to an underestimate of grain size.

These findings stress the importance of clear and comprehensive discussion of the methods used for data processing and grain size determination. If this is not the case variations between studies could be due to either a geological or data processing control. A final consideration is whether EBSD should be used, or a correction factor implemented, for piezometers and flow laws derived from optical methods.

Extensive sub-arc decarbonation of subducting slabs

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CO_2 release from subducting slabs is a key element of Earth's carbon cycle, consigning slab carbon either to mantle burial or recycling to the surface through arc volcanism, however, what controls subducted carbon's fate is poorly understood. Fluids mobilized by devolatilization of subducting slabs play a fundamental role in the melting of mantle wedges and in global geochemical cycles [1]. The effect of such fluids on decarbonation in subducting lithologies has been investigated recently [2-5] but mechanisms of carbon transfer from the slab to wedge are poorly understood [2-6]. Several thermodynamic models [2-3], and experimental studies [6] suggest that carbon-bearing phases are stable at sub-arc depths (80-140 km; 2.6–4.5 GPa), implying that this carbon can be subducted to mantle depths of >140 km. This is inconsistent with observations of voluminous CO_2 release from arc volcanoes [7-10], located above slabs that are at 2.6-4.5 GPa pressure. Here, we show that continuous hydrated of sediment veneers on subducting slabs by H_2O released from oceanic crust and serpentinised mantle lithosphere [11-13], produces extensive slab decarbonation over a narrow, sub-arc pressure range, even for low temperature subduction pathways. This explains the location of CO_2-rich volcanism, quantitatively links the sedimentary composition of slab material to the degree of decarbonation and greatly increases estimates for the magnitude of carbon flux through the arc in subduction zones.

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Shear regime controls on permeability during magma extrusion at Unzen volcano, Japan

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Permeability is a major control on the eruptive behaviour exhibited by volcanoes. In this study we investigate how shear causes permeability variation within a volcanic conduit, and how different shear regimes may overlap within one volcanic system.

The 1990-1995 eruption of Unzen volcano, Japan, culminated in the extrusion of a dacite spine, which exposes the petrographic architecture of magma in shallow conduits. Close examination of the spine structure during a field campaign is combined with laboratory experiments to constrain the permeability of magma in the shallow conduit. We studied a ~6 m wide section of extruded spine which displays a gradation from seemingly unsheared rock in the conduit core to rocks increasingly sheared towards the conduit margin, spatially defined by a fault gauge zone. Rock samples were collected for laboratory characterisation (porosity, permeability, mineralogy). A second section of spine (extruded after the example) further shows that the conduit core may be sheared as we observe large tensile fractures; here, sampling was not possible, but non-destructive *in-situ* characterisation of permeability was performed using a portable permeameter.

Laboratory measurements show a permeability decrease across the shear zone from core to gouge of approximately one order of magnitude, with the lowest permeability observed in the most highly sheared block. In this block, permeability is almost one order of magnitude higher in the plane of shear than parallel to shear. Our measurements thus show a clear influence of shear on permeability in the conduit, with significant anisotropy in the shear zone. The strongly micro-fractured nature of the sheared rocks results in a pressure-dependent porosity (of up to 4%) and permeability (of up to one order of magnitude).

In contrast, our field measurements of the second spine section reveal that dilational shear can result in an increase in permeability of approximately three orders of magnitude. The shear zone hosts a 2 cm width by 3 m long fracture from which permeability could not be measured directly.

We attribute these contrasting shear zone architectures to different shear regimes likely occurring at different depths during magma ascent. Compactional shear appears to dominate deeper in the system, with dilational shear becoming dominant at shallower level in the volcanic conduit.

The role of micas in deformation and strain partitioning within mid-crustal shear zones.

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Large-scale mid-crustal shear zones accommodate a significant proportion of crustal strain resulting from plate tectonics. Despite their importance with regard to the strength of the crust, the rheology and mechanisms of deformation within these systems are still not fully understood. In particular, the role of phyllosilicates, as a weak phase relative to other silicate minerals, in localising and facilitating this deformation, is likely to be more significant than has previously been accounted for. The Cossato-Mergozzo-Brissago line in Northern Italy is a phyllosilicate rich shear zone inferred to have formed under amphibolite facies conditions in the mid-crust. Detailed fieldwork and systematic sampling has been conducted on several transects across this lineament. This has been coupled with microstructural analysis using optical, scanning and transmission electron microscopy techniques in order to ascertain the deformation mechanisms active within the mica component of these mylonites, as well as the extent of strain partitioning into this phase. Determination of the degree to which micas influence the strength of crustal shear zones could have implications on our understanding of the rheology of the crust as a whole and feed into future models of large-scale crustal deformation.

Using trace element mapping to identify discrete magma mixing events from the Astroni 6 eruption.

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The Astroni volcano, located within the Agnano-Monte Spina volcano-tectonic collapse zone, formed 4.23 cal. ka BP, during the third epoch of activity within the Campi Flegrei caldera (CFc; Southern Italy). The evolution of Astroni deserves further study for two main reasons: (1) Unlike other documented activity within the CFc, the preserved tuff ring of the volcano has been formed from seven eruptions, of varying magnitude, over a relatively short timescale; (2) it has been postulated that the style and magnitude of the Astroni 6 eruption may represent a medium-sized event within the CFc should renewed activity ensue.

Previous studies of Astroni have investigated crystals, as well as whole rocks, for Sr, Nd and B isotopic variations. Results indicate that mixing/mingling processes occurred within the volcano's plumbing system. However, studies aimed at measuring the composition of discrete growth zones within individual crystals would give a more in-depth comprehension of the dynamic history of Astroni and possibly the CFc in general.

In this study, we focus on samples from the Astroni 6c and 6f layers. Plagioclase, sanidine and diopside crystals, as well as groundmass glass and glassy melt inclusions, were first characterised for major and trace element geochemistry through in-situ point analysis. High resolution trace element mapping was then undertaken to investigate crystal histories, this method aimed at detecting discrete zoning events which may otherwise be missed with simple point analysis.

Feldspars show a distinct variation in both major and trace elements between core and rim, with around 20% of measured crystals showing an anti-rapakivi texture. In contrast, with respect to major element geochemistry, diopside crystals are relatively homogeneous. However, initial multidimensional trace element mapping, using LA-ICP-MS, has highlighted diopsides with discrete zones enriched in compatible elements such as Cr and Ni. This further supports the hypothesis that mixing/mingling involving variably evolved magmas occurred prior to, and possibly during, the Astroni eruption.

A new barometer from stress fields around inclusions

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A key step in understanding geological and geodynamic processes is modelling the pressure-temperature paths of metamorphic rocks. Traditional thermobarometry relies on mineral assemblage equilibria and thermodynamic modelling to infer the pressures and temperatures of chemical equilibration. This approach requires the presence of specific mineral assemblages and compositions, which narrows its applicability. In this study we aim to develop a geobarometer based on mechanical interactions between inclusions and their host grains. Exhumation of minerals with inclusions causes heterogeneous residual stress fields due to the different, and often anisotropic, elastic properties of the inclusion and host. Recent studies[1] measure residual stresses within inclusions using Raman spectroscopy and use those stresses as a barometer. In contrast, we measure each component of the stress field around inclusions using high angular-resolution electron backscatter diffraction (HR-EBSD). This technique provides higher spatial resolution and increased sensitivity to elastic strains relative to Raman spectroscopy. We focus on quartz inclusions in garnet, a common feature in metamorphic rocks. This assemblage also provides an opportunity to test our results with compositional thermobarometry. We analyse samples metamorphosed at pressures ranging from ~300 MPa to ~1600 MPa, as recorded by independent geobarometers. HR-EBSD reveals concentric and lobate signals around the inclusions, with elastic strains and residual stresses of the order 10^3 and 10^2–10^3 MPa, respectively. We implement Eshelby's solution for the inhomogeneity problem[2] to simulate the elastic strain/stress field around an anisotropic ellipsoidal inclusion surrounded by an isotropic, homogeneous, infinite matrix. The simulations reproduce the general pattern of the elastic fields that we observe from HR-EBSD and account for different geometries of the inclusion. The simulations provide the basis for quantitatively relating the stress fields measured by HR-EBSD to the entrapment pressures of inclusions.

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Anisotropic permeability in shale rocks: Evidence from acoustic, pressure, chemical and X-ray nano-CT analyses.

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Finely laminated mudstones are the source and reservoir of unconventional shale gas plays explored for in gas-mature basins. These reservoirs have trapped the gas content in "tight" mudstone during thermal maturation, due to the ultra-low permeability of the rocks. We present new insights into the permeability controls of shale rocks, by combining experimental and rock mechanical data with high resolution X-ray computed tomography of laminated mudstones sampled from depths of 3700 metres. Pore pressure oscillation experiments record up to 2 orders of magnitude higher permeability in the lamination-parallel orientation of the mudstones, of 10^{-18} to 10^{-19} m^2, compared to lower 10^{-20} and 10^{-21} m^2 flow perpendicular to bedding. Micro- and nano-scale X-ray imaging of the samples illuminate the scaly fabric of clay minerals and wavy bedding-parallel fractures that follow the clay morphology. Tortuosity factors calculated using diffusive flux-based models of pore space volumes that correlate to the grain-scale clay fabric reproduce the flow anisotropy measured in experiments. These new high-resolution images together with the permeability analyses suggest that the alignment of the clay minerals has a governing nanoscale control on permeability. Any flow present in the shale rocks around the natural and induced fracture network will be primarily in the bedding-parallel orientation. Vertical fractures propped open during fracking injections provide accessible pathways for low permeability flow through the laminated mudstones. We suggest that the longevity of low-rate shale gas recovery recorded in exploitation boreholes correlates to the slow depletion of gas migrating along bedding planes towards fractures and then out of the borehole.

Shallow conduit architecture associated with cyclic vulcanian explosions at Galeras volcano, Colombia

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Vulcanian eruptions are a form of explosive activity that recurs cyclically at many arc volcanoes. These transient explosions are thought to repeatedly destroy and eject an outgassed, crystal-rich and densified plug of magma that has stalled in the shallow conduit. Despite the hazardous nature of this activity, controls on eruption magnitude and timing remain poorly understood.

We present results from an ongoing textural and volatiles study of a suite of andesitic ballistic bombs produced by cyclic vulcanian explosions of the 2004-2012 phase of activity of Galeras volcano, Colombia. Textural observations are combined with measurements of volatiles in the rhyolitic matrix glass of each bomb to estimate the final storage pressure of the bomb prior to its ejection from the conduit.

We identify 3 bomb types with distinctive textures and volatile contents. Dense bombs have very low porosity and low water content (0.08-0.29 wt% H_2O), corresponding to very low storage pressures (0.3-2.3 MPa). Poorly vesicular bombs have higher porosity, in the form of large, interconnected vesicles with complex shapes, and similar water content to dense bombs (0.05-0.35 wt% H_2O), corresponding to similarly low storage pressures (0.2-3 MPa). Both dense and poorly vesicular bombs show no evidence of syn-eruptive vesiculation. Inflated bomb types typically have a breadcrusted texture formed by rapid quenching of an exterior rind and vesiculation of the bomb interior upon eruption. The water contents of the quenched bomb rinds are the highest in the sample suite (0.4-1.01 wt% H_2O) and correspond to higher storage pressures (1.6-9.9 MPa).

We interpret this sample suite as evidence of the repeated development and destruction of stratified magma plugs in the conduit of Galeras volcano throughout 2004-2012. The plugs consisted of deeper, dense and relatively "water-rich" magma that gave rise to inflated bombs upon eruption; a shallow, porous and permeable zone of water-poor magma that gave rise to poorly vesicular bombs; and a shallow, densified and water-poor cap. The vesicles in poorly vesicular bombs formed a permeable porous network that efficiently degassed the "water-rich" magma to form the dense and degassed cap, and were in the process of viscous collapse immediately prior to each vulcanian explosion.

Quantifying the Relationship Between Intra-Continental Magmatism and Dynamic Topography: North Africa

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In the continents, dynamic topography is difficult to determine because the density structure of the lithosphere is poorly known. It is generally agreed that hot upwelling mantle produces dynamic uplift whilst cold downwelling mantle causes regional subsidence. Calculating asthenospheric potential temperatures from basalts provides one important constraint on dynamic uplift at the present day and in the geologic record. The spatial and temporal distribution of eruptive products together with the compositional variation of lavas allows the origin of continental volcanic events to be interpreted. The Cenozoic Libyan volcanic field is characterized by a series of long wavelength topographic swells that may reflect sub-lithospheric dynamic processes. Admittance analysis of gravity and topographic data as well as seismic tomographic imaging suggest that a low density anomaly sits beneath the lithospheric plate. A new regional basaltic database of 188 XRF and ICP-MS analyses has been assembled. The Libyan volcanic field has been active from at least 17 Ma until the present day. Inverse modeling of rare earth elemental distributions shows that Libyan basalts were generated by melting of a predominantly anhydrous mixed peridotitic mantle source with an asthenospheric potential temperature of ~ 1400 ^{o}C. Our results suggest that the existence and distribution of volcanism is caused by the combination of warm, upwelling asthenospheric mantle and thinner (< 100 km) lithosphere beneath Libya whereby melts may ascend to the surface through metasomatized lithospheric channels.

Temporal variations in the mantle source beneath Fogo, Cape Verde

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Fogo is the most volcanically active island of the Cape Verde archipelago. Therefore Fogo provides a high resolution stratigraphic record of historic lavas from Cha de Caldeiras. The Cape Verde archipelago is morphologically and geochemically divided into two island chains. The geochemistry reflects the underlying mantle heterogeneity, with the northern islands displaying HIMU and DMM affinities[1]. Whereas the southern island chain, of which Fogo is part, exhibits HIMU and EM1 components[1]. A significant role of pyroxenite has been postulated for Cape Verde in general[2] and older volcanics at other islands in Cape Verde show a substantial contribution from eclogite and pyroxenite[3,4]. We employ samples from the historic eruptions at Fogo to investigate temporal variations in mantle heterogeneity and the role of pyroxenite in the mantle source.

Our samples of the historic lavas from Fogo span from 1799 to 2014/2015 and are clinopyroxene-olivine-phyric basanites to tephrites. The historic lavas have MgO of 5.0 to 11.1 wt% and TiO_2 3.4 to 4.0 wt%. Profiles of REE show enrichment in LREE. Key trace element ratios for the historic lavas from Fogo are La/Sm of 4.3 to 4.9, Sm/Yb of 4.0 to 5.1, and Zr/Y of 9.8 to 11. In addition the historic lavas show La/Nb of 0.67 to 0.75, where Ba/Th increases with decreasing La/Nb and $\delta^{18}O$ of olivine from 5.9 to 4.9‰.

The geochemistry combined with a model for melting of a heterogeneous source suggests 2 to 6% melting of a garnet-pyroxenite mantle source. In addition temporal variations in geochemistry indicate that the contributions of the EM1-like component and the pyroxenite mantle lithology have increased with time in the recent historic volcanism at Fogo.

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Magma recharge and mingling events recorded by clinopyroxene in the Ditrău Alkaline Massif, Romania

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The Ditrău Alkaline Massif is a rift-related, Mesozoic igneous complex in the Eastern Carpathians, Romania. Ultramafic to mafic cumulates, diorite, syenite, nepheline syenite, camptonite and tinguaite dykes with ijolite enclaves contain various types of clinopyroxenes.

Major and trace element concentrations of the studied clinopyroxenes reveal three compositional types of pyroxenes in the Ditrău Alkaline Massif: (1) pale brown, primitive diopside ($Di_{77–94}$), (2) green, intermediate pyroxene ($Hd_{20–32}Aeg_{12–43}$) and (3) green to dark green coloured, evolved aegirine-augite crystals (up to Aeg_{90}). Clinopyroxene-melt equilibrium calculations were used to identify co-genetic and co-magmatic crystallisation sequences in the Ditrău pyroxene populations.

Textural observations together with calculated pyroxene equilibrium melt compositions suggest antecryst origin for the primitive diopside in camptonite and tinguaite dykes, and ijolite enclaves. An antecrystic origin has also been identified for the intermediate pyroxene in diorite, syenite and tinguaite. The green Na-rich diopside-hedenbergite population is in equilibrium with the host ijolite and interpreted as phenocryst phase. The aegirine-augite crystals in nepheline syenite are also characterised as phenocrysts.

The overall similar trace element patterns for all the calculated primitive diopside equilibrium melts indicate the same magma source for the primitive pyroxene crystals pointing to an early basanitic parental magma (M1). Slight differences in the trace element distributions of these calculated melts suggest repeated events of M1 magma recharge.

The ijolite green clinopyroxene phenocrysts represent another melt (M2) in the magmatic system which fractionated towards to the ijolitic (M2') magma composition represented by overgrowth rims on ijolite phenocrysts and antecrysts, and ijolite groundmass microlite crystals. Further fractionation produced nepheline syenitic melts (M3) which crystallised aegirine-augite phenocrysts in nepheline syenite and aegirine-augite groundmass in tinguaite.

The intermediate pyroxene antecrysts incorporated into the syenitic, dioritic and tinguaitic magma are identified representing M2 melts and also proving M2 magma recharge and mingling with the syenite, diorite and tinguaite crystal mush.

Deforming porous rock: yield curve evolution and the implications for compaction, dilatation and localisation.

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Critical state theory has been widely used to model the deformation of porous rock. In this theory, the yield curve – defining where yield occurs on a plot of differential stress versus effective mean stress - is typically assumed to be a smooth elliptical surface. This curve can be divided into two regimes, where the low-pressure side is associated with localised brittle deformation (dilatation) and the high-pressure side with distributed ductile deformation (compaction). Experimental studies have been in general agreement with this. However these studies often have a significant amount of data scatter due to sample variability that may hide subtleties in the true shape of the yield curve and have implications for the mode of deformation. There is also a lack of data on how yield curves evolve as a rock accumulates both volumetric and shear strain. Here, novel triaxial experiments are performed to map precisely the yield curve of a single sample by repeated axial loading at different confining pressures.

We use polycrystalline bassanite, formed by the dehydration of gypsum prior to deformation, to investigate the nature of its yield curve. This material has a starting porosity of approximately 27.5% and is intrinsically weak with $P^* \approx 6$ MPa allowing for the post-yield evolution of the curve to be analysed in detail. Repeated probing of the yield curve greatly reduces the scatter of data in comparison to studies where multiple samples are used. Rather than showing a smooth curve, we discover a kink on part of the yield curve typically associated with compaction and strain-hardening. The aspect ratio of the curve also changes as the sample accumulates inelastic volumetric strain. The effect of inelastic shear strain was also investigated. We find that as the sample accumulates more shear strain the peak of the curve forms a plateau where both compaction and dilatation occur together. The development of this brittle-ductile transitional regime might help explain why localisation has previously been observed in many experimental studies under conditions where it isn't typically expected.

Does the geological record support the heat-pipe Earth model?

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A heat-pipe model, with rapid volcanic resurfacing similar to that in operation on Jupiter's moon Io, has been proposed as a possible method of heat transport operating on earth prior to the initiation of modern-style plate tectonics. This study aimed to investigate whether simple geological observations could provide evidence of such sustained global volcanism in the Archean record.

Bed thickness measurements of volcanic sequences found in greenstone belts of the North Shaw, Marble Bar, Split Rock and Coongan regions of the Pilbara Craton, Western Australia, were taken in order to calculate rates of volcanism from 3500-2700 Ma. Preliminary measurements were also taken from other cratons, Yilgarn, Barberton and Isua, collectively spanning a much larger age range in order to establish whether trends could be observed on a global scale. The heat-pipe mode is believed to have been in operation prior to 3200 Ma, after which an abrupt drop in volcanism resulted due to the onset of plate tectonics. Results from Pilbara appear to somewhat conform to this hypothesis, with rates reaching a high of 4.368 mm/yr prior to 3200 Ma followed by a sharp decline to 0.06 mm/yr at 3200 Ma. A lack of activity is then observed until 2775 Ma when volcanism is renewed but at a reduced rate of 0.74 mm/yr, reaching as low as 0.004 mm/yr at 2740 Ma. Measurements from Barberton appear to show a similar trend to that of Pilbara, whilst unexpectedly low rates of <0.725 mm/yr were found in the relatively older rocks of Isua as well as unusually high rates of 14.4 mm/yr in the younger Yilgarn region.

Thermal models show that a global volcanic resurfacing rate of 1-2 mm/yr would be essential in order to maintain equilibrium through heat-pipes. Consequently, the effects of tectonic thinning in greenstone belts must be implemented in order to account for rates which are orders of magnitude lower than required for heat-pipe Earth. Therefore, using this method, and based upon this data set alone, it is inconclusive as to whether the geological record shows evidence of volcanic rates high enough to sustain the heat-pipe earth model, particularly on a global scale. However, the heat-pipe mechanism cannot be ruled out without the collection of further data, coupled crucially with quantitative estimates of tectonic thinning in Archean greenstone terranes.

Complex plagioclase crystal cargo: Insights into magmatic processes

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Textures and zoning patterns of plagioclase phenocrysts have the potential to reveal a range of processes within the magma plumbing system of volcanic systems. Here, we present an analysis of 1464 plagioclase crystals from mid-ocean ridge basalts collected along the length of the ultra-slow spreading Gakkel ridge (Arctic ocean). High-resolution backscatter images reveal a high degree of complexity, which we relate to processes in the Gakkel Ridge plumbing system.

Individual samples contain multiple textural and chemical plagioclase populations with crystals arranged individually or as mono-mineralic glomerocrysts formed through synneusis. Crystal habits are varied and include tabular, acicular, resorbed and skeletal forms. Resorption is ubiquitous, with the extent and number of resorption events often varying within a single sample. Resorbed high-An cores are commonly mantled by lower An rims. Crystals often exhibit more than one type of zoning pattern (e.g., normal, reverse, oscillatory and patchy) and are rarely simply zoned. Patchy zoning, sometimes overprinting a previous zonation pattern, presents as either elongate boxy or amoeboid patches and is often associated with melt inclusions. Melt inclusions have circular, boxy, elongate, negative crystal and amoeboid forms.

Observed plagioclase features can be attributed to a combination of magma mixing, high degrees of undercooling and melt decompression. Magma mixing explains the presence of multiple chemical and textural populations within a single sample, with the mixing between chemically distinct magmas potentially inducing disequilibrium in the system leading to resorption. Resorption may have additionally occurred through decompression during melt ascent. Subsequent re-crystallisation and infilling of internal voids formed through decompression-induced resorption produces zoning characterised by large circular to amoeboid patches. Multiple resorption surfaces within crystals can be explained by staged decompression or multiple mixing events. High degrees of undercooling induced by melt emplacement into cold lithosphere facilitated skeletal growth. Following initial skeletal growth, these crystals mature through the crystallisation of trapped melt, producing zoning characterised by elongate patches.

Damage localisation and fracture in volcanic basalts

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A large number of volcanic ocean island flank collapses are known, including those in El Hierro and Tenerife (Canary Islands, Spain) and Stromboli (Aeolian Islands, Italy). These can involve significant volumes of rock mass, with upper volume estimates for known collapses reaching hundreds of cubic kilometers. The pressure and temperature evolution on these islands is often complicated, involving cyclic pressurisation and deflation, and regional tectonic stresses that generate a variety of pore, fracture and fracture networks that in turn may exhibit itself as a pronounced anisotropy. With the increasing use of surveying methods on volcanoes (such as geophysical refection and P-wave tomography surveys) a more thorough understanding of hoe stress and deformation influences on elastic wave velocity under in-situ conditions is becoming more important.

To learn more about these effects, we have used a suite of rocks from three volcanic islands that are known to exhibit flank instability. Triaxial deformation experiments focussed on generating a fracture damage zone using either constant strain rate tests, or constant stress (creep) deformation. In both cases strain was monitored via non-contact axial displacement transducers, and conditions representative of around 800m depth using a conventional triaxial cell.

We observe seismic wave velocities decrease systematically as rocks approach failure, with an increased effect at high angles relative to the final failure plane. In comparison, the dependence of velocity on initial porosity is minor, suggesting that development of fresh damage is more significant to elastic wave velocity changes than the initial matrix. These data illustrate that elastic velocity data are extremely sensitive to the changing strain evolution, and that a pronounced anisotropy is generated due to both deformation, due largely to the fracture damage zone itself.

WORKS

The Role of Water in Subduction Zone Dynamics

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Ultra-high pressure (UHP) metamorphism has long been associated with deep subduction. UHP minerals, such as coesite and microdiamond, are often found in discrete mafic units, hosted in larger scale continental terrains. It is widely accepted that the entirety of these continental terrains must also have been subducted to UHP conditions. However, evidence that the felsic material transformed at eclogite facies conditions is lacking.

The UHP eclogites of Tso Morari in Ladakh, Himalaya share some similarities with other UHP terrains such as the Western Gneiss region in Norway and Kaghan in Pakistan. The UHP eclogite boudins are hosted in granite gneiss and exposed over a 50x100km area. The granites have been overprinted by amphibolite facies, Barrovian metamorphism, so their early history is difficult to decipher. Using a combination of petrography, geochronology and thermodynamic modelling, we aim to decipher the metamorphic history of these granites and determine whether or not they transformed at eclogite facies conditions. Geodynamic modelling of continental subduction has been undertaken, in order to understand the mechanisms for exhumation of UHP material. One such mechanism is known as ‘transformation weakening’, where the transformation of continental material to eclogite facies, weakens the rock, causing it to detach and buoyantly rise back up the subduction channel. The transformation of granite depends on the availability of water in the mid to lower crust. There is evidence for multiple hydration events in the granite on their retrograde path. However, the role of water in the mid to lower crust, particularly in the early stages of subduction, and how this influences the geodynamics of continental subduction is not understood, and forms a key facet of our research.

Faulting and fluid flow controlled by cleavage, shear zones and crenulations at Kainantu gold-copper mine, Papua New Guinea.

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Previous deformation fabrics may influence the geometry of fault zones. Epithermal veins and breccias at the Kainantu gold-copper deposit in Papua New Guinea host gold mineralization in NW-SE steeply dipping lodes. However, there was a complex early deformation history before mineralization. The earliest deformation event at Kainantu resulted in a generally steep NW-SE greenschist facies cleavage (S_1), which guided the orientation of m wide mylonitic shear zones in a dextral strike-slip shear zone network, with strong S_m fabrics. S_1 and S_m were crenulated by S2, producing moderately SE plunging intersection L^1_2 lineations and crenulation hinges. Gold mineralization occurred after S_2 in the form of breccias and extensional veins. High Au grades correlate with areas of obliquity between the shear zone fabrics and the cleavage, and plunge at ~40° southeast in the plane of the lodes - coincident with minor fold hinges and L^1_2. The cleavage, shear zones, crenulations, veins and mineralization are all cut by dextral strike-slip faults. Fluid flow and mineralization were influenced by all three previous deformation structures, and later dextral faulting was affected by all four previous events. The north-south shortening recorded through most of the tectonic history can be related to Tertiary convergence along the major plate Australian/South Bismark plate boundary located ~ 15 km north of the mine. Mineralization occurred under a different tectonic regime from the current north-south convergence, when there was a change of tectonics between 9 and 6 Ma, possibly related to delamination. The Kainantu example shows that several generations of deformation structures may leave a structural legacy that influences subsequent faulting and fluid flow.

Heterogeneity in tectonometamorphic systems; insights from Rb–Sr mica ages from the Cycladic Blueschist Belt, Syros (Greece).

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Heterogeneity in tectonometamorphic systems is well documented. This heterogeneity impacts on the interpretation of geochronological data used to determine the tectonic evolution of metamorphic terrains. An outstanding question in our understanding of these systems is whether metamorphism and the causative tectonics is best viewed as a series of punctuated events or as a continuum? We address this question through examination of the timing of exhumation of the Cycladic Blueschist Belt, Greece. The cause of scatter, beyond analytical error, in Rb–Sr geochronology was investigated using a suite of 39 phengite samples, drilled from specific microstructures in thin sections of calcschists and metabasites from the Cycladic Blueschist Belt on Syros. The majority are from samples that have well-preserved blueschist facies mineral assemblages with limited greenschist facies overprint. Peak metamorphic temperatures are below the closure temperature for white mica so crystallization ages are expected to be preserved. This is supported by the coexistence of microstructures of different relative age; in one sample phengite from the dominant extensional blueschist facies fabric preserves an age of 35 Ma while post-tectonic mica, millimetres away, has an age of 26 Ma. In the North of the island phengite Rb–Sr ages are generally between 53 and 46 Ma, comparable to previous dates from this area. South of the Serpentinite Belt phengite in blueschist facies assemblages associated with extensional fabrics linked to exhumation have ages that range from 42 Ma down to **c**. 30 Ma; two rocks with greenschist facies assemblages gave phengite ages that overlap with the blueschist samples, suggesting blueschist facies phengite is preserved in these rocks. Two samples yielded ages below 27 Ma. The data are consistent with a model of deformation that is continuous on a regional scale, despite local heterogeneities. The results suggest that micro-sampling techniques linked to detailed microstructural analysis are critical to understanding the timing and duration of deformation in tectonometamorphic systems.

High Resolution Mapping of Icelandic Rootless Cones using UAVs

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Structure from motion is a technique used to construct high resolution 3D models from a series of overlapping photographs. Using a commercially available UAV and structure from motion, we were able to rapidly map rootless cone sites in Iceland and produce high resolution DEMs.

Rootless cones are formed by the explosive interaction of a lava flow with environmental water such as lakes, rivers or swamps. They are abundant in Iceland and have been identifies in several other locations on Earth and on Mars. They come in a variety of morphologies and compositions, from large isolated cones made of coarse ash and scoria to small, tightly clustered hornitos made of welded spatter. The spatial distribution and morphology of rootless cones is linked to their composition (spatter, scoria or ash), which in turn reflects the explosivity of the lava-water interaction.

Morphology data are needed to examine these relationships and how they are affected by changes in the lava and water involved. However, rootless cones are too small to be visible in available DEMs of Iceland. Satellite imagery and aerial photography can be used to map the spatial distribution of cones but cannot resolve the smaller rootless cones and provides no information on morphology. Previous studies have used DGPS to map individual cones or groups of cones, but this is a very time intensive technique[1,2].

We used a small quadcopter with and on-board camera to capture high resolution photographs of rootless cone sites across Iceland. We then used structure from motion to construct high resolution (~10cm per pixel) DEMs of the areas mapped.

This approach provides a cost and time-effective way to obtain morphological data of field sites where existing data are unavailable. Fine detail and textures are captured by the UAV camera and preserved in the DEM. The quick nature of the technique makes it easy to deploy across multiple sites. Our resulting DEMs allow more detailed analysis of the link between cone morphology and the environmental factors governing cone formation.

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Low temperature plasticity of plagioclase from nanoindentation

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Understanding the rheology of the lower crust is critical to discriminating between first order models of the strength of the lithosphere. Yet, despite the high abundance of plagioclase feldspar in the lower crust of both the oceans and continents, experimental studies to determine constitutive relationships for the deformation of plagioclase, particularly at low temperatures, are still relatively scarce. We performed spherical nanoindentation experiments on single crystals of plagioclase to better constrain their mechanical behaviour.

Recent advances in protocols for spherical nanoindentation analysis enable extraction of full elasto-plastic stress-strain curves from raw load-displacement data, allowing determination of the plastic behaviour of plagioclase (Pathak & Kalidindi, 2008). High angular-resolution electron backscatter diffraction (HR-EBSD) maps of deformation around the indents link the mechanical properties to crystal orientation and anisotropic dislocation activity. We use high-temperature microhardness tests to assess the temperature dependence of plagioclase hardness. Crystal plasticity finite element modelling provides a tool to estimate critical resolved shear stresses for multiple plagioclase slip systems from mechanical data using the slip rule developed by Dunne et al. (2007). Our goal is to develop an anisotropic mechanical model for plasticity of plagioclase to be included in future simulations of lithospheric dynamics.

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Rapid geomagnetic secular variation during the Swarm era and its impact on global field models.

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Global geomagnetic field models are designed to represent the sources of Earth’s magnetic field and their variation in space and time. Such models are used to study the dynamics of the core, aid satellite operation and make global digital navigation possible – from smartphones to guided drilling. While current models capture the long-period and large-scale features and variations well, it is often difficult to represent the poorly understood small-scale and rapid behaviour of the field, thus making prediction difficult. The mantle and crust filter and mask small-scale spatial and temporal features and field sources external to the Earth contaminate the observations we have. Geomagnetic jerks represent the most rapid observed variations of the internal field, on the scale of months–years.

With the prompt provision of ESA Swarm satellite constellation (<4 days) and auxiliary ground observatory measurements (3 months), it is possible to quickly construct up-to-date models of the geomagnetic field and its variations. We derive such a model based on Swarm era (2013–present) data and investigate the occurrence and spatiotemporal characteristics of recent jerks. Previous reports suggest that global models show regions of high secular acceleration associated with the 2014 jerk and that expressions might be seen at European observatories post-2014. We find limited evidence of a jerk in European observatories but do find globally widespread evidence, our models of this signal are in agreement with independent global geomagnetic field models. We also find evidence of a new jerk in 2015 in auxiliary observatory data.

In response to these events we show the impact on early, and potential future, discrepancies between International Geomagnetic Reference Field (IGRF) predictions and observations in the period of 2015-2020 as a result of the unpredictable, non-linear secular variation of jerks. With the 2014 jerk occurring during / immediately after the data collection period for IGRF-12 and the new 2015 jerk occurring within one year of release we highlight the deviation from observations, the comparable performance of both simple and complex predictive models and the importance of utilising the ability to regularly update field models. This is likely to remain the case until the rapid dynamics of the core are better understood.

A model to forecast magma chamber rupture

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An understanding of the amount of magma available to supply any given eruption is useful for determining the potential eruption magnitude and duration. Geodetic measurements and inversion techniques are often used to constrain volume changes within magma chambers, as well as constrain location and depth, but such models are incapable of calculating total magma storage. For example, during the 2012 unrest period at Santorini volcano, approximately 0.021 km^3 of new magma entered a shallow chamber residing at around 4 km below the surface. This type of event is not unusual, and is in fact a necessary condition for the formation of a long-lived shallow chamber. The period of unrest ended without culminating in eruption, i.e the amount of magma which entered the chamber was insufficient to break the chamber and force magma further towards the surface. Using continuum-mechanics and fracture-mechanics principles, we present a model to calculate the amount of magma contained at shallow depth beneath active volcanoes. Here we discuss our model in the context of Santorini volcano, Greece. We demonstrate through structural analysis of dykes exposed within the Santorini caldera, previously published data on the volume of recent eruptions, and geodetic measurements of the 2011–2012 unrest period, that the measured 0.02% increase in volume of Santorini's shallow magma chamber was associated with magmatic excess pressure increase of around 1.1 MPa. This excess pressure was high enough to bring the chamber roof close to rupture and dyke injection. For volcanoes with known typical extrusion and intrusion (dyke) volumes, the new methodology presented here makes it possible to forecast the conditions for magma-chamber failure and dyke injection at any geodetically well-monitored volcano.

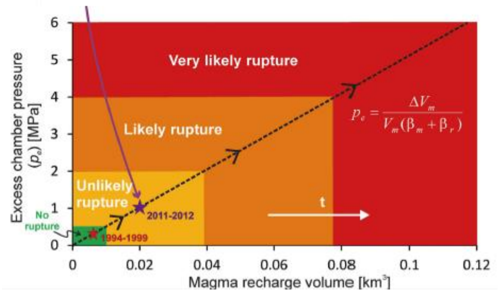

Fig. 1: Excess pressure (p_e) within a shallow magma chamber as a function of the volume of new magma (ΔV_m) entering the chamber from a deeper source over time. The method can be applied to any active volcano for which (1) there exist estimated extrusion and intrusion volume estimates and (2) geodetic data as to inflation volumes. Rupture probability statements based on increasing excess pressure within the shallow chamber allow forecasts of dyke formation to be made in real time during magma recharge events.

Pore geometry controls rock strength

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The strength of porous rocks in the subsurface is critically important across the geosciences, with implications for fluid flow, mineralization, seismicity, and the deep biosphere. Most studies of porous rock strength consider the scalar quantity of porosity, in which strength shows a broadly inverse relationship with total porosity, but pore shape is not explicitly defined. Here we use a combination of uniaxial compressive strength measurements of isotropic and anisotropic porous lava samples, and numerical modelling to consider the influence of porosity *and* pore shape on rock strength. Micro computed tomography (CT) shows that pores in lavas range from sub-spherical, to elongate and flat ellipsoids. Sample strength shows a general inverse relationship with porosity, but samples that contain aligned flat pores exhibit a large strength anisotropy, dependent on the compression direction relative to pore short axes. When compression is applied parallel to the pore short axes (i.e. across the minimum curvature), samples are weak; compression applied parallel to the long axes (i.e. across the maximum curvature) are stronger by nearly an order or magnitude. Numerical models for elliptical pores show that compression applied across the minimum curvature results in a relatively broad tensile stress perturbation, compared to compression applied across the maximum curvature, supporting UCS results. At a larger scale, certain pore shapes may be relatively stable and remain open in the upper crust under a given remote stress field, facilitating persistent cavities. These high permeability zones could provide sustained conduits or stores for economic resources, or even sites for subseafloor microbial reservoirs. Quantifying the shape, orientations, and statistical distributions of pores is therefore a critical step in strength testing of rocks.

Relating the physical properties of volcanic rocks to the characteristics of ash generated by experimental abrasion

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Within the hot and turbulent flow of a pyroclastic density current (PDC), interactions between clasts generate volcanic ash. This ash, termed co-ignimbrite ash, can pose a risk to aviation if it is dispersed into the atmosphere. This project closely examines the effects that the vesicularity and crystal content of the material in a PDC have on the amount, componentry and shape of the ash generated by abrasion.

A series of experiments were designed to replicate natural abrasion using a planetary ball mill. Prior to the experiments, the vesicularity and crystal content of two juvenile populations were characterised. The products used were: (1) basaltic-andesitic rocks from Fuego volcano (Guatemala) with ~31-47% vesicularity, high phenocryst and microlite content and (2) tephri-phonolitic Avellino pumice (Vesuvius, Italy) with ~45-73% vesicularity and an intermediate-low crystal content.

The highly vesicular Avellino pumice generally generated more ash than the Fuego juveniles. The total grain size distributions produced by abrasion and BSE imaging of clasts revealed that the ash generating potential of a single clast relates to subtle differences in crystal content and vesicularity that are independent of clast density. Most the ash generated was finer than 4φ (63μm) and the starting material properties strongly influenced the componentry of the ash generated. There is evidence that phenocrysts act as resistant phases (attached matrix grains) but also cleavage planes provide structural weaknesses (free crystal grains). The shape of the ash was assessed using two approaches. The projected ash area method was rapid and statistically significant whereas the cross-sectional area method was better at describing the small-scale roughness and internal structure of ash grains.

The results of this study provide valuable insight into the effects that the vesicularity and crystal content of PDC material have on the ash generated by abrasion. This project provides an opportunity to thoroughly examine the characteristics of fine ash which is important as fine material poses the greatest challenge to ash dispersion modelling.

Syn-emplacement fracturing of laccoliths

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Laccoliths are dome-shaped intrusions at shallow depths in the crust. Studies of laccolith emplacement have shown that the evolution of a sill into a laccolith is accommodated by fracturing, faulting, and uplift of the overlying rocks. However, we present new field evidence indicating that host-rock deformation is not the only significant mechanism of strain accommodation during laccolith emplacement.

In the Miocene Chachahuén Volcano, Argentina, we studied four hornblende-bearing andesitic laccoliths emplaced within lava and pyroclastic flows. Given the size of the laccoliths (hundreds of m - 1 km across), these host-rocks exhibit little deformation, such as upbending, fracturing, or faulting,. Instead, we observed belts of brecciated rock forming the outer parts of the laccoliths. In the 1 km-wide Cerro Bayo laccolith, the breccia is up to 200 m wide and surrounds a belt of systematically fractured laccolith rock, up to 100 m wide. The laccolith interior is in turn characterised by a low fracture density. We present our mapping results of Cerro Bayo together with detailed measurements of the orientation of flow banding and magnetic foliation and lineation obtained using Anisotropy of Magnetic Susceptibility (AMS).

The rhyolitic Sandfell laccolith, Eastern Iceland, was emplaced into almost flat-lying basaltic lava flows, which were deflected by up to 90°. Despite this deformation, the host rock exhibits little fracturing. Our mapping of the laccolith interior revealed that the 1.2 km × 2.5 km laccolith contains a 50-100 m wide breccia in contact with the wall rock. Towards the interior of the laccolith, we observed discrete bands of shear fractures parallel to the contact. The density of these bands increases towards the contact. Within the laccolith, the bands are related to flow banding, which we mapped and compare with AMS data.

In summary, our field observations indicate that magma emplacement in the fluid state, as evident from flow banding and AMS, was accompanied by brittle deformation of the outer, cooling parts of the laccoliths. This may explain the limited fracturing observed in the host-rocks. We suggest therefore that strain accommodation during laccolith emplacement should be reevaluated, taking into account deformation of both the host-rock and the intrusion itself.

Initial Development of an NIR strain measurement technique in brittle geo-materials

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Visible-Near Infrared Spectroscopy (VIS-NIR) is a technique developed for the non-contact measurement of compositional characteristics of surfaces. The technique is rapid, sensitive to change in surface topology and has found applications ranging from planetary geology, soil science, pharmacy to materials testing. The technique has also been used in a limited fashion to measure strain changes in rocks and minerals (Ord and Hobbs 1986). However, there have been few quantitative studies linking such changes in material strains (and other rock physics parameters) to the resulting VIS-NIR signature. This research seeks to determine whether improvements in VIS-NIR equipment means that such a technique is a viable method to measure strains in rock via this remote (non-contact) method.

We report new experiments carried out using 40 mm Brazilian Tensile discs of Carrera Marble and Darley Dale Sandstone using an Instron 600LX in the University of Portsmouth Rock Mechanics Laboratory. The tensile test was selected for this experiment as the sample shape and sensor arrangements allow access to a ‘flat’ surface area throughout the test, allowing surface measurements to be continuously taken whilst the discs are strained to failure. An ASD Labspec 5000 with 25 mm foreoptic was used to collect reflectance spectra in the range 350-2500 nm during each tensile test.

Results from Carrera Marble experiments show that reflectance at 2050 nm negatively correlates (by polynomial regression) with axial strain between 0.05-0.5%, with r2 of 0.99. Results from Darley Dale Sandstone data show that reflectance at 1970 nm positively correlates with axial deformation between 0.05-0.5%, with r2 of 0.98. Initial analyses suggest that the VIS-NIR possesses an output that scales in a quantifiable manner with rock strain, and shows promise as a technique for strain measurement. The method has particular application for allowing our laboratory measurements to “ground truth” data taken from drone and other remote sensing techniques that could employ this method. However, further work is underway to understand the exact nature of the correlations – for instance, whether reflectance is related to deformation to the mineral lattice, macro-surface or micro-surface.

The role of gravity on Martian volcanism and tectonism from rock deformation studies

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The surface gravitational acceleration (i.e., surface gravity) of Mars, the second-smallest planet in the Solar System, is one-third that of Earth. A direct consequence of this lower surface gravity is that lithostatic pressure is lower on Mars than on Earth at any given depth.

We have collated published data from deformation experiments on basalts and find that, throughout its geological (and thus thermal) evolution the Martian brittle lithosphere has been much thicker (i.e., the brittle–ductile transition is deeper) than that of Earth as a function solely of surface gravity. We also conclude, again as a consequence of its lower surface gravity, that—compared with Earth—Mars’ lithosphere is more porous, that Martian fractures remain open to greater depths and are wider at a given depth, and that the maximum penetration depth for opening-mode fractures (i.e., joints) is much deeper.

A major consequence of a relatively weak Martian lithosphere is that dykes—the primary mechanism for magma transport on both planets—can propagate more easily and can be much wider at a given depth on Mars than on Earth. We suggest, in turn, that the efficiency of magma delivery to the Martian surface was enhanced during its volcanic past, assisting the growth of the planet’s enormous volcanoes (the grand heights of which are supported by the thick Martian lithosphere) and facilitating the extensive flood-mode volcanism responsible for much of the Martian crust. The pervasively fractured, porous (and permeable) Martian lithosphere likely also greatly assisted the subsurface storage of and transport of groundwater within Mars. And so it is that surface gravity, influenced by the mass of a planetary body, can greatly modify the mechanical and hydraulic behaviour of its lithosphere with manifest differences in geomorphology, tectonic and volcanic character, and hydrology.

Architecture and growth of oblique slip fault zones in heterogeneous multilayer sequences.

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Faults and their associated fault zones are key controls on many processes within the brittle upper crust and their individual properties contribute towards the fluid transport properties and capabilities of their host rock protoliths. To better understand fault zone growth, architecture, and hydraulic properties in Carboniferous heterogeneous coal bearing sequences, we studied oblique-slip faults with displacements of up to 30 m at Spireslack Open Cast Coal Site (OCCS), Midland Valley, Scotland (UK).

Observations indicate that the effect of heterogeneous mechanical stratigraphy exerts a strong control on early stage fault formation, which in turn has a strong impact on subsequent fault growth. Both centimetre and deci- to decametre-scale faulting show extreme variability in complexity both down dip and along strike. Changes in fault zone geometry from single to multiple soft-linked fault strands are clearly seen to be associated with discrete changes in protolith competency.

Faulted strata containing a greater proportion of mudstone and shale typically form wide, low permeability fault zones with multiple low displacement fault surfaces, wide fault cores and limited damage zones. Conversely, high permeability damage zones become far more prevalent where more brittle siliciclastic sandstones and carbonate rocks (limestones) dominate, and movement on the fault is limited to narrow, high displacement fault cores.

Bárðarbunga sulfur dioxide (SO_2) emission estimate from IASI.

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The Bárðarbunga eruption, from September 2014 to February 2015, is the largest eruption in Iceland in more than 200 years and its emissions exceeded daily SO2 emissions from all anthropogenic sources in Europe. Due to low solar irradiation during winter time at high latitude only thermal infrared sensors can follow the plume for the whole period. Here we reports results from the spectrometer IASI on board METOP.

We simultaneously use the IASI spectral range from 1000 to 1200 cm−1 and from 1300 to 1410 cm−1 (the 7.3 and 8.7 μm SO_2 absorption bands), to retrieve both the SO_2 amount and altitude, applying an iterative optimal estimation scheme (Carboni et al 2012, 2016). A comprehensive error budget for every pixel is included in the retrieval.

We compare with ground-based Brewer measurements from Sodankyla (Finland) and find consistency for all the SO_2 episodes (with SO_2 amounts larger than 2 DU).

Using IASI SO_2 retrieval we can follow the plume with maps of column amount and altitude, twice a day. The plume is transported all over the northern hemisphere from 30 to 90 deg North and the SO_2 layers are mainly confined to altitudes below 6 km.

We present the time series of the total mass present in atmosphere and its vertical distribution, and we estimate the emission flux of SO_2 as function of day from September 2014 to February 2015.

We obtain a total mass of emitted SO_2 of 3.7 +-0.8 Tg with an average lifetime of 2.4 +- 0.6 days. This may underestimate the total emission as part of the plume can be missed where thermal contrast is low or the plume is obscured by higher level cloud.

Ophiolite halogens and noble gases: quantifying subducted volatiles

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The notion of a "subduction barrier", which prevents the transmission of volatile elements into the deep Earth, is being increasingly challenged by studies of the halogens and noble gases in oceanic basalts, altered oceanic crust and exhumed eclogites. The imperfect operation of such a barrier, potentially allowing recycling of volatiles into the convecting mantle, has huge implications for mantle compositional heterogeneity, global geochemical cycles and elemental budgets. However, while dredging and deep-ocean drilling yield useful insights into the upper kilometre of oceanic crust, attempts to holistically quantify the composition of the subducted oceanic lithosphere, and hence the potential elemental fluxes, currently require significant extrapolations from the available data.

By contrast, many ophiolites contain complete sections through the oceanic lithosphere, facilitating sampling and interrogation of the geochemical variation through the entire oceanic slab with excellent control on spatial context. Ophiolites thus have great potential for developing our understanding of mantle heterogeneity and the geochemical stratigraphy of the oceanic lithosphere.

Recent analytical advances have extended neutron-irradiation Ar-Ar geochronological techniques to allow the accurate determination of halogen contents at very low abundances, significantly reducing the analytical difficulties associated with many geological materials.

The aim of this study is to apply this novel method to the halogen and noble gas systematics of ophiolites, which have not been extensively explored to date. We will initially focus on the well-exposed ~ 497 Ma Leka Ophiolite Complex, Norway.

Here we discuss applying the halogens and noble gases to spatially and chemically resolve "normal" oceanic lithosphere from its slab-derived supra-subduction zone overprint. This will potentially allow quantification of the supply of volatiles into the subduction zone and the fluxes of volatiles lost from the dehydrating slab. In turn, this will help to develop a more accurate volatile budget for the subduction cycle as a whole, while also enabling interrogation of the geochemical legacy of tectonic cycles, the mixing efficiency of the convecting mantle and the effect of serpentinistation on noble gas and halogen systematics.

Experimental petrology constraints on magma storage conditions for explosive and effusive eruptions at Kelud volcano, Indonesia

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The parameters that govern the eruptive style at volcanoes are critical to understand, since the volcanic hazards posed to the nearby populations are directly related on whether an eruption is explosive or effusive. Eruptions from Kelud volcano located in East Java, Indonesia are difficult to forecast in that sense, because the eruptive style varies considerably, from effusive eruptions e.g. 1920 & 2007 to explosive eruptions in 1990 and 2014. Experiments were undertaken to constrain the magma storage conditions such as pressure, temperature and volatile contents prior to both explosive and effusive eruptions at Kelud. A gas-pressurized TZM cold-seal pressure vessel was used, whereby the sample (coarsely-crushed aliquots of the 2014 Kelud pumice contained in a AgPd capsule) were held at upper crustal conditions for several days to equilibrate, and then rapidly quenched using a water-cooled coupling system to prevent further crystallisation. The experiments were held near the NNO oxygen buffer using a double-capsule method. A range of pressures (25-200 MPa), temperatures (950-1100 °C), H_2O-saturated and mixed H_2O-CO_2 conditions were explored in this study. Experimental matrix glass and mineral rim compositions, as well as crystal contents were measured and compared to the natural mineral and groundmass characteristics erupted in explosive (1990, 2014) and effusive (2007) eruptions. The experiments were conducted on crystal-rich basaltic andesite pumice from the 2014 eruption, as this has a near identical bulk composition to the other effusively and explosively erupted products. The 2014 pumice therefore represents an ideal experimental starting material which can be applied to other Kelud eruption types investigated. This presentation will discuss the preliminary results from these experiments, which are the first to be conducted on Kelud volcanics, with the aim of elucidating magma storage conditions that precede Kelud's different eruption styles. We learn that subtle changes to intensive magmatic parameters such as temperature and water content can result in major differences to the eruption style.

The effects of Water and Temperature on Etnean Limestone

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Volcanic edifices are commonly unstable, owing to their construction and geometry, and the nature of rocks forming the edifice basement. Stress field distributions, magmatic and non-magmatic fluid circulation, elevated temperature gradients, and the rate and distribution of edifice growth all influence the mechanical strength of edifice and basement rocks. At Mount Etna, Sicily, carbonate rocks represent an important fraction of its sedimentary basement. Carbonate strength has been investigated at high temperature (up to 800°C) in uniaxial and triaxial experiments. At these temperatures, chemical reactions such as calcite decarbonation leads to degradation of material strength and dehydroxylation of clay fractions (400°C to 500°C). However, the influence of intermediate temperatures (below 400C) is poorly understood. In this study we focus on the influence of low temperature effects (<450°C, representing a distant heat source) and increasing effective confining pressure ranging from 5 MPa to 50 MPa (representing a burial depth range of about 0.2 to 2.0 km), using the abundant Comiso Limestone.

We applied a hydrostatic pore fluid pressure using water; pore fluid pressure was calculated accordingly as hydrostatic pore pressure. Dry and water-saturated triaxial experiments were performed on natural samples, and on samples suites that were thermally pre-treated at 150°C, 300°C, and 450°C. Fracture development during compression was monitored using an array of 12 acoustic emission sensors. Natural and thermally treated sample strength is indistinguishable despite changes in rock physical properties following pre-heating. Our data show how the presence of water deeply influenced the mechanical strength of Comiso limestone, which is as expected decreased in all the experiments (± 30 MPa).

Investigating the role of oceanic plateaus in early continental growth

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The generation of Earth's first continental crust is fundamental to the evolution of the early oceans and atmosphere, and could have had a significant impact on early life. The majority of early juvenile continental material is composed of tonalites, trondjhemites and granodiorites (TTG). The oldest of these, the Eoarchaean (3.6 - 4.0 Ga) TTGs (ETTG), are compositionally unique and may be derived from relatively enriched basaltic source regions similar in composition to Mesozoic oceanic plateaus.

Most work on TTGs has focused on adakites, modern arc lavas with similar geochemistry to TTGs. Adakites are commonly attributed to direct melting of an abnormally hot subducting slab, and this has given rise to a similar "hot subduction" model for TTGs. However, intra-crustal melting of thick basaltic sources can also produce melts with TTG compositions.

Recent studies in the Caribbean have led to the discovery of a subgroup of adakites, the Jamaican-type adakites (JTA). JTA are geochemically analogous to ETTG, particularly regarding their low MgO, Ni and Cr contents. JTA are shown to be derived by fusion of oceanic plateau material, and recent experimental studies have successfully produced liquids similar to ETTG using oceanic plateau starting materials.

Therefore, with JTA as an analogue, ETTG could be derived by shallow subduction and partial melting of thick oceanic crustal slab(s), without significant mantle wedge interaction or alternatively by intra-crustal partial melting of oceanic plateau-like and/or island arc-like crust.

Using new and published major and trace element data from volcanic rocks in Panama and Colombia, we show possible new sites where the JTA could be generated in the southern Caribbean region allowing us to better establish the setting of ETTG petrogenesis.

Stackpole Quay: A case study on the applicability of virtual outcrops in structural model building

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Virtual outcrops derived using UAV platforms and Structure from Motion (SfM) photogrammetric software are increasingly being used by the Earth science community as a source of data. Affordability of these off the shelf UAV systems and greater automation of modern photogrammetric software allow a rapid and efficient workflow from data acquisition to virtual outcrop generation. The large amounts of easily accessible, high resolution data potentially available using this streamlined process has accelerated the adoption of these techniques in a wide range of geological studies. There remains a need however, to assess the applicability of SfM derived virtual outcrops for studies in the field of structural geology. Of particular interest is the fidelity of SfM surface reconstructions to plane orientations measured in the field.

To assess the accuracy of structural measurements extracted from SfM derived virtual outcrops, we test these against traditional data collection methods and LiDAR derived surface reconstructions. We find that UAV acquisition of imagery for photogrammetric reconstructions, using readily available equipment and software, yields accurate results, comparable to LiDAR. Terrestrially derived digital reconstructions, however, are of lower accuracy in this study, primarily due to the negative effects of occlusion. Furthermore, we find that fidelity of bedding orientation in virtual outcrop to direct measurements is critical if accurate structural models are to be constructed. This has important implications for along-strike predictions.

This new method for data acquisition and processing is a potentially powerful tool, but careful consideration should be given to the aims of the study and the required resolution of the dataset. Based on our results, we provide a discussion on strategies when undertaking field campaigns for the purpose of creating SfM derived virtual outcrops. With a suitable workflow, we believe reliable structural models and along-strike predictions can be made using virtual outcrops derived using UAV platforms and SfM software.

Crystallographic control on microstructural evolution of coarse grained quartz veins.

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The strain-dependent microstructural evolution of mylonitic quartz veins from the Rieserferner Pluton (Eastern Alps) have been investigated by electron backscattered diffraction and computer-integrated polarization microscopy. Deformation occurred during pluton cooling at 400-450°C. Coarse grained (mm-cm) protomylonitic veins are characterized by elongated ribbons and show 10% of recrystallization and a Type-I crossed girdle c-axis crystallographic preferred orientation (CPO) at shear strain $\gamma<2$. Mylonitic veins show partially recrystallized ribbons and high recrystallization values (~48%) at $3<\gamma<6$. c-axis CPO for recrystallized matrix is composed by an inclined partial girdle. Non-recrystallized ribbons show a Type-I crossed girdle almost parallel to the YZ kinematic plane. Ultramylonites are almost completely recrystallized (>90%) at $\gamma>10$ and show a banded microstructure. The c-axis CPO displays an inclined partial girdle with a strong Y maximum. During the entire evolution, recrystallization grain size remains constant (about 10-20μm).

In protomylonitic veins, ribbons with c-axis close to the Y-direction (Y-ribbons) show high aspect ratio (up to 17) and low incipient recrystallization values, whereas ribbons with c-axis plotting on the XZ plane (XZ-ribbons) have low aspect ratio and high recrystallization values (up to 22%). Recrystallization occurs by subgrain rotation (SGR) in Y-ribbon suitably oriented for slip on {m}<a>. Recrystallization in XZ-ribbons is triggered by microfracturing. Recrystallization exploits microfractures leading to micro-shear zones (μSZ). μSZ' microtextural features suggest the occurrence of dislocation creep, dynamic recrystallization by SGR and possible grain boundary sliding. In ultramylonitic veins, recrystallization occurs by SGR. In the Rieserferner mylonitc quartz veins the microstructural evolution, grain size reduction mechanisms and recrystallization is controlled by crystallographic orientation of former vein crystals. Microfracturing, crystal plasticity and dynamic recrystallization, and possible GBS are active at the same time in different microstructural sites. Recrystallization seems to slightly modify the crystallographic orientation of former vein crystals.

The influence of temperature on permeability evolution in Volcán Chaitén rhyolite: An experimental approach

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Rhyolitic volcanic eruptions are amongst the largest and most explosive, yet due to their rarity have not been directly observed or monitored to the same extent as more common types of volcanism. Two recent rhyolitic eruptions in Chile, Volcán Chaitén in 2008-09 and Cordón Caulle in 2011-12, allowed the first direct observation and monitoring of rhyolitic activity with modern techniques and provided insights into the evolution of highly silicic eruptions, particularly the explosive-effusive transition. Both eruptions exhibited at one stage simultaneous explosive and effusive behaviour with both lava and ash columns being emitted from the same vents. The ability of gas to efficiently decouple from magma in the shallow conduit is believed to control such behaviour, and evolving modes of conduit outgassing and their respective efficiencies hold the key to understanding such hybrid activity.

This study reports the results of a systematic experimental investigation into the permeability of dome material from Volcán Chaitén at magmatic temperatures and shallow conduit pressures, with various pore fluids, using the Rocchi Cell (a high temperature triaxial deformation rig at UCL). Tests were conducted at temperatures up to 600^{o}C with an effective pressure of 5MPa using the steady-state flow permeability technique. The influence of cyclicity and temporal variation on the development of permeable networks was also explored through the experimental program. The results show a complex permeability evolution that includes a reduction in permeability by approximately 3 orders of magnitude up to 600^{o}C with further decreases over periods of several hours at high temperature. Together with porosity data, P and S wave velocities, acoustic emissions and SEM analysis these experimental permeability results are applied to not only draw general conclusions regarding the permeability of volcanic material at high temperature, but also to enhance our understanding of the specific setting of Volcán Chaitén and the observed evolution of eruptive behaviour.

Simulated crack propagation trajectories in transversely anisotropic media

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During mode-I fracture propagation experiments within anisotropic materials such as shale, it is seen that fractures propagating in the (bedding perpendicular) Arrester orientation commonly kink into the weaker (bedding parallel) Short-Transverse orientation (*Lee et al, (2015), Chandler et al,(2016)*).

This crack-kinking can be investigated in terms of the stress field around the crack-tip and the anisotropy in the material, in order to better understand the conditions when kinking will occur (*Cotterell & Rice, (1980)*).

A simulation was developed in which the stress intensities at the tips of a 2D crack under specified loading conditions are calculated using a singular integral equation (SIE) method based on that of *Galybin and Dyskin (2004)*. These stress intensities are then used in combination with an anisotropic maximum energy release rate criterion, to determine the angle in which the fracture will progress. A small segment of crack is then added to the original crack, at the calculated angle, and the process is then repeated iteratively, so that the crack propagates over a series of steps.

Here we investigate how the fracture toughness, K_{Ic}, varies as a function of angle from bedding parallel in transversely anisotropic media by comparison of peak load and crack trajectory found during Brazilian disk experiments, with those found during simulations.

From continental hyper-extension to seafloor spreading: New insights form South Porcupine Basin

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Observations of continental rifted margins play an important role in understanding the geological process of continental extension. The Porcupine Basin is a large V-Shaped sedimentary basin offshore Ireland of Late Palaeozoic to Cenozoic age, which act as a natural laboratory to study rifting process due to the fact that a 3-D rifting process is observed within 200 km. Here we use three wide-angle seismic profiles (two across the basin axis and one along the axis) to study the crustal structure of the South Porcupine Basin. Both refractions and reflections recorded by OBSs are inverted jointly for a travel-time tomography, following a layer stripping strategy. The three P-wave velocity models clearly image the deep structure of the basin for the first time and we interpret them in the context of coincident seismic reflection profiles. In the southernmost part of the basin, the sedimentary sequence reaches ~12 km in the middle of the basin, and the top basement exhibits a rough and hummocky morphology at both flanks, while gets smooth in the middle of the basin. Two layers of crust were observed with velocities ranging from 5.8 – 6.5 km/s and 6.6 – 7.1 km/s, with respective thickness of 2 – 3 km and 4 – 6 km, suggesting oceanic layer 2 and oceanic layer 3 with extrusive volcanism involved. A transition with exhumed mantle along rift axis was observed ~40 km to the north, whereas hyperextended continental crust was observed further north. Therefore, we propose a 3-D rifting process initialized by a non-uniform stretching mode, which leads to narrow oceanic seafloor spreading and localized melt generation. This project is part-funded by the Irish Shelf Petroleum Studies Group (ISPSG) of the Irish Petroleum Infrastructure Programme Group 4.

A quantitative description of fault zone internal structure.

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Fault zones comprise multiple anastomosing slip surfaces that each accommodate some portion of the total fault displacement. The numbers of slip surfaces and amounts of displacement on each are a measure of the localisation of strain within the fault zone and may contain information on how strain localisation is achieved. Conceptual geometric models of fault zone evolution attribute the development of multiple anastomosing slip surfaces to a variety of processes. Arguably the most important of these is the linkage between initially unconnected segments of a fault array and also shearing-off of wall-rock asperities. To establish the validity of these models and use them for a variety of practical purposes a quantitative description of fault zone structure and the distribution of displacement within fault zones is required. Here we present results of ongoing efforts to achieve these aims.

Using high quality 3D seismic reflection data and detailed 2D and 3D outcrop mapping, we have collated data on the distribution of displacement within normal fault zones together with data that underpin conceptual models of fault zone growth, including the frequency of segmentation of faults and the strains at which fault segments become connected to form a through-going fault. Despite the large variability in displacement partitioning observed over individual faults and within individual datasets, this is less than the variation between datasets and statistically significant differences in these parameters forms a basis for better understanding the controls on fault zone structure.

Post-eruptive dike seismicity following the 2014-15 Bárðarbunga-Holuhraun fissure eruption, central Iceland

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Over a 13-day period in 2014, magma propagated at depth from the subglacial Bárðarbunga volcano in central Iceland. The lava breached the surface in a 6-month fissure eruption at Holuhraun lasting from September 2014 to February 2015. Earthquakes highlight the 48 km long dike path and are located at 5-7km depth throughout the propagation, co-eruptive and post-eruptive phases. Accumulated strain in the rift zone was released by predominantly left-lateral strike-slip faulting, with the lack of non-double-couple implying aseismic dike opening. Continued seismicity is observed in the 6 months following the eruption, suggesting continued deformation or magma cooling and contraction. This work analyses the earthquakes in the Northernmost segment of the dike path over a period of 6 months following the end of the eruption. We look for patterns in hypo-central location, dominant fault mechanisms and deviations from non-volumetric faulting. We then compare our findings from the post-eruptive period, March-August 2015, to the propagation and eruption phases to build a picture of earthquake source mechanisms in an eruptive rift zone setting.

Peralkaline Rhyolite Achneliths with Evidence of Post-Emplacement Vesiculation at Aluto Volcano, Main Ethiopian Rift: What can these unusual pyroclasts tell us?

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In peralkaline rhyolitic melts, Na+ and K+ combined with halogens act to disrupt silicate polymers reducing melt viscosity in comparison to other melts of equivalent silica content. As a result, such magmas are often associated with somewhat unusual deposits for which the associated eruptive behaviours are relatively poorly understood. We have discovered unusual globule-shaped clasts within an unconsolidated pyroclastic succession associated with a pumice cone at Aluto volcano in the Main Ethiopian Rift. The clasts are lapilli to ash sized, often have a droplet-like morphology and are characterised by a distinctive obsidian skin indicative of having been shaped by surface tension. We adopt Walker's term *achneliths* for these clasts. These achneliths however, unlike their mafic counterparts, are highly vesicular (~ 78 vol %), and the glassy skin often shows a bread-crusted texture. Importantly, there is strong evidence for post-depositional, *in-situ*, inflation, including expanding against other clasts and in some cases fusing together. The unconsolidated nature of the deposit at Aluto means that these peralkaline achneliths are easily separated and investigated in 3D, providing an unprecedented opportunity to study their features in detail using µCT, SEM and EPMA. Textural observations and preliminary 3D vesicle size distribution data suggest that surface tension is an important factor in shaping these clasts, and that vesiculation and degassing occurs over a prolonged period post-emplacement. MELTS model calculations on the EPMA analyses assuming dry conditions, suggest maximum liquidus temperatures of ~ 1030 °C and viscosities of ~ 5 [Log Pa.s]. These observations have important implications for understanding the nature of late stage degassing, fragmentation and eruption style in peralkaline rhyolite systems as well as incipient welding in peralkaline pyroclastic units.

Seamount – Subduction Zone Interactions: Impact of ocean floor relief on subduction accretion/erosion & subduction channel heterogeneity

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The tectonic processes of subduction accretion — where oceanic material is transferred to the upper plate by the downward migration of the subduction zone fault — and subduction erosion — where upper plate material is entrained within the subduction zone fault as it migrates upwards — are traditionally considered to be mutually exclusive along convergent margins. Sediment volume at the trench is a major control on this behaviour (Clift & Vannucchi, 2004). High relief features on the ocean floor, such as seamounts, introduce localised perturbations in sediment volume and influence subduction erosion where they interact with the subduction zone. (Von Huene et al. 2000). Total or partial offscraping of seamounts within the subduction channel has been inferred from seismic and onland observations (Cloos & Shreve, 1996).

Our work in southern Costa Rica suggests that subduction of a seamount chain can result in frontal accretion of oceanic sediments and mass-wasted igneous blocks originally deposited in the flexural moat surrounding the seamount chain. The Osa Mélange in SW Costa Rica consists of basalt and carbonate blocks in a pelitic matrix comprised of feldspar and pyroxene grains with rare quartz, closely matching sediment recovered from the Hawaiian arch and distal moat by ODP leg 136 (Tribble et al., 1993). All igneous blocks exhibit geochemical affinity with Galapagos-hotspot-derived seamounts.

This mélange has previously been interpreted as the tectonised flanks of subducted seamounts (Vannucchi et al., 2006) or trench-fill sediments (Buchs et al., 2009). Our work reveals higher sediment volumes than would be expected on seamount flanks, which are typically sites of sediment bypass. Likewise, the lack of arc or forearc-derived material preclude a trench-fill origin.

Seamount flexural moats provide significant volumes of sediment to the trench, promoting the development of a localised frontal accretionary prism. At depth, the composition of the subduction channel is strongly determined by the erosive or accretionary nature of the subduction zone: accretionary subduction channels are composed of marine sediments, whereas erosive subduction channels contain entrained blocks of upper plate material. Subduction of seamount chains and their flexural moats facilitates concurrent erosion and accretion along the trench axis and introduces heterogeneity into the subduction channel. Such heterogeneity has important implications for seismicity within the subduction zone fault.

An investigation of the effect of crystals on magma flow and failure.

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Rheology has a primary control on magma ascent; it is a key influencer on flow rate and hence governs volcanic eruption style. The presence of crystals in a volcanic melt impacts magma rheology, due to physical interactions, which result in an increase in viscosity and a strain-dependent flow behaviour. Current rheological models require detailed information from experimental studies in order to constrain the full spectrum of observed behaviours.

This project aims to gain insight into the manner in which crystal-bearing (0-50 vol.%) magma flows and fails. Synthetic sintered samples of TiO_2 crystals and Spheriglass©, densified to less than 3% pores, are used for uniaxial compressive experiments (*ex situ* at the University of Liverpool and *in situ* at Diamond Light Source) to test the rheological behaviour of magmatic suspension. X-ray computed tomographic scans of samples allow the determination of phase distribution in the material. *In situ* testing utilises high speed X-ray tomography which allows 4D (3D plus high time resolution) visualisation of magma, deformed at volcanic temperatures in a uniaxial press.

Thermal analysis of the synthetic glass indicates a glass transition temperature of 580°C (at rates of 10^{o}C/min). Dilatometric measurements were used to determine the softening temperature (defined as the temperature at which samples no longer expand upon heating at a rate of 10^{o}C/min, but contract by 0.5% due to a uniaxial load of 3 N) of magmatic suspensions which increases from 591 to 637°C with an increase in crystallinity from 0 to 50 vol.%, reflecting an increase in viscosity with crystal fraction.

Preliminary *ex situ* tests suggest that whereas the viscosity increases with crystallinity, the strength decreases. From our *ex situ* tests we anticipate that 4D visualisation during *in situ* experiments will soon reveal the importance of crystal-crystal interactions on bulk flow properties and the evolution of fracture networks as a function of applied conditions.

Understanding the degassing of young volcanic systems using noble gases

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Incompatible inert trace elements He, Ne and Ar are widely used to characterize magmatic reservoirs and to study volcanic processes. Their isotopic signature and fractionation (e.g. $^{4}He/^{40}Ar$ ratio) provide useful information on magma source, magma differentiation and contamination. Several studies have investigated sources, reservoirs and chemical controls of noble gases, but few efforts have been made to study which factors control noble gas incorporation and release during degassing episodes.

The aim of this research is to identify these factors and to test how they influence noble gas behaviour in volcanic rocks with different degassing histories. This will help improve our understanding of how noble gases are recycled into the atmosphere during volcanism.

Particular attention will be given to the behaviour of Ar because of its use in $^{40}Ar/^{39}Ar$ dating. A better knowledge of how Ar is trapped and released from volcanic rocks will help find a solution to the 'excess argon problem': the presence of an excess portion of Ar inside rocks that is not related to atmospheric Ar nor to the radiogenic decay of ^{40}K, complicates $^{40}Ar/^{39}Ar$ age dating. Younger volcanic rocks are more affected by this problem due to their lower concentrations of radiogenic Ar with respect to non-radiogenic Ar.

In this study, samples from 0 to 2 Ma are used to study rocks with different proportion of radiogenic and excess Ar. A variety of materials (pumice, ash, non-vesicular glass, crystals) and deposit types (pyroclastic fall, ignimbrites, lavas, and Pele's hair) from Tenerife (Spain), Etna (Italy) and Masaya (Nicaragua), will be used to test how noble gases vary in response of cooling rate (Pele's hairs vs. lavas vs. mode of pyroclastic emplacement), depositional environment (distal vs. proximal) and physical characteristics of the deposit (grain size, crystals vs. bubbles, rock porosity).

Petrographic, SEM and XRF analysis will be conducted to characterise mineral assemblages, textures and chemistry of the samples; noble gas concentration and distribution will be determined by laser ablation mass spectrometry; the internal structure and topology (e.g. form, distribution and connectivity of vesicles) will be quantified using X-ray microtomography in order to identify fast-pathways for the release of noble gases from volcanic materials during degassing episodes.

The Relationship between Sub- and Supra-salt Deformation in Salt-Influenced Rifts: Observations from the Halten Terrace, offshore Norway.

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The structural style and evolution of salt-influenced rifts significantly differs from those that form in simple, predominantly 'brittle' crust. For example, ductile, evaporite-rich units can effectively decouple brittle deformation in sub- and supra-salt strata, resulting in the sub-salt fault becoming mechanically decoupled from, but responsible for, a forced fold in the supra-salt strata. Salt-influenced rifts therefore contain greater degrees of folding when compared to their non-salt-influenced counterparts, which is often ignored when estimating extension below and above salt. Fundamental to determining whether sub- and supra-salt fault systems balance (*i.e.* sub- ≈ supra-salt extension), and the relative contributions of thin-skinned, gravity-driven and thick-skinned, whole-plate stretching driven deformation, is the ability to accurately measure extension in salt-influenced rifts.

We address these issues and seek to understand how extensional strain is partitioned between faulting and folding using high quality 2D and 3D seismic and well data from the Halten Terrace, offshore Norway. Given that the salt in this location is relatively thin and immobile compared to other salt-influenced basins in the North Sea, diapirism is minimal and no allochthonous salt bodies are developed. This permits the study of salt-influenced rift structures without significant structural overprinting.

In this study, we: (1) describe the structural style and evolution of the sub- and supra-salt fault populations, (2) apply various methods to estimate extension at sub- and supra-salt levels, and (3) deconvolve the contributions of purely thin- and thick-skinned strain in deforming the overburden. We find that despite similar amounts of extension in sub- and supra-salt strata, the supra-salt strata preferentially accommodate strain by folding, whereas sub-salt strata tend to fault. This suggests that while the system is kinematically linked, strain is expressed differently above and below the salt. These results highlight that different structural styles that are stratigraphically-separated by salt should not be interpreted as isolated systems.

Curved Seismic Source for LP Events: Model and Radiation Patterns.

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While classic earthquake seismology considers double couple sources on simple fault planes, volcano seismicity presents a wider range of source features where fault planes can be curved. Volcanic seismic events are usually classified as short-period and long-period events, which are related to rock fracture and fluid movement, respectively. In this work we focus on the seismic source of long-period events (LP) which occur during accelerated magma ascent. Magma is injected from a magma reservoir ascending through the volcanic conduit and behaving as a fluid. Once a certain ascent velocity is reached the strain rate increases and brittle failure in the magma can occur. To model this trigger process we consider a cylindrical fault in an elastic half space, filled with a viscoelastic magmatic fluid whose behaviour is governed by the constitutive relationship of Maxwell. We model the rupture using a double couple acting on infinitesimal plane faults and then integrate over the entire cylinder surface or parts of it. The resulting seismic radiation pattern is calculated and compared to classic earthquake solutions. LP earthquakes comprise two parts; brittle failure generates a P wave which travels across the elastic medium, while part of the energy is trapped in the conduit as a dispersive, slow wave explaining the coda of the signal. Considering both phases, we obtain the waveforms in a homogeneous half space, which we will compare with LP observations from Montserrat and other volcanoes.

Advances in the understanding of the key parameters determining carbonate fault rock permeability.

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Faults have been shown to exert significant control on fluid flow within the subsurface. Considerable amounts of research has been directed towards determining the conditions in which faults act as conduits, barriers or partial barriers to flow in siliciclastic reservoirs. This understanding can help to reduce uncertainty when estimating the hydraulic properties of fault zones in the subsurface. However, limited research has been undertaken on the impact of faults on fluid flow in carbonate reservoirs despite their importance in global hydrocarbon reserves; around 60% of global oil reserves and 40% of global gas reserves are stored in carbonates. To assess cross fault flow potential, and consequent reservoir compartmentalisation, the distribution and petrophysical properties of fault rock within a fault zone must be determined. Fault zone architectural models consist of a localised fault core composed of high strain products exhibiting low permeability (i.e. fault rock). However, the porosity of the protolith lithology has a major control on what kind of fault core is observed; in siliciclastics, it has been well documented that high porosity rocks tend to deform via compaction, resulting in a permeability decrease, whereas low porosity rocks tend to deform in a dilatant manor, resulting in a permeability increase. This is not necessarily true for carbonates, where lithotype and pore type also have controls on the deformation mechanism. Accordingly, this research works towards a predictive method to estimate fault rock production in carbonate rocks based upon key lithological and fault parameters. To this goal, samples of fault rocks in both high and low porosity carbonates from a variety of settings have been studied from both outcrop and core. Fault zone mapping is used to assess the continuity of fault rocks and how the spatial distribution of fault rock is controlled by fault zone architecture. The deformation mechanisms that form such fault rock fabrics are determined using microstructural analyses, allowing for an insight in to the architectural controls on deformation microstructures. This is combined with fault rock petrophysical properties derived from the lab to develop a combined understanding of the impact of fault displacement, carbonate lithotype, and lithotype juxtaposition on the potential for cross fault fluid flow. Ultimately aiding the development of a predictive model for cross fault fluid flow in carbonate reservoirs.

Plutonic xenoliths from Martinique and Statia: A window into Lesser Antilles crust.

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The islands of Martinique and Statia in the Lesser Antilles contain an exceptional abundance and variety of erupted plutonic xenoliths. Here, we present petrological, in-situ geochemical, and Sr, Pb and Nd isotopic data from plutonic xenoliths in order to compare and contrast the petrogenesis, storage conditions and the compositions of the melts within the plumbing systems of both islands.

There is a large variation in whole-rock Sr, Pb and Nd isotopes from both plutonic xenoliths and their volcanic counterparts. The isotopic signatures from each island are distinct and therefore Martinique and Statia have a unique source. In Martinique, the isotopic signatures of the volcanic rocks are mirrored by the plutonic xenoliths. Therefore the isotopic variation is either entirely controlled by the source, or the plutonic xenoliths were crystallised throughout the differentiation of the arc lavas. In contrast, plutonic xenoliths from Statia cover a larger isotopic range than the lavas, suggesting part of the isotopic signature of the lavas is imparted during open-system differentiation in shallow crust.

Many of the plutonic xenoliths represent cumulates from mush zones, and provide both textural and geochemical evidence of open system processes and crystal ‘cargos’. In order to explore the composition of the melts that were present in these mush zones, we analysed cumulate hosted melt inclusions and interstitial glass from Statia. Melt inclusion water concentrations vary from <0.5 to 9 wt.%. Glass compositions span a large range, but fall into two groups, with a compositional gap at 56-66 wt.% SiO_2 and 1.2-2.5 wt.% MgO. We compare the measured melt inclusion data with estimated melt compositions modelled using major element amphibole compositions. The chemometric equations are based on multiple regression analysis of experimental amphibole-melt compositions. Model melt compositions from both Martinique and Statia show a continuous range from basaltic-andesite through to rhyolite.

The plutonic xenoliths provide a window into both source variation and differentiation within volcanic arc crust and reveal the plumbing systems of each island have unique magmatic conditions and processes.

Crust and upper mantle structure of the North Anatolian Fault, Turkey.

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As part of the multi-disciplinary Faultlab project, we present detailed images of a major continental strike-slip fault system that bisects a complex geological region. We focus on the near the epicentres of M7+ earthquakes at Izmit and Düzce in 1999 and where estimates of present day slip rate are ~25 mm/yr. We use earthquake and ambient noise data from a rectangular seismometer array spanning the NAFZ with 66 stations at a nominal inter-station spacing of 7 km to build a detailed 3-D image of velocity structure and anisotropy and illuminate major changes in the architecture and properties of the crust and upper mantle, both across and along the two branches of the NAFZ, at length scales of less than 20 km. We show that the northern NAFZ branch depth extent varies from the mid-crust to the upper mantle and it is likely to be less than 10 km wide. Sharp lateral changes in lithospheric mantle velocity and anisotropy are constrained as the NAFZ is crossed, whereas crustal structure and anisotropy vary considerably both parallel and perpendicular to the faulting. We use our observations to test current models of the localisation of strike-slip deformation and develop new ideas to explain how narrow fault zones develop in heterogeneous lithosphere.

Constraining the velocity structure of the Alaskan-Aleutian subduction zone using guided waves

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Subduction zone guided wave arrivals from earthquakes at 60-250 km provide insight into the velocity structure of the subducting oceanic crust as it dehydrates. The subducted oceanic crust has a slower velocity than the surrounding mantle, and acts as a waveguide for high frequency energy, while lower frequency energy travels in the faster surrounding mantle. This generates a characteristic dispersion at the surface with low frequency energy arriving before higher frequencies.

This dispersion is constrained by comparing waveforms recorded in the Alaskan-Aleutian subduction zone with simulated waveforms, produced using finite difference full waveform modelling techniques. This method has shown that hydrated minerals in the oceanic crust could persist to greater depths than accepted thermal petrological subduction models would suggest in Japan (Garth and Rietbrock, 2014a) and South America (Garth and Rietbrock, submitted). These observations also suggest that the subducting oceanic mantle may be highly hydrated at intermediate depth by dipping normal faults (e.g. Garth and Rietbrock, 2014b).

The structure of the Aleutian arc is complex due to the accretion of the Yakutat Terrane to the east, which is partially coupled with the subducting Pacific plate. Furthermore, both the age of the Pacific plate and the subduction angle vary dramatically along strike. Earthquake locations from global and local catalogues are used to constrain the slab geometry for multiple cross sectional profiles perpendicular to the trench, and the NEIC PDE catalogue is used to identify potentially dispersive events and analyse dispersion.

Earthquake locations give a shallow subduction angle to the east of Anchorage which progressively steepens to the west. Dispersive arrivals are seen at stations close to the trench in the subduction fore-arc (within 150 km of the southern Alaska shoreline). Observations show that high frequency (>1-3 Hz) energy is delayed by up to 2-3 seconds. Models are then iterated to match synthetic waveforms produced to these observations. Modelling of sources at 85-140 km depth, in the eastern section of the arc, reveals a thick, slow low velocity layer (with thickness of ~10 km and velocity of ~7000 ms^{-1}), whereas preliminary results further west, beneath Kodiak Island, show a much thinner, faster waveguide with pervasive low velocity normal faulting.

Caldera collapse at near-ridge seamounts: an experimental investigation

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Collapse calderas are sub-circular volcanic depressions caused by subsidence of the magma reservoir roof during an eruption. Scaled physical models of caldera collapse using flat topography have been instrumental in investigating the spatial and temporal development of calderas, in particular, two distinctive sets of concentric ring faults, one reverse and one normal. More recent analog studies have investigated the effect of non-flat topography which alters the principle stress trajectories and resulting collapse structure. This work provides the basis for investigating how naturally scaled topographic loads may affect caldera collapse in relation to shallow magma reservoirs. The objective of this study is to understand how a near-ridge seamount affects caldera collapse from both a central and offset position as the seamount migrates above the magma reservoir as a result of plate motion. We utilize scaled analog models of caldera collapse in conjunction with three-dimensional (3D) laser scanning and digital particle image velocimetry (DPIV) to investigate caldera collapse dynamics at near-ridge seamounts. Experiments using a seamount cone positioned centrally above the magma reservoir result in (1) increased subsidence along the interior outward-dipping faults and (2) a preference to more symmetric collapse patterns as indicated by the subsidence profile and structure of the caldera relative to experiments with an offset cone. When the cone is offset, the collapse is asymmetric and trapdoor in nature, with the center of greatest subsidence displaced away from the region of largest topographic load. For these latter experiments, subsidence is focused where the roof is thinnest along an initial reverse fault, followed by a transition to an antithetic graben structure. The asymmetric collapse in the experiments results in a caldera with a tilted profile. Offset calderas at near-ridge seamounts are tilted towards the ridge axis, suggesting that they may have collapsed asymmetrically similar to our experiments. Furthermore, the graben structure observed in asymmetric collapse experiments is consistent with structures observed in some natural trapdoor basaltic volcanoes.

Petrological Journey Through an Icelandic Magma Plumbing System in Simulated Real Eruption Time.

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Diffusion modelling of erupted crystals is routine for investigating pre-eruptive timescales within magma storage bodies and transport systems. The technique typically produces results some time after a volcanic eruption has commenced.

This contribution employs a user-friendly petrological method for deployment in near-real time during an eruption, enabling rapid timescale assessment whilst retaining reliability. A ‘stress test’ was undertaken to simulate analysis during an evolving eruption involving multiple tephra layers, to test method performance and rapidity. The first tephra cycle was processed in 25 working hours, faster than current traditional methods.

Traditional limitations include slow data processing rates, measurement of crystal orientations and sectioning angles, crystal shape uncertainties, and possibilities of crystal growth and/or changing boundary conditions. These constraints have been considered for the new methodology with corrections applied at a crystal population level.

Tephra samples from *Vatnaöldur*, Iceland were the study material for the stress test. 39 magmatic timescales from Mg-Fe inter-diffusion across 25 olivine crystals were retrieved from the basal tephra layer representing eruption onset. Timescales range from ~400 days to ~160 days with olivine cores giving Forsterite (Fo) values of 82-84 and rim values ~79 indicating a single olivine population showing normal zoning (Mg-rich core). The distribution of timescales is consistent with a single pulse of magma migrating from depth into a shallow system ~1year before eruption onset. Magma arrival slows, then ceases by ~5 months before eruption with no new magma entering the system in the days and weeks immediately before eruption.

At the time of abstract writing, work is ongoing regarding the signals from later tephra units. Preliminary results indicate tapping of a source with longer crustal residence. Being able to retrieve this information within a day or so of the start of an eruption has exciting implications for eruption monitoring and hazard mitigation.

Magma storage and evolution beneath Antuco volcano, Chile

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Antuco is an understudied, Pleistocene to Holocene stratovolcano within the Southern Volcanic Zone (SVZ, 33 – 46ºS) of the Andean Volcanic Chain, Chile. Further segmentation, based on geochemistry and/or tectonic structure of the SVZ by many authors has placed Antuco (37.4ºS) in both the Transitional (TSVZ) and Central SVZ (CSVZ) segments. Additionally, Antuco marks the point along the arc at which volcanic products of basaltic composition dominate southwards, but are rare north of Antuco.

Activity at Antuco can be divided into two units – Antuco 1 and Antuco 2 – separated by a major edifice collapse event in the early Holocene. The westward directed collapse marks the end of the Antuco 1 phase, which was immediately followed by large-volume lava flows. Subsequent activity has rapidly constructed a new cone within the collapse scar, with relatively monotonous compositions, and a parasitic cone on the north-east flank, representing the Antuco 2 phase. Limited existing data show that Antuco 1 lavas range from basaltic to dacitic compositions, whereas Antuco 2 lavas are restricted to basalts and basaltic-andesites.

The current study will expand the existing dataset on Antuco volcano, using both whole-rock (XRF, ICP-OES/MS), mineral and melt-inclusion analyses (LA-ICP-MS, EPMA) to place constraints on the magma storage system beneath Antuco. Our first aim is to test how magma chemistry, mixing and storage conditions changed before and after the sector collapse event, and the relationship between the younger magmas and those that were erupted immediately around the time of the collapse. Our second aim is to use Antuco as a site within a regional study, to evaluate the processes controlling chalcophile element distribution within the arc (e.g., sulphide saturation and degassing), and how this relates to the crustal processing of magmas beneath arc stratovolcanoes (in this case, between magmas spanning ~6.7 – 1.7 wt.% MgO). Antuco will be compared with other volcanoes further south in the Chilean arc (Villarrica and Yate magma systems) to identify whether the controls on chalcophile element distribution is common between these systems, and between mafic melts feeding minor eruptive centres and those feeding the major regional stratovolcanoes.

The observational signature of modelled torsional waves and comparison to geomagnetic jerks

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Torsional Alfvén waves involve the interaction of zonal fluid flow and the ambient magnetic field in the core. Consequently, they perturb the background magnetic field and induce a secondary magnetic field. Using a steady background magnetic field from observationally constrained field models and azimuthal velocities from torsional wave forward models, we solve an induction equation for the wave-induced secular variation (SV). We construct time series and maps of wave-induced SV and investigate how previously identified propagation characteristics manifest in the magnetic signals, and whether our modelled travelling torsional waves are capable of producing signals that resemble jerks in terms of amplitude and timescale. Fast torsional waves with amplitudes and timescales consistent with a recent study of the 6 yr ΔLOD signal induce very rapid, small (maximum ~2 nT/yr at Earth's surface) SV signals that would likely be difficult to be resolve in observations of Earth's SV. Slow torsional waves with amplitudes and timescales consistent with other studies produce larger SV signals that reach amplitudes of ~20 nT/yr at Earth's surface. We applied a two-part linear regression jerk detection method to the SV induced by slow torsional waves, using the same parameters as used on real SV, which identified several synthetic jerk events. As the local magnetic field morphology dictates which regions are sensitive to zonal core flow, and not all regions are sensitive at the same time, the modelled waves generally produce synthetic jerks that are observed on regional scales and occur in a single SV component. However, high wave amplitudes during reflection from the stress-free CMB induce large-scale SV signals in all components, which results in a global contemporaneous jerk event such as that observed in 1969. In general, the identified events are periodic due to waves passing beneath locations at fixed intervals and the SV signals are smoothly varying. These smooth signals are more consistent with the geomagnetic jerks envisaged by Demetrescu and Dobrica than the sharp 'V' shapes that are typically associated with geomagnetic jerks.

Hyperextension and Fault Linkage

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In 2013, we collected a ~68x20km 3D seismic survey across the Galicia margin, NE Atlantic. Processing through to 3D PSTM (12.5 m bin-size) and 3D depth conversion reveals the key structures, including an underlying detachment fault (the S detachment), and the intra-block and inter-block faults. These data reveal two approximately N-S trending fault systems: 1) a margin proximal system of two linked faults that are the upward extension (breakaway faults) of the S; in the south they form one surface that splays northward to form two faults with an intervening fault block. These faults were thus demonstrably active at one time rather than sequentially. 2) An oceanward relay structure that shows clear along strike linkage. Faults within the relay trend NE-SW and heavily dissect the basement. Faults can be traced from the S through the basement and eventually die out in the syn-rift sediments, suggesting that the faults propagated up from the S detachment surface.

Analysis of the fault heaves within each fault system show that as extension ceased on one strand of a fault system; it was taken up on other strands, requiring several faults in each system to have been active simultaneously. The along strike transfer of extension also seems to have occurred between the two main fault systems, suggesting at some period both systems were active at the same time, and thus that faulting cannot have been fully sequential.

Multiple phases of faulting, that overlap spatially and temporally, have thinned the crust to between zero and a few km thickness, producing 'basement windows' where crustal basement has been completely pulled apart and sediments lie directly on the mantle. Internally the fault blocks are highly deformed, with packages of early syn-rift sediments rotated in various directions and by various amounts, suggesting intense intra-block deformation as the edge of continental basement is approached. This level of deformation highlights the 3D nature of final breakup.

Mechanics and seismic signature of semi-brittle deformation in antigorite

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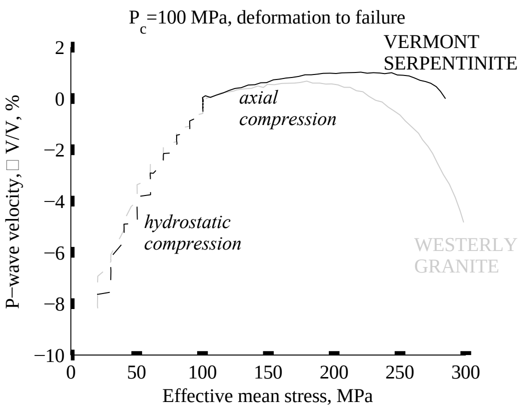
It is well recognised that serpentinites play a major role in subduction zone processes, such as tectonic evolution of the oceanic lithosphere, earthquake nucleation, or recycling of water in the upper mantle. However, it is not yet clearly known how and by which micromechanical process serpentinites deform, and what is their signature on seismic properties.

Deformation experiments were conducted on 90%-rich antigorite polycrystalline serpentinite in the brittle field, under varying conditions of confining pressure, with simultaneous measurements of axial and radial strains, and P and S-wave velocities at various directions with respect to the applied stress. Failure, controlled-failure, and cyclic-loading tests were performed to investigate the strength, dissipation of mechanical energy, seismic signature and resulting microstructures of a suite of antigorite specimens.

The brittle deformation of antigorite is mostly non-dilatant and accommodated by shear microcracks localised over a very narrow zone near the failure plane – as confirmed by microstructural observations. Antigorite serpentinites display a failure strength as high as for crystalline rocks, and a yield point occurring close to failure. The spectacular absence of any wave velocity evolution during axial compression confirms that microcracking is very localised, especially if compared to a Westerly granite specimen tested in similar conditions (*cf.* figure). Such results may have strong implications for the understanding of subduction zone dynamics, which remain to be complemented by mechanical tests conducted in the ductile regime.



Exploring vesicle (pore) geometry and orientation on basalt strength.

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Experimental data shows that vesicle (pore) shape and density have an effect on the resultant strength of basalt. The orientation of vesicles in respect to the maximum principal stress dramatically changes the failure strength of the rock[1]. Analytical models show circular voids under uniaxial tension concentrate the remote stress at the hole edges by a factor of 3. Reducing one axis of this hole to 0 so it is a planar crack causes almost infinite stress concentrations at the crack tips. These analytical models show how even simple isolated flaws can have dramatically different stress concentrations.

In this study the displacement discontinuity boundary element method is employed, to model stress concentrations in a 3D isotropic linear elastic medium. This is used to quantify stress concentrations due to flaws in vesicle (pore) shape and the interaction of stresses around vesicles in close proximity. Data is used from basalt plugs that have been deformed in uniaxial rock deformation apparatus[1]. Specific vesicles in these plugs are discretised from X-ray microCT laser scan data and used as inputs into the numerical model. This allows comparison of the model predictions to the known deformations of the samples.

The displacement discontinuity method used here allows for the effects of vesicle (pore) orientation, shape and interaction to be separated and viewed independently. The modelling quantifies the effect to which each of these mechanisms has on concentrating stress, indicating as to why the core data in Bubeck et al. (2016), had such strongly anisotropic strength.

[1]Bubeck, A., Walker, R.J., Healy, D., Dobbs, M. Holwell, D.A. 2016. *Earth and planetary science letters, accepted manuscript.*

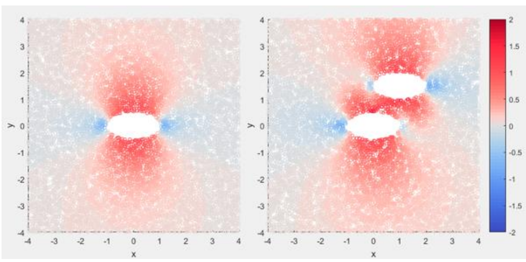

Figure showing the magnitudes (MPa) of maximum extensional stresses (positive) around voids loaded with a purely compressive stress along the Y axis of 1MPa.

Constraints on the thermal structure of the Iceland plume from olivine crystallisation temperatures.

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Spatially distributed measurements of mantle potential temperature provide important constraints on global variation in mantle rheology and dynamics. A multitude of proxies for mantle temperature, such as crustal thickness, basalt chemistry and crystal-melt equilibria have been employed to this end. Since each such proxy is not uniquely controlled by mantle temperature, unconstrained variables such as mantle fusibility and flow field trade-off against mantle temperature. A combined approach using multiple proxies can constrain the magnitude of these trade-offs, and therefore reduce the uncertainty in mantle temperature estimation.

Global variation in olivine crystallisation temperatures derived from the olivine-spinel aluminium exchange thermometer has been observed in a number of recent studies, and linked to variations in mantle temperature. The conversion of the crystallisation temperatures into mantle potential temperature estimates requires deconvolving the cooling associated with crustal processing and melt evolution with the cooling arising from the latent heat of melting. Whilst petrological constraints can be placed on the evolution of melt in the crust, the magnitude of the latent heat correction remains largely uncertain. In particular, uncertainties arise from mantle fusibility and the thermal consequences of melt transport following its generation. Using proxies for the extent of melting, such as crustal thickness, we place tighter constraints on the amount of the cooling associated with mantle melting, and therefore the magnitude of the correction needed to convert crystallisation temperatures to mantle temperature.

We present a new data set of olivine crystallisation temperatures, calculated using the olivine-spinel exchange thermometer, for three eruptions distributed along the Reykjanes ridge spreading centre, SW of Iceland. The Reykjanes Ridge system shows pronounced geochemical and geophysical gradients away from Iceland, as the influence of the Iceland plume decreases Southwards. Using a simple thermal model of mantle melting, combined with our new petrological observations, and existing geochemical and geophysical datasets, we place new constraints on mantle temperatures along the Reykjanes ridge. This novel combination of a suite of observations and simple modelling provides insights into the long wavelength thermal structure of the plume.

Protracted weakening during lower crustal shearing along an extensional shear zone.

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This study investigates grain-scale deformation mechanisms in the mafic continental lower crust. The investigated extensional shear zone is hosted in the Finero mafic-ultramafic complex in the Italian Southern Alps. Strain localized in ultramylonites exploiting gabbroic layers where the primary mineralogical assemblage contained amphibole. The ultramylonites contain porphyroclasts of amphibole, garnet, clinopyroxene and orthopyroxene, embedded in a matrix of plagioclase, amphibole, clinopyroxene, orthopyroxene, and Fe-Ti oxides. The grain-size is consistently below 30 µm for all phases. EBSD results are consistent with deformation by grain-size sensitive creep. Amphibole shows a CPO of the [001] axes preferentially aligned parallel to the stretching lineation, which is explained by oriented grain growth during heterogeneous nucleation. Pyroxenes and plagioclase lack a CPO and evidence for dislocation creep and dynamic recrystallization. Protracted shearing was initiated by syn-kinematic metamorphic reactions forming symplectites of orthopyroxene + plagioclase around garnet and of pyroxene + plagioclase around amphibole. The latter reaction indicates that strain localization initiated with dehydration of the magmatic amphibole. Estimated P, T conditions of shear zone initiation are 850°C, 8kbar on the basis of the composition of neocrystallized clinopyroxene-orthopyroxene pairs. Plagioclase-amphibole pairs in the indicate P, T conditions of ca. 800°C and 6kbar during amphibole formation. This suggests that protracted shearing in the ultramylonites occurred at decreasing pressure. We speculate that the fluids released during the dehydration reaction assisted the subsequent nucleation of amphibole in dilatant sites during creep cavitation in the ultramylonites, when the shear zones deformed at P, T conditions at which amphibole was stable again. This study highlights the importance of dehydration reactions for grain size reduction and strain localization in the lower crust, as well as the possibility that fluids can be channelized in discrete shear zones during protracted tectono-metamorphic events.

The role of pre-eruptive exsolved volatiles in changing the eruptive style at Quizapu volcano (Chile)

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Eruptions of silicic magma can shift from effusive outpourings of lava to violent explosions of a gas-pyroclast mixture. The expansion of the gas phase during ascent provides the driver for explosive eruptions. However, the development of permeable foam and fractures can create pathways for efficient gas escape, which will prevent fragmentation and lead to an effusive eruption. It is now getting increasingly recognized that the physical processes leading up to an eruption in the shallow magma reservoir will strongly influence the outgassing mechanisms and thus the eruptive style. Quizapu volcano (Chile) presents an excellent natural laboratory to study these processes. Two significant eruptions (~5 km^3) of dacitic magma occurred within a relatively close time interval of about 85 years. The 1846-47 eruption produced a lava flow, while the 1932 eruption lead to a Plinian eruption. Despite these different styles, the two eruptions have similar erupted volumes, bulk-rock composition, storage depth and water content and both show evidence of andesite recharge before the eruption. The 1846-47 eruption showed abundant mafic enclaves (up to 20-30 % volume) and a significant temperature increase (>50 °C) related to a recharge event, while the 1932 eruption showed a very limited amount of mafic recharge and a negligible increase in temperature [1]. This brings the question of why a magma reservoir would respond so differently to recharge of new magma. We use a thermo-mechanical model of a shallow magma reservoir exposed to transient recharge events [2] to explore different recharge scenarios. We demonstrate how the thermo-mechanical state of the reservoir dramatically changes when exsolved volatiles are present. The combination of (i) latent heat of exsolution, (ii) changes in the bulk heat capacity and (iii) the bulk compressibility of the system amplify the temperature increase prior to eruption and the volume needed to provoke an eruption. This results in strongly different magma conditions upon ascent and can cause the switch in eruptive style observed at Quizapu.

[1] Ruprecht P., Bachmann O. (2010), Geology, **38**, 10, p. 919-922

[2] Degruyter W., Huber C. (2014), Earth Planet. Sci. Lett., **403**, p. 117-130

From an initially unsegmented normal fault to a complex fault zone: The role of bed-parallel slip.

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The structure of the normal faults in Kardia lignite mine in the Ptolemais Basin, NW Greece was significantly influenced by the action of bed-parallel slip during their growth. As the normal faults grew they were intermittently offset by bed-parallel slip resulting in vertically segmented faults. Following offset by a bed-parallel slip-surface further fault growth occurred by reactivation on one or both of the offset fault segments. Where one fault is reactivated the site of bed-parallel slip is a bypassed asperity. Where both faults are reactivated a relay zone is formed transferring displacement between two sub-parallel slip-surfaces and, with further increase in displacement, the formation of a fault-bound lens.

Fault surface asperities and relay zones usually form during fault propagation but, with coeval bed-parallel slip can form at any time in the growth of a fault. Geometrical restoration of cross-sections through selected faults shows that repeated bed-parallel slip events during fault growth leads to complex internal fault zone structure that can mask it's origin.

Faults affected by bed-parallel slip are characterised by enormously high displacement gradients on individual fault segments and repeated or missing parts of the stratigraphic sequence within the fault zone. In three-dimensions, bed-parallel slip can result in fault zones with highly variable thickness and internal structure.

Bed-parallel slip in Kardia lignite mine has a persistent slip direction towards the north, ranges from a few cm up to 4.5 m and the average spacing between the slip-surfaces is ca 13 m. Bed-parallel slip, in this case, is attributed to flexural-slip arising from hanging wall rollover associated with a basin-bounding fault outside the study area.

Coseismic origin of foliated cataclasites and their preservation potential during the seismic cycle

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Foliated gouges and cataclasites are commonly interpreted as the result of aseismic faulting in the brittle upper crust. However, the occurrence of foliated cataclasites associated with possible indicators of earthquake ruptures (mirror-like slip surfaces with truncated clasts, in-situ pulverized rocks, etc.) suggests that some examples may have a coseismic origin.

Here we present the results of friction experiments and microstructural analysis performed on mixtures (50/50wt%) of calcite-dolomite gouges to ascertain the conditions of foliation formation. The gouges were sheared for 40 cm in a rotary shear apparatus (SHIVA, INGV-Rome) under constant normal stress of 17.5 MPa and slip rates (i.e., V) ranging from 30 µm/s to 1 m/s.

In room-humidity conditions, a striking foliated fabric was formed only at V = 1 m/s, associated with strain localization, thermal decomposition and possible crystal-plastic deformation in a slipping zone less than a few micrometres-thick. Instead, in water-dampened conditions, strain localized within an ultrafine (grain size << 1 µm) fluidized layer whose thickness decreased with increasing velocity. A slight foliation was formed only at 30 µm/s. To investigate the preservation potential of these microstructures during the seismic cycle, we also conducted experiments that stepped from slow (30 µm/s for 10 cm slip) to high (1 m/s for 30 cm slip) velocity and vice-versa. In the 30 µm/s to 1 m/s experiment, in room-humidity conditions, typical microstructures of both slip velocities were preserved and the overall fabric strongly resembles that found in natural foliated cataclasites from the active Vado di Corno Fault Zone, Italian Central Apennines.

Our experiments suggest that foliations defined by compositional banding and/or grain size variations in gouge and cataclasite can form during coseismic sliding ($V \geq 1$ m/s) in dry conditions and that foliation is likely to be preserved during the seismic cycle. Recognition of such foliated cataclasites in the geological record would provide a marker of seismic ruptures, especially along active faults in areas of recent human settlement or with poor historical seismic catalogues.

What really controls friction in phyllosilicate fault gouges?

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Phyllosilicate-rich foliations in fault rocks are often thought to reduce overall fault strength and promote fault stability when forming an interconnected network. Indeed, laboratory measurements have shown that the average friction coefficient of dry phyllosilicates of ~0.5 is reduced to ~0.3 when wet or even 0.1 for smectite. A widely accepted interpretation of these observations is that the strength of phyllosilicates is controlled by breaking of interlayer bonds to form new cleavage surfaces when dry and by the low strength of surface-bound water films when wet. However, the correlation between phyllosilicate shear strength and interlayer bond strength, which formed the basis for this interpretation, was not reproduced in recent experiments (Behnsen and Faulkner, 2012) and is not supported by the latest calculations of the interlayer bond energies (Sakuma and Suehara, 2015). The accepted explanation for phyllosilicate friction also fails to account for the velocity dependence or (a-b) values, which decrease with temperature, reaching a minimum at intermediate temperatures, before increasing again at higher temperatures (Den Hartog et al., 2013, 2014). In this study, we developed a microphysical model for phyllosilicate friction, involving frictional sliding along atomically flat phyllosilicate grain interfaces, with overlapping grain edges forming barriers to sliding. Assuming that the amount of overlap is controlled by crystal plastic bending of grains into pores, together with rate-dependent edge-site cleavage, our model predicts the experimentally observed temperature dependence of (a-b) and provides a basis for extrapolation of laboratory friction data on phyllosilicates to natural conditions.

Hydrocarbon exploration in volcanic rifted margins: an analogue from the Hreppar Formation, Iceland

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Hydrocarbon exploration within frontier basins such as the Faroe-Shetland Basin (FSB) of the NE Atlantic Margin, is problematic due to the significant extent of subaerial lavas. The FSB has proven large oil and gas discoveries, including the significant Rosebank Field. Rosebank was discovered in 2004 and the main reservoir intervals are fluvial clastic sequences, interbedded with basaltic lavas, hyaloclastites and volcaniclastic sedimentary units. Predicting the geometry and continuity of clastic units within lava-dominated sequences in volcanic margins is problematic as they are typically laterally discontinuous, relatively thin and often poorly imaged in the subsurface.

This work uses the Hreppar Formation (HF), Iceland, as an analogue to understand such systems and reduce the challenges and risk associated with hydrocarbon exploration within volcanic-dominated basins. The HF at Flúðir comprises basaltic lavas and interbasaltic sediments of Plio-Pleistocene age (3.3-0.7Ma). Detailed mapping, graphic and gamma logging have been combined with field panoramas and photogrammetry to characterise the sequence in detail and to identify the lateral (dis)connectivity of the clastic units, the main lithofacies, the different facies architectures, structural elements and drainage pathways. Volcanic, fluvial and glacial systems have competed for available accommodation space within the HF, resulting in a complex facies architecture, strongly influenced by tectonics. Two large NE-SW trending oblique faults have generated a Riedel shear zone, which has controlled deposition in the area. This has resulted in horsts and grabens forming on a km scale with evidence of reactivation having occurred.

The data collected in the HF can inform every stage of the development of a hydrocarbon field in a volcanic margin, from determining the architecture of a potential reservoir to defining the main structures and fluid pathways and informing seismic imaging. The advantage of using an analogue such as the HF is the level of detail that can be recorded. This enables the gap in scale between field and seismic/well to be bridged. As hydrocarbon exploration becomes more challenging, it is necessary we enhance our understanding of how volcanism affects petroleum systems and analogue studies are key to this.

Magmas on the Move: in situ 4D Rheology of Three-Phase Magmas Using Ultra Fast X-ray Tomography

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A key challenge to understanding the nature of flow in magmatic systems is our inability to quantify the processes that occur within the magma during transport. We can measure non-Newtonian behaviour in the laboratory using well established rheological methods but we still do not understand the mechanisms that lead to this behaviour. The mechanisms operate on the scale of individual crystal-crystal interaction, yet can have macroscopic effects on the entire reservoir system. These same processes ultimately control the relative movement of crystals, bubbles and melts, and so influence the compositional, mechanical and thermal evolution of the reservoir on all spatial scales.

We present the first real time experimental observation of these microstructural behaviours. We use ultra fast x-ray tomography (TOMCAT beamline, Swiss Light Source) and a bespoke XRheo in situ rig to drive the mobilisation and flow of two- and three-phase magmas. With a variety of bubble and crystal contents we record “traditional” rheological data while simultaneously observing every crystal, bubble and interaction non-destructively during the experimental run. Using this unique 4D (3D + time) data we define 3D and 4D maps of local microstructure, identify deformation & strain localisation, and quantify the evolving multi-scale heterogeneous distribution of solid, melt and gas phases through time. From this we discuss 4D models of microstructure, mechanisms and rheology that enable us to relate experimental data to the more macroscopic processes we can observe in natural system, and ultimately improve our understanding of magma reservoir behaviour.

How damaging is caldera collapse for a volcanic edifice?

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Piston-like caldera collapse along bounding circumferential ring-faults partially destroys the volcanic edifice. What effect this faulting and rapid subsidence has on the surrounding edifice in terms of deformation and damage is not well studied. However, fault related damage has previously been shown to be important for fluid transport and mineralization, which may influence the future stability of the fault. Furthermore, damage surrounding the ring-fault can influence magma propagation paths influencing, for example, when and if a ring-dyke is formed.

To address some of these problems we have undertaken a field campaign at Santorini volcano, Greece. We have mapped sections of the northern caldera wall with specific interest in the dyke swarm and associate lavas and eruptive units which are partially cut by a series of historic caldera collapses (Fig 1). The dykes represent elastic inclusions in the otherwise heterogeneous and complex edifice which makes up the Santorini volcano. By measuring the macro and micro fracture damage in different orientations and at varying distances from the caldera fault in the stiff units (dykes and lavas) we hope to be able to quantify the input of damage resulting from caldera collapse.

Also by coupling the field data with numerical and analytical models we aim to understand the stress distribution in a volcanic edifice which has undergone, or is undergoing piston-like caldera collapse.

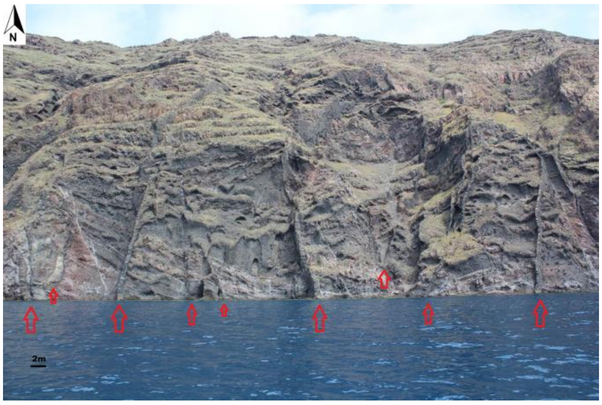

Fig 1:Dykes (red arrows) within the northern caldera wall of Santorini. The dykes are exposed partly due to historic caldera collapses.

Application of Independent Component Analysis to multi-temporal InSAR with volcanic case studies.

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A challenge in the analysis of multi-temporal Interferometric Synthetic Aperture Radar (InSAR) data is the separation of volcanic, tectonic and anthropogenic displacements from each other and from atmospheric or orbital noise. Independent Component Analysis (ICA) is a method for decomposing a mixed signal based on the assumption that the component sources are nongaussian and statistically independent. ICA has particular advantages for the analysis of sets of SAR interferograms in that it separates signals on the basis of either their spatial or temporal independence rather than their contribution to combined signal variance, as in more widely used Principal Component Analysis. It also requires only very limited *a priori* information about signal characteristics, making it suitable for exploratory analysis. As a tool for separating displacement from atmospheric signals, it is useful where displacements occur on a similar time-scale to measurement interval and are therefore hard to remove using low pass temporal filtering.

I presents tests of the applicability of ICA to InSAR using synthetic data simulating a range of different deformation sources . The ICA method is then applied to Sentinel-1A archive images from two volcanoes spanning periods of constrasting displacement style. At Calbuco and Osorno volcanoes (Chile), tropospheric water vapour signals are separated from co-eruptive deformation captured in just one interferogram and turbulent atmospheric features. Deformation at Paricutin lava fields (Mexico) is not discernible in individual interferograms, but is extracted as an independent component of small sets of ascending and descending interferograms. Three distinct patches of lava subsidence are extracted as a single component at Paricutin, and correspond to previously identified regions of thick lava, all subsiding with a linear rate.

An advantage of the identification of independent components is that their statistical significance can be tested using cluster analysis of their spatial patterns. This provides a useful method for (a) automatically identifying which components capture true displacements and (b) distinguishing between displacements that are caused by independent or connected processes.

How mechanical properties effect permeability within the Krafla reservoir, North-East Iceland

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Krafla volcano, North East Iceland, holds an active hydrothermal system, exploited for geothermal energy by Landsvirkjun National Power of Iceland. The system generates ~60 MW_g from 18 wells tapping into fluids at 200-300°C. In order to satisfy the demand for sustainable, environmentally-safe energy, Landsvirkjun is aiming to drill deeper and source fluids in the super-heated, super high-enthalpy system which resides deeper (at 400-600°C and <220 bar). In relation to this, the first well in the Icelandic Deep Drilling Project (IDDP) was drilled at Krafla in 2009. Drilling stopped at a depth of 2.1 km, when the drill string penetrated a rhyolitic magma body, which could not be bypassed despite attempts to side-track the well.

During field surveys in 2015 and 2016, and through information gathered from drilling of geothermal wells, five main rock types were identified and sampled: basalts (5-60% porosity), hyaloclastites (<35-45% porosity), obsidians (0.25-5% porosity), ignimbrites (13-18% porosity), and intrusive felsites and microgabbros (10-16% porosity). Samples are primarily from surface exposures, but selected samples were taken from cores drilled at Krafla caldera.

The porosity of all samples has been determined using a helium-pycnometer. The mechanical properties of the different rocks have been tested via uniaxial as well as triaxial compressive strength tests, and by indirect tensile strength test using the Brazilian disc method. The results show the rock tensile and compressive strength is inversely proportional to porosity, and show that porous lithologies may undergo significant compaction at low loads.

Special focus has been given to the generation of tensile fractures and their role as permeable pathways for fluids (akin to thermal stimulation and fracking). The permeability of intact and fractured rocks has been measured at different confining pressures (5 MPa – 100 MPa). We find that low porosity rocks (<15%), are more heavily affected by the presence of a tensile macrofracture (i.e., permeability increase by up to 2-3 orders of magnitude), compared to porous rocks (>20%). Interestingly, imparting a second fracture does not increase the permeability further. The permeability and porosity of intact and fractured rocks were found to nonlinearly decrease with effective pressure in the system.

Exploring the micro-scale controls on fracturing in a Carboniferous limestone, and their implications for carbon capture and storage.

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Characterising subsurface fracture properties is important for understanding their structure, distribution, and effect on fluid flow. Fractures often act to compartmentalise fluids in the crust, which has implications across a number of subsurface applications, including carbon-dioxide (CO_2) storage. Within the U.K., limestone-rich Carboniferous strata are becoming increasingly economically important and as such it is vital to gain a better understanding of their mechanical properties in the subsurface.

To help achieve this, core plugs (Ø 38mm) from one naturally fractured sample and one protolith (undisturbed) sample of the Namurian McDonald Limestone, exposed in the Spireslack Surface Coal Mine in East Ayrshire, were taken. To understand controls on newly formed fractures, i.e. those that may form as a result of CO_2 injection, the protolith sample was deformed in axi-symmetric compression at 25 MPa confining pressures. The sample was deformed and then unloaded in order to replicate early stage deformation features. Early results indicate that fossil fragments in part control fracture propagation pathways.

Carbonation (i.e. CO_2-brine-limestone) experiments on the samples were conducted for 7.2 weeks in a batch high temperature/high pressure experimental system, in order to investigate their reactivity when in contact with supercritical CO_2 under conditions representative of a CO_2 storage reservoir in the North Sea region. XRT was performed on original and reacted samples to characterise fractures and deformation features occurring within the plugs. Early results indicate that, due to rock-fluid interactions, fracture surfaces have been partially dissolved and as a result are smoother and wider. Debris recovered in the batch cylinder after the experiment suggests that the induced fracture network (in the protolith sample) allowed for a higher interaction rate compared to the naturally fractured and un-fractured samples.

Geodetically constrained slip on the Main Himalayan Thrust fault from the 2015 Gorkha earthquake

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Here we use geodetically-derived surface displacements to show that whilst the Gorkha earthquake was blind, it ruptured the Main Himalayan Thrust (MHT), highlighting its ramp-and-flat geometry. Reconciling independent geological, geomorphological, geophysical and geodetic observations, we quantify the geometry of the MHT in the Kathmandu area. Present-day convergence across the Himalaya is mostly accommodated along the MHT, and no out-of-sequence thrusting is required to explain the higher uplift and incision rates at the front of the high range. Whilst the vast majority of slip is buried at depth, triggered near surface slip was imaged in the Sentinel-1 coseismic interferograms along a 26 km long discontinuity, 10 km north of the Main Frontal Thrust. This surface break follows the trace of the Main Dun Thrust (MDT), a relatively minor splay. This displacement is seen to grow in the central portion of the splay in the preceding week. Slip from the largest (Mw 7.3) aftershock that occurred 17 days later fills in most of the eastern gap in the slip contours of the mainshock at the lower edge of the fault rupture. In addition to the region west of the Gorkha rupture, a large portion of the MHT remains unbroken south of Kathmandu presenting a continuing seismic hazard. At the shallow end of the rupture, slip tapers off sharply and is markedly uniform along strike for the 140 km length rupture, and at a near constant depth of 11 km. Such a sharp limit on slip could result from the soleing out of other thrusts such as the MBT onto the MHT, resulting in structural complexity on the fault interface and a wide damage zone impeding up-dip rupture propagation. This leaves a locked fault width that is at least as wide as that which ruptured in the 2015, but at a shallower depth.

Rupture of the Karakul-Sarez fault in the 7 Dec, 2015 M7.2 Murghob, Tajikistan earthquake: implications for secondary hazards and the enigmatic 1911 event in the Pamirs

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On 7 Dec, 2015 a M7.2 strike-slip earthquake occurred in the Pamir Mountains of Tajikistan. Strongest shaking occurred near the Usoi landslide dam, which formed during a poorly understood earthquake in 1911, impounding the Murghob River to produce Sarez Lake. Overtopping of the dam represents one of the greatest natural hazards in Central Asia, warranting a comparison of the sources and effects of the 1911 and 2015 earthquakes. We measure the displacement field of the 2015 earthquake using the full gamut of space-based geodetic techniques, revealing left-lateral offset along 60 km of the SSW-striking Karakul-Sarez fault (KSF), and numerous coseismic landslides. Sentinel-1 interferograms reveal up to 1.5 m of left-lateral surface displacement along 40 km of the KSF, with an additional 10-15 km of buried, blind rupture at both ends. This matches the extent of the dislocation we determine from pixel-tracking of pre- and post-event Landsat-8 scenes. Both of these far-field deformation maps indicate that the rupture ended northward around a 3-km step in the fault trace, and southward beneath Sarez Lake. Direct comparison of pre- and post-event SPOT6/7 images shows discontinuous new scarps and small stream offsets along 30 km of the KSF from the shore of Sarez Lake northward, corroborating this surface rupture extent. We difference pre- and post-event topography derived from the tristereo SPOT images to identify throughgoing strike-slip rupture. Our detailed height-change maps also reveal massive slope failures around the shore of Lake Sarez, indicating that overtopping of the Usoi dam by a landslide-induced seiche remains one of the principal secondary seismic hazards in the region.

We find that the 2015 rupture occupies the least recently ruptured reach of the KSF. To the north fresh scarps and a clear moletrack represent the prior event, the extent of which does not overlap the 2015 rupture. The location of these ruptures along the KSF requires that the 1911 Sarez earthquake, constrained by seismology to be centered 70 km closer to Europe than the 2015 event, could not have occurred on the Karakul-Sarez Fault, and must represent further, as yet unidentified left-lateral faulting in the high Pamirs.

The effect of cooling rates on lithium in rhyolites

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Lithium remains a key element in terms of quantifying the cycling of various components through subduction zones. Despite this, much remains unknown about the behaviour of Li in shallow magmatic and volcanic systems.

Here, we use a suite of eight welded ignimbrites from the Yellowstone- Snake River Plain (YSRP) volcanic province to illustrate how post-eruptive effects control the lithium inventory of a deposit. YSRP ignimbrites have a common lithological stratigraphy with rapidly quenched glassy vitrophyres found at the top and base of individual units separated by a more slowly cooled microcrystalline lithology. In all cases, plagioclase and sanidine phenocrysts from the slowly cooled interior of an ignimbrite contain more Li than the same crystals from the quenched part. The increase in Li between the two lithologies varies from a factor of 2 to more than an order of magnitude. This variability in Li contents of feldspars is decoupled from any other variability in either major or trace elements, precluding the variability in Li from reflecting a pre-eruptive process (e.g. magma mixing). Rather, we interpret the higher Li contents in slowly cooled lithologies to reflect increased partition coefficients due to the lower temperatures and water contents prevailing in the post-eruptive realm.

We further investigated these processes using Li isotopes from glassy and microcrystalline portions of the Tuff of Knob. Bulk and groundmass samples from the microcrystalline lithology had lower Li contents and higher δ^7Li values compared to their glassy counterparts. These data are consistent with degassing during slow post-eruptive cooling. In addition, the δ^7Li in the high-Li feldspar crystals from the microcrystalline lithology was several per mil lighter than that of the low-Li feldspar crystals from the glassy lithology. This indicates that the ingress of Li into the feldspars primarily involves the movement of ^{6}Li.

These results indicate that the post-eruptive cooling history of a deposit may have a profound effect on both where Li resides in the deposit and the isotopic character of bulk samples. Given this post-eruptive over-printing, studies using Li isotopes to address deeper, magmatic processes should be attempted with caution.

Emplacement and inflation of the Al-Halaq al Kabir lava flow-field, central part of the Al Haruj Volcanic Province, Central Libya

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Numerous of lava rises and tumuli developed in the medial and distal portions of the Al-Halaq al Kabir lava flow-field during the last eruption (sometime during the Holocene) in the central part of the Al Haruj Volcanic Province (AHVP). These inflation features can be used to better understand the emplacement mechanism and to estimate the lava volumetric flow rate in this part of the Al Haruj region. We report the results of detailed measurements of the widths and lengths (diameters) of 551 lava rises and 289 tumuli from the distal part of the Al-Halaq al Kabir lava field using ArcGIS and field observations. Tumuli and lava rises may be divided into subpopulations according to the abrupt change in the scaling exponents on log-log plots of their frequency versus diameters. The stiffness (Young's modulus) for the basaltic rocks in the study area is estimate in the range of 10-34 GPa. Numerical and analytical results show that theoretical maximum tensile stress in the inflated upper crust reaches 44 to 570 MPa. This theoretical stress is orders of magnitude higher than typical in-situ tensile strengths of rocks (0.5-9 MPa), which mean that the tensile stresses are high enough to rupture the crust. These high tensile stresses are generated through crustal doming driven by a very low excess pressure (1 MPa or less). Our findings partly explain the abundance of tension fractures at the surface of the Al-Halaq al Kabir lava flow-field. The widespread occurrence of tumuli and lava rises are strongly suggestive of low lava supply rates. Tumuli observed in the area are remarkably similar in morphology and aspect (height/width) ratios to the flow-lobe tumuli which have been studied in Holocene lava shields (monogenetic shield volcanoes) in Iceland. This geometric similarity suggests that they may have been emplaced through an analogous mechanism and effusion rates (average around 10^{-3} m^3/s). These results of the mechanisms of formation of these lava-flow fields may also be of importance in connection with extinction in the area. There appears to be a coincidence between the age of an initial volcanism in the AHVP and mass extinctions in the As-Sahabi area, NE the Sirt Basin, during Messinian-Zanclean time (≈7 to 5 Ma).

Provenance of Metasedimentary Rocks in the North Atlantic

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The Faroe-Shetland basin contains sedimentary deposits that were metamorphosed during the Caledonian orogeny. Consequently the provenance of the metasedimentary rocks is expected to record the geological evolution of the North Atlantic basin. Little is known about the metasedimentary rocks sampled by drill core in the Faroe-Shetland Basin. To shed light on the nature and origin of the metasedimentary rocks we employ petrology and geochemistry to classify the metasedimentary rocks and compare them with data from previous studies conducted in potential source areas such as Greenland, Norway and Scotland.

The petrography and major element data show that the metasedimentary rocks span a wide variety of rock types. The protoliths include sandstone, mudstone and limestone lithologies although the most common are mica-schist and meta-arkose. Furthermore the radiogenic isotope ratios indicate that the majority of the samples can be divided into two different geochemical groups. Group 1 contains higher Nd and Pb isotope ratios compared to Group 2. The Nd isotope ratios found in Group 1 range between $^{143}Nd/^{144}Nd$ 0.5116 and 0.5122 with $^{206}Pb/^{204}Pb$ of approximately 19.1 and the range in Sr isotopes is between $^{87}Sr/^{86}Sr$ 0.704 to 0.741. Whereas the isotope ratios in Group 2 are $^{143}Nd/^{144}Nd$ of 0.5107 to 0.5110 and $^{206}Pb/^{204}Pb$ of 16.7 to 17.5 with a narrower range of $^{87}Sr/^{86}Sr$ 0.705 to 0.708.

The origin of the metasedimentary rocks found in the Faroe-Shetland basin is somewhat complex. The majority of the metasedimentary rock can be correlated with parts of the Scottish bedrock. Hence Scotland is thought to be the main source area, although some samples also show similarities with the bedrock on Greenland. We suggest that Group 1 correlate with the Torridonian and Dalradian bedrock of Scotland while Group 2 samples have isotopic similarities with Archean gneiss similar to those found on Greenland and in the Lewisian of Scotland. This indicates that the metasedimentary rocks in the Faroe-Shetland basin cannot be uniquely tied to one sedimentary source area.

Mitigating volcanic ash risks with ultraviolet spectroscopy

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Volcanic ash poses a serious hazard to health and infrastructure; it can cause short term breathing difficulty and eye irritation or aggravate any pre-existing respiratory conditions as well as damaging electricity and transportation networks. Aircraft flying through ash clouds can suffer large amounts of damage due to abrasion, as well as possible engine failure due to ash melting and re-solidifying within jet engines. The 2010 eruption of Eyjafjallajökull in Iceland is a good example of the widespread disruption large ash clouds can cause, especially to air travel.

By detecting and characterising ash remotely these risks can be potentially reduced. Here, we examine the possible application of ultraviolet absorption spectroscopy to the detection and quantification of airborne ash loading. This utilises backscattered UV solar radiation as a light source behind the plume, and so the analysis is simpler compared to that of IR measurements which requires prior knowledge of the ash plume temperature. Furthermore, the equipment used is both relatively cheap and lightweight, allowing for rapid deployment to on-going eruptions, and potential airborne deployment. In addition, UV spectrometers are already used in volcanic monitoring for trace gas measurements (for example with SO2 cameras) and so much of the infrastructure is already in place.

We will present an overview of the state of the art in volcanic ash detection using UV absorption spectroscopy, and highlight research frontiers which could lead to progress in risk mitigation.

Subduction megathrust creep governed by pressure solution and frictional-viscous flow

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Subduction megathrust slip speeds range from slow, steady creep at plate boundary convergence rates (cm/yr) to fast, episodic, earthquake slip (m/s). This geophysically observed variation in seismic style arises from processes within a fault zone in subducting sediments on top of potentially rugged ocean floor. The deformation mechanisms controlling whether fast slip or slow creep occurs, however, remain unclear.

The megathrust interface is commonly inferred to be seismogenic at depths shallower than where temperature exceeds the approximately 350˚C required for crystal plasticity in quartz, or than the intersection with the hanging wall Moho, whichever is shallower. In a number of subduction margins, however, recent geodetic inversions have revealed aseismic creep, accompanied by moderate magnitude earthquakes, shallower than both the onset of crystal plasticity and the hanging wall Moho. The question therefore arises: How do some megathrust segments accommodate both detectable aseismic creep and moderate size earthquakes, both originating in the same depth range, and both occurring under what is considered seismogenic conditions?

We present evidence that pressure solution creep, deformation by fluid-assisted, stress-driven mass transfer, is an important deformation mechanism in megathrust faults. We quantify megathrust strength using the laboratory-constrained microphysical model of Den Hartog and Spiers (JGR, 2014) for fault gouge friction, involving viscous pressure solution and frictional sliding in a quartz-phyllosilicate mixture. We find that at plate boundary deformation rates, aseismic, frictional-viscous flow is the preferred deformation mechanism at temperatures above 100˚C. The model thus predicts aseismic, velocity-strengthening, creep at temperatures much cooler than the onset of crystal plasticity, and shallower than the hanging wall Moho. Earthquake nucleation requires a change in the boundary conditions. Within this model framework, earthquakes may nucleate when a local strain rate increase triggers velocity-weakening slip, which becomes preferred at high slip velocities. We speculate that slip area, and therefore also earthquake magnitude, then depends on the spacing of strong, topographically derived irregularities in the subduction thrust interface, with giant earthquakes requiring this spacing to be large.

A single eruption "snapshot" through a complete magma reservoir

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Pyroclasts ejected during explosive eruptions on Tenerife include crystal “mush”: a combination of frozen magma and crystal cumulate. Cumulate mush nodules from the Fasnia Fm. represent a catastrophic disaggregation of a partially molten magma reservoir during a caldera-forming eruption. They represent a complete magma chamber stratigraphy, spanning the entire range of proto-cumulate material: wehrlites, through pyroxenites and hornblende gabbros, to monzonites and feldspathoid-syenites. The nodules contain up to 80% interstitial melt: the final liquid that was in contact with the cumulate at the time of eruption. This melt was quenched during the Fasnia eruption and preserves the magma present from all levels of the stratified reservoir, enabling us to examine the compositional diversity at the moment of eruption. Cumulate mush nodules from Tenerife offer a unique opportunity to develop our understanding of magma genesis, storage and transport, and Plinian eruption dynamics in hot-spot volcanoes. Interstitial melt analyzed for major, trace and Pb isotope analysis show that the magma reservoir contained a range of intercumulus liquids at the moment of eruption, which span the entire alkaline series. Melt is isotopically heterogeneous, spreading along a mixing line between two end members implying interaction of at least two isotopically distinct magmas in the reservoir. Fasnia pumice however, is isotopically homogeneous, indicating the presence of a well-mixed and voluminous supernate magma. Cumulate crystals in contact with melt have more evolved chemistries close to the rim, suggesting an interaction with the felsic magma similar to the pumice. These findings suggest that melt was able to infiltrate all types of the cumulate, distributing its chemical and isotopic signature. Hence either the melt was able to move throughout the magma reservoir, or lumps of cumulate mush were introduced to the well-mixed felsic magma storage where interaction occurred.

Variations in pore and crack fabrics with stress in triaxially deformed sandstone

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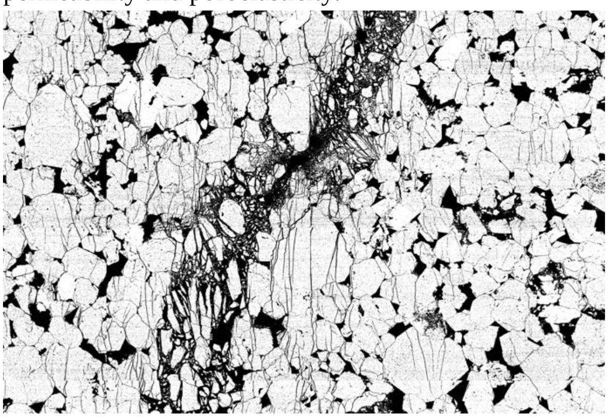
Compressive deformation tests were conducted at a range of stress conditions on a suite of sandstone core plugs to quantify the effect of stress on the resultant pore fabric in the failed rock. Using open source image analysis software, comprehensive datasets of pore and crack fabrics have been produced from thin sections of the deformed samples that can be used to model fluid flow and poroelastic behaviour in faulted rocks.

Our results show that although the peak compressive strength of core plugs was higher at higher effective pressure (up to 30 MPa), all samples failed in a brittle (dilatant) manner, with similar failure plane orientations, and deformation mechanisms of microfracturing followed by grain comminution on the sliding fault surface (Figure).

We stitched mosaics of back-scattered electron (BSE) digital images from polished thin sections taken parallel to the axis of the deformed core plugs (Figure). We used ImageJ and FracPaQ software to quantify lengths, orientations, intensity, density and connectivity of both intergranular and microfracture voids (cracks). Quantitative analysis of experimentally deformed sandstone pore fabrics showed changes to the spatial density and orientation of microfracture porosity as a function of the applied stress conditions. Intergranular porosity also changed with increasing deformation as cataclasis reduced grain size and compaction altered grain boundaries. Macroscopically (mm to cm-scale), these rock samples look identical after failure, and yet their microscopic (micrometre to mm-scale) fabrics reveal significant differences. Changes in pore property distributions, as well as the relative proportions of pore types, generates variations in pore fabric anisotropy of the faulted rock that, in turn, have implications for permeability and poroelasticity.



Overestimation of strains due to multiscale cracking in clayrock

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Clay rocks are considered as potential repositories for high-level radioactive waste in several industrial countries. In the Underground Research Laboratory of Tournemire (France), fractures associated with the desaturation of argillaceous rocks have been observed on gallery fronts (Hédan et al., 2014). Among the critical issues related to the long-term safety assessment of such geological repositories, the study of the so-called excavation damaged zone (EDZ) around the galleries is particularly important. In the laboratory, a centimeter sample of Tournemire clayrock was subjected to a desiccation process in relative humidity and temperature controlled conditions. During desiccation, the sample was filmed by two cameras so that the evolution of fractures (displacement fields, aperture, patterns) could be studied by Digital Image Correlation H^k-DIC (Valle et al., 2015). The strains were quantified at three different scales: whole sample, macroscopic and mesoscopic scales (Fauchille et al., 2016). Then the microstructure of the sample was mapped by a multi millimetre mosaic of SEM images to superimpose strains, fracture apertures and microstructure in high resolution (Fauchille, 2015).

Our results demonstrated that: (i) the mean strains are heterogeneous and depended on the scale investigated; (ii) the difference of strain intensity between the scales is due to the opening and closing of desiccation fractures during desiccation; (iii) the volumetric strain of the sample is overestimated up to 61% compared to the mesoscopic scale if fractures are not considered, and (iv) fractures are also present at the micrometer scale. As a consequence, the presence of fracture questions the strain values calculated by H^k-DIC in a continuous medium at lower scales.

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Measuring magma decompression rates for explosive basaltic eruptions of Kilauea using melt embayments

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The decompression rate of magma as it ascends during volcanic eruptions is an important but poorly constrained parameter that controls many of the processes that influence eruptive behaviour. In this study, we quantify decompression rates for basaltic magmas using volatile diffusion in olivine-hosted melt tubes (embayments) for three contrasting eruptions of Kīlauea volcano, Hawaii. Incomplete exsolution of H2O, CO2, and S from the embayment melts during eruptive ascent creates diffusion profiles that can be measured using microanalytical techniques, and then modeled to infer the average decompression rate. We obtain average rates of ~0.05–0.45 MPa/s for eruptions ranging from Hawaiian style fountains to basaltic subplinian, with the more intense eruptions having higher rates. The ascent timescales for these magmas vary from around ~5 to ~36 min from depths of ~2 to ~4 km, respectively. Decompression-exsolution models based on the embayment data also allow for an estimate of the mass fraction of pre-existing exsolved volatiles within the magma body. In the eruptions studied, this varies from 0.1 to 3.2 wt% but does not appear to be the key control on eruptive intensity. For these eruptions, the observed decompression rates are proportional to independent estimates of mass discharge rate. Although the intensity of eruptions is defined by the discharge rate, based on the currently available dataset of embayment analyses, it does not appear to scale linearly with average decompression rate. Our work demonstrates the utility of the embayment method for providing quantitative constraints on magma ascent during explosive basaltic eruptions.

Deformation mechanisms in plagioclase investigated by HR-EBSD

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Plagioclase is the primary mineral in Earth's lower crust, and hence its mechanical behaviour significantly influences the strength distribution of the lithosphere. This behaviour can be especially dynamic (for instance leading to extreme strain localization), particularly if transitions in deformation mechanism occur. Changes in microstructural characteristics are often interpreted to reflect such changes in the dominant mechanism in exposed, naturally deformed rocks.

We have collected microstructural data from a gabbro that, in a manner similar to previous work, suggests that the dominant deformation mechanism changed with progressive strain. This sample was collected from the Semail Ophiolite in the UAE, and we investigated the microstructural evolution that occurred across a transect of a centimetre-scale shear zone. Deflections of foliation planes indicate that shear strains exceeded 1000%. Our analysis reveals that plagioclase grain size decreases both with increasing shear strain and increasing proportion of second phase minerals. This grain-size reduction is associated with a decrease in the strength of plagioclase crystallographic fabrics. These features are commonly interpreted to indicate a transition from dislocation to diffusion creep.

To further test the hypothesis that these rocks suffered a transition in deformation mechanism, we analyse the substructure within plagioclase crystals using high angular-resolution EBSD (HR-EBSD). With HR-EBSD, we have the ability to measure the density of geometrically necessary dislocations of each dislocation type in plagioclase. 2-D Fourier analysis of maps of dislocation density will be used to assess how the plagioclase substructure evolves with increasing strain and secondary phase content. Additionally, we will quantify the relationship between dislocation density and proximity to grain boundaries. These data sets will allow us to test theoretical predictions concerning the evolution of substructure for a variety of deformation mechanisms and inform us on the reliability of common microstructural indicators.

The Spatio-Temporal Evolution of Rift Magmatism: Insights from Hf in Gardar Magmas

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The Gardar Province of Southern Greenland is the term given to the products of alkaline magmatism associated with intraplate rifting in the Mesoproterozoic. Gardar rocks include two large critical metal deposits (Motzfeldt and Ilímaussaq), a large Ti-V deposit at Isortôq and the Ivigtut cryolite mine. To understand further the sources of heavy REE and Hf in the Gardar, we have analysed the Lu-Hf isotope systematics of several Gardar centres, chosen to represent both early (Motzfeldt, North Motzfeldt, Ivigtut) and late (Ilímaussaq, Østfjordsdal, Narsarsuk, Nunarsuit, Paatusoq) Gardar magmatism and encompassing the geographical extent of the Province from Ivigtut in the West to Paatusoq in the East. The Gardar magmas intruded Archaean crust (Ivigtut), Ketilidian metasediments (Paatusoq) and Ketilidian granitoids (the others).

Age-corrected Hf isotope data show low Hf values that are inconsistent with sourcing from depleted mantle in Gardar times and Early Gardar zircons have significantly lower age-corrected Hf values than those formed in the Late Gardar. Hf signatures in Early Gardar zircons project back to Ketilidian or older mantle extraction ages (> 1.8 Ma). One might interpret such data to indicate that Hf in the Early Gardar zircons was scavenged from the Ketilidian basement with lower Hf ratios than the mantle source. However, primary Gardar melts are unlikely to have contained negligible Hf, such that an unrealistic proportion of assimilated Ketilidian Hf is required. Instead, the low data are consistent with a model whereby subduction of Archaean crust (i.e. very low $^{176}Hf/^{177}Hf$) during the Ketilidian orogeny permeated the subcontinental lithospheric mantle beneath southern Greenland with Archaean Hf. In Gardar times, mantle decompression preferentially accessed this subducted (Archaean) mantle component, providing magmas with anomalously low Hf isotopic ratios. As rifting continued, proportionately more of the primary ‘Gardar’ Hf component was present in the melts. These Hf isotopic data indicate ‘recycling’ of Archaean crust via the mantle in Gardar times.

Water loss and the origin of thick ultramylonites

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Shear zones widen when the shear zone hardens or the host rock weakens. A number of factors can initiate these processes and one of the most important is the movement of water into or out of the shear zone since it weakens rocks and minerals in a number of ways. When water resides in crystals it decreases the strength of Si-O bonds, a process known as hydrolytic weakening. Hydrolytic weakening has been suggested as a major facilitator of strain localization, in line with many studies that found a positive correlation between water content and intensity of deformation. We examine the role of water in the unusually thick ultramylonite of the El Pichao shear zone, northwestern Argentina. We used Fourier Transform Infrared spectroscopy to measure water content in quartz and feldspar comparing ultramylonitic rocks deformed by diffusion creep to mylonites and weakly-deformed rocks deformed by dislocation creep. We found that quartz and feldspar in ultramylonites contained half the amount of water of weakly-deformed rocks, a result contrary to previous studies of water in shear zones. We propose that the thick ultramylonite formed in three stages: (1) localized deformation and recrystallisation caused release of intracrystalline water to grain boundaries and, once a critical grain size was reached, promoted dissolution-precipitation, which gave rise to an ultramylonite, (2) high pressure in the shear zone compared to the surroundings continuously expelled intercrystalline water, gradually drying the grain boundaries and leading to strain hardening (3) water migrated to neighbouring, less-deformed rocks causing hydrolytic weakening, initiating diffusion creep, and repeating the cycle, widening the ultramylonite.

Lithospheric structure of the East African Rift System: mantle controls on rifting, volcanism & plate boundaries

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Investigating the present-day structure of the upper mantle plays a key role in understanding the tectonic evolution of continental rifting. The East African Rift System offers the opportunity to observe rifting at a variety of points through this process, from the formation of new material in the north, through rifting of regions of thick lithosphere, to the transition of the system from continent to ocean.

Surface wave tomography provides images of the variations in seismic velocity through the upper mantle, and, due to the ability to recover structure in areas with, and without, seismic stations is the ideal tool to look at the structure of the whole rift system.

The results from the final velocity models cover the uppermost mantle and are presented as a series of depth slices from 50 – 300 km depth. The most intriguing feature of the models is that, irrespective of the lithospheric thickness, slow shear velocities are observed in the uppermost mantle beneath the rift system; to depths of approximately 75km. Where underlain by fast velocities (typical of thicker lithosphere) it is difficult to explain the slow shallow velocities by temperature variations. Instead, variations in terms of composition, or the presence of volatiles, must be used to explain the velocities. These could either reflect pre-existing structures that lead to preferential localization of the rifting, or could have been generated by the rifting process itself.

The strongest anomalies in the model are, as expected, in regions of current/recent volcanism, and here the lithosphere is modelled as relatively thin. Extremely slow velocities (<4 kms-1) are observed in Afar and the Central Ethiopian Rift, and agree with more detailed local studies. Other significant anomalies are observed in the eastern Democratic Republic of Congo, and at the northern end of Lake Malawi, around the Rungwe Volcanic Province.

Offshore of southeast Africa, the mantle structure appears to delineate features that have a striking correlation with the location of boundaries defined from kinematic studies. As such, it appears that almost all the EARS and adjacent microplates are bounded by structures that can be observed through much of the lithospheric mantle.

Multi-scale velocity structure of an active seismogenic normal fault zone

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The petrophysical characterization of fault zones (e.g., ultrasonic velocities, porosity and fracture intensity of the fault zone rocks) is a relevant topic in reservoir geology (exploration and exploitation) and fault mechanics (for both long-term quasi-static and fast dynamic fault evolution).

Here we characterized the shallow subsurface velocity structure of the active Vado di Corno normal fault zone (Campo Imperatore, Central Apennines, Italy). Based on a detailed structural mapping of the fault footwall block, four main structural units separated by principal fault strands were recognized: (i) cataclastic unit, (ii) breccia unit, (iii) high-strain damage zone, (iv) low-strain damage zone. The single units were systematically sampled along a transect (~ 200 m) orthogonal to the average strike of the fault and characterized in the laboratory in terms of petrophysical properties (i.e., V_p, V_s and He-porosity). The cataclastic and breccia units ($V_p = 4.68\pm0.43$ kms^{-1}, $V_s = 2.68\pm0.24$ kms^{-1}) were significantly "slower" compared to the damage zone units ($V_p = 5.43\pm0.53$ kms^{-1}, $V_s = 3.20\pm0.29$ kms^{-1}). A general negative correlation between ultrasonic velocity and porosity values was reported; moreover measured acoustic anisotropies were related to deformation fabrics (i.e., open fractures, veins) observed at the sample scale.

A V_p - V_s seismic refraction tomography was performed in the field along a profile (~ 90 m) across the fault zone. The tomographic results clearly illuminated fault-bounded rock bodies characterized by different velocities (i.e., elastic properties) and geometries which match with the ones deduced from the structural analysis of the fault zone exposures.

Fracture intensity measurements (both at the sample and outcrop scale) were performed to investigate the scaling relation between laboratory and field measurements. These results were then coupled with ultrasonic velocity vs. confining pressure (0-30 MPa) profiles measured in the laboratory to extrapolate the subsurface velocity structure of the fault zone to larger depths (up to ~ 1 km). Such observations are potentially relevant to better understand the petrophysical evolution and geophysical expression of active fault zones during the seismic cycle and will be integrated in both static and dynamic fault mechanics models.

Thermodynamic modelling of mafic minerals and melt can illuminate lower crustal heterogeneity

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Rocks of mafic composition are important constituents of both oceanic and continental crust. They are involved in significant petrological and tectonic processes that relate to changes in density and water content, and to the generation of melts in subducted oceanic crust or heated lower continental crust. The deep crust is heterogeneous at a range of intermediate scales: the distribution and compositional variation of mafic and other rocks affects the physical properties and melt fertility of the lower crust. Such rocks are inaccessible at the present day but partly preserved in orogenic belts.

Until very recently, appropriate thermodynamic models for complex solid solutions and melts in mafic systems have not been available. This project aims to test the ability of new activity models (Green et al., 2016, J metamorphic Geol., doi: 10.1111/jmg.12211) to predict behaviour and reproduce observed phase compositions (especially pyroxene and amphibole) in (a) the melting interval of hornblende-bearing mafic rocks, and (b) the formation of dense and dry garnet granulites from lower-grade precursors.

We are using samples from existing collections to investigate (1) the formation and partial hydration of the high-temperature metamorphic sole beneath the Oman ophiolite, (2) relationships between garnet granulites and garnet-free metagabbros from the base of the Kohistan arc, northern Pakistan, (3) partial melting, granulite formation, and interactions among lithologies in the Namaqualand Metamorphic Complex, South Africa, and (4) melting promoted by fluid influx at Cone Peak, California, USA.

The controls on the transformation and melting of mafic rocks are sensitive to the presence or absence of sources and sinks for H_2O in their neighbourhood. By considering fluid availability, we are also able to address the potential for metastable behaviour to contribute to heterogeneity in the deep crust.

Long-term mass balance at andesitic volcanoes

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Andesitic stratovolcanoes can exhibit a range of behaviours from no activity to effusive dome building behaviour to highly hazardous explosive eruptions.

Based on over twenty years of observations at the Soufrière Hills Volcano, Montserrat; Christopher et al. (G3, 2015) presented a Magma System Destabilisation Model as a framework for understanding the apparent generation of more SO_2 during activity than the erupted magmatic fluxes of andesitic volcanic systems can account for, known as the ‘excess sulphur’ problem.

A number of key questions arise when evaluating this model. Does the model present any new predictive capability when analysing the results of monitoring efforts during eruptive phases? Are there implications made that we can test geochemically and petrologically? For example, the model suggests that re-amalgamation of long-separated melts and fluids results in periods of unrest. Is this feasible? What textures would we expect in the erupted products? Can we test the ‘age’ of the degassing fluids?

We evaluate whether the model makes reasonable predictions about the long term (10^3 – 10^5 yrs) mass balances of other andesitic volcanic systems, with particular focus on Popocatépetl, Mexico; Santorini, Greece; and La Soufrière, St Vincent. By combining volatile emission data for eruptive and non-eruptive periods with stratigraphic and cultural records of activity, we provide order of magnitude estimates for the volatile fluxes at these volcanoes over long timescales. Fluid saturation and volatile partitioning models are then used to estimate the magmatic budgets required to account for the ‘excess sulphur’ and assess whether these are reasonable.

Dyke tip processes and large-scale deformation: implications for geodetic modelling

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There are numerous examples of geodetic measurements associated with the emplacement of dykes in active volcanic areas. Common practise when modelling such geodetic measurements assume that (1) dykes propagate solely as tensile fractures and (2) the host deforms elastically. However, field observations, experimental and theoretically studies have shown that the fracture process zone ahead of a magmatic intrusion involves both tensile and shear failure of the host. Shear failure at the scale of the process zone may result from pushing of the dyke tip ahead rather than lateral opening through the host (for ascendant vertical dykes), and may have a significant impact on the overall surface deformation.

In this contribution, we show that dyke tip processes should not be neglected when interpreting geodetic measurements. We performed two series of laboratory models of dyke emplacement, during which we monitored surface deformation using a high-resolution and high-precision photogrammetry setup. In the first series, a fluid was injected into elastic gelatine and produced a dyke that propagated as tensile fracture; the resulting surface deformation was comparable with the predictions of the elastic Okada model, i.e. an elongated topographic trough above the dyke apex, surrounded by two uplifted zones. Conversely in the second series, a fluid was injected in cohesive silica flour and produced a dyke that propagated as viscous indenter; the resulting surface deformation was only uplift.

The first-order differences between the two series of models show that local tip processes do control large-scale deformation induced by propagating dykes, and therefore surface deformation patterns. Our results question the systematic use of tensile elastic fracture models to interpret geodetic measurements associated with dyke emplacement. Finally, our results show that a relevant interpretation of geodetic measurements requires a proper physical understanding of dyke propagation mechanisms.

Quantifying grain boundary sliding during pressure solution

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Strongly deformed rocks from an Alpine extensional shear zone provide an opportunity to quantify the effects of grain boundary sliding on inherited crystallographic preferred orientation (CPO) domains.

Originally Ca-rich plagioclase from a gabbroic protolith has been metamorphosed at greenschist facies via epitaxial nucleation, producing a fine-grained (~10-50 μm) matrix of albite grains. Electron backscatter diffraction (EBSD) reveals the matrix grains preserve distinct CPO domains. These are thought to be inherited from mm-to-cm scale parent grains, as each domain has a unique orientation in which common slip systems in plagioclase are not aligned with the kinematic reference frame, as would be expected to occur during dislocation creep. Besides this, dislocation creep is not expected to be active in plagioclase at greenschist facies.

Subsequent deformation in the presence of an aqueous fluid has led to the readjustment of the matrix albite by pressure solution. This is recorded on the thin section scale by the overall shape of the CPO domains, which are now aligned subparallel to foliation. Diffusion accommodated strain requires grain rotations and grain boundary sliding (GBS) to prevent voids from opening during deformation. Microstructural indicators of GBS can include the weakening of a pre-existing CPO and associated higher angle peak in a neighbour-pair misorientation angle distribution, the presence of quadruple junctions (due to neighbour switching), phase mixing and a strong shape preferred orientation – all of which are present in our samples. Matrix albite grains are elongate rather than equant which is not expected during diffusion creep (although see abstract by J Wheeler). A protected albite CPO domain shows we can assume that grains within domains shared very low misorientations prior to deformation, and so we can begin to quantify to what extent grain rotations and GBS have modified the matrix, and how grains from neighbouring domains have interacted whilst retaining a signature of their original orientation, despite significant relative readjustment during deformation.

Constraints on subduction zone hydration from guided wave observations from three Pacific subduction zones

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Subduction zone guided waves are sensitive to fine scale low velocity structure in the subducting plate, which is not well resolved by other established seismic imaging methods. The low velocity structure of subducting slabs is thought to be primarily related to the hydration of the subducting lithosphere. Studying subduction zone guided waves arrivals can therefore provide new insights into the hydrated structure of subducted slabs, helping to understand the role of fluids in generating Wadati-Benioff zone (WBZ) seismicity, and quantifying the amount of water delivered to the mantle through subduction, as well as revealing the depth to which fluids are delivered.

We present guided wave observations and analysis from three subduction zones in the Pacific rim where different ages of oceanic lithosphere are being subducted. Results are presented from the Alaskan-Aleutian, Northern Chile, and Northern Japan subduction zones. Certain features of the low velocity structure, such as a low velocity layer (LVL) at the top of the slab that persists to at least 200 km, and low velocity normal faults in the subducted lithospheric mantle, appear to be common in several subduction zone settings.

There are however significant variations in the thickness of the LVL, and character of hydrated faults, suggesting significant variations in the hydration of the subducting lithosphere. The LVL is interpreted as metastable oceanic crust, and appears to be thicker in older subducted slabs (e.g. 8 km thick in Northern Japan), than in the younger crust subducted slabs (e.g. 1-2 km beneath South America). A much thicker LVL is seen beneath Alaska due to the subduction thickened oceanic crust. The lithospheric mantle also appears to be more highly hydrated in the older subducting lithosphere. Coupled with the thicker WBZ seen in the older subducting material, this suggests that older subducting material is able to carry more water to the deeper mantle.

Fluid driven fracture mechanics in highly anisotropic shale: a laboratory study with application to hydraulic fracturing

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Significant unconventional hydrocarbon resources have been found in the UK, leading to a recent surge of interest in mudrocks and exploration techniques. Hydraulic fracturing is a common process for extracting hydrocarbon resources from low permeability rock formations. Here, we report data using new laboratory approaches in order to better understand this topical and important issue in applied geosciences. We have derived a controlled laboratory method to develop a permeable network via tensile fracture generation using pore fluid overpressure. Using Acoustic Emission (AE) location (the laboratory analogue to field scale seismic events), we assess the fluid driven mechanical fracture process and its dependency upon rock permeability, the overpressure generating the fracture set, and confining pressure (representing burial depth). In addition, new links between these data and the inherent anisotropy of the shale samples are presented.

To conduct this study we have developed a new technique using steel guides to pressurize a section of borehole approximately 20 mm long and 12.5 mm in diameter, drilled within a sample core of 90mm length and 40mm diameter. Unlike previous designs this allows the pore fluid to contact the rock directly, and to generate micro tensile fractures from the inside of the sample. An array of 12 AE sensors is used to record and map the nucleation and development of the micro-fracture network. We apply different stress environments to modify the inherent anisotropy, and assess whether these environmental parameters influence geomechanical properties that are of importance for the ‘frackability’ of the rock and the fracture pattern (itself linked to permeability). Our data suggest that the effect of inherent anisotropy in the shale is a key parameter on the subsequent fracture orientation, and is independent of confining and fluid pressure. Elastic wave velocity measurements indicate a high anisotropy of the shale with values around 50%. Compressive and tensile strength tests also show a significant strength anisotropy of the rock, which has been found to also hold for the fracturing via pressurized fluids.

The injection of volcanic dust into the mesosphere by electrostatic levitation

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Energetic plumes associated with the largest volcanic eruptions can reach the top of the stratosphere (50 km) and have significant implications for global climate [1]. Volcanic particulates are delivered to high altitude through convection, which is resisted by temperature inversion within the stratosphere, preventing their transport to the mesosphere. Volcanic plumes, however, are often associated with large electrical fields, giving rise to volcanic lightning, and can develop net charges through charge separation into gas [2]. Electrostatic interactions between a plume and charged fine-dust particles will result in non-thermal forces that will influence dynamic behaviour.

Electrostatic levitation of charged dust particles occurs on atmosphere-less bodies such as the Moon where dust can be levitated to many kilometres above the surface [3]. A model of the dynamic behaviour of charged dust grains over large volcanic columns with significant net charges (-10C), including distributed plume charge and the effects of gas drag, is presented. The results suggest that 100 nm particles reach 67 km in ~2.5 hr, 10 nm particles reach 129 km in ~2.7 hr and 1 nm particles can reach 240 km altitude. Maximal altitude is, however, highly dependent on prevailing mesospheric wind speed. High velocity winds at altitudes >100 km are a significant barrier to levitated dust, but allow provide long period entrainment.

Injection of electrostatically levitated volcanic dust into the mesosphere may explain a major issue in ionospheric physics. The D-ledge of the ionosphere has a net positive charge owing adsorption of electrons by cosmic dust, however, the flux of extraterrestrial dust should produce a significantly more positive charge than observed [4]. The injection of negatively charged volcanic nanoparticles may explain this disparity. Observations that the 1991 Pinatubo eruption caused disturbances in the ionosphere are consistent with the addition negatively charged volcanic particles [5].

Volcanic particulates added to the mesosphere may act as nuclei for notilucent clouds formed at 75-85 km altitude. Although notilucent clouds were first recognised after the 1883 Krakatau eruption, they have until now been considered only to nucleate on meteoric dust [6]. Large volcanic eruptions may, therefore, have climatic effects that extend farther than previously considered.

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Assessing the mobility of crystals and mush cohesion in magma chambers

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The evolution of magma chambers at all scales is fundamentally driven by cooling, which results in complex fluid dynamic processes during solidification. In this study we consider the various forces that may act on crystals growing within magma chambers and assess whether they may cause mobilisation of the crystals.

We have performed experiments by driving thermal convection in a tank filled with fluid and a particle pile composed of two types of inert, spherical particles of the same size but different densities. These show different styles of mobilisation due to the forces exerted on the particles by the convecting fluid. We mixed the two particles types to create a range of density profiles. The different piles experience different mobilisation behaviour depending on the mixing regime, mixing ratios (ratio of light to heavy particles), the density contrast between fluid and particle and the temperature contrast driving convection. The degree of mobilization increases as more low density particles are brought closer to the interface. When light particles are overlain by heavy particles no mobilisation is observed until the thickness of the high-density layer is sufficiently thin. When the dense “crust” is less than this critical thickness, the light particles can break through and erupt over the dense layer.

We also studied the effects of particle cohesion in the mush in experiments measuring the viscosity of ice-sucrose suspensions in a stirred pot. In these suspensions ice sinters together and the force required to break apart networks is measured. Sintering is a function of the average crystal size through time and the time during which crystals are in contact.

Our results can be applied to cumulates and porphyritic lavas.

Global trends in volcanic arc sulfur outgassing

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Over the past decade an enormous quantity of volcanic sulfur outgassing data has been acquired for a range of tectonic settings worldwide. The data show that SO_2 emissions from volcanoes are highly variable and persistent degassing between eruptions is as important as eruptive emissions for the global volcanic sulfur outgassing budget. Some tectonic settings, or in particular arcs, tend to be more prolific outgassers than others. Despite the abundance of volcanic outgassing data, we understand little about the controls on sulfur cycling between our surface environment and the Earth's interior. Sulfide and sulfate in subducting altered oceanic crust are responsible for much of the sulfur outgassing from arcs. The metamorphic reactions responsible for such devolatization reactions are only just beginning to be understood, with anhydrite and pyrite breakdown occurring at different temperatures and depths (Tomkins and Evans, 2015). In this study, global volcanic sulfur gas fluxes and isotopic composition data are compiled and compared to the structure and composition of the downgoing slab (from IODP core data offshore of a number of subduction zones worldwide); the inferred thermal structures of subducting slabs; and a wide range of other geochemical data to establish the primary controls on volcanic outgassing flux (magma flux, slab parameters, subducted input, or contamination by the overriding crust). We find that arc volcanoes vary widely in their gas fluxes, with the Central American Arc and Indonesian Arc volcanoes perhaps emitting the largest amounts of sulfur-rich gases, and that downgoing slab parameters may exert a first-order control on the levels of sulfur-rich gases emitted from an arc.

Tomkins AG, Evans KA. Separate zones of sulfate and sulfide release from subducted mafic oceanic crust. Earth and Planetary Science Letters. 2015 Oct 15;428:73-83.

The enigmatic magma plumbing system of Askja volcano (Iceland)

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Askja is an active volcano in the Northern Volcanic Zone of Iceland, lying within a spreading segment of the mid-Atlantic ridge. Its eruptions can be very powerful such as the 1875 VEI-5 caldera-forming Plinian event and a better understanding of its complex magmatic system is needed to forecast future episodes.

Subsidence centred on the main caldera has been recorded using different geodetic measurements since at least 1983. It has been postulated that rifting extension and shallow magmatic processes, e.g. outflow and/or crystallisation, could be responsible for this subsidence. All models using surface deformation data agree that there is at least one shallow magmatic source at 3-3.5 km depth, undergoing volumetric changes at a rate of approximately -0.0014 to -0.0021 $km^3\ yr^{-1}$. However, recent results from seismic tomography revealed the presence of two melt storage regions at about 6 and 10 km depth.

Microgravity data have been acquired at Askja since 1988. A residual gravity decrease (mass loss) was observed during 1988-2003 and a residual gravity increase (mass gain) from 2007 to 2009. These changes, which did not affect the subsidence, were interpreted as being due to magma drainage and magma intrusion, respectively.

Our aim is to constrain the potential physical processes that could cause the changes measured in both surface deformation and microgravity. In particular, we aim to constrain the nature of any fluid involved by inferring its density.

Here, we present an InSAR and microgravity time-series analysis extended to summer 2016. In our study, we carefully quantify the uncertainty associated with the residual gravity changes using a newly developed approach.

Plume-ridge interactions and the transfer of volatiles at the Galápagos Spreading Centre

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Sea floor bathymetry and basalt geochemistry from 30% of the global mid-ocean ridge system is affected by high-temperature, mantle plume material. The Galápagos is an archetypal example of plume-ridge interaction and one of the world's most active volcanic regions. Isotopic data from previous studies has shown that basalts erupted along the adjacent Galápagos Spreading Centre (GSC) contain a greater contribution of enriched material from the Galápagos plume than basalts erupted from islands in the north of the archipelago (closer to the axis of plume upwelling). This contradicts previous models of plume-ridge interaction which envisage lateral spreading of plume material along the base of the thermal lithosphere, resulting in progressive dilution of plume material with distance from the plume stem. Recent studies have instead suggested that plume-ridge connection is maintained by deep-channelised flow of volatile-rich melts beneath the anhydrous peridotite solidus. This model is based on data from the distal Western GSC and accurate volatile data from the more proximal Eastern GSC is required to confirm this hypothesis.

In this study we will couple SIMS analysis of volatile elements (H, F, Cl) with LA-ICP-MS analysis of trace elements in samples from the Eastern GSC and create inversion models to determine the depth of magma generation and flow in the mantle. Previous geochemical investigations of the Galápagos archipelago have indicated that at least four isotopically distinct mantle reservoirs intrinsic to the mantle plume contribute to the composition of basalts erupted across the archipelago. There is currently no constraint on which of these mantle reservoirs are volatile-rich. However, isotopic data indicates that different mantle components contribute to melting beneath different sections of the ridge. Therefore, by combining volatile data from the Eastern GSC with data from the Western GSC, it should be possible to determine the nature of the material being transferred from the plume stem to the adjacent spreading centre (i.e. primordial mantle or recycled oceanic crust). This will be achieved using Principal Component Analysis to determine whether the volatile contents correlate with a particular isotopic mantle source.

Characteristics of seismicity in Eritrea (2011-2012): Implication for rifting dynamics

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Eritrea hosts the final stages of on-land East-African rifting, yet questions remain about how rifting transits from the Afar Depression to the Red Sea. In this study we use data from recent deployments of 6 broadband seismometers in Eritrea together with deployments in Ethiopia to locate seismicity and determine the current focus of strain. Over 1000 events have been located with local magnitudes 0.7-5.0. A significant period of seismicity was observed on 1 July 2012 around Nabro volcano and is associated with the biggest event of m_L 5 preceded by 33 events in the previous two days. It may be related to magma movement below Nabro. Other significant seismicity was observed on 25 December 2011 and is located within Ethiopia. Five clusters of events: Massawa, Zula, Bada, Alid and Nabro within the mainland of Eritrea have been identified. We use double difference relocations to improve accuracy and show two main orientations of seismicity, one oriented NW-SE in the Bada-Alid axis along the northwestern boundary of the Danakil microplate and the other NE-SW, following the trend of the Biddu-Nabro volcanic complex. The new estimates of seismicity demarcate the boundary between the Nubian, Somalian, and Danakil Microplate and suggest that the Danakil microplate may be broken in two along the Biddu-Nabro Volcanic complex. We also estimate b-values for the different clusters of events and show that close to the major border faults near Massawa, average b-values are lower (0.9) than that found near the volcanic centres (1.2 – Biddu-Nabro). This may indicate that the stress is less in the volcanic regions and the seismicity is due to movement of magma fluids and strain is accommodated by the injection of magma. In contrast the earthquakes around Massawa occur in relatively stronger rocks suggesting strain may be accommodated by movement on larger faults. The focal mechanism solutions indicate 7 reverse faults, one strike slip and one normal fault.

Evolution of extensional faulting and its flexural isostatic response during ocean-continent transition formation at rifted margins

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Extensional fault geometry and the flexural isostatic response to extensional faulting during rifted margins formation are controversial. During the formation of magma-poor rifted margins, lithosphere stretching and thinning progressively evolves through continental rifting, crustal necking, hyper-extension, mantle exhumation and eventual magmatic sea-floor spreading (Mohn et al., 2012). Initially lithosphere extensional faulting is achieved by steep normal faults rheologically decoupled from distributed mantle deformation but, as crustal thickness decreases, extensional faults couple into the mantle.

We examine extensional faulting at slow spreading ocean ridges, the final end-member of magma-poor rifted continental margins, in order to better understand the evolution of extensional faulting. At slow spreading ocean ridges, it has been shown that large extensional faults lead to flexural isostatic rotation of exhumed footwall (Buck, 1988), producing low fault surface emergence angle (15°-20°) and sub-horizontal exhumed fault footwall. This same process (known as the rolling-hinge model) can be used to explain the formation of extensional allochthon blocks at magma-poor rifted margins and requires a very low flexural strength (Te < 1km) consistent with findings at slow spreading ocean ridges (Smith et al., 2008; Schouten et al., 2010).

We use a kinematic forward model to examine the evolution of fault geometry and its flexural isostatic response during the formation of the ocean-continent transition at magma-poor rifted margins. In particular we study how this response controls the structural development of hyper-extended crust, exhumed mantle and the resulting sedimentary record.

We investigate the dimensions of extensional allochthon blocks located in the distal part of hyper-extended continental crust using both field observation and forward modelling. Examination of the Bardella allochthon block (Alpine Tethyan margin) suggests that its length in the dip sense is less than approximately 2-3 km, consistent with our modelling results.

One of many remaining questions concerns extensional fault geometry within lower-plate distal hyper-extended continental crust; are the seismically observed extensional fault blocks in this region allochthons underlain by extensional detachments or are their faults linked into distributed mantle deformation below?

Global surface ground deformation monitoring using Sentinel-1 mission

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For over two decades, radar interferometry has been a successful tool for measuring ground deformation. However, until now, satellite radar data have been acquired on an ad-hoc basis. The Sentinel-1 mission, operational since October 2014, is the first to systematically acquire these data on a global scale. Moreover, the default mode of radar acquisition for Sentinel-1 is the new Terrain Observation by Progressive Scans (TOPS) mode. Processing these data requires a major shift in methodology in comparison to traditional approaches. We have developed a new re-engineered and adapted InSAR time series processing approach, which efficiently processes the data from this new type of SAR constellation, with the goal to deliver ground deformation products with the highest possible precision. A core component of this approach is a newly-developed, almost unsupervised system that integrates methods to obtain time-dependent surface deformation estimates. Over the next 1-2 years, the resulting ground velocity maps should meet the desired accuracy of 1 mm/yr/100 km to measure strain-rates (10 nanostrain/yr) at a comparable level to existing sparse regional GPS networks.

In this communication we present LiCSAR, a processing chain developed to achieve seamless stack/time series products (linear velocity and displacement time series) using Sentinel-1 TOPS SAR images. LiCSAR is created to address particular aspects of Sentinel-1 data, which differ from traditional stripmap mode interferometry. Here we describe the different steps we have adopted to solve various issues, including; how to generate consistent image SAR stack of images for interferometry based on heterogeneous Sentinel-1 data slice products, how to coregister TOPS SAR image stacks containing 10s to 100s of images acquired over many years and how to efficiently ingest and process newly acquired data. We illustrate some of the special features of our processing system with new results for selected target regions.

The Arran Volcanic Formation: eruption and collapse of a well-preserved Scottish caldera.

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The Central Arran Igneous Complex (CAIC) contains the best preserved caldera within the British Palaeogene Igneous Province. The pyroclastic and sedimentary rocks that make up the caldera-fill succession (the Arran Volcanic Formation) display a near-complete record of explosive volcanism and intra-caldera processes throughout a significant part of the volcano's history.

At least six distinctive pyroclastic units are preserved, but it is likely that others have been buried or lost to erosion. The oldest of these is a thick unit of massive lapilli tuffs (the Allt Ruadh Member), which records highly explosive volcanism, and is thought to be related to a major phase of caldera subsidence. This was followed by eruption of a large volume, rhyolitic, lapilli-poor lava-like ignimbrite with a thickness of up to 100 m. This is thought to represent a series of less explosive, hot, low-fountaining 'boil-over' eruptions. There are remnants of this ignimbrite preserved outside the caldera, suggesting it may have had a very large areal extent. The other units are more compositionally and texturally heterogeneous, in some places containing lithic fragments of other ignimbrites, and often showing variably-welded to lava-like features.

The pyroclastic units are separated by erosional surfaces, many of which preserve extreme palaeo-topography (i.e. hills, cliffs, canyons, etc.). This suggests long periods of volcanic quiescence during which intra-caldera erosional processes were dominant, possibly accompanied by piecemeal caldera subsidence. Overlying the Allt Ruadh Member are breccias and conglomerates containing clasts of mostly country-rock material. This suggests collapse of the caldera walls following the initial period of subsidence.

Canyon-filling conglomerates on the slopes of Binnein na h-Uaimh contain rounded boulders of schist unlike anything now seen in southern or central Arran. We suggest that these were deposited by a large river system that flowed into the caldera late in its evolution.

Zircon U-Pb dating of pre-caldera and post-caldera granites within the CAIC, as well as from some of the eruptive units, is in progress and will help to constrain timescales of volcanism, erosion, and caldera collapse.

Seismic velocity structure of volcanic rift zones in Iceland

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The structure of oceanic spreading centres and subsurface melt distribution within newly formed crust is largely understood from marine seismic experiments. In Iceland, however, sub-aerial rift elevation allows both accurate surface mapping and the installation of large broadband seismic arrays. We present a study using ambient noise Rayleigh wave tomography to image the volcanic spreading centres across Iceland. Our high resolution model images a continuous band of low seismic velocities, paralleling all three segments of the branched rift in Iceland. The upper 10 km contains strong velocity variations, with velocities 0.5 kms^{-1} faster in the older non-volcanically active regions compared to the active rifts. Slow velocities correlate very closely with geological surface mapping, with contours of the anomalies paralleling the edges of the neo-volcanic zones. The low velocity band extends to the full width of the neo-volcanic zones, demonstrating a significant contrast with the narrow (8 km wide) magmatic zone seen at fast spreading ridges, where the rate of melt supply is similarly high. Within the seismically slow rift band, the lowest velocity cores of the anomaly occur above the centre of the mantle plume under the Vatnajökull icecap, and in the Eastern Volcanic Zone under the central volcano Katla. This suggests localisation of melt accumulation at these specific volcanic centres, demonstrating variability in melt supply into the shallow crust along the rift axis. Shear velocity inversions with depth show that the strongest velocity contrasts are seen in the upper 8 km, and show a slight depression in the shear velocity through the mid crust (10–20 km) in the rifts. Our model also shows less intensity to the slow rift anomaly in the Western Volcanic Zone, supporting the notion that rift activity here is decreasing as the ridge jumps to the Eastern Volcanic Zone.

Seismic velocity structure of Corbetti, Ethiopia

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The Main Ethiopian Rift (MER) links the Afar depression to the north with the East African rift system to the south and caused by extension between Somalia and Nubia at a rate of 6.1 mm yr^{-1}. Corbetti, a volcano in the South of the MER consists of a caldera ~15 km across formed ~200,000 years ago and two resurgent domes within the caldera where more recent volcanic and fumarolic activity is focused. Corbetti is currently one of the fastest deforming volcanoes in the world, having uplifted 0.5 m since 2009. Repeated microgravity surveys suggest that the uplift must be caused by an injection of melt into a shallow magma body, but the depth of this body is currently unconstrained. More half a million people live within 10 km of Corbetti, so constraining the deep structure and current activity is important in assessing the hazard the volcano poses.

Since February 2016 a seismic network consisting of 13 instruments has been deployed around Corbetti as part of the multi-institute RiftVolc project. We use the first 8 months of data to constrain seismic velocity structure and focal mechanisms of the volcano. We use an automatic earthquake detector and locator to image the seismicity at Corbetti. We manually refine the travel time picks and use the polarities to constrain focal mechanisms within the caldera. The accurate travel time picks are used to image the velocity structure beneath the volcano using local earthquake tomography. This can be used to update elastic and rheological models of the volcanoes subsurface and improve magma volume estimates.

The 2016 Amatrice-Vettore Earthquakes: linked faults, multiple earthquakes, and repeated rupture

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The Amatrice-Vettore Earthquake sequence ruptured in three separate main shocks on the 24th August (M_w 6.2), 26th Oct (M 6.0), and the largest on the 30th Oct (M 6.6). Sequences of earthquakes of similar or larger magnitudes are common in the historical catalogue in central Italy. Here we report on the complicated nature of this sequence using multiple techniques and observations at a range of spatial and temporal scales.

The first earthquake ruptured across two faults systems thought previously to be separate, even independent, structures – the Laga and Vettore faults. Two months later, the second event occurred along the northern end of the Vettore fault, which did not fail in the previous event. Based on radar interferometry (InSAR) and body wave seismology, both of these events ruptured shallow and long patches with ~20 cm of slip observed along portions of the ruptures at the surface. The largest earthquake shortly followed, and preliminary InSAR models suggest that the deeper portion of the Vettore fault accommodated significant slip but propagated to the surface along the same patches that broke in the previous two events, with greater than 1.5 m of displacement measured in places.

We will show preliminary results from satellite radar and field observations (including extensive laser scanning and mapping of the ruptures), and discuss these observations in the context of how the sequence evolved in time and space. We highlight the important observation of surface rupture along the same >6 km segment in the first and last event, and what this implies for the preservation of earthquake sequences in the geological record. These events are critical for understanding how faults form hard links and how the disconnected nature of faults in central Italy lead to sequences of events, rather than a single larger-magnitude earthquake.

Synchronous intraplate volcanism on the African and South American conjugate margins: coincidence?

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Alkaline rocks dominate Cenozoic volcanism in Northeast Brazil (ca. 1-52 Ma), and represent the only large-scale occurrence of volcanic rocks for the period along the entire eastern passive margin of South America. The Cameroon line in West Africa is also formed by alkaline volcanism, and likewise is the only large-scale occurrence of volcanic rocks along the western passive margin of Africa for the same period. The volcanic rocks from the two areas are geochemically similar and show a precise geometric correlation, even though their onset came around 40 m.y. after the two continents broke apart. They follow the failed rift of the Benue trough on the African side and its small extension in Northeast Brazil, on the other side, but do not match the rifts precisely, being somewhat offset. Both also straddle continental and oceanic lithosphere, and like most intraplate volcanism, seem to have sublithospheric origins and, in this case, follow similar lithospheric controls somehow connected to continental breakup but not coeval with it. The contemporaneous outbreak of apparently identical magmatism on these conjugate margins ca. 40 m.y. after continental separation is unlikely to be purely coincidence and challenges our current ideas about intraplate volcanism. Nonetheless, the issue has attracted very little attention. This project aims to rectify this in the hope that it will shed light on the origin of these enigmatic magmatic provinces.

Timescales of Magma Storage and Transport in the Krafla Volcanic System.

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The Krafla volcanic system has experienced a number of basaltic fissure eruptions during the Holocene, the most recent being the 1975 – 1984 series. These eruptions brought up basaltic magma containing a small proportion of macrocrysts and gabbroic clots containing plagioclase, olivine and clinopyroxene. This eruption series was one of the first to be closely monitored by seismic and geodetic techniques, and these studies' observations have provided estimates of magma chamber depth to be roughly 3-4km under the Krafla caldera [1, 2].

Samples from the 1984 eruption have been collected and characterised by EPMA and SEM. We have collected major element profiles across a number of zone boundaries of plagioclase, olivine and clinopyroxene macrocrysts. These will be modelled using both finite difference (DiPrA) and finite element (FEniCS) diffusion modelling techniques to constrain timescales of magma storage in this system. We use the textural relationships of zones in different phases to constrain the relative timings of growth of these zones. This can then be used to compare the respective timescales obtained from different phases, and assess the accuracy of the chronometers. We also use a new parameterisation of the clinopyroxene-liquid barometry to constrain the depths of this crystal storage [3]. This barometry is performed on different growth zones within the macrocrysts by selecting potential melts that would be in equilibrium with each zone from a large database of Icelandic melt compositions. In addition we will apply OPAM barometry using the glass composition of crystal-poor samples to help further constrain the pressure of the final growth phase. Preliminary results give timescales of storage in the final carrier liquid of between 20 and 50 days, and pressures of roughly 4kbar.

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Seismically Imaging Melt

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Volcanism at the surface is driven by the partial melting of rocks in the upper mantle and subsequent buoyancy driven melt ascent to the surface. However, melt follows complex pathways and can pond at many depths before eruption. Additionally, the presence of melt in the mantle can affect the strength of rocks and thus effects mantle dynamics in tectonically active regions. If we are to understand the processes which form the crust, drive tectonic plates and give rise to volcanoes we must understand the mechanisms by which melt is stored and transported. Seismology is often used to try and image partial melt beneath volcanic regions, where low seismic velocities and strong seismic anisotropy are often interpreted as being caused by the presence of partial melt, yet interpretations of these anomalies remain qualitative and the details of melt storage are poorly constrained. Using numerical models we show the sensitivity of different seismic phases commonly measured in volcanic settings to the presence of partial melt. We show that seismic velocities are more sensitive to the shape than the amount of melt and that seismic anisotropy is a more useful tool than absolute velocities in understanding melt storage. We apply this new understanding to invert seismic velocities and anisotropy beneath the Main Ethiopian and Red Sea rifts in Ethiopia and place constraints on the likely melt geometries and amounts present in the mantle. We show that vertically aligned melt must be present beneath the MER compared to horizontal melt beneath Afar supporting ideas of strong shear-derived segregation of melt in the narrow MER compared to that observed beneath the Afar Depression.

Size effects in olivine: Reconciling 40 years of study into plasticity near the brittle-ductile transition

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The depth of the brittle-ductile transition zone in Earth's lithosphere and the strength of rocks therein are intimately linked to plastic deformation of olivine at low temperatures. Low-temperature plasticity has been investigated in numerous experiments on olivine over the past 40 years, but these studies are contentious because of the wide variability in their results.

We investigated plasticity in olivine using nanoindentation, revealing effects not seen before in geological materials and providing an explanation for the disagreement in published data. First, we indented olivine single crystals with a Berkovich (three-sided pyramidal) indenter tip at room temperature. These tests revealed that the hardness of olivine decreases with indentation depth, and therefore with the size of the plastically deforming region under the indenter tip. Second, we indented olivine crystals with a variety of spherical tips of different radii. These tests also revealed a decrease in hardness with an increase in the size of the plastically deforming region.

This 'indentation size effect' is well known in the materials sciences to arise from the increased density of geometrically necessary dislocations as the volume of deforming material is decreased. Several theoretical treatments have related this effect in indentation of single crystals to a similar size effect in large-scale deformation of polycrystals. In the latter, decreasing grain size leads to increased plastic strength. Motivated by this link, we compiled results from four decades of experiments measuring the plasticity of olivine and revealed that the variability in strength amongst these studies is well explained by variations in the length-scale characterizing each experiment (e.g., grain size). This result suggests that (1) the strength of relatively coarse-grained upper mantle is best characterized by the lowest of published estimates and (2) the strength of olivine will be considerably increased in fine-grained ultramylonites or at small-scale asperities on frictional surfaces.

An experimental investigation of earthquake rupture in granite at hydrothermal temperatures (20-160^{o}C)

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Fault zone frictional behaviour is strongly dependent on many differing factors, particularly those which control the distribution and evolution of asperities and the amount of frictional contact. Indentation hardness is one such parameter. It is well-known that granitic fault rocks under aseismic slip conditions may transition from unstable to stable behaviour at temperatures of 300°C. In addition to this, recent results from high velocity experiments suggest that at moderately elevated initial temperatures (25-300°C), dynamic weakening is less abrupt than at room temperature, and that the weakening velocity increases. Thus moderately elevated temperature may alter rupture behaviour and, in particular, the rupture velocity which is governed by frictional evolution of the sliding surface. In order to investigate this under spontaneous conditions we have systematically varied temperature in the range 20-160^{o}C, and at a fixed normal stress of 100MPa, using Westerly granite blocks (Z_{rms} = 3.2μm) in a direct shear configuration in a Triaxial apparatus. Results show that faults transition from unstable sliding at room temperature, manifested by repetitive fast stick-slip and frictional melt generation, to slow stick slip above 100^{o}C which is accompanied by cataclasis. We interpret this to be due to a reduction in flash weakening efficiency which limits the final rupture velocity, and possibly the nucleation length. This highlights that temperature may play an important role in determining the energy budget of earthquakes and the rupture propagation velocity.

Ocean-Continent Transition Structure of the Pelotas Magma-Rich Continental Margin, South Atlantic

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Rifted continental margins in the southern South Atlantic are magma-rich showing well developed prograding extrusives known as seaward dipping reflectors (SDRs) as well as magmatic intrusions.

Here we examine the magma-rich rifted continental margin of the Pelotas Basin, offshore Brazil. ION line PS1-0110 displays a large package of reflectors with an approximate width of 200km and a varying thickness of 10km to 17km that have previously been interpreted as SDRs. We examine these SDRs to explore if they are composed predominantly of volcanic material or sedimentary material with subsidiary volcanic contribution. We also ask if these SDRs are underlain by thin 'hyper-extended' continental crust or are they deposited on magmatic basement. This information is important in understanding the structure and formation processes of magma-rich continental margins.

We use an integrated quantitative analysis (gravity inversion, RDA and subsidence analysis) with a focus on the joint gravity and seismic inversion in order to investigate the identification of top basement, the seismic velocity and density of the SDR sequence and the density, seismic velocity and thickness of the underlying basement.

Our analysis suggests that the SDRs have densities that are not consistent with purely volcanic or sedimentary composition. Instead, our results suggest a combination of both materials with an increase in the amount of sedimentary material ocean-ward. The underlying basement appears to be denser than average crustal basement at ~3000 kg m^{-3} if the SDR package is assumed to be predominantly sedimentary. However if the overlying SDR package is a mixture of both volcanic and sedimentary material, then the basement density will be less. Further investigation of the proportion of sedimentary and volcanic material in the SDR sequences is required to resolve this.

Evolution of mechanical properties of dome rock across eruptive periods

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Collapse of lava domes can generate pyroclastic flows and debris avalanches that are devastating to areas surrounding volcanic edifices. Numerical modelling is a key method of understanding the mechanisms causing such collapses. Mechanical data (e.g. strength, density, porosity, permeability) are critical to build accurate foundations for these models, yet these data rarely exist in published literature. Models to date commonly adopt “typical” values, thus creating unrealistically high estimates of dome strength.

We investigate the mechanical properties of dome rock from eruptions at Soufrière Hills Volcano in Montserrat (1995-2010) and Mount Unzen in Japan (1990-1995). We employ a combination of in-field Schmidt hammer and laboratory compression testing, finding a decrease in strength over time during the recent Soufrière Hills eruptive period. Particularly from rocks thought to be from the later period of the eruption, we find a decrease in in-situ strength estimates that correlate to a 51% decrease in uniaxial compressive strength (UCS). Density measurements also suggest an average decrease of 14%. This makes it clear that adopting an average value for the entire eruption would incorrectly estimate modelled dome strength.

In contrast we find very consistent mechanical properties of the dome rock at Mount Unzen (although access was limited, so the tested material may not cover the full spectrum of erupted products). For samples dating from 1991 and 1995, correlating the Schmidt hammer data to estimate UCS values suggests only a 7% variation in UCS, which corresponds to the natural variation expected between samples.

We supplement the mechanical testing with additional data regarding density, porosity and permeability and draw the results together to describe a conceptual evolution of the volcanic system in each case.

Holuhraun 2014-2015: Geochemical constraints on magma storage and transport during a major volcano-tectonic episode

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The 2014-2015 Holuhraun eruption on the Bárðarbunga volcanic system, central Iceland, presents a unique opportunity to link petrological and geochemical data with geophysical observations during a major rifting episode. We present major and trace element compositions from 62 whole-rock samples collected over the course of the eruption, alongside major, trace and volatile elements in vitreous melt inclusions and glasses from a subset of 10 samples.

Holuhraun whole-rock compositions are remarkably homogeneous, indicative of efficient mixing and homogenization within the magmatic system. The diversity of trace element ratios such as La/Yb in the melt inclusions reveals that the magma evolved via concurrent mixing and crystallization of diverse primary melts in the mid-crust.

Using olivine-plagioclase-augite-melt (OPAM) barometry we calculate melt inclusion equilibration pressures between 4.5 and 0.7 kbar. The carrier melt equilibrated at 2.1±0.7 kbar, which is within error of pressure estimates derived from clinopyroxene-liquid barometry and the depths of earthquakes between Bárðarbunga and the eruption site in the days preceding eruption onset. Diffusion chronometry reveals minimum residence times of 0.1-6.7 days for melt inclusion-bearing macrocrysts in the Holuhraun melt. We also calculate magma ascent rates of 0.24-0.28 ms^{-1}.

Our data are consistent with lateral magma transport from Bárðarbunga to the eruption site in a shallow- to mid-crustal dyke, as has been interpreted from seismic and geodetic datasets. However, in the absence of these geophysical data, the simplest interpretation of the petrological data would be that the eruption was fed via a vertically stacked series of interconnected magma storage reservoirs. We suggest that whole-rock and melt inclusion petrology and geochemistry, combined with diffusion chronometry, may provide a powerful toolkit for the reconstruction of melt transport pathways that will be applicable to fissure eruptions that occurred before the advent of modern geophysical monitoring techniques, both in Iceland and further afield.

Physical properties of felsic melts in the upper crust: implications for the built-up of large explosive eruptions

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The rheological behaviour of magma and residual melt depend on pressure, temperature, composition, water, crystal and bubble content, and the rate of deformation. We investigate the physical properties of magma and residual melt during progressive crystallization of dacitic magma in the upper crust. Variations in residual melt composition and magma crystallinity as function of temperature are obtained from the available experimental datasets and are complemented with Rhyolite MELTS calculations.

We calculate the evolution of density and viscosity during cooling for hydrous magma (> 2 wt.% H_2O) at 200 MPa. Water solubility increases from 6 to 7 wt.% H_2O with decreasing temperature, leading to an overall decrease in density of the residual melt for water saturated magmas. A decrease in density up to 10% is observed in the residual melts for water under-saturated magmas as the result of increasing silica and water contents during cooling and crystallisation. Calculated viscosities increase from $10^{2.3}$ Pa*s to $10^{5.7}$ Pa*s, however, the increase of viscosity is more rapid at lower temperatures for under-saturated magmas. Viscosity decreases, in some cases, before water saturation is reached. The total amount of excess water decreases with decreasing water content, however, the effect of shear thickening or shear thinning in bubble bearing magmas is delayed to lower temperatures for lower initial water contents. This would imply that water under-saturated magma remain mobile at lower temperatures in a shear thickening environment compared to magmas that reach water saturation at higher temperatures.

Crystallising dacitic magmas reach about 50 percent crystallinity at 800° C to 760° C. Until this point, the rheological behaviour of the magma is dominated by the particle suspension. However, once the magma has become a rheologically locked crystal mush, the effect of bubble suspension in magma dominates.

Our results show that the initial amount of water dissolved in magmas plays an important role in controlling the probability of residual melt to be extracted during progressive magma crystallisation.

FracPaQ: a MATLAB™ toolbox for the quantification of fracture patterns

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The patterns of fractures in deformed rocks are rarely uniform or random. Fracture orientations, sizes, shapes and spatial distributions often exhibit some kind of order. In detail, there may be relationships among the different fracture attributes e.g. small fractures dominated by one orientation, larger fractures by another. These relationships are important because the mechanical (e.g. strength, anisotropy) and transport (e.g. fluids, heat) properties of rock depend on these fracture patterns and fracture attributes. This presentation describes an open source toolbox to quantify fracture patterns, including distributions in fracture attributes and their spatial variation.

Software has been developed to quantify fracture patterns from 2-D digital images, such as thin section micrographs, geological maps, outcrop or aerial photographs or satellite images. The toolbox comprises a suite of MATLAB™ scripts based on published quantitative methods for the analysis of fracture attributes: orientations, lengths, intensity, density and connectivity. An estimate of permeability in 2-D is made using a parallel plate model. The software provides an objective and consistent methodology for quantifying fracture patterns and their variations in 2-D across a wide range of length scales.

Our current focus for the application of the software is on quantifying the fracture patterns in and around fault zones. There is a large body of published work on the quantification of relatively simple joint patterns, but fault zones present a bigger, and arguably more important, challenge. The method presented is inherently scale independent, and a key task will be to analyse and integrate quantitative fracture pattern data from micro- to macro-scales. Planned future releases will incorporate multi-scale analyses based on a wavelet method to look for scale transitions, and combining fracture traces from multiple 2-D images to derive the statistically equivalent 3-D fracture pattern.

Micromechanisms of ductile deformation in volcanic materials

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We performed high-temperature (up to 800 °C) triaxial (effective pressure = 40 MPa) constant strain rate deformation experiments on porous andesite in the ductile regime. The micromechanism facilitating compaction is localised cataclastic pore collapse at all temperatures below the glass transition of the amorphous groundmass glass T_g. In this regime, porosity is only reduced within the bands of crushed pores; the host rock porosity remains unchanged. The strength of andesite is a positive function of temperature below the threshold T_g due to thermal expansion driven microcrack closure. At temperatures above T_g, the micromechanism driving compaction switches to distributed viscous flow. This change in deformation mechanism is accompanied by a substantial reduction in strength and a substantial decrease in porosity, the result of widespread viscous pore flattening and closure.

We consider these data relevant for the region of the conduit margin zone (defined here as the wall rock and the magma at to the conduit margin) that precludes brittle failure (depth ≥1 km). To explore the implications of these findings, we use a simple model of heat transfer from a hot magma-filled conduit to the country rock. When the magma remains hot, analogous to high ascent rates, the T_g isotherm can move into the country rock, producing an annulus of country rock that can deform viscously. Conversely, when stagnant magma cools, the T_g isotherm moves into the conduit, quenching the magma and narrowing the viscous core of the conduit. The processes are operative over hours to days and extend to maxima of meters. Our study highlights that small changes in temperature can change the deformation micromechanism, drastically altering the mechanical and hydraulic properties of the magma and adjacent wall rock, with implications for pore pressure augmentation leading to explosive behaviour.

Mechanical and thermal controls on volcano deformation and magma supply

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Ground deformation commonly precedes volcanic eruptions, and results from complex interactions between source processes (such as magma migration and accumulation) and the thermomechanical behaviour of surrounding rock. Geodetic models aimed at constraining source processes consequently require the implementation of realistic mechanical and thermal rock properties. However, most generic models ignore this requirement and employ oversimplified mechanical assumptions without regard for thermal effects. Topographical effects are also commonly neglected. Here we show how spatio-temporal surface deformation and magma reservoir evolution are fundamentally controlled by three-dimensional thermomechanical heterogeneity. Seismic tomography data and heat flux measurements are used to infer material properties, and the effects of topography are also explored. Using the example of GPS-recorded continued inflation at Aira caldera, Japan, we demonstrate that despite on-going eruptions magma is accumulating faster than it can be ejected at the co-located Sakurajima volcano, and the current uplift is approaching the level inferred prior to the deadly 1914 Plinian eruption. Our results from inverse and forward numerical models using the Finite Element method are consistent with petrological constraints and highlight how the location, volume, and rate of magma supply, ~0.014 km^3/yr, are thermomechanically controlled. Magma storage conditions coincide with estimates for the caldera-forming reservoir ~29,000 years ago, and the inferred magma supply rate indicates a ~130-year timeframe to amass enough magma to feed a future 1914-sized eruption. Analysis of the results also allows us to infer the timing and mechanism of magma supply. These new inferences are important for eruption forecasting and risk mitigation, and have significant implications for the interpretations of volcanic deformation worldwide.

Magma mixing in effusive flank eruptions at Popocatépetl volcano (Mexico): A textural and chemical study of pyroxenes.

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Popocatépetl is an active stratovolcano 80km southeast of Mexico City; it has been reshaped by at least five Plinian eruptions in the last 23,000 years with effusive dome-growth, Vulcanian dome-clearing eruptions and effusive flank eruptions in between. Most research on Popocatépetl has focused on explosive eruptions, however, it is important to study effusive eruptions to better understand the transition from one eruptive style to the other. We focus on four young, 2-14ka, effusive flank eruptions. We have analysed pyroxene populations from these lava flows using EPMA and BSE images to gain insight into the recent plumbing system and pre-eruptive processes. Two main populations were identified on the basis of their core composition; Type 1 pyroxenes of an evolved composition, Mg# 63-79, that originate in a shallow evolved magma reservoir, Type 2 pyroxenes have a core of mafic composition, Mg# 74-91, and originate from a more primitive source. Type 1 can be split into Type 1a and 1b, with Type 1a cores associated with apatite. Both Type 1a and 1b cores contain Fe-Ti oxide inclusions but are more abundant in Type 1a cores, and Type 2 cores may be associated with chromium-spinel. All populations show compositional zoning as bands, rims or diffusive fronts, with Mg# values between Type 1 and Type 2, suggesting magma mixing. Mixing is also evident in the large range of compositions and textures present: xenocrystic altered olivine with pyroxene coronae, compositional zoning, symplectite assemblages replacing amphibole and olivine, and various stages of core resorption are all visible. The proportion of mixing was quantified by crystal counting using high-resolution BSE images. The cores of the pyroxene populations represent two distinct magmatic endmembers: an evolved melt of andesitic-dacitic-rhyolitic composition, 59.8–73.0 wt.% SiO2, and a mafic melt of disputed origin, likely a basaltic-andesite or magnesian andesite. This study, provides a detailed characterisation of the magmatic endmembers and confirms that magma mixing is the driving force behind not only explosive eruptions, as is well documented, but also for effusive eruptions on which the literature is sparse. Further quantitative research will elucidate how mixing during effusive events differs to Plinian events.

A systematic study of the rheology and viscoelastic range of gelatine for modelling magma chamber growth

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Analogue modelling is a very useful technique in Earth Sciences, where the processes studied can occur at a wide range of scales and across time periods of a few seconds to thousands or millions of years. Some processes also occur at depth and are obscured from direct observations.

Selection of appropriate analogue materials is of fundamental importance in analogue modelling. Ideally, the material should be scaled geometrically, kinematically and dynamically. However, one common challenge to using analogue models is that there are limitations and simplifications therefore need to be made to model the complex behaviours of the Earth processes.

Gelatine is a viscoelastic material, which means that it can express both viscous and elastic behaviour depending on the extent and timescale of deformation. This range of material behaviour makes gelatine a highly relevant material to be used in the study of formation of large magma intrusions, where it is hypothesised that the initially elastic host rock becomes increasingly plastic or viscous due to the progressive deformation and heating from the magmatic intrusion.

We present results from a series of Young's modulus measurements carried out in cylindrical containers of equal dimensions with volumes of 2, 3 and 4-litres of pig-skin gelatine (260 bloom, 20 mesh, supplied by Gelita UK) with concentrations ranging between 1.0 wt% and 3.5 wt% at a constant temperature of 5^{o}C. These Young's modulus experiments (run continuously over 140 hours) measures the deflection caused by placing a load of known mass and dimensions onto the gelatine surface and how this changes with time due to the evolving elastic properties and increased stiffness of the gelatine. A small portion of the gelatine from each batch was tested in a rheometer using a parallel plate geometry to carry out a series of oscillatory and rotational tests to characterize the rheology of the gelatine at different concentrations and temperatures. Our results show that gelatine's viscoelastic properties can be successfully studied in the laboratory using simple Young's modulus experiments as well as by studying its rheology by using a rheometer, such that the material properties can be tailored to the experimental needs.

Long term residence of subduction-derived halogens in the Earth's ancient lithospheric mantle

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The abundance, distribution and residence time of halogens in the sub-continental lithospheric mantle (SCLM) is virtually unconstrained. Yet, the SCLM is subject to metasomatism, and so may be a significant repository for volatile elements, including halogens, in the mantle. The North Atlantic Craton (NAC) in South Greenland is one such example. The SCLM at the southern boundary of the NAC of South Greenland is interpreted to have undergone metasomatism from fluids emanating from an oceanic plate subducting from the south at ~1.8Ga.

We present novel, combined elemental (F, Cl, and Br) and isotopic (δ^{37}Cl) halogen data for two Late Jurassic ailikites from the NAC, Nigerdlikasik and Pyramidefjeld. These ailikites formed through rift-induced asthenospheric upwelling and melting of overlying metasomatised SCLM. Both ailikites display positively fractionated δ^{37}Cl compositions of +0.80 ± 0.2‰ and +0.54 ± 0.2‰ versus SMOC (standard marine ocean chloride), consistent with recycled material either within the upwelling asthenosphere or the K-rich subduction modified SCLM. The elemental halogen composition of both ailikites (Br/Cl ~0.0048) is inconsistent with an asthenospheric source on account of its remarkably uniform Br/Cl of ~0.0028. Thus, the halogen composition of both ailikites is implied to result from interaction with old subduction-modified K-rich SCLM.

We envisage a scenario in which halogen-enriched fluids were liberated during dehydration of antigorite from serpentinized oceanic peridotite subducting beneath the NAC of South Greenland at ~1.8Ga. These fluids percolated at the base of the SCLM, imparting the supra-subduction signature. Jurassic rifting of the NAC promoted asthenospheric upwelling and low-degree partial melting of this metasome. The halogen-depleted character of the upwelling asthenosphere allowed the SCLM component to dominate the halogen inventory of the ailikite magma. This implies that the SCLM preserves subduction-related halogens; potentially over billion-year timescales, as a consequence of its isolation from mantle convection.

Segmentation, growth and linkage of large, normal faults

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Dubbed the 'longest continuous continental normal fault on Earth', the 100-km Bilila-Mtakataka fault, Malawi, in the immature, amagmatic southern section of the East African Rift System (EARS), provides a fantastic insight into how large, continental normal faults develop and deform. Changes in fault strike and displacement-length profile are used as evidence for the growth, interaction and linkage of isolated faults. Here we use multi-scale satellite (i) SRTM 30m, (ii) Pleiades 1m, (iii) UAV photogrammetric <1m, and fieldwork data to measure geometry and displacement along the fault. The displacement-length profile has several peaks and troughs, suggesting the fault comprises a number of segments. Variations in fault strike are greatest at lithological boundaries or when the fault switches between following and crosscutting older foliation. A case example is the intersection at the Mtuta river, Golomoti, where the northern segment crosscuts and southern follows the strike of the gneissic foliation. A break in the surface trace between these segments suggests two individual, isolated faults; however, displacement-length profiles show skewed distributions characteristic of segment interaction and linkage at depth. Thus, the geomorphology of the Bilila-Mtakataka fault suggests that the segments do not behave independently and most recent earthquake event was either a continuous rupture, which would equate to a M_W8.0 earthquake (Jackson and Blenkinsop, 1997), or a sequence of smaller events closely spaced in time. To further understand how large, continental normal faults develop and deform, this work should be undertaken for other active faults on the EARS. It is also transferable to other extensional environments such as Central Italy, Lake Baikal, Greece, the Gulf of Suez, and Tibet.

Reinterpretation of the tectonics and evolution of the Pernambuco Plateau, Brazil.

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The continental margin from Alagoas to Natal represents arguably the most frontier region for exploration on the Brazillian margin. High quality seismic data was not collected in the region for many decades as it was believed that only a few kilometres of sediment existed, and thus there was no exploration potential.

Here we present the results of work done as part of an IODP virtual site survey. The work has resulted in a total reinterpretation of the basin, finding sediment filled grabens with up to 8km of sediment. Grabens are found to trend N-S, and can be seen in the gravimetric signal. Evidence for the two deepest grabens representing rift jumps is seen, which may imply different age sediments in the different grabens. The basin is also found to contain a sizable salt accumulation, previously uninterpreted due to hard overlying carbonates hampering seismic imaging. This salt can be seen to have been highly mobile in the past, and has developed into Kilometer scale diapirs flanked by classic rollover anticlines.

Furthermore, previous analysis of the basin had implied NE-SW trending grabens based on magnetic interpretation. Our analysis finds that the magnetic signal is dominated by the presence of a large suite of previously unmapped submarine volcanics. The volcanics are clearly seen to postdate rifting, in contrast with drilled basins onshore, and in some places outcrop on the present day seafloor.

In conclusion, our work finds accumulations of salt which extend the limit of salt on the Brazillian margin by around 400 miles to the north, and due to the presence of very deep grabens, salt structures, carbonate build ups and large scale normal faults, shows that potential could exist for the basin to be prospective for hydrocarbons.

Implications of a weak geomagnetic field ~370 million years ago for the effects of whole-mantle convection on long-term geomagnetic variation

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The palaeomagnetic record for the last 600Myr suggests there may be a pattern to geomagnetic field behaviour over the timescale of ~200Myr. Between 170-120Myr the record shows a rapidly reversing, weak field becoming a strong, stable field with a lasting single polarity for ~30 million (the Cretaceous Normal Superchron; CNS)). This transition suggests both a) that geomagnetic field strength and reversal frequency may be coupled and b) that this transition in field behaviour may be evident preceding other two Superchron during this time. Whole-mantle convection operates on these long timescales and its control on heat flow across the core-mantle boundary (CMB) may explain this long-term pattern in field behaviour. Numerical modelling is in agreement with this, showing that an increase in the total heat flow or to the spatial variation heat flow across the CMB would cause an increase in reversal frequency and decrease in field strength. However, issues with testing this theory arise as the nature of the geomagnetic field preceding the earlier Permo-Carboniferous Reversed Superchron (PCRS; 262-318Myr) is poorly understood due of a lack of data for this time. New evidence for the strength of the field just prior to the PCRS comes from Microwave and Thermal palaeointensity experiments on samples from the Yakukst Large Igneous Province, Siberia (~376-364Myr). Results from these experiments give low site mean values between 2.6-14μT (Virtual Dipole Moments 7-25 ZAm2), approximately an order of magnitude weaker than the present day field and is in agreement with a weak field preceding the PCRS just as it did the CNS. Further work to constrain the field strength preceding the PCRS is ongoing on samples from the Northern UK for sites ranging in age 420-320Myr but the initial results also suggest the field was weak during this time.

The behaviour of immiscible silicate liquids in a crystal mush

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The physical behaviour of immiscible Fe- and Si-rich melts within a crystal mush has significant implications for magma evolution and the formation of ore deposits in layered intrusions, particularly if there is relative movement of the two conjugate liquids. We use laboratory experiments and natural examples of immiscible melts in rapidly cooled bodies to assess the effect of key variables on emulsion formation and evolution over varying timescales.

Within both the tholeiitc basalt experimental charges and the natural samples, an immiscible Fe-rich melt forms heterogeneously nucleated (attached) and homogeneously nucleated (isolated) globules (<1 – 5 µm diameter) dispersed in an immiscible Si-rich melt. At high temperatures, isolated globules preferentially nucleate in small melt pockets in the framework formed by plagioclase laths. At lower temperatures they are attached to plagioclase, despite the presence of ferromagnesian minerals with which they have more chemical affinity. Wetting angle decreases with increasing anorthite content. In more evolved samples, some Fe-rich globules enclose a turret of plagioclase which protrudes from (010) faces.

We hypothesise that, at the cooling rates experienced in the experiments and natural examples, a compositional boundary layer enriched in ferromagnesian elements forms around growing plagioclase, facilitating heterogeneous globule nucleation. With decreasing temperature, as the binodal widens, the affinity between plagioclase and the attached Fe-rich globules decreases, increasing the wetting angle.

The boundary layer hypothesis is supported by the observation that while immiscibility in some liquid compositions is characterized by globules attached to plagioclase, in others the Fe-rich conjugate forms a continuous 0.5 – 2 µm thick layer around plagioclase grains, with the maximum thickness adjacent to the fastest growth face. Our preliminary results suggest this layer forms when the bulk liquid intersects the top of the binodal, resulting in spinodal decomposition.

The relative movement in a gabbroic crystal mush of the two conjugate liquids under the influence of gravity depends on connectivity and wetting properties. A continuous film of Fe-rich liquid coating plagioclase grains will greatly facilitate the downwards movement of this dense, inviscid liquid, relative to an emulsion in which the Fe-rich liquid forms individual globules.

Forecasting of flood basalt eruptions: lessons from Holuhraun

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The 2014-15 Holuhraun eruption was the largest Icelandic eruption since the Laki in 1783-84, producing ~1.6 km^3 of lava. Nevertheless, the recent eruption was still an order of magnitude smaller than Laki and some previous eruptions of Bárðarbunga Volcano, the source of the recent Holuhraun eruption. The eruption was accompanied by a gradual caldera collapse, which provides a plausible mechanism for producing the largest flood basalts that have occurred in Iceland. This raises the question of whether Bárðarbunga currently has the potential for a larger eruption and, more generally, can we predict how large this type of eruption is going to be once unrest has started?

Here we investigate the potential for larger eruptions through coupled modelling of the caldera collapse and eruption. Our model provides predictive capacity in terms of the end date and final volume of eruption, based on a simple model of piston collapse constrained by subsidence data from a continuously operating GPS station within the caldera. We have extended our modelling to consider the effects of episodic pressure change due to earthquakes on ring faults beneath the caldera, constrained by GPS and InSAR. Our model constrains the aerial extent and volume of the magma body and thus its potential to develop into a larger eruption. The model can be applied to future eruptions that are accompanied by gradual caldera collapse, to forecast the duration and eventual erupted volume, which is critical information for civil authorities.

Insights into rare earth petrogenesis using luminescence

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Physical and chemical properties of minerals, such as luminescence, encode insights into speciation and redox in the mineral and therefore of magmatic and pegmatitic systems.

Rare earth (RE) ions emit distinct spectral lines when excited within a mineral lattice. However, luminescence displayed by minerals is complex and involves energy interactions between the crystal lattice and local defects (including chemical substitutions). Energy cascades within f-electron shells in RE ions produce luminescence when an orbital electron relaxes to the ground state from an excited singlet state by emitting a photon. Many minerals contain multiple REE and energy transfers non-radiatively between REE. Hence interaction between REE and with the lattice is not taken into account in models presenting minerals as simple systems. Further complexity arises from the presence of radiation damage to the lattice, influencing the energy transfer between REE and determining which REE is detected and also their quantum efficiency. Luminescence of RE ions encodes the local co-ordinations, energy cascades, lattice and defect interaction in a complex way within each mineral system – processes which in detail remain poorly understood.

Instrumentation at the Mineral Spectroscopy Suite, University of St. Andrews (XEOL, TL, UV Vis) has been utilized to investigate emission spectra for naturally occurring REE-bearing minerals from different localities. We have compared RE minerals, such as ancylite, bastnäesite, catapleiite eudialyte, and wöhlerite, to determine the fundamentals of each system. Preliminary data provides evidence of REE energy transfer, thermoluminescence, hysteresis, and differences in colour expressed in UV Vis spectra.

In addition to understanding the fundamentals of REE luminescence, this study will provide insights into the concentration of lanthanides, substitution states, redox environments and transport of U and Th in magmatic and pegmatitic systems.

Exploring deep melt migration before and after an Icelandic eruption

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Understanding deep magmatic plumbing and melt movement within an active volcanic system preceding and following an eruption are important for future predictions of when and where an eruption might occur. “Where?” is a particularly significant question for many volcanoes in Iceland, such as Bardarbunga. The significance lies in ascertaining whether an eruption will either come up vertically through the ice or erupt as a fissure eruption away from the ice cap, critical in predicting hazard risks such as ash clouds and flooding. Here, we observe melt movement using micro-seismicity induced by rock or melt fracture. This activity is detected using a network of seismometers in south-east Iceland that provide sufficient constraint to allow for fault plane solutions associated with the melt movement to be derived. Melt is observed to migrate from depths of 15-20 km, within the usually ductile region of the earth’s crust, approximately 10 km south-east of the Bardarbunga caldera. Moment tensor analysis of the induced rock fracture clearly indicates thrust faulting with positive tensile crack behaviour. This is consistent with the deep melt movement hypothesis. The location of the seismicity is of particular interest since it occurs in close proximity to the path of the dyke during the 2014 Bardarbunga-Holuhraun fissure eruption. Activity observed before and after the eruption provide insight into the existence, location and role of deep melt movement at Bardarbunga and also contribute to an increased understanding of volcanic systems in other regions of the world, such as Kilauea, Hawaii.

Evidence for off-axis magma pathways in the Central Main Ethiopian Rift as imaged by Magnetotellurics

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The Main Ethiopian Rift (MER) is part of the great East African rift with its unique geological setting as an active continental breakup zone. The MER includes a number of understudied active volcanoes with potentially high risks for the densely populated developing country of Ethiopia. In a multi-disciplinary attempt to investigate the past (as eruption histories), the present (e.g. through geophysical models) and the future (risks and hazards) volcanism in the central MER, the RiftVolc consortium including several universities in the UK and Ethiopia and the British Geological Survey was formed to collect and analyse new geophysical, geological and geochemical data.

Using newly recorded (2016) broadband and long-period magnetotelluric (MT) data along a 110 km long transect crossing the whole width of the rift, we present a regional 2-D model of electrical resistivity of the crust with a number of distinct anomalies. The derived model endorses a previous study that drew the surprising conclusion that there was no highly conductive region associated with a magma chamber directly under the central-rift-volcano Aluto. Instead the existence of a strong conductor under the Silti-Debre Zeyit Fault Zone 40 km to the north-west is confirmed. It is associated with the Butajira volcanic field, which hosts a number of scoria/cinder cones at the boundary between the NW plateau and the rift. Conductive anomalies with this amplitude (<10 Ωm) are very likely to be associated with partial melt and/or fluids in dikes or faults. The Butajira area was previously classified as a failed volcanic segment with a high number of volcanic vents but low seismicity. With the evidence presented by MT new light can be shed onto potential magma pathways in the crust, as this offset between a central rift volcano and a potential deeper magmatic source is enigmatic.

Infiltration of a syenitic crystal mush by evolved, late-stage, volatile-rich melts

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Located in the anorogenic Gardar Igneous Province of South Greenland, the 3 x 4 kilometre Klokken gabbro-syenite intrusion (1166 ±3 Ma) shows evidence of infiltration of syenitic crystal mush by evolved, late-stage, volatile-rich melts. The intrusion comprises a laminated syenite (LS) series that hosts large fragments of the roof cumulate sequence (granular-textured syenite, GS) that repeatedly delaminated during crystallisation. Ultramafic residual melts from the LS form a suite of filaments or ‘wisps’, comprising amph + bi + ol + ox + apatite, infiltrating the GS.

The morphology of the infiltration textures varies systematically with stratigraphic position relative to the inferred paleo-roof zone. This is interpreted as a reflection of systematic changes in the deformation behaviour of the GS crystal mush. GS in proximity to the roof zone contains extensive, planar-sided fractures that have been exploited by both the LS and the late-stage ultramafic melts. In comparison, stratigraphically lower GS sheets are infiltrated by an interconnected network of irregular wisps, generally up to 3-4 cm in width. The spacing and the number of wisps appears to be influenced by grain size and crystal orientation of the GS crystal mush, the width of the individual GS sheet and the nature of the GS-LS contact. The lowermost sheets of GS appear to be hybridised; here infiltration and deformation of the mush is characterised by disaggregation. We interpret this progressive variation in rock fabrics as a manifestation of changes in rheology of the GS crystal mush, from brittle to ductile, with changing temperature and crystallinity.

Magmas within the Gardar Igneous Province are typically enriched in LILE, HFSE and F. The region hosts a number of Tier 1 REE-Nb-Ta-Zr ± U deposits (e.g. Kvanefjeld, Kringlerne and Motzfeld). Better characterisation of the migration of late-stage, evolved melts such as those identified at Klokken has wider implications for our understanding of ore forming processes in magmatic environments.

Understanding the role of friction in volcanic environments

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Volcanoes are inherently unstable structures formed by superimposition of layers of variably porous volcanic materials, including weaker layers of ash and pumice and discontinuous lava flows. This heterogeneity can facilitate flank or sector collapses. In addition, dynamic stress fields due to regional tectonics, overburden of deposited materials and the stress caused by magma movement and emplacement can further destabilise the structure. The presence of pore fluids, hydrothermal alteration as well as anomalous geothermal gradients also add to the complexity of the system.

Recent work conducted on lubrication within faults observed significant drops in frictional coefficients with high slip rates (<90% reduction) for a variety of rock types [1]. This is attributed to many factors including the lubrication potential of fault gouges and frictional melts. Few studies have linked frictional melts to volcanic settings, though increasing experimental data suggests that volcanic rocks may be susceptible to undergo melting at slip rates similar to those found in extrusive pulses in volcanic conduits [2] and at the bases of mass material movements e.g. volcanic debris avalanches [3].

For volcanic rocks several factors complicate the development of slip. First, the presence of interstitial glass can cause them to act as viscous liquids during frictional heating to temperatures above their glass transition temperature (typically ~650-750 ^{o}C). Second, volcanic materials have a wide range of porosities not encountered in other lithologies, which changes the localisation of strain and comminution at the slip surface. To investigate these influences, controlled experiments are required where parameters can be varied systematically. Friction tests using a low to high velocity rotary shear apparatus on sintered glass samples (porosity 0-25%) formed by densification of glass beads at high-T [4] allow us to analyse the effects of porosity on friction in a standardised glass.

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The structure and past behaviour of peralkaline volcanoes in the Main Ethiopian Rift

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The silicic peralkaline volcanoes of the Main Ethiopian Rift (MER) are among the least studied on Earth, yet more than 9 million people live within 30 km of a volcano listed in the GVP database (Aspinall *et al.*, 2011). Ongoing activity at several volcanoes is observed in the form of hydrothermal activity (e.g. Hutchison *et al.*, 2015) and ground deformation (e.g. Biggs *et al.*, 2011). The first has led to a burgeoning geothermal industry, and subsequent investment in infrastructure with unquantified risk. It is therefore essential that we increase our understanding of how peralkaline volcanoes behave – the history, location and style of past eruptions.

This study aims to use very high resolution satellite imagery to characterise and compare a set of peralkaline volcanoes along the MER. Remote sensing techniques are powerful tools of investigation, able to cover a large scale and access otherwise potentially hazardous areas. Digital elevation models have been generated and will be analysed, including the identification and morphometric study of lava and ash flows, faults, calderas and cones. Previous studies have suggested structural controls on vent location and caldera shapes, with an influence from both the rift-parallel (NNE) normal faulting and cross-rift, older features (e.g. Acocella *et al.*, 2003).

Where possible (e.g. Fentale volcano and Chabbi mountain), lava flow volumes will be estimated. Some flows exhibit levees and folds that can be used for viscosity analysis (e.g. Pyle & Elliott, 2006). Further work may include a field campaign to test satellite observations, leading to chemical analyses, comparison with morphology and dating of specific flows in order to constrain average eruption rates.

Results of this study will have implications for how volcanism and tectonics interrelate in continental rift settings, and subsequent impacts on local populations.

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New insights into magma ascent and emplacement from alkaline roof zones of Southern Greenland

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The contact between a magma reservoir and the overlying country rock (or 'roof zone') is impossible to directly observe at active volcanic systems and very rarely exposed at ancient plutonic systems. Key processes take place at this interface. For example, melts and volatiles concentrate in the roof and inject dykes and veins into the host rock, these disintegrate the layers of surrounding country rock and cause them to be assimilated into the magma. Although these processes are commonly invoked to explain certain volcanic-magmatic processes, rarely can they be examined in the field and as such they remain poorly understood.

The Gardar Province in South Greenland preserves an ancient rift that was volcanically and tectonically active between 1300 and 1100 Ma. Uplift and glacial erosion has subsequently removed 3–4 km of cover exposing exceptional three-dimensional sections through the roofs zones of several ancient alkaline complexes. Here we present the first field observations and structural interpretations from the roofs of two world-famous alkaline complexes (Ilímaussaq and Motzfeldt) that also host major REE deposits.

At both complexes the contact between the magma and country rock is highly irregular. Bedded siliciclastic rocks and lavas are crosscut by a network of microsyenite dykes and sills that are typically 1–5 m thick. Longer sills form parallel to bedding planes, while dykes are discordant and cut up vertically sometimes along existing joints. Connecting dyke-sill networks calve off rectangular blocks of country rock from the roof (tens of meters across). Once detached these xenoliths can sink to hundreds of meters; providing evidence that the magma reservoir was not a completely locked crystal mush. The stoped blocks are mechanically disintegrated and chemically digested, and the predominance of basaltic over quarzitic xenoliths in the magma implies that the latter were more easily broken down and consumed by the alkaline melt.

Future work will assess the role of volatile elements (F, Cl, OH and S) in the roof of these complexes to quantify chemical assimilation processes and also evaluate their role in transporting and remobilizing REE.

Reservoir architecture beneath peralkaline volcanoes, Main Ethiopian Rift

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Peralkaline magmatism is commonly associated with continental rifting. The Main Ethiopian Rift features peralkaline calderas that punctuate the central rift axis. Despite frequent explosive Holocene eruptions, generating large pyroclastic flow deposits and thick, widespread ash-fall deposits, little is known about their plumbing systems or behaviour. Erupted products are compositionally varied, from alkali basalt through to highly evolved peralkaline rhyolites, separated by a distinct compositional gap.

Despite seemingly simple petrographic relationships dominated by fractional crystallisation, there is abundant evidence for more complex processing prior to eruption. Deposits from explosive peralkaline episodes display compositional changes throughout the eruption and samples often contain inclusions of less evolved material. Magma reservoir systems beneath peralkaline central volcanoes are likely to be complicated and compositionally stratified. Stratification is expected to be more prevalent than in metaluminous systems on the basis of magma rheology, with crystals settling relatively rapidly from low viscosity peralkaline rhyolite melts. Compositional stratification may also cause bimodality, with intermediate magmas forming mush zones, from which more evolved melts are preferentially extracted into a rhyolitic cap and primed for eruption.

This study presents a systematic comparison between whole rock, feldspar and glass compositions at the Aluto and Kone volcanoes. Trace element behavior is used to assess the importance of mush formation/disaggregation and magma mixing in peralkaline melt evolution. Zr, Ba and Sr concentrations in glasses are used to evaluate the relationship of crystal cargoes to their carrier liquids. Zr is incompatible in peralkaline melts, whilst Ba and Sr are compatible in alkali and plagioclase feldspars respectively. The crystal cargo of the suite reflects the structure of the magma reservoir at depth, with the eruption of liquid-rich lenses producing aphyric rhyolitic products and regions of syenitic mush being disaggregated to form trachytic lavas and porphyritic ignimbrites.

Formation of an oceanic transform fault during continental rifting

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Oceanic transform faults are a fundamental feature of plate tectonics, connecting offset extensional segments of mid-ocean ridges. Despite the prevalence of transform faults across the Earth’s oceans, their formation has never been directly observed. In addition the terminations of fracture zones, the inactive extension of transform faults, are used as a marker for the continent-ocean boundary. Therefore, understanding at which point in the rifting cycle transforms faults form is important for reconstructing past plate configurations. The current consensus is that transform faults are generated after the initiation of seafloor spreading, and are not inherited from continental rifting. This conclusion stems from a comparison between early-stage continental rifts and seafloor spreading segments. However, we lack observations of late stage continental rifts that enable us to test whether they play a role in transform fault formation. In this study, we integrate evidence from surface faults, geodetic measurements, local seismicity, and numerical modelling of the subaerial Afar continental rift and show that a transform fault is forming during the final stages of continental breakup, prior to seafloor spreading. This is the first time that the formation of a transform fault has been directly observed and answers long standing questions about how such features form. In addition it demonstrates that transform faults form earlier in the rifting cycle than previously thought. This results means that fracture zone terminations cannot reliably be used to trace the continent-ocean boundary. This has significant implications for many fields including evolutionary biology' global climate modelling, and palaeontology, which rely on accurate reconstructions of rifted margins.

Aerosol and gas emissions from Holuhraun eruption 2014-2015: size-resolved chemistry at source and in exposed communities

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Holuhraun eruption in Iceland 2014-2015 was the first modern opportunity to directly observe the emission and dispersion of a volcanic plume from a flood basalt eruption. This types of eruptions can greatly impact the environment due to their richness in reactive gas and aerosol.

We present a comprehensive dataset which characterises the chemistry of aerosol and gas in the Holuhraun plume. The plume was sampled at the eruptive vent, and in two populated areas in Iceland located at different distances downwind of the volcano: Reykjahlíð town (100km), and Reykjavík capital area (250km). The dataset comprises analysis of major and trace species in the volcanic plume, including size-resolved chemistry of the aerosol phase. We also present a time series of volcanic air pollutants (SO_2, $PM_{2.5}$ and sulphate aerosol) in the populated areas.

The results show that the plume was hugely diverse in its chemical composition, and the volcanic aerosol was predominantly in the $PM_{2.5}$ size fraction. The plume caused repeated air pollution events in the populated areas, exceeding existing health exposure guidelines, in particular for SO_2 and sulphate aerosol particles. The increase in $PM_{2.5}$ mass at ground level was relatively modest but the composition of the aerosol mass was greatly affected with sulphate accounting for ~90% of the PM mass. The volcanic SO_2 and aerosol concentrations did not always increase simultaneously, which was explained by presence of both ‘young’ (high SO_2, low sulphate concentrations) and ‘aged’ (low SO_2, high sulphate) plumes. The composition of both the young and aged volcanic plume has implications for negative health impacts and we make a recommendation that both ‘types’ of plume are forecasted and monitored during future eruptions.

Earth's Outer Core Properties Estimated Using Bayesian Inversion of Normal Mode Eigenfrequencies

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The outer core is arguably Earth's most dynamic region, and consists of an iron-nickel liquid with an unknown combination of lighter alloying elements. Frequencies of Earth's normal modes provide the strongest constraints on the radial profiles of compressional wavespeed, V_{Φ}, and density, ρ, in the outer core. Recent great earthquakes have yielded new normal mode measurements; however, mineral physics experiments and calculations are often compared to the Preliminary reference Earth model (PREM), which is 36 years old and does not provide uncertainties. Here we investigate the thermo-elastic properties of the outer core using Earth's free oscillations and a Bayesian framework.

To estimate radial structure of the outer core and its uncertainties, we choose to exploit recently expanded datasets of normal mode centre frequencies. Under the self-coupling approximation, centre frequencies are unaffected by lateral heterogeneities in the Earth, for example in the mantle. Normal modes are sensitive to both V_{Φ} and ρ in the outer core, with each mode's specific sensitivity depending on its eigenfunctions. We include a priori bounds on outer core models that ensure compatibility with measurements of mass and moment of inertia, and other geophysical constraints.

We use Bayesian Monte Carlo Markov Chain techniques to explore different parameterizations for the structure of the outer core, each of which represents different a priori constraints. We test how results vary (1) assuming a smooth polynomial parametrization, (2) allowing for structure close to the boundaries of the outer core. The first approach allows us to develop acceptable models, complete with their uncertainties, which could be used to represent the gross properties of the outer core. In the second approach we recognize that the outer core may have distinct regions close to the core-mantle and inner core boundaries and investigate models which parameterize the well mixed outer core separately from these two layers.

We discuss our results in terms of added uncertainty to the light element composition of the outer core and the potential existence of anomalous structure near the outer core's boundaries.

New insights into volatile-rich mantle metasomatism at the Bultfontein diamond mine, Kimberley, South Africa

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Mantle xenoliths provide a unique insight in to the composition of the Earth's sub-continental lithospheric mantle. Previous studies have shown that this has undergone widespread metasomatism, especially beneath the cratons (Dawson, 1980). The mantle suite from Bultfontein diamond mine in S. Africa is of especial interest because the 85 Ma kimberlite has sampled a diverse range of mantle xenoliths from the Kaapvaal craton. These range from cryptically metasomatised harzburgites to patently metasomatised peridotites, with Ca-rich clinopyroxene veins and associated phlogopite crystallisation (Jones et al., 1982; Kramers et al., 1983). Most studies have attributed the metasomatism at Bultfontein to the infiltration of silicate melts with a kimberlite affinity (e.g. Jones et al., 1982). This study explores the possibility of a dolomitic or carbonatitic metasomatic agent at Bultfontein.

Major and trace element concentrations of metasomatic clinopyroxenes preserved in a spectacular large vein from Bultfontein have been analysed by EPMA and LA-ICP-MS. The calculated composition of the melt in equilibrium with the clinopyroxene has a low Ti/Eu and high La/Yb ratio, which is typically interpreted as characteristic of mantle–derived carbonatite melts (Rudnick et al., 1993). While the Ti/Eu ratio in the equilibrium melt is much lower than that of average Group I South African kimberlites, and both ratios are within the global range of carbonatite, a closer similarity is observed on primitive mantle normalised incompatible-trace-element plots with high-density Mg-rich carbonatite fluids entrapped in diamonds (Weiss et al., 2011).

We propose that diopside veins are being produced by the reaction:

Mg-carbonatite + enstatite = diopside + forsterite + CO_2

(Dalton and Wood, 1993)

The co-existence of large zircon and sulfide crystals (>2mm) and high Zr concentrations in the clinopyroxene indicate that the metasomatic agent which produced the veins in the lithospheric mantle was rich in Zr and S. Since enstatite has low partition coefficients for incompatible trace elements we assume that these have been introduced by an infiltrating Mg-carbonatite melt or fluid during reactive percolation.

Metasomatised regions within cratons are a large repository of the Earths volatile budget and therefore new insights into carbonatite metasomatism, such as that observed at Bultfontein diamond mine, are key to understanding this important yet poorly constrained part of the global carbon cycle.

Complex evolution of the magmatic system beneath a monogenetic volcano: evidence from olivine crystals and their spinel inclusions

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Analysing the crystal growth stratigraphy, i.e., the textures, zoning and chemistry of rock-forming minerals is a powerful tool in recording magmatic processes and compositions, thus providing a unique insight into the evolution of magmatic systems. In spite of this, detailed studies focusing on the sequences of monogenetic basaltic volcanic centres generally only rest on whole-rock major and trace element and isotopic compositions. Here, we present the alkaline basaltic volcanics of a monogenetic eruption centre which serve as an excellent example for basaltic rocks resulted from the contributions of several magmas, crystals and fragments of various origins.

The Fekete-hegy volcanic complex is one of the largest (> 10 km^2) and most complex eruptive centres in the intracontinental monogenetic Bakony–Balaton Highland Volcanic Field (western Pannonian Basin). It is characterised by a complex volcanic facies architecture consisting of at least four maars, lava flows and two scoria cones suggesting multiple eruption episodes. The two main eruptive phases are represented by the phreatomagmatic eruptions and the magmatic explosive – effusive eruptions.

The juvenile pyroclasts of the phreatomagmatic products contain a remarkably diverse mineral assemblage (olivine + clinopyroxene + orthopyroxene + spinel + amphibole + quartz ± plagioclase) as well as various fragments (peridotite, sandstone, siltstone, claystone). In contrast, the samples of the magmatic explosive – effusive eruptive unit only comprise olivine + clinopyroxene ± plagioclase phenocrysts.

The intra-crystal compositional variations observed in olivine crystals characterised by various textural and zoning patterns and the diverse chemistry and position of the spinel inclusions within the olivine indicate that the evolution of the deep magmatic system that fed the phreatomagmatic eruptions was very complex where open-system processes played an important role. Magma accumulation, stalling, fractionation, replenishments and mixing occurred in the storage system as well as foreign fragments and crystals were incorporated from the wall rocks that led to the mixed character of the erupted products. In contrast, the magmatic system that fed the later magmatic explosive – effusive phase experienced a simple evolution by fractional crystallization.

The Permeability evolution of Etna Basalt during Brittle Creep

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The rocks surrounding a volcanic edifice are often subjected to periods of constant stress. As the pressures within magma chambers grow with each injection of fresh magma, the stress applied to the adjacent rocks will increase. It has been hypothesised that the final stages of rock fracture prior to an eruption are dominated by the slow fracture of the rock between the body of magma and the surface. It would be expected that the migration of gases and liquids would be influenced as this fracture network develops. Due to the addition of a pore pressure, the presence of fluid within a rock is known to mechanically weaken it, which could then lead to rock failure and an eruption. Therefore, it is essential that we understand how the permeability of a rock, and hence the migration of fluid, evolves under periods of constant applied stress.

Here we present results from triaxial deformation experiments carried out on Etna Basalt, with continuous measurements of permeability and P-wave velocity conducted throughout. A set of samples were deformed at a constant strain rate of $2x10^{-6}s^{-1}$ and an effective confining pressure of 30 MPa. Another set of samples were loaded at the same strain rate and effective pressure to ~85-95% of the measured peak stress, before being held at a constant stress level, in a brittle creep test.

The constant strain rate experiments exhibit results akin to previous studies, where permeability drops for the first 1% of strain, before plateauing for 0.25% of strain and rising for the final 0.3% of strain before failure, as a result of increased micro-fracturing. The brittle creep experiments exhibit similar results for the first 1.25% of strain, with permeability continuing to decrease before plateauing. The pre-failure permeability measurements however show contrasting behaviours. During brittle creep the rise prior to failure is over a much shorter amount of strain, 0.1% compared to 0.3%. By contrast, the P-wave velocity evolution in relation to strain is very similar between the two test types. This suggests that the evolution of microcrack density with deformation depends weakly on the type of tests, while the connectivity or tortuosity evolution is more abrupt at the onset of failure during creep.

Petrogenesis of the peralkaline ignimbrites of Terceira, Azores

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The recent (< 100 ka) volcanic stratigraphy of Terceira, Azores includes at least seven peralkaline trachytic ignimbrite formations, attesting to a history of spasmodic explosive eruptions. In this study, the petrogenesis and pre-eruptive storage conditions of the ignimbrite-forming magmas are investigated via whole rock geochemistry, melt inclusion and groundmass glass major element and volatile compositions, mineral chemistry, thermobarometric models, and petrogenetic modelling. The primary aims of this contribution are to (1) identify the petrogenetic processes that generated the ignimbrite-forming peralkaline trachytes, (2) constrain the P-T-fO_2 conditions at which they were stored, and (3) evaluate the factors controlling their eruptive behaviour.

Results indicate that the ignimbrite-forming trachytes are generated by fractional crystallisation of basaltic parental magmas at redox conditions around 1 log unit below the fayalite-magnetite-quartz buffer. This was achieved via a polybaric fractionation pathway, in which mantle-derived basalts stall and fractionate to hawaiitic compositions at lower crustal depths (~ 14 km), before ascending to a shallow crustal magma storage zone (~ 3 to 4 km) and fractionating towards comenditic trachytic compositions. The most evolved pantelleritic magmas of Terceira are generated by continued fractionation from the comenditic trachytes. Syenite ejecta represent portions of peralkaline trachytic melt which crystallised *in-situ* at the margins of a silicic reservoir. Trachytic enclaves hosted within syenitic ejecta provide direct evidence for a two-stage mixing process, in which ascending hawaiites are mixed with trachytic magmas in the shallow crustal magma storage zone, and the resulting hybridised trachyte then ascends further and mixes with more evolved peralkaline trachytes, passing first through a syenitic crystal mush. The reduced viscosities of these peralkaline magmas relative to their metaluminous counterparts facilitates rapid fractionation via crystal settling, generating compositionally zoned magma bodies and relatively crystal-poor erupted magmas. This may also inhibit the formation of stable eruption columns, leading to 'boil-over' eruption styles.

Searching for structure in the mid-mantle: Observations of converted phases beneath Iceland and Europe

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Until recently, most of the lower mantle was considered to be well-mixed with strong heterogeneity restricted to the lowermost several hundred kilometers above the core-mantle boundary, also known as the D" layer. However, several recent studies have started to hint at a potential change in earth structure at mid-mantle depths, with evidence from both seismic tomography (Fukao and Obayashi 2013, French and Romanowichz, 2015) and global viscosity structure (Rudolph et al., 2015).
We present a continental-wide search for mid-mantle P to S wave converted phases and find most observations come from approximately 1000 km depth beneath Iceland and Western Europe. Conversions are identified using a data set of ~50,000 high quality receiver functions which are systematically searched for robust signals from the mid-mantle. Potential P to s conversions are analysed in terms of slowness to determine whether they are true observations from depth or simply surface multiples arriving at similar times. We find broad regions with robust signals from approximately 1000 km depth in several locations; beneath Iceland and across Western Europe, beneath Ireland, Scotland, Eifel.
Similar observations have previously been observed mainly in subduction zone settings, and have been hypothesised to be caused by down-going oceanic crustal material. Here we present observations which correlate with slow seismic velocities in recent tomographic models (Rickers et al., (2013); French and Romanowicz, (2015)). These low velocities appear to be a channel deviating from the broad mantle plume beneath Iceland at mid-mantle depths. We hypothesise that the mid-mantle seismic signals we observe are caused by either a phase transition occurring locally in a specific composition or by small-scale chemical heterogeneities swept along with upwelling material and ponding around 1000 km.

Assessing the volcanic styles and types of the North Atlantic igneous province: new insights from the Greenland margin

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The North Atlantic Igneous Province (NAIP) covers a vast area as well as a significant time span, having formed at 60-55 Ma. Importantly, its' formation is implicated in the climatic perturbations at the Palaeocene-Eocene Thermal Maximum (PETM), and the margins are today a target for petroleum exploration. Volcanism in the NAIP ranges from lava flows and hyaloclastites to more explosive tephra forming eruptions from both basaltic and more evolved types. The explosive end members of both mafic and felsic volcanism also produce ash beds in the rock record at key times. Hydrothermal vent structures which are predominantly related with the emplacement of large (>1000 km3) intrusions into the subvolcanic basins in the NAIP are another style of eruption, where climate-forcing gases can be transferred into the atmosphere and hydrosphere, and which form structures that alter the subsurface permeability pathways for fluids. The types and volumes of gas produced by intrusions is heavily dependent on the host-rock sediment properties that they intrude through. The distribution of vent structures can be shown to be widespread on both the Norwegian and the Greenland margins of the NAIP. In this overview we assess the main eruption styles, deposits and their distribution within the NAIP using mapped examples from offshore seismic data as well as outcrop analogues, highlighting the variability of these structures and their deposits. As the availability of 3D data from offshore and onshore increases, the full nature of the volcanic stratigraphy from the subvolcanic intrusive complexes, through the main eruption cycles into the piercing vent structures, can be realised along the entirety of the NAIP margins. This will help greatly in our understanding of the evolving palaeo-environments during the evolution of the NAIP. Furthermore, the roles of volcanic eruptions, magmatic intrusions, associated vent complexes and how these may have influenced the development of the PETM crisis can be better constrained.

Exchange flow within a dyke: an analogue experimental study

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Basaltic fissure eruptions can pose a serious threat to infrastructure, agriculture and health, on a local scale (through lava flows), and regional scale (through emission of toxic gases). These eruptions typically initiate as a fissure (the surface expression of a dyke), then, on timescales varying from hours to days, they localize to a small number of vents. This study addresses the subsurface processes that operate during localization. It is well known from SO_2 measurements during basaltic eruptions that much more magma degasses within the subsurface than the volume of magma that is erupted. Additionally, zonation in plagioclase crystals indicate repeated cycles of ascent and decent of basaltic magma. The most plausible explanation for these observations is that there is a convection system within the dyke that constitutes an exchange flow between upwelling, gas-rich magma, and downwelling, gas poor magma. These conditions correspond to upwelling magma that is of low viscosity and density and descending magma of high viscosity and density. Convective processes play an important role during magma transport at persistently degassing volcanoes.

Previous work has focused on the exchange flow between two Newtonian fluids in a pipe, replicating the geometry of a cylindrical conduit. Here, we perform scaled analogue experiments in a slot (a rectangular duct of high aspect ratio) allowing replication of a dyke-like geometry. In detail, we stratify two Newtonian fluids such as air, vegetable oil, glycerol, golden syrup and dilutions thereof. Initially the low density, low viscosity fluid is place upon on a high density, high viscosity fluid. The fluid tank is then inverted to initiate overturn whilst we film to document the resulting flow behaviour. The convective system is described with the dimensionless Grashof number, which is a ratio of viscous to buoyancy forces. Our experiments span a wide range of Grashof numbers (10^{-2} to 10^{2}) that spans most of the range expected in the natural system (10^{-2} to 10^{4}). At low Gr we observe laminar flow with broad, well-defined fingers of downwelling dense, viscous fluid separated by narrower upwelling fingers of less dense and less viscous fluid. At high Gr the flow is locally turbulent and chaotic with a greater bulk volume flux. Ultimately, these experiments aid our understanding of the sub-surface timescales, volume fluxes and flow patterns that operate during basaltic fissure eruptions.

Mixed populations of distal tephras – friend or foe?

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The study of explosively-erupted, unconsolidated pyroclastic products of volcanic eruptions (tephra) has advanced greatly and now has many applications beyond the study of volcanoes and their products, such as in archaeology or paleo-environmental studies. Tephrostratigraphy requires reliable correlations of individual (or packages of) beds from one archive to another as well as, ideally, to the source volcano. These correlations are commonly based on chemical composition and age of the tephra layer. Problems can arise e.g. when a volcano produces several eruptions of indistinguishable composition, when dealing with incompletely or inadequately characterised records and when the reworked character of tephras is not recognised. As the sedimentary features of a sampled tephra bed are commonly not extensively considered or published in tephrostratigraphy papers, many beds may falsely be assumed to be of primary fallout origin. Increasingly, we are finding evidence for the reworking of ash and tephra in the marine and other realms by e.g. bottom currents or bioturbation (e.g. Kataoka et al., 2016; Griggs et al., 2014).

Here, attention is drawn to reworking as indicated by mixed geochemical populations. Several tephra layers from Pantelleria, Italy, are found intimately associated with those from other volcanoes (e.g. Etna), indicating the likely feeding of several eruption products to the deposition site from across the seafloor.

Five examples (ODP-2, W-0, LC-21, P-14, I-13/14) of these mixed populations are presented from marine sediment cores from the Mediterranean Sea (out of a total of 25 studied tephras), highlighting that they are more common than previously appreciated and that extensive reworking and re-deposition may affect many tephra deposits. We consider whether these layers should be used for correlations or are best avoided. We recommend distinguishing between background and event tephras, if possible; thus raising awareness of a more or less continuous supply of volcanic material to the seafloor in areas up to several hundred kilometres around volcanic sources.

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Pulses of Phanerozoic magmatism and associated high-T/low-P metamorphism in the Bird's Head, New Guinea

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The Bird's Head is the northwesternmost peninsula of New Guinea. The peninsula is dominated by a mountain range exposing a basement of metamorphosed Silurian-Devonian turbidites cross-cut by various granitoid bodies. It offers a unique window to study pre-Cenozoic tectono-thermal events at the northeastern margin of eastern Gondwana.

We present new field, geochemical, and U-Pb zircon data from this remote, relatively unstudied region. We focus on the granitoids and show that these intruded the basement rocks in two distinct phases in the Devonian-Carboniferous and the Permian-Triassic. Both events produced highly evolved peraluminous granite and granodiorite. Abundant country rock xenoliths, associated migmatites, as well as mineralogical and geochemical data show that the felsic rocks were generated by partial melting of the continental crust (i.e. S-type granitoids). The Permian-Triassic event is further characterised by structures indicating syn-intrusive extension.

We propose that Permian-Triassic magmatism in the Bird's Head occurred in an evolved continental-arc environment. Mantle-wedge-derived melts underplated and intruded the lower crust, providing the necessary heat to induce partial melting of the overlying metasedimentary crust. These melts were emplaced during a phase of crustal extension and are the likely cause of high-T/low-P regional metamorphism in the surrounding country rocks.

These considerations challenge models where the occurrence of strongly peraluminous S-type granitoids is restricted to crustal shortening in intracontinental collisional belts. Partial melting in a continental arc setting has been proposed for the generation of S-type granitoids of the Andes and along the western Pacific. The paired metamorphic and igneous rocks that we observe also show similarities to the Buchan type area in NE Scotland and the Cooma Complex in SE Australia, the latter of which is considered to have formed in an Andean-type margin.

Investigating changes to pre-eruptive storage conditions of Kelud volcano prior to the 1990, 2007 and 2014 eruptions

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Kelud volcano in East Java, Indonesia has erupted regularly over the past century, posing a range of hazards to local populations. The three most recent eruptions, in 1990, 2007 and 2014, show sharp contrasts in eruption style, despite each eruption having a broadly similar volume and erupting compositionally very similar magmas (basaltic andesite). The 1990 eruption produced an explosive eruption column reaching a height of ~14 km, and generated relatively thick fall deposits (40 cm at a 5 km distance) around the volcano. The 2007 eruption was entirely effusive, producing a lava dome 260 m high and 400 m wide. In contrast to the earlier eruptions, the 2014 eruption was highly explosive, with an unusually intense but short-lived eruption reaching columns height of 17-25 km. The 2014 deposit was highly dispersed and ash rich, producing relatively thin fall deposits (~5 cm) in proximal regions, but affecting a much larger area than the 1990 eruption and disrupting aviation over most of Java. Kelud thus presents an interesting example of significantly different eruption styles (with very different consequences) produced by similar magma compositions.

Here, we explore the magma storage conditions prior to each of these eruptions, aiming to assess if there are systematic differences between them (e.g. evidence of mixing and/or heating involving a secondary magma) that might explain the differences in eruption style. We will present preliminary petrographic observations and mineral compositional analyses that aim to characterise each of the magmas. To investigate evidence of pre-eruptive mixing, we have compiled Fe-Mg zoning diffusion profiles in orthopyroxene phenocrysts, using BSEM imaging and element abundances from electron probe data. We will summarise the range of zoning patterns observed, and use diffusion profiles to estimate the pre-eruptive timescale recorded by the zoning. These results will be presented alongside a range of textural and compositional information that document the nature of the magmas feeding each of the three most recent eruptions at Kelud.

Microstructure of deformation bands in carbonates.

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Deformation bands are one of the most common strain localization structures found in deformed porous rocks. Numerous documented studies on deformation bands in siliciclastics found that they experience a reduction in permeability due to: i) grain reorganisation, ii) cataclasis, and iii) dissolution and cementation. The deformation mechanisms and permeability-reduction processes that affect deformation bands in carbonates are nowhere near as well understood. To fill this knowledge gap, faults were studied in high porosity carbonates from various locations in Europe to investigate deformation mechanisms occurring within a range of carbonates. Varying mechanisms were detected depending on the composition of a rock. For instance, the main process responsible for a reduction in porosity of the deformation bands in the Upper Cretaceous chalk in Pegwell Bay appears to be pore collapse, particularly the collapse of voids within foraminifera. Deformation bands in the Upper Pliocene-Lower Pleistocene bioclastic calcarenites in Sicily show several different deformation mechanisms including: i) cataclasis, ii) peloid mechanical alteration and subsequent aggrading neomorphism, and iii) pressure solution at grain contacts. Deformation bands in the Upper Pliocene-Lower Pleistocene Gravina calcarenite formation in Gargano promontory, SE Italy, show dilational components and cementation. Different microstructure of the deformation bands corresponds to their varying architecture, thus detailed maps of study areas were produced from aerial photographs obtained using a drone, and then overlapping the stitched images with a map drawn by hand in the field. Based on varying architecture these faults were divided into three groups: single deformation bands, clustered deformation bands and zoned deformation bands.

Fracture toughness controls on the propagation of magma-filled fractures: Insights from analogue experiments

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Analogue experiments using gelatine were carried out to investigate the importance of the mechanical properties of rock layers and their bonded interfaces on the formation and propagation of magma-filled fractures in the crust. Water was injected at controlled flux into superposed and bonded layers of solidified gelatine through the base of a clear-Perspex tank. Experimental dykes and sills were formed, as well as dyke-sill hybrid structures where the ascending dykes crosses the interface between layers but also intrudes it to form a sill. Stress evolution in the gelatine was visualised using polarised light as the intrusions grew, and its evolving strain was measured using digital image correlation (DIC, Fig. 1). During the formation of dyke-sill hybrids there are notable decreases in stress and strain in the vicinity of the dykes as the connecting sills form, which is attributed to a pressure decrease within the intrusive network. Additional fluid is extracted from the open dykes to help grow the sills, causing dyke protrusions in the overlying layer to be almost completely drained. We define K_{Ic}* as the fracture toughness of the lower gelatine layer K_{IcG} relative to the interface between layers K_{IcInt}; our results show that K_{Ic}* strongly influences the type of intrusion formed (dyke, sill or hybrid). K_{IcInt} impacted the growth rate of the sills and was controlled during setup of the experiment by the temperature of the upper layer T_m when it was poured into place. The experiments help to explain the dominance of dykes and sills in the rock record, compared to intermediate hybrid structures.

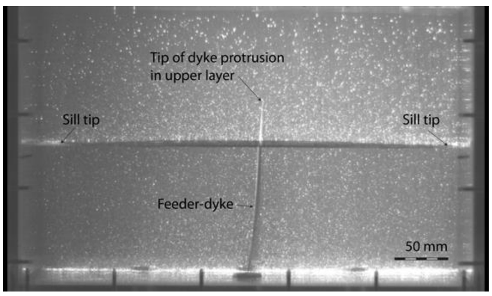

Figure 1: Image of a dyke-sill hybrid experiment with fluoresced tracer particles for DIC analysis.

Imaging faults in anisotropic rocks.

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Knowledge of fault zones at depth is vital in identifying seismic hazard and characterizing crustal structure. Seismic investigations are often used to image fault zone structure at depth. Fault zones often occur within anisotropic phyllosilicate-rich rocks. This seismic velocity anisotropy, will influence seismic imaging. However, anisotropy is not always taken into account in seismic imaging and the extent of the anisotropy is often unknown. The Carboneras fault is a left-lateral strike-slip fault in SE Spain that cuts through phyllosilicate-rich mica schist. Laboratory measurements of the velocity and velocity anisotropy indicate 10-15% compressional-wave velocity anisotropy in the gouge of the Carboneras fault zone and 40% anisotropy in the mica schist protolith. Cyclic loading of the protolith, designed to replicate and quantify the fracture damage in fault zones, reveal only small changes in measured velocities. Greater differences in velocity are observed between the fast and slow directions in the mica schist rock (5500 - 3500 ms^{-1} at 25 MPa), than between the fault gouge and the slow direction of the rock (3500-3000 ms^{-1} at 25 MPa). This implies that the orientation of the anisotropy with respect to the fault is key in successful seismic imaging of the fault. For example, if the slow direction is oriented perpendicular to the fault, waves travelling along the fault will be sensitive to a large velocity contrast between the fault gouge and the fast orientation of rock. However, waves travelling perpendicular to the fault will see a much smaller velocity contrast. This highlights the importance of considering the orientation (or potential range of orientations) of the foliation in design and interpretation of seismic experiments of faults in anisotropic media.

Cycling of halogen-bearing fluids in the Rum Layered Suite, NW Scotland

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Layered mafic-ultramafic intrusions (LMIs) host some of the largest known platinum-group element (PGE) ore deposits; for example, ~75% of the World's Pt resources come from the Bushveld Complex, South Africa. Discussion has traditionally centred around two theories for PGE-enrichment processes; a high-temperature magmatic model and a late-stage metasomatic model. Although the latter of these two models has arguably been more contested in the literature, evidence from some LMIs, (including the Bushveld and Stillwater intrusions), are permissive of ore formation via chemical modification and recrystallisation by post-magmatic halogen-rich fluids[1,2].

The 60.53 ± 0.08 Myr[3] Rum Layered Suite (RLS) preserves evidence for cycling of volatile-rich fluids, both at the levels of stratigraphy where PGE-mineralisation occurs, and also in late-stage pegmatites that formed when solidification of the intrusion was at an advanced state. Preliminary electron probe microanalysis (EPMA) of Cr-spinel-hosted amphibole inclusions show that they contain ppm levels of F, and significantly lower Cl contents. Amphiboles contained in various pegmatites contain significantly greater amounts of F (commonly in excess of 1 wt.%), and coexisting apatite has compositions close to the fluorapatite end-member. An important aim of this study will thus be to interrogate the degree to which volatile-rich fluids changed their character over the lifetime of the Rum intrusion.

Looking forward, we will employ the neutron-irradiation noble gas mass spectrometry (NI-NGMS) method for further halogen analyses. This technique allows for high-precision measurements of the heavy halogens Cl, Br and I in small (~1-5 mg) sample sizes and enables characterisation of bulk halogen geochemistry and spatially-resolved *in situ* distribution of halogens. We anticipate that this approach, combined with detailed consideration of the presence of the halogens in mineral phases and fluid/solid inclusions, will give new insights into the nature, source and role of volatile-rich fluids in LMIs.

[1] Boudreau *et al.* (1986). *Journal of Petrology*, 27(4), 967-986. [2] Hanley *et al.* (2008). *Journal of Petrology*, 49(6), 1133-1160. [3] Hamilton, *et al.* (1998). *Nature*. 394, 260-263.

Transient creep of single crystals of San Carlos olivine

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Time-dependent viscosity in the upper mantle can significantly modify large scale geodynamic phenomena such as glacial isostatic adjustment (GIA) and post-seismic relaxation. Although the transient processes responsible for this behaviour have been incorporated in large-scale models, microphysical models for transient creep are poorly calibrated. To address this gap in knowledge we aim to calibrate a new model for transient creep based on a series of laboratory experiments.

Experiments are being conducted on single crystals of olivine, the primary mineral in Earth's upper mantle. We are performing uniaxial compression experiments at temperature of 1200–1350°C. Applied loads are held constant until steady state strain rates are reached, after which loads are either increased or decreased instantaneously, and the evolution of the strain rate is observed. To relate the mechanical behaviour to the underlying dislocation processes we use high angular-resolution electron backscatter diffraction (HR-EBSD) to map densities of geometrically necessary dislocations. We will carry out this analysis on a variety of crystal orientations to characterise the anisotropy in transient behaviour.

Our ultimate goal is to apply this calibrated model to a 1-D model of GIA to look at the effects of transient creep on sea level rise.

Shear zone development in high-viscosity magmatic systems

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The frequent and, as yet, unpredictable transition from effusive to explosive volcanic behaviour is common to active composite volcanoes, yet our understanding of the processes which control this evolution is poor. The rheology of magma, dictated by its composition, porosity and crystal content, is integral to eruption behaviour and during ascent magma behaves in an increasingly rock-like manner. This behaviour, on short timescales in the upper conduit, provides exceptionally dynamic conditions that favour strain localisation and failure. Seismicity released by this process can be mimicked by damage accumulation that releases acoustic signals on the laboratory scale, showing that the failure of magma is intrinsically strain-rate dependent.

This character aids the development of shear zones in the conduit, which commonly fracture seismogenically, producing fault surfaces that control the last hundreds of meters of ascent by frictional slip. High-velocity rotary shear (HVR) experiments demonstrate that at ambient temperatures, gouge behaves according to Byerlee's rule at low slip velocities. At rock-rock interfaces, mechanical work induces comminution of asperities and heating which, if sufficient, may induce melting and formation of pseudotachylyte. The viscosity of the melt, so generated, controls the subsequent lubrication or resistance to slip along the fault plane thanks to non-Newtonian suspension rheology. The bulk composition, mineralogy and glass content of the magma all influence frictional behaviour, which supersedes buoyancy as the controlling factor in magma ascent.

In the conduit of dome-building volcanoes, the fracture and slip processes are further complicated: slip-rate along the conduit margin fluctuates. The shear-thinning frictional melt yields a tendency for extremely unstable slip thanks to its pivotal position with regard to the glass transition. This thermo-kinetic transition bestows the viscoelastic melt with the ability to either flow or fracture: velocity-dependence then acts as an important feedback mechanism on the slip plane, accentuating stick-slip cycles that bring the magma, step-wise, to the surface accompanied by characteristic repetitive seismic events[1]. Hence it is of vital importance to recognise the frictional behaviour of volcanic rocks and magmas to understand the continuation of an eruption.

1. Kendrick, J. E., Lavallee, Y., Hirose, T., Di Toro, G., Hornby, A. J., De Angelis, S., and Dingwell, D. B., 2014, Volcanic drumbeat seismicity caused by stick-slip motion and magmatic frictional melting: Nature Geosci, v. 7, no. 6, p. 438-442.

A bigger splat: rock fall impact processes in wet sediment.

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Convincing evidence for highly energetic and destructive seismogenic events can be sparse in the ancient geological record. At Clachtoll in NW Scotland, a previously unrecognised decametre-scale fractured megaclast of Lewisian gneiss basement is found lying close to the basal landscape unconformity of the Mesoproterozoic sedimentary rocks of the Stoer Group (ca. 1.2 Ga). The basement foliations in the megaclast are significantly misoriented relative to the adjacent areas of Lewisian gneiss below the Stoer Group. The megaclast is highly fractured and contains numerous fractures filled with red sandstone. Filled fractures in the upper part of the block display laminations and other sedimentary features indicating deposition into gaping open voids. In sharp contrast, those on the base and lateral flanks of the block display evidence of forceful injection of wet sediment slurries. Preliminary numerical calculations suggest that a basement megaclast of the observed size falling from a height of a few tens of metres would be sufficient to cause rapid over-pressuring and liquefaction of the underlying unconsolidated sediment leading to hydrofacture and injection. The fracture kinematics (e.g. trend, opening directions, shear sense) indicates an incomplete syn-emplacment disaggregation of the megaclast consistent with gravity-driven transport from the NE. The basal part of the Stoer Group contains abundant evidence of soft sediment deformation, including faulting, slumping, convolute bedding, dewatering structures and sandstone dyke emplacement. All these features are consistent with repeated episodes of seismogenic shaking during or immediately following deposition. It is therefore logical to propose that the gravity-driven emplacement of the Clachtoll megaclast was triggered by an earthquake ca. 1.2 Ga during the formation the Stoer Group rift basin. This event significantly predates the Stac Fada bolide impact event which did not occur until the basal part of the Stoer Group described here lay buried underneath several hundred meters of younger sediment.

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Investigating the source and structural controls of volcano-seismic unrest at Nisyros Volcano (Greece).

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Nisyros is a Quaternary strato-volcano located in SE Aegean Volcanic Arc (Greece). It hosts an active hydrothermal system and has generated historic phreatic eruptions. Significant seismic activity began in the area of Nisyros volcano in July 2014, together with increased intensity of fumarolic and hydrothermal activity on Nisyros itself. This unrest represents the highest peak in activity since the 1995-1998 volcano-seismic crisis, which was attributed to local magmatic inflation and degassing. In response to the increased activity, we deployed a local seismic and GPS network on Nisyros and surrounding islands (2014-2015) and took repeat measurements of hydrothermal features (temperature, pH, CO2) on Nisyros, to better constrain the source and implications of unrest. Here we present some of our preliminary results. We recorded frequent micro-seismic events, many of which had low-frequency signals, typical of hydraulic fracturing and indicative of shallow boiling/degassing activity and subsurface fluid propagation beneath Nisyros. Fumarolic outlet temperatures and the extent of hot-spring activity were also observed to increase during this time. We recorded significant growth of a large fracture and sink-hole network that has developed in the caldera floor since 2001, and suggest that this may be related to deeper magmatic-hydrothermal activity. Recognising the signals and source of unrest at volcanic-hydrothermal systems is vital in identifying anomalous behaviour and potential precursor activity of magmatic and phreatic eruptions, which often occur without significant warning. Understanding the importance of structural controls on the distribution of activity can additionally help us identify areas of higher phreatic risk. Our investigation into the Nisyros unrest is ongoing.

The anatomy of the plumbing system of Nisyros volcano, Aegean arc

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Arc magmas are typically mixtures of multiple crystal, volatile and melt components that are often not in equilibrium with each other. Any whole rock analysis will therefore yield a mixed result and obscure a major part of the variation present within a sample. In contrast, the composition and textural relationships of mineral phases in arc magmas provide a wealth of information that can be used to investigate petrogenetic processes. To unravel the intricacies of differentiation and diversification of arc magmas, we have undertaken a detailed petrographic study of Nisyros volcano, the easternmost volcanic centre of the Aegean arc.

We introduce a new division of the volcanic rocks of Nisyros based on field evidence and petrography. Two distinct suites can be recognized: low-porphyricity andesites (LPA suite) and a high-porphyricity (rhyo)dacites (HPRD suite). The latter show pronounced evidence for magma mixing and mingling in a shallow mush system, such as the presence of up to 20 vol.% mafic enclaves, wide variation in zoning patterns and crystal transfer from enclaves to the (rhyo)dacitic host and vice versa. Most textural features are thus acquired during shallow processes, but evidence for differentiation at the base of the arc crust is also preserved. Rare high-Al clinopyroxene (up to 7 wt.% Al_2O_3) attests to plagioclase-absent fractionation at higher pressure. Amphibole-plagioclase cumulates, in which amphibole replaces clinopyroxene, suggest that the rhyodacitic melts are generated by reactive processes involving amphibole at the base of the crust.

These high-pressure features are absent in the LPA suite. Early plagioclase saturation indicates that differentiation of the LPA suite occurred in the middle to upper crust. Mixing of multiple magma batches is recorded by minor and trace elements in plagioclase, but large variations in An content suggest that changes in intensive parameters and do not directly correlate with changes in melt composition. Trace element compositions do not suggest that the LPA and HPRD suites are derived from distinct primary magmas; rather, differentiation at different crustal levels led to their diversification. The lack of hybridisation between the two suites suggests that they evolved in distinct and isolated parts of the volcanic plumbing system of Nisyros.

Using magmatism to link mantle temperature and dynamic topography beneath western North America

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The region in western North America encompassing the Basin and Range Province, Snake River Plain and Colorado Plateau lies at an elevation 2 km higher than cratonic North America. This difference broadly coincides with variations in lithospheric thickness: <120 km beneath western North America, ~240 km beneath the craton. Thermochronology of the Grand Canyon area, sedimentary flux to the Gulf of Mexico, and inverse modelling of river profiles all suggest that regional uplift occurred in at least two discrete phases. USArray seismic tomographic models have imaged low velocity material beneath most of western North America, including a ring-shaped anomaly around the edges of the Colorado Plateau. Magmatism coincides with these low velocity zones and shows an overall increase in volume at ~40 Ma as well as a change from lithospheric to asthenospheric signature at ~5 Ma. To investigate the relationship between seismic imaging and basaltic magmatism, we have analysed >260 samples from volcanic centres across western North America for major, trace and rare earth elements using ICP-MS and XRF. For asthenospheric samples, we observe a strong correlation between slow velocity anomalies and both location and composition of basalts. Using a combination of petrological observations, forward and inverse modelling of major and rare earth elements, integrated with results from tomographic models, we determine depth of melting and melt fraction. We explore the possibility that volatiles, source composition and/or temperature cause magmatism and uplift of this region. In this way, we use a variety of methods to constrain lithospheric thickness and mantle potential temperature. A dynamic topographic model of progressive lithospheric erosion over an anomalously hot upper mantle could account for regional uplift together with the temporal and spatial distribution of magmatism across western North America.

Deep seismic reflections at volcanic margins: The petrological Moho or from within the mantle?

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Advances in deep long-offset seismic-reflection acquisition and processing now frequently provide imaging of strong and laterally continuous reflectors in the TWTT range of 10 to 14 seconds. Examples of deep laterally-coherent reflectivity can be seen within the ocean-continent transition of the Argentine, Uruguayan and S Brazilian volcanic margins of the S Atlantic. Qualitative interpretation of the seismic data suggests the presence of deep crustal "keels" or crustal roots underlying well developed seaward dipping reflectors (SDRs). Do these deep reflectors correspond to the petrological Moho or could they be located within the mantle?
Joint inversion of the PSTM time-domain seismic reflection and gravity anomaly data has been used to determine the average interval density and seismic velocity between base sediment and the deep seismic reflectivity. Joint inversion densities and seismic velocities for this depth interval reach values in excess of 3000 kg/m3 and 7.0 km/sec for the entire thickness of the interval, substantially in excess of densities and velocities observed for normal oceanic and continental crust. The high densities determined from joint seismic-gravity inversion under the SDR regions are also consistent with results from flexural subsidence analysis.
One interpretation is that the strong deep reflectivity corresponds to the base of the petrological crust and that the crust has an abnormally high average density and seismic velocity due to high-temperature mantle-plume-related magmatism. An alternative interpretation is that the deep seismic reflectivity is located within the mantle beneath the petrological Moho, and that the high density and seismic velocity result from averaging of crustal basement and mantle values. Additional analysis of the deep seismic reflection data suggests that the latter interpretation is correct i.e. the strong deep seismic reflectivity is located within the mantle. The presence of well developed SDRs above suggests that the strong deep seismic reflectivity within the mantle may be magmatic in origin.

The role of fault segmentation and relay ramp geometries on the formation of Irish-type deposits.

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The Lower Carboniferous marine carbonate succession of the Irish midlands is host to one of the world's major base metal provinces, comprised of a number of important Irish-type Zn-Pb deposits. Using 3D modelling, this study aims to accurately and quantitatively constrain the nature and scale of fault segmentation, relay ramp geometries and associated breaching within the Silvermines and Lisheen deposits.

A series of EW to ENE-trending, north dipping, normal faults with throws of 150-200m exists at Lisheen. These faults are laterally discontinuous and form a left-stepping, en echelon array linked by NE-trending ramp relays. Similar structures can be observed on a regional scale as the various deposits in the Rathdowney trend (i.e. Lisheen, Rapla, Galmoy, etc.) are also linked by a large-scale, left-stepping segmented fault array. Structures at Silvermines have been described as a trend of synchronous and interrelated WNW striking, north dipping faults. These fault have close spatial relationships to mineralisation and two areas at which the faults bifurcate initiating a monocline (i.e. relay ramp).

An important determinant of the degree of relay ramp breaching is the scale of segmented fault arrays, in particular fault separation and displacement, with larger scale, relatively intact relays separating individual ore zones, and smaller scale, strongly breached relays potentially providing conduits for up-fault flow.

At Lisheen, larger scale relay ramps with fault separations of 300-500m are incipiently breached and control the location of mineralisation along the segmented fault array. Smaller scale relay ramps with fault separations of <300m, are potential zones of up-fault flow and may control the feeder zone where ore forming fluids enter the host lithology. At Silvermines, a very large scale, rhombic relay ramp with fault separation of 600m controls the location of mineralisation along the segmented fault array. This relay ramp is breached, leading to fault segment linkage and the generation of a second style of feeder at the intersection of the faults. Therefore, in these Irish-type deposits: 1) fault separations of 600-1000m will typically not be breached, 2) fault separations of 300-600m will be incipiently breached and 3) fault separations of <300m are fully breached. Hence, at multiple scales, these segmented fault arrays are responsible for the emplacement and spatial location of mineralisation within Lisheen and Silvermines.

Ultimately, this study highlights that fault segmentation, relay ramp geometries, and associated breaching, play a key role in the development of the Irish-type Zn-Pb deposits.

Key role for syn-eruptive plagioclase disequilibrium crystallisation in basaltic magma ascent dynamics

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Magma ascent dynamics in volcanic conduits play a key role in determining the eruptive style of a volcano. The lack of direct observations inside the conduit means that numerical conduit models, constrained with observational data, provide invaluable tools for quantitative insights into complex magma ascent dynamics. The highly nonlinear, interdependent processes involved in magma ascent dynamics require several simplifications when modelling their ascent. For example, timescales of magma ascent in conduit models are typically assumed to be much longer than crystallisation and gas exsolution for basaltic eruptions. However, it is now recognized that basaltic magmas may rise fast enough for disequilibrium processes to play a key role on the ascent dynamics. The quantification of the characteristic times for crystallisation and exsolution processes are fundamental to our understanding of such disequilibria and ascent dynamics. Using observations from Mount Etna's 2001 eruption and a magma ascent model we are able to constrain timescales for crystallisation and exsolution processes. Our results show that plagioclase reaches equilibrium in 1–2 h, whereas ascent times were ~1 h. Furthermore, we have related the amount of plagioclase in erupted products with the ascent dynamics of basaltic eruptions. We find that relatively high plagioclase content requires crystallisation in a shallow reservoir, whilst a low plagioclase content reflects a disequilibrium crystallisation occurring during a fast ascent from depth to the surface. Using these new constraints on disequilibrium plagioclase crystallisation we also reproduce observed crystal abundances for different basaltic eruptions: Etna 2002/2003, Stromboli 2007 (effusive eruption) and 1930 (paroxysm) and different Pu'u' O'o eruptions at Kilauea (episodes 49–53). Therefore, our results show that disequilibrium processes play a key role on the ascent dynamics of basaltic magmas and cannot be neglected when describing basaltic eruptions. Quantifying the characteristic times for crystallisation and exsolution represents a major step towards a more complete, realistic and general model of basaltic volcanism.

High-resolution geochemistry of volcanic ash highlights complex magma dynamics during the Eyjafjallajökull 2010 eruption

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The April-May 2010 eruption of Eyjafjallajökull volcano (EFJ, Iceland) was characterized by a change in eruptive style and a large compositional variability of erupted products. Lava deposits of the initial phase consist of evolved Fe-Ti-basalt (~47 wt% SiO_2), whereas fallout deposits of the explosive phases are characterized by a wider compositional spread. Here, we present new EMPA and LA-ICP-MS analyses on groundmass glasses of ash particles erupted from 14th April to 22nd May 2010 to unravel the genesis of the compositional variance using petrological, mineralogical and geochemical implications. The glasses define two well-separated groups: a basalt composition ranging from ~50 to 52 wt% SiO_2 and a second group of trachyandesitic and rhyolitic compositions between ~57 to 71 wt% SiO_2. The common occurrence of reversely zoned clinopyroxene (core: Mg# 0.51-0.60, rim: Mg# 0.56-0.71), plagioclase (An_{81-10}) with varying textures (i.e. some are partly resorbed), homogeneous and zoned olivine (Fo_{83-48}) is taken as evidence for mixing between a felsic and basaltic magma. Magma mixing modelling and element concentration frequency diagrams indicate the occurrence of incomplete mixing between a trachyandesite and a basaltic magma, next to another mixing process between trachyandesite and rhyolite melt, causing the great compositional variability during the explosive phase. We suggest the EFJ plumbing system is composed of distinct sills of varying compositions that have been generated and emplaced prior to the eruption. Refilling of the shallow plumbing system by another magma coming from deeper levels is the process that likely triggered the EFJ 2010 eruption. The intrusion remobilized separated magma batches and caused mingling and mixing between them during eruption.

Changes in long-term eruption dynamics at Santiaguito, Guatemala: Observations from seismic data

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Santiaguito (Guatemala) is an ideal laboratory for the study of the eruption dynamics of long-lived silicic eruptions. Here we present an overview of seismic observations of ash-and-gas explosions recorded between November 2014 and June 2016 during a multi-disciplinary experiment by the University of Liverpool. The instruments, deployed around the active dome complex between 0.5 to 7 km from the vent, included 5 broadband and 6 short-period seismometers, as well as 5 infrasound sensors. The geophysical data is complemented by thermal images, optical images from a UAV, and geochemical measurements of eruptive products.

Regular, small-to-moderate sized explosions from the El Caliente vent at Santiaguito have been common since at least the early 1970s (Harris et al., 2003; Rose, 1987). However, in 2015, a shift in character took place in terms of the regularity and magnitude of the explosions. Explosions became larger and less regular, and often accompanied by pyroclastic density currents. The larger explosions caused a major morphological change at the vent, as a rubble-filled vent was replaced with a crater of ~150 m depth. This shift in behaviour likely represents a change in the eruptive mechanism in the upper conduit beneath the Caliente vent, possibly triggered by processes at a greater depth in the volcanic system.

This experiment represents a unique opportunity to use multi-disciplinary research to help understand the long-term eruptive dynamics of lava dome eruptions. Our observations may have implications for hazard assessment not only at Santiaguito, but at many other active volcanic systems worldwide.

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Compression to extension: Evidence for a complete orogenic cycle from Naxos, Greece

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Lithospheric extension is widely believed to be the driving mechanism behind the formation of Cordilleran style metamorphic core complexes. However, in Naxos in the Cycladic archipelago, the cause of metamorphism and the nature of high-grade footwall structures remains controversial. In particular, very little is known about the pre-extensional evolution and the relative timing of peak metamorphism. Here we present new structural mapping, petrography, thermodynamic pseudosection-modelling and in-situ LA-ICPMS U-Th-Pb dating. The metamorphic footwall comprises several nappes that record a prolonged history of orogenesis and metamorphism from ca. 50-15Ma. Cycladic Blueschists at the top of the sequence record M1 metamorphic conditions (~14 Kbars, 450^{0}C) in a subduction zone setting at ca. 45Ma. Continued burial of the continental shelf resulted in crustal thickening, leading to peak kyanite-grade M2 conditions (~10 Kbars, 670^{0}C) at ca. 20Ma. Whilst the underlying sillimanite-grade anatectic core crossed the hydrous solidus at ~8 Kbars in the kyanite stability field at ca. 17.6 Ma, before decompressing to M3 sillimanite conditions (~6.5 Kbars, 720^{0}C) via muscovite dehydration-melting, at ca. 15.9 Ma. We account for this pressure inversion and younging with depth by thick-skinned thrusting during the Early Miocene, that is overprinted and reactivated by extensional fabrics forming the carapace of the Naxos dome. Petrographic evidence from the overlying carapace hanging-wall suggests a lower-pressure thermal M3 overprint on a near-peak mylonitic fabric, at an identical age of ca. 15.93 Ma. Zircon dating of cross-cutting leucogranite melts which are syn- to post-deformational record ages as young as ca. 13 Ma, placing minimum age constraints on the timing of deformation at the deepest levels of the carapace, which is associated with juxtaposition of the M3 migmatites against M2 kyanite-grade nappes. This age discrepancy between peak M2 kyanite- and M3 sillimanite-grade metamorphism of different units can be accounted for by a period of regional crustal thickening resulting in metamorphism and differential exhumation via a combination of thrusting and relative extensional movements on passive roof normal faults during the early Miocene. Our model places formation of the Naxos gneiss dome in a wholly compressional environment, with extension truncating earlier structures, occurring immediately post-peak conditions, and associated with retrogression and exhumation.

Tensile fractures impact on fluid flow in dynamic geological settings.

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The mechanics of tensile fractures is of prime importance to the understanding of how and where fluids circulate within different geological settings. In extensional regions, or in reservoirs undergoing tensile stresses (e.g. columnar joints), the fluid flow is enhanced in direction(s) parallel to fractures opening. In environments capable of building and relaxing stresses (e.g. volcanic systems), fractures can open as a response to gas overpressure and close due to confining pressure (sealing) or to chemical diffusion across the fracture plane (healing), resulting in dynamic changes in permeability.

Here we combine three experimental protocols to investigate: 1) The formation and propagation of tensile macro-fractures in columnar jointing environments by cooling down an Icelandic basalt from magmatic temperature while gripping the sample extremities in constant position; 2) The effect of tensile fractures on the permeability of porous (1 - 41%) volcanic rocks at varying effective pressures (-0.001 - 30 MPa) by comparing, under the same conditions, the permeabilities of both intact and experimentally fractured samples; and 3) The timescale required for fracture healing in glass by monitoring the tensile stress required to break the contact between two rods at high temperature as a function of time in contact.

First, we show that the formation of columnar joints occur well within the elastic regime. Indeed, our results show that, for any cooling rate induced (0.05 – 10 ºC/min), tensile stress builds up only below the solidus temperature, and that 80-100 ºC of undercooling is necessary to induce fracturing.

Then, we show that the presence of a tensile macro-fracture drastically changes the permeability-porosity relationship of rocks. Our results suggest that a single macro-fracture has the ability to efficiently localise the flow in low porosity rocks (<18%) by becoming the dominant structure in a previously micro-fracture dominated porous network. At higher porosities (>18%) fluid flow remains controlled by pore connectivity.

Finally, we show that fracture healing can occur over short timescales, limited by the liquid viscosity and, to a first order, is independent of the applied stress and liquid composition.

By combining the results from 1) and 2), we can model the permeability evolution of cooling magmatic bodies. While combining the results of 2) and 3) can help understanding fluid flow in volcanic conduits through time.

Strain Localisation in Magma: a multidisciplinary collaboration

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The heterogeneous distribution of structures in the Earth enhances strain localisation. Just as magmatism is a manifestation of strain localisation in the lithosphere, volcanism reflects the degree of strain localisation in magma (SLiM). Amongst the many volcanic processes that threaten our environment, the spectacular switch from low-risk effusive to high-risk explosive eruptive behaviour is a direct consequence of SLiM during transport in volcanic conduits.

Our understanding of volcanic eruptions has increased manifolds in recent decades as a result of growing interdisciplinary research strategies worldwide. In particular quantification of the physico-chemical processes underlying eruptive activity is advancing, thanks in part to controlled laboratory experimentation, which provides an opportunity to access the fundamentals of materials behaviour and gauge eruption simulations. Here, we review how laboratory studies on strain localisation in magma have contributed to answer some of the questions raised by geological, geophysical and geochemical studies, discussing processes ranging from volatile exsolution and outgassing to deformation and seismogenic faulting processes associated with volcanic unrest.

Imaging lithospheric discontinuities benath the Afar Rift using S-to-P receiver functions

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The Afar depression is at the northern end of the active, continental, East African rift system, where it forms a triple junction between the Nubian, Somalian, and Arabian plates. The key to understanding how extensional and potentially hotspot tectonics modify tectonic plates during progressive continental breakup is to image the lithosphere. We use S to P extended time multitaper receiver functions on a network of 182 seismic stations that recorded 1616 teleseismic earthquakes in Ethiopia, Djibouti, Eritrea and Yemen. The receiver functions are migrated to depth to investigate and constrain robust lithospheric structures in 3D.

The results show two distinct seismic velocity discontinuities. A strong increase in velocity with depth is observed between 10 to 50 km, interpreted as the Moho. This discontinuity is thinning beneath the Main Ethiopian Rift (MER) and the triple junction, compared to the adjacent plateaux. We identify a negative discontinuity at 50-75km. This anomaly disappears beneath the Afar depression and the MER. This discontinuity is likely related to the lithosphere-asthenosphere boundary (LAB). Locations where the LAB is absent may indicate a velocity gradient that is too gradual (> 60 km) to be imaged by receiver functions, potentially because of melt infiltration.

Petrological and geochemical evolution of the Kyushu-Palau (proto-IBM) volcanic arc, Western Pacific.

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The Kyushu-Palau Ridge (KPR), an Eocene remnant arc of the presently active Izu-Bonin-Mariana (IBM) volcanic arc-basin system in the Western Pacific, marks the original site of Pacific Plate subduction beneath the Philippine Sea Plate. Determining the nature and temporal evolution of post subduction initiation magmatism and subsequent arc volcanism is fundamental to our understanding of arc crust generation and continental crust formation.

In 2014, the Integrated Ocean Discovery Program Arc Origins Expedition 351, successfully recovered a complete record of KPR volcanic activity at site U1438 in the Amami Sankaku Basin, ~500 km southeast of Kyushu (Japan) and ~100 km west of the now extinct KPR (proto-IBM arc). The site U1438 core contains 1461m of volcaniclastic sediment, overlying 150 m of igneous basement and spans the lifetime of the arc from inception to extinction (~52-25 Ma).

This study focussed on retrieving the largest and freshest volcaniclasts, 16 in total and their mafic minerals. The results presented here are major and trace element bulk rock compositions of the volcanic rocks and in-situ major element compositions of clino- and orthopyroxene grains. These are unique samples and present a tremendous opportunity to study the post arc initiation composition variations.

In the absence of olivine, abundant and well-preserved pyroxenes provided an effective proxy of the KPR's primary magma evolution. The results are discussed within the context of existing models of early IBM subarc mantle and/or crustal structure, composition and evolution. The pyroxenes and host volcaniclasts record evidence in support of a model for progressive mantle depletion during the first phase of post subduction magmatism (52-44 Ma), followed by transitional high-Mg andesite volcanism (44-37 Ma) as the first products of explosive arc activity. The bulk rock results from the Oligocene (34-29 Ma) volcaniclasts and their pyroxene chemistry suggest that the mantle source below the KPR was replenished by hotter, more fertile and Indian-type MORB mantle at ~38-37 Ma, coinciding with the eruption of compositionally diverse volcanic rocks, the appearance of co-existing clino- and orthopyroxenes and stronger slab-derived sediment signatures.

Crustal deformation mechanisms of migmatites and mylonites from the Western Gneiss Region, Norway.

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Strain and fluids localise into shear zones while crustal blocks remain comparatively dry, rigid and deform less. However when H_2O is present in the crustal blocks they start to melt, deformation becomes more distributed and is no longer strongly localised into the weak shear zones. Using examples from the Western Gneiss Region (WGR), Norway, we show the deformation characteristics when mylonitic shear zones and migmatites coexist.

The WGR is the lowest structural level of the Caledonian Orogeny, exposing Silurian to Devonian metamorphism and deformation of the Precambrian crust. WGR is predominantly composed of amphibolite-facies quartzofeldspathic gneiss that has undergone partial melting. This study focuses on the southwestern peninsula of the island of Gurskøy. Over a 1.2 kilometre section there is a diverse deformation sequence of migmatized gneiss, mylonitic shear zones, sillimanite bearing garnet-mica schists, augen gneiss and boudinaged amphibolite dykes resulting in a large competence differences between the lithologies over the area. The strongly deformed mylonitic shear zones extend from 5 to over 100 meters in width, but deformation is also high in the migmatitic layers as shown from S-C fabrics and isoclinal folding of leucratic and restitic layers. Microstructural evidence of dynamic recrystallization, symplectite textures and magmatic flow show deformation is widespread over the peninsula.

Strain localisation, melting, and their interactions are studied by a combination of outcrop and quantitative modelling that uses field data, microstructural analysis, crystallographic preferred orientations and numerical Eshelby modelling. Detailed field mapping and microstructural analysis of samples from across the peninsula allows melt quantification and thus an understanding of strain mechanisms when melt is present. This area is important as it reveals the heterogeneity of deformation within the partially melted lower crust on the sub-seismic scale.

SCARP: a Scottish Carboniferous Research Park.

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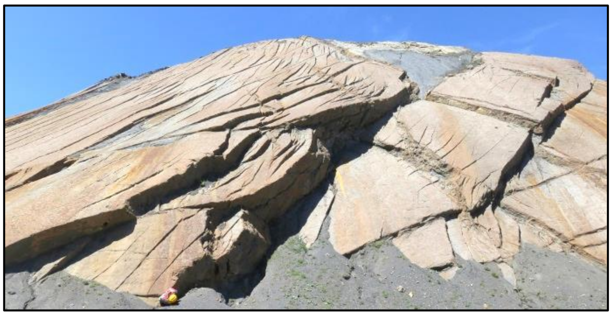
The abandoned Spireslack surface coal mine in East Ayrshire, Scotland, provides stunning and unique sections of Scottish Carboniferous geology. The exposures comprise faulted and fractured Namurian fluvial to marine deposits, and give an insight into the sedimentology of these strata from grain to basin scale. The extensive nature of the outcrop allows for research to be constructed at a fractured (and folded) reservoir scale, comparing remotely sensed data to a real world reality check.

Whilst such a site may be seen as an environmental threat for some, Spireslack can be turned into a learning asset for national good. There is a strong case for retaining such large-scale and superb geological sections that might otherwise be lost to future generations, along with their relevant digital social geological datasets and other industrial records. The aim therefore for the Geoscience community should be to take advantage of this opportunity and develop what is already being referred to as the **S**cottish **Ca**rboniferous **R**esearch **P**ark, or **SCARP**.

This is an exciting opportunity to deliver an anthropogenically enhanced rock laboratory for University training and research and for Industry-led professional development. The site can deliver sub-reservoir scale outcrops particularly suited to studies of the structure and mechanics of fault zones in heterolithic successions such as the North Sea Carboniferous. BGS intend to work with a broad group of University collaborators including Heriot Watt, Keele, Strathclyde and Leeds Universities to unlock more of the secrets of Spireslack and make a digital sub-surface accessible to all.



Complex faults displacing the McDonald Limestone at Spireslack surface coal mine. Rucksack for scale.

Sulfide saturation and breakdown during the 2014-2015 Holuhraun eruption, Iceland

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The 2014 Holuhraun eruption was a basaltic fissure eruption within the Bárðarbunga volcanic system, Iceland. The eruption lasted for six months (from 29 August 2014 to 27 February 2015) and was remarkably sulfur-rich, emitting large quantities of SO_2. The gas flux varied through the eruption, with maximum emission rates measured in early September 2014. Sulfide globules, representing quenched droplets of an immiscible sulfide melt, are preserved within erupted tephra. In this study, we investigate the extent to which shallow breakdown of co-existing sulfide phases may have modulated the efficiency of sulfur outgassing.

Quenched sulfide globules in erupted tephra from early September 2014 are observed both within matrix glass and as inclusions in crystals. The size distribution of sulfide globules ranges from <1 μm to ~25 μm, with a modal diameter of ~10 μm. The spatial distribution of sulfides is not uniform, and instead appears to be clustered. Sulfide globules are most commonly observed in association with 0.3–0.6 mm diameter clinopyroxene-plagioclase crystal clots, but do not directly wet the crystal surfaces.

Globules are predominantly Fe-Cu-Ni sulfides, with average elemental compositions (n=15; measured by EDS) of 42.6 ± 1.26 (Fe wt%), 25.2 ± 0.69 (S wt%), 17.4 ± 2.13 (Cu wt%) and 2.57 ± 0.20 (Ni wt%). Cu and Fe concentrations are strongly negatively correlated, with an R^2 of 0.91. S concentrations are weakly to moderately positively correlated with Fe content. All sulfide globules appear to be breaking down, although the degree of breakdown is variable. Sulfide textures appear related to composition, with the most decomposed sulfides characterised by the most Cu-poor and Fe-rich compositions. Whilst sulfide populations within individual lapilli are generally compositionally similar, heterogeneity between multiple lapilli from the same sample suggest varying degrees of dissolution on a scale larger than that of an individual clast.

Further research aims to (a) quantify the spatial relationships between sulfides, bubbles, and crystals, (b) reconstruct chalcophile element budgets from analysis of glass and of volcanic plume aerosol chemistry; (c) use sulfur concentration profiles in the matrix glass as an indicator of sulfide breakdown timescales, and (d) explore temporal changes in sulfide abundance and/or composition in erupted tephra, and how these variations relate to changing SO_2 emissions during the eruption.

Storage and transportation of magma at a continental rift caldera

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Accumulation of magma in the shallow crust at continental rifts plays an important role in accommodating extension. To understand how and where this magma is stored and transported, we model surface deformation at the Corbetti caldera, Main Ethiopian Rift.

Corbetti is a large (~11 by 13 km) caldera in the southern Main Ethiopian Rift, within which there are two major centres of post-caldera volcanism, Urji and Chabi. Urji and Chabi are both composed of aphyric pantellerites, but their eruption styles are very different. The eruptive products of Urji are primarily pumiceous. By contrast, Chabi erupts obsidian flows.

Near the caldera centre, between Chabi and Urji, we observe continued, rapid uplift between 2009 and the present day, using InSAR. We use data from the ALOS, Cosmo-SkyMed and Sentinel 1A/B satellites and determine an average line-of-sight deformation rate of ~6.6 cm/yr, an unprecedented rate for a rift caldera. Since 2009 >40 cm of deformation has been observed at Corbetti.

We perform a Bayesian inversion for the best fitting deformation source geometry using a Markov-Chain Monte Carlo algorithm of complementary ascending and descending interferograms. We compare the best fitting Mogi, McTigue, Penny shaped crack, Okada Sill, and Yang sources to test theories of magma storage and transport during continental extension, and investigate the controlling factors.

We compare our modelling results to GPS, and microgravity data, which indicates the deformation is caused by a source of magmatic (pantelleritic) density, and evaluate this in the context of available petrology. We consider the possible connection between the source geometry, local tectonics and a pre-rift rift-oblique fault. We also consider how storage and transportation of magma in the shallow crust is related to the surface volcanism; an important consideration in understanding volcanic hazard.

Analysis of crystal plasticity from EBSD datasets based on Schmid factor and critical resolved shear stress: possibilities and caveats.

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Development of electron backscatter diffraction (EBSD) has led to a proliferation of crystallographic orientation data in statistically viable datasets for many different minerals, permitting application of standard materials sciences techniques and concepts to geological samples. One such concept, crystal plasticity, can be analysed based on Schmid factors (SFs), describing stress orientations, and critical resolved shear stresses (CRSSs), describing slip-system strength. Such analysis is increasingly being applied to geological materials deformed at high temperature. To explore the viability of SF/CRSS analysis of common geological minerals, which can exhibit multiple slips systems each with complex yield and post-yield behaviour, we analysed EBSD datasets of calcite and quartz deformed by dislocation creep. Detailed analysis of potential slip system activities reveals that, in general, CRSS-SF analysis, whether or not EBSD-based, needs to consider/involve the following elements:

1. accurate definition of the kinematic framework (e.g. simple shear) via the appropriate deviatoric stress tensor;

2. accurate parameterisation of the variation in CRSS per crystal slip system with environmental variables, especially temperature;

3. understanding of the yield and post-yield behaviour of single crystals, as low stress exponents and/or strain hardening/softening behaviour make the concept of a specific CRSS difficult to apply;

4. impact of magnitude and distribution of applied stress, as increasing applied stress reduces SFs necessary to initiate dislocation glide, but stress states can be highly heterogeneous at the grain-scale;

5. recognition of finite state – SF analysis considers the state at the *end* of the deformation responsible (i.e. state at the start of any subsequent deformation) not the initial state.

Thus, rigorous SF/CRSS analysis of slip-system activity requires numerous detailed and specific constraints on environmental conditions and the rheological behaviour of both single crystals and polycrystalline aggregates.

Megacrysts in tephra of the Manzaz Volcanic District (Central Hoggar, Algerian Sahara)

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The Manzaz volcanic district is a part of the Hoggar Cenozoic volcanic province. The Neogene volcanic activity was mainly caused by reactivation of mega-shear zones crossing the Tuareg Shield, trending either North-South, inherited from Pan-African transcurrent faults, or SE-NW and SW-NE, formed during the Mesozoic. Tephra, ash and tuffs, deposited by air-fall spread around the volcanic edifices. They contain megacrysts that are mainly cm-size brown Ti-rich amphibole (magnesio-hastingsite) and mm to 1 cm-size olivine (Fo94), clinopyroxene (diopside), titanite and plagioclase (oligoclase). Analysed crystals were sampled in the western zone of the district around Oukcem maar and Menzez strombolian cone, and in the central zone at the foot of V1 strombolian cone. Mineral major-element compositions, measured by electron microprobe (EPMA), were used to estimate thermodynamic parameters existing at depth.

The Al-in-amphibole geobarometer (Schmidt, 1992; Anderson & Smith, 1995) suggests one large, or several smaller reservoirs emplaced at a depth of 32 ± 2 km, which corresponds to the crust-mantle boundary under the district. The CpxBar geobarometer (Nimis & Ulmer, 1998) suggests, with a larger error of ± 6 km, additional reservoirs emplaced within the crust at a depth of 25 km in the west and only 10 km in the centre of the district.

The Ti-in-amphibole geobarometer (Féménias et al., 2006) indicates values of 1100 to 1000 ± 15°C. Calculated temperatures are consistent with deep mafic liquids, which amphibole megacrysts crystallized from.

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Corrugations on the S reflector west of Spain: kinematic implications.

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The west Galicia margin (western Spain) provides favorable conditions to study the processes of continental extension and break-up through seismic imaging. It is considered as a world-class example of a magma-poor rifted margin and as such has dominated currently accepted 2D models of breakup. But natural processes are rarely 2D and to better understand continental breakup, a 3D multi-channel seismic dataset was acquired over the Galicia margin in summer 2013. It has been processed through to prestack time migration in collaboration with Repsol, followed by depth conversion using velocities extracted from new velocity models based on wide-angle data across the Galicia margin and applied to a structural interpretation of the fault block structure.

Beneath the tilted fault blocks of the margin is a bright reflection, the S reflector. The faults that bound the present-day tilted blocks detach downward onto the S, showing it is a rooted detachment surface. Both the topographic and amplitude maps of the S reveal a series of linear and parallel low ridges and troughs. We interpret them as slip surface "corrugations" that show direction of slip during the rifting. The orientation of the corrugations changes oceanward, from E-W to ESE-WNW. We support that the rifting of the margin occurred as a clockwise rotation of the COT, reliable with a "V" shape opening to the south formed in the bathymetry by the edges of the Galicia Bank and the Galicia Escarpment. It is also consistent with the southward increasing internal deformation of some of the basement blocks along the margin. It then shows the importance of the 3D component to understand the extension processes leading to breakup.

Clastic meteorite from Mars: petrological & textural insights

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The first clastic meteorites from Mars [1,2] provide a unique opportunity to study the processing and oxidation history at a Martian impact site. Formed in an impact ejecta blanket from precursor magmatic assemblages, with zircons of 4.4 Ga (U-Pb) [3], the whole rock ages of 2.1 Ga (Rb-Sr) [1] and 1.5 Ga (U-Pb) [4] are associated with impact regolith processes. The rocks were ejected from Mars by another impact ~5 Ma ago [5] and found in 2012. Our study combines mineralogical work [6, 7] with the textures, size and shape distribution of the clasts and compares it with terrestrial pyroclastic material and impact ejecta.

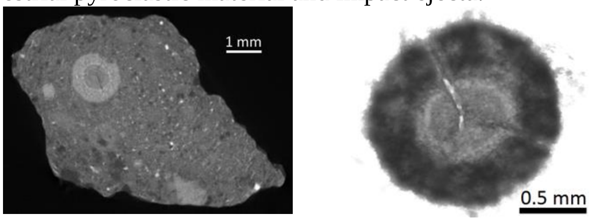

Fig. 1: CT-scan images showing a spherical accretionary pellet-like structure.

Figures 1 and 2 show the range of mineralogy, sizes, shapes and textures. Some pyroxene clasts ($Wo_2En_{65-72}Fs_{26-33}$) have a porous texture and feldspar border, some have exsolution lamellae varying in width, indicating a crystallisation temperature above 900°C, while others ($Wo_{12-18}En_{31-34}Fe_{47-56}$) are more oxidised and show partial breakdown to iron oxide and aluminium silicate [6]. Cryptoperthite alkaline feldspar $Ab_{8-20}Or_{80-92}$ and plagioclase An_{24-43} indicate more than one magmatic source and slow cooling. Feldspar-rich veins ($An_{20-43}Ab_{55-71}Or_{0-16}$) show evidence of subsequent regolith melting. The presence of goethite requires low temperature rock/water interaction [7].

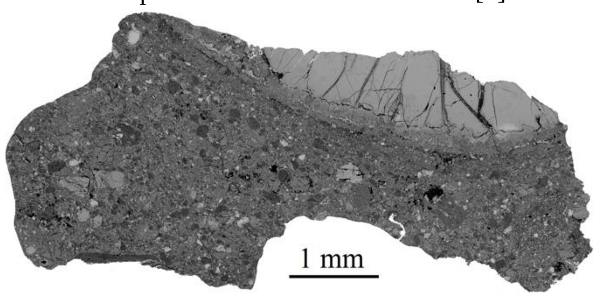

Fig. 2: Backscattered electron image of NWA 8114.

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Carbonate Clumped Isotopes: An Innovative Technique for Geo-Resource Characterisation

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In the search for new energy resources, advanced analytical techniques in geochemistry can provide improved resource characterisation and reduce the financial risk on resource development. A relatively new analytical method which is gaining traction various resource industries is that of carbonate clumped isotopes.

This technique is based on the thermodynamic relationship between carbonate mineral growth temperature and the abundance of chemical bonding ("clumping") between ^{13}C and ^{18}O isotopes (expressed as Δ_{47}) within single carbonate ions (e.g. Eiler, 2007). In the gas phase, isotopic exchange between CO_2 molecules and water is continuous and so CO_2 gas will record the ambient fluid temperature. When the CO_2 is trapped in a solid mineral phase, the isotope ratio is fixed. As a result, clumped isotopes will record the temperature of crystallisation, enabling the application of clumped isotope palaeothermometry to a range of geological problems.

In the context of geo-resources, clumped isotopes has been applied to characterise the conditions of dolomitisation in carbonate hydrocarbon reservoirs (MacDonald et al., 2015; MacDonald et al., in press). Clumped isotope analysis indicates burial dolomitisation in the Cretaceous Pinda reservoir in Angola at 100-120 °C, something not picked up from previous palaeothermometric studies utilising fluid inclusions (MacDonald et al., in press). Gaining this type of temperature evolution constraint is a key part of basin thermal models.

Ongoing research is indicating the utility of clumped isotopes in geothermal energy systems as well. Fracture filling with calcite is a major problem in some geothermal fields. Clumped isotopes can give us constraints on the temperature of fracture filling and the source of the fluid from which the calcite is precipitating. Having this understanding of fracture filling conditions can lead to focused development of remediation measures.

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Magma storage depths under Icelandic volcanoes from refreshed petrological barometry

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Petrology provides fundamental constraints on the nature of the magmatic plumbing system of active volcanoes, informing our understanding of the processes that precede eruptions and improving interpretation of monitoring data. One key problem that can be addressed through petrological investigation is the depth of magma storage. Such barometry relies upon the application of parameterisations of experimental observations of mineral-melt equilibrium to natural systems. However, the relative ease with which published barometers can be applied to natural systems which depart significantly from equilibrium presents a serious problem for the reliability of the petrological contribution to studies of volcanic systems.

One widely-used barometer, the OPAM method, was should only be applied to basalt melts that are in co-saturated in olivine, clinopyroxene and plagioclase [1]. The parameterisation expresses Ca, Al and Fe as a function of pressure and other melt components and is based on multivariate linear regression of experimental data. Widely used realisations of this barometer have been based on rearrangement of the expressions from the regression – such rearrangement is not permitted under the mathematics of regression. What is more, melts from sample suites where there is scarce evidence for OPAM co-saturation have also been processed through the barometer, producing some erratic and notably unreliable results in the published literature.

We have used the original regression result to cast the problem as one of misfit minimisation. This allows us to assess the likelihood of the fit and to start to eliminate melt compositions that are far from OPAM saturation. By comparison with experimental databases, we are able to provide a quantitative measure of uncertainty of the barometer. We apply this new barometer to a large dataset of Icelandic basaltic glass compositions to provide an updated view of the depth distribution of magma chambers under Icelandic volcanoes. These results are compared with those from a new clinopyroxene-liquid barometer [2].

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Volatile loss from ignimbrites: Evidence for fiamme-vesicle interactions

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Degassing of ignimbrites is an important process in their post-emplacement evolution. This study investigates the degassing behaviour of a ~15 m thick, high-grade ignimbrite located near Villanova, Sardinia. Post-emplacement degassing of high-grade ignimbrites is usually associated with fumarole pipes (Freundt & Schmicke 1995), however, in this deposit fiamme are decorated by vesicles.

Measurements of cross-sectional area (CSA) were undertaken by image processing techniques to investigate the mechanisms of degassing. The CSA is used as a proxy for volume. A positive linear relationship exists between the CSA of the fiamme and vesicle cavities. The ratio between the CSA of vesicles above and below fiamme (asymmetry ratio) furthermore reveals that 62% percent of the 78 structures have more vesicles below than above with a minimum ratio of 0.07.

The positive relationship between the CSA of vesicles and fiamme implies that vesicles are produced by degassing of the pumice clasts. To evaluate the low asymmetry ratio, an analysis of the forces that acted on the volatiles as they were exsolved was undertaken and suggests that buoyancy forces are negligible compared to the surface tension that resists gas loss. An equal volume of volatiles will, therefore, be expelled above and below the fiamme. The low asymmetry ratio, therefore, indicates a process unrelated to simple compressional expulsion of volatiles

Vesicle loss and capture might explain why the majority of fiamme have a larger volume of vesicles below than above. To test whether vesicles can rise sufficiently to enable capture, a model of vesicle migration within rhyolitic ignimbrites containing 2 and 4 wt% H_2O, cooling from temperatures of 800 and 1200 ^{o}C was conducted. The results show that it is possible for vesicles to rise more than the separation distance between fiamme, estimated to be 50cm. Escaped vesicles can, therefore, be trapped by overlying fiamme, increasing gas volume below fiamme.

Vesicle-fiamme interactions have significant implications for the degassing of ignimbrites. Fiamme can act as baffles that channel volatile flow providing a mechanism for the collection of volatiles into fumarole columns, which typify ignimbrites, and facilitate rapid gas loss.

Seismic imaging of a Permian-Carboniferous dyke swarm offshore southern Norway

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Dyke swarms play a fundamental role in continental rifting and breakup. For example, numerous studies from a range of Earth Science disciplines have demonstrated that break-up in East Africa is, in places, being driven by dyke intrusion. The lack of suitable field outcrops and the typically low-resolution of geophysical imaging techniques, however, means that the 3D structure of dyke-dominated extensional zones remains poorly constrained. Over recent decades, the widespread availability of high-quality 3D seismic reflection data from the rifted margins has revolutionized our understanding of magma plumbing systems and the role that magmatism plays in rifting. However, seismic reflection data typically cannot image sub-vertical structures; i.e. sills are often well-imaged in seismic data but dykes are rarely resolved.

In this study we use borehole-constrained, closely-spaced 2D seismic reflection data from offshore southern Norway to examine the first seismically recognised, dense swarm of dykes that have been rotated following post-emplacement basin flexure. The swarm has a WSW-ENE orientation and covers a *c.* 2000 km^2 area. Within the seismic data, individual dykes are expressed as prominent high-angle reflections that cross-cut, but do not offset, Permian-Carboniferous stratigraphy, with the density of the reflections decreasing away from the centre of the swarm. These high angle reflections are truncated at the base upper Permian unconformity and are interpreted as having been emplaced during the Permian-Carboniferous. We correlate this dyke swarm along-strike to the east to the Permian-Carboniferous Skagerrak-centred Large Igneous Province (LIP), and to the west to the Midland Valley dyke suite, onshore UK; the swarm therefore forms a system over 800 km long and, in our study area, likely accommodates approximately 10 km of extension.

Two sets of faults are concentrated above the dyke swarm; one set is Triassic and is truncated above by the base Jurassic unconformity, whereas the other also initiated in the Triassic, but was reactivated in the Early Cretaceous due to margin flexure. We show that the presence of dyke swarms may act as preferential nucleation sites for later flexure-related faults.

Emplacing a cooling limited rhyolite flow

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The eruption and emplacement of high silica rhyolite lavas is poorly understood due to the infrequency of eruptions. The 2011-2012 eruption of Puyehue-Cordón Caulle, Chile, provided the first scientific observations of the emplacement of an extensive rhyolite flow. This flow was observed to advance before halting prior to breakout formation from the stalled flow front and margins. This cooling limited flow behaviour suggests that the crust had a controlling influence on the flow emplacement.

The 2011-2012 eruption of Cordón Caulle presents an unparalleled opportunity to understand the emplacement and rheological controls of rhyolite flows. Numerical models of flow lengthening can be used to infer whether a flow was controlled by its Newtonian viscosity, bulk yield strength or crust yield strength. Typically these models are applied with a high degree of freedom in the parameters used. Here we attempt to constrain flow parameters from observations of the flow advance before using this understanding to inform flow-lengthening models.

The flow observations and numerical models suggest that the flow was controlled in its initial phases by its Newtonian viscosity and then by its cooled surface crust. This surface crust greatly influenced the flow advance as well as controlling the characteristic features generated.

3D modelling of roughness evolution and gouge production in faults

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The frictional sliding behaviour of faults is intrinsically linked to fault roughness and gouge production during slip. The processes may also control the dynamics of rock-slides, avalanches and sub glacial slip thus are of general interest in several fields. Here we investigate the interplay between fault roughness evolution and gouge production using 3D Discrete Element Method (DEM) Boundary Erosion Models. Our fault walls are composed of many particles or clusters stuck together with breakable bonds. When bond strength is exceeded, the walls fracture to produce erodible boundaries and a debris filled fault zone that evolves with accumulated slip. We slide two initially bare surfaces past each other under a range of normal stresses, tracking the evolving topography of eroded fault walls, the granular debris generated and the associated mechanical behaviour. The development of slip parallel striations, reminiscent of those found in natural faults, are commonly observed, however often as transient rather than persistent features. At the higher normal stresses studied, we observe a two stage wear-like gouge production where an initial ‘running-in’ high production rate saturates as debris accumulates and separates the walls. As shear, and hence granular debris, accumulates, we see evidence of grain size based sorting in the granular layers. Wall roughness and friction mimic this stabilisation, highlighting a direct link between gouge processes, wall roughness evolution and mechanical behaviour.

A pyroxenic view on major effusive and explosive eruptions at Popocatépetl volcano, Mexico, in the last 2000 years

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Popocatépetl is one of Mexico’s most active volcanoes, and with about 20 million people living within 80 km from the crater also one of the most dangerous ones. Continuously active since 1994, Popo has had at least five Plinian eruptions in the last 23 ka, with intercalated phases of effusive to mild explosive activity. Similar whole-rock characteristics for both effusive and explosive eruptions suggest no significant changes in the volcano’s feeding system, raising the question which processes control the transition between different styles of activity. We examine zoned pyroxene phenocrysts from the most recent Plinian eruption (Pink Pumice, 1100 yrs BP) and the preceding effusive Nealticán flank eruption (<2000 yrs BP), to assess the potential role of mafic injections as a primary control on eruptive style.

In both rock types, two orthopyroxene populations of distinct core compositions (Mg# 63-68 and 82-88, respectively) imply at least two separate magma storage regions, and common intermediate bands (Mg# 69-83) testify to frequent mixing and hybridisation of the corresponding mafic and evolved melts at depths of 3-6 km and temperatures of 930-990°C. Fe-Mg diffusion modelling of pyroxene crystal stratigraphies indicates that such mixing events occurred days to weeks before both the Nealticán and the Pink Pumice eruption, tracing magma remobilisation by mafic injections at similar timescales for both eruptive types. However, some pyroxenes record a longer and more complex history, with distinct injection events preceding the eruptions by years to decades, suggesting the presence of a stagnant shallow magma body with a complex crystal cargo. In the Pink Pumice, such crystals are more abundant and show longer residence times than in the Nealticán lavas, which indicates that the injection triggering the Pink Pumice eruption remobilised a larger volume of crystals in the storage region.

Melt & Trace Element Transport in a Heterogeneous Mantle

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Trace element distributions of MORB, obtained from lavas and fluid inclusions, vary significantly over small spatial scales. This variability has been attributed to channelised melt transport, in which enriched low-degree melts are transported rapidly, in isolation from the inter-channel melts (Spiegelman and Kelemen, 2003). We aim to reconsider this hypothesis by evaluating the role of mantle source heterogeneity in melt transport, and how this shapes trace element concentrations in erupted basalts. Our primary goal is to understand whether the signal of source heterogeneities is evident in erupted MORB products. We investigate how correlations between major and trace element heterogeneities in the source shape the distributions. Are the correlations and amplitudes of these source heterogeneities preserved or destroyed in the final distributions? Moreover, how does this behaviour vary with equilibrium state and volatile content?

We investigate these questions via two-phase computational melting-column models formulated with mantle volatiles (Keller and Katz, 2016). We simulate the underlying mantle heterogeneities by varying the amplitude, wavelength and correlation of the heterogeneity fields. This is coupled with consideration of the effect of volatiles contained in the melt, as well as considering the system in both equilibrium and non-equilibrium formulations (Spiegelman, 1996). As a post-processes step, we use consider different methods of sampling trace-element model output for comparison with geochemical data.

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Multi-bowl sills – interpreting their mode of emplacement

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Intrusive sills are commonly 'saucer-shaped' in that they have bases which are close to concordant to stratigraphy and peripheries which transgress upwards through stratigraphy. Most saucer-shaped sills have single concordant areas, however, some sills have multiple concordant areas with transgressive margins. Each of these structures have broadly 'bowl-shaped' geometries, hence, these sill have been named in this study 'multi-bowl sills'. The 'bowls' are connected by junctions, however, it remains an open question whether the 'bowls' are fed individually by dykes or whether the sills propagate from bowl to bowl sequentially.

Multi-bowl sills from offshore Norway (Vøring Basin) have been investigated within three seismic volumes. The Vøring Basin was intruded by numerous sills ~56 Ma during the break-up between Norway and Greenland.

The multi-bowl sills are all asymmetrical in the vertical direction in that the bowls are always concave upwards, with the junctions between bowls being either sharp crests or relatively concordant portions. In a particularly clear example, the magma is observed to have generated two magmatic pipes connecting three bowls together, suggesting that magma propagated from bowl to bowl sequentially. This implies that multi-bowl sills can form as magma propagates downwards into the bowls, and upwards out of the bowls. The transition from downward to upward propagation within the bowls is approximately symmetrical in the horizontal direction and continuous (at a seismic scale), while the initial downward propagation into the bowls is much more abrupt.

Shallow multi-bowl sills are interpreted to be related to a class of shallow sills which exhibit very little transgression, but exhibit 'flow-related features' such as magma tubes or ridges. These types of sills have previously been interpreted to have their distinctive geometries because they propagated forming peperites. Peperites form as magma vaporises water in shallow unconsolidated sediments so that the host becomes fluidised. This is distinct to deeper sill propagation which has been interpreted to be principally the result of brittle fluid-filled fracture propagation. Multi-bowl sills are suggested to form at the transition between a shallower peperite forming regime and a deeper brittle fracture regime, in order to explain the bowl geometries, magmatic pipes, lobate geometries and the oscillatory magma propagation paths from bowl-to-bowl. This is interpreted to be a newly recognised mode emplacement for saucer-shaped sills.

Emplacement mechanisms of the Alpe Morello peridotite, Ivrea-Verbano Zone, NW Italy: insights from microstructural analyses.

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Textures, microstructures and mineralogy of peridotite from the Alpe Morello ultramafic body are investigated to assess the evolving deformation mechanisms and metamorphic conditions during the body's exhumation from the upper mantle through the lower crust. The mechanisms of juxtaposition of the Alpe Morello peridotite with upper crustal rocks of the Serie dei Laghi through the Cossato-Mergozzo-Brissago (CMB) shear zone are also explored. Petrographic analysis of Cr-spinel lherzolite reveals that peak metamorphic conditions were attained within sub-continental upper mantle at 1100°C. An amphibolite facies overprint at <1000°C is evidenced by the appearance of pargasite. Pigeonite exsolution lamellae observed in orthopyroxene are likely to have formed below 800°C. Partial and whole serpentinization of the peridotite is seen in the easternmost part of the body and is indicative of significant fluid flow and fluid-rock interaction late in its geological history. Considerable grain size reduction can be observed in localised zones within the peridotite and near its eastern and western boundaries. Lattice distortion in coarser grains is caused by intracrystalline plasticity during dislocation creep. From crystallographic preferred orientations (CPOs) in olivine the activity of (010)<001> slip system is inferred, and may be indicative of 'low' T dislocation creep between 700°C and 1000°C. Pyroxene CPO shows dislocation glide along (100)<001> during deformation within the upper mantle. Localised within serpentine fabrics, brittle deformation is seen through faulting and cataclasis, recording the later stages of deformation at shallower crustal levels. This heterogeneity of the microfabrics is interpreted to represent the propagation of the Permian low-angle extensional fault (CMB shear zone) into the mantle, and subsequent exhumation of the peridotite to retrograding conditions during Alpine orogenesis.

Using seismic and tilt measurements to forecast eruptions of silicic volcanoes – an introduction.

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Both seismicity and tilt measurements have been independently used to assess the eruption potential of active silicic volcanoes. Tilt measurements are highly sensitive indicators of ground deformation and in basaltic systems, fluctuations in tilt have been interpreted to coincide with inflation and deflation of a shallow magma reservoir. However, observations at Soufriere Hills volcano, Montserrat, suggest that in silicic systems, an increase in tilt may arise from viscous magma pulling up the surrounding edifice via shear stress. The onset of seismicity is observed to coincide with an inflection point in the tilt measurements, which suggests an intrinsic link between the two measurements exists. It has been interpreted that brittle failure of magma during ascent releases this shear stress from the system, observed as a decrease in tilt, each a function of ascent rate. In this study we will use data from the ongoing eruption at the Tungurahua volcano, Ecuador, to develop a forecasting tool to be used on an operational level in volcano observatories.

Unmasking the Kalkarindji: the effects of long term weathering on the primary magmatic signature

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The Kalkarindji flood basalt province was erupted onto a mid-Cambrian continental margin on the North Australian Craton of Gondwana. The volcanic pile outcrops over an area the size of Ireland (c. 50,000 km^2) in the semi-arid Northern Territory desert. Since eruption, the lavas have been largely unaffected, remaining at, or near, the surface of a continent which has been situated in humid tropical regions, enhancing the effectiveness of chemical weathering.

We investigate the extent of alteration to have affected the Kalkarindji basalts over 500 Myrs since their eruption on the North Australian continent and the effect this has on deciphering the correct geochemical signature. Investigations of the physical weathering through a stratigraphic log discovers the extent and depth of pervasive weathering affecting the crystallographic structure, whilst chemical indices of alteration highlight the nuances and complexities involved in unravelling the chemical signature of this province.

This study identifies saussuritisation as the primary method of mineral replacement. Fluids entering the system leached, and mobilised specific elements with secondary growth of clays initiated by the need to precipitate elements into a solid state, largely as sericite, saussurite chlorite and Fe-oxides. This chemical alteration is low and nearly undetectable in many classic indices. Alteration has occurred as a near-closed system with the effect being that bulk chemistry remains largely unchanged even though the basalts are highly altered on a crystallographic scale.

Further geochemical analysis across the province displays the influence of fractional crystallisation on the magma source, highlighting a common parentage for all samples associated with the Kalkarindji volcanic event. Late stage lavas do not exhibit evolved signatures, indicating magma recharge and indications in trace elements suggest crustal contamination, possible assimilation and fractional crystallisation of minerals from the magma between 5 -10 km depth.

Recording magma flow variation across sill thickness: insights from magnetic anisotropy studies

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Investigating the factors that influence magma transport and emplacement within the crust is vital for understanding the behaviour of volcanic systems. Studying extinct volcanoes where erosion has exposed their plumbing systems provides insights into a range of stages of magma movement however unravelling which parts of the transport history are preserved is challenging. Detailed sampling and analysis indicate that structures preserving magma flow within intrusions suggest flow may be highly variable over small distances. Subsequently, understanding the implications these signals have on interpretations of magma flow dynamics may require reconsideration.

Fieldwork was conducted on well exposed sills near Inver Tote, Isle of Skye, Scotland. Here olivine dolerite sills from the Little Minch Sill Complex (c.60 Ma) have intruded Jurassic sediments. The sills are 6 to >15 m thick; with the occurrence of gabbro lenses, crystal layering, and variations in the mineral proportion, size and composition differentiating them. Two basaltic dykes cross-cut the site in a NNW-SSE orientation.

Closely-spaced sampling was carried out on a selected sill to analyse its magnetic fabrics using Anisotropy of Magnetic Susceptibility (AMS) and Anisotropy of Anhysteretic Remanent Magnetization (AARM). AMS identifies the signal from larger magnetic minerals (>50 μm) and AARM identifies the signal from smaller grains that record a remanent magnetization (<5 μm). When AMS and AARM tensors have similar orientations, a normal fabric is observed and can be directly used to infer magma flow direction, whereas when the tensor axes do not compare directly, further investigation is required to understand the implications for magma flow.

Results from the sill suggest that AMS tensors have a K_1 axis (long axis) parallel to the sill length, originating from ferromagnetic grains with hysteresis properties suggestive of multi- to pseudo-single domain titanomagnetite. The orientations of the K_1 axis rotate around the vertical axis (K_3, shortest axis) from a N-S orientation to NE-SW orientation with increased distance from the sill margins, remaining parallel to sill length. At the lower contact AARM K_1 axes are parallel to AMS K_1 suggesting normal fabric and magma flow in a N-S orientation, however with increased distance from the margin they become more oblique (AARM between N-S and NW-SE and AMS in NE-SW) suggesting anomalous fabrics and as such interpretation of the magma flow direction requires further investigation.

Earth's exhaust pipe: carbon isotope systematics in volcanic arc gases

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Of the total amount of carbon contained in Earth, the mantle is the largest reservoir. Cycling of carbon between the surface environment and the mantle takes place via carbonate subduction and volcanic outgassing. Imbalance in this cycle has huge significance for atmospheric CO_2 concentration and consequently for atmosphere-ocean temperature over geological timescales. Carbon isotopes, combined with other geochemical tracers, may provide a means to isolate sources and mechanisms of carbon cycling. Carbon in subducting slabs takes the form of organic sediments (with a $\delta^{13}C$ of -40 to -20‰) and carbonate fixed in the oceanic crust during hydrothermal circulation (with $\delta^{13}C$ of ~0‰). The $\delta^{13}C$ composition of the depleted upper mantle has been proposed to be -6±2.5‰. Volcanic gases might be expected to be influenced by these sources, as well as by crustal contamination and interaction with hydrothermal systems. We have created an updated compilation of $\delta^{13}C$ values of emissions from arc volcanoes, in tandem with He and N isotopic data (where available) to provide additional constraint on subduction inputs and crustal contamination. While a small number of arc volcanoes emit gases that fall within typical mantle values, there is a dominance of heavier-than-mantle values in much of the compiled arc volcanic data, particularly when weighted by CO_2 flux. Heavy carbon volcanic outputs, with low $^3He/^4He$, are particularly common in continental settings. We propose that whilst the heavy carbon signature of arcs may be influenced by a contribution from subducted inorganic carbon, there is also a strong signature of contamination by carbonate contained within the overriding crust (accreted as carbonate platforms during ocean closure), particularly among volcanic arcs of the Tethyan margin. Observations of modern day volcanic carbon isotope systematics may be used to infer how the volcanic signal might have changed accompanying Wilson cycle supercontinent formation and rifting through the Phanerozoic.

Magma genesis and storage conditions in the Ethiopian Rift: new constraints from oxygen isotopes and phase equilibria models

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The Ethiopian Rift hosts a number of peralkaline volcanic centres, with many showing signs of recent unrest. Although huge volumes of chemically evolved silica-rich rocks have been erupted across and along the rift, there are few constraints on the magma storage conditions and petrogenetic origins of these melts.

We investigate magma storage conditions at Aluto, a typical restless caldera system, by comparing empirical analyses of erupted deposits with theoretical liquid lines of descent modelled under different conditions. This petrological approach provides independent constraints on magma storage, which can be compared with interpretations from geophysical datasets.

We ran ~150 fractional crystallisation models, using the Rhyolite-MELTS thermodynamic software and assessed the liquid lines of descent produced using two different starting compositions, which represent estimates of the parental melt feeding the system. The best agreement between models and natural samples is at low pressures (150 MPa), low initial H_2O concentrations (0.5 wt%) and relatively high oxygen fugacity (QFM). The depth of magma storage derived from these results (~5.6 ± 1 km) agrees well with InSAR measurements of ground deformation at Aluto in 2008.

The best-fit Rhyolite-MELTS models suggest that peralkaline rhyolites are generated via fractional crystallisation from a rift-related basaltic composition, without the need for significant crustal assimilation. To explore this further, we undertook oxygen isotope ($\delta^{18}O$) analyses on suite of samples from across the Ethiopian Rift. Although subtle crustal contamination signals are identified in rare comendite samples (up to 7.8 ‰) the bulk of the new $\delta^{18}O$ data fall on typical MORB fractional crystallisation trajectories (i.e. 5.5–6.5‰). These new geochemical and modelling constraints suggest that the diversity of silicic melts in the Ethiopian Rift is primarily a function of fractional crystallisation and magma storage processes, and that crustal melting plays a fairly limited role.

Olivine crystallisation temperatures as a proxy for mantle temperature

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Variations in mantle temperature are a primary control on the melting behaviour of the mantle. Despite its importance for understanding present day volcanism and the thermal evolution of the Earth, mantle temperature has remained difficult to quantify. Proxies, such as crustal thickness, seismic velocity, and melt chemistry must be used; however, each suffers from its own uncertainties and trade-offs with other equally uncertain parameters. Melting anomalies, such as Iceland, have been variously linked to raised mantle temperature, unusually fusible mantle, or enhanced mantle flow.

Several studies have recently used olivine crystallisation temperatures, derived from olivine-spinel aluminium-exchange thermometry, as a proxy for mantle temperature. When offsets in olivine crystallisation temperatures are used to infer mantle temperature variation directly, it is implicitly assumed the method does not suffer from trade-offs arising from greater mantle fusibility or enhanced mantle flow.

Using a new set of crystallisation temperatures determined for four eruptions from the Northern Volcanic Zone of Iceland, we demonstrate crustal processes, rather than mantle processes, are responsible for the crystallisation temperature variation within our dataset. However, the difference between Icelandic crystallisation temperatures and those from MORB, are most easily accounted for by substantial mantle temperature variations.

The thermal structure of the mantle melting region will determine the chemical and thermal properties of the melts entering the crust. As lithological heterogeneity can exert a large effect on the thermal structure of the melting region, we assess its effect on crystallisation temperature using a forward thermal model of multi-lithology melting. Using crystallisation temperature estimates from Iceland and MORB as examples, we demonstrate that in the absence of further constraints on the thermal structure of the melting region (e.g. crustal thickness), crystallisation temperature provides only a weak constraint on mantle temperature.

By inversion of our thermal model, fitting for crystallisation temperature, crustal thickness, and fraction of bulk crust derived from pyroxenite melting, we demonstrate that a mantle temperature excess over ambient mantle is required for Iceland. We estimate a mantle temperature of 1480^{+37}_{-30}°C for Iceland, and 1318^{+44}_{-32}°C for MORB.

Textural analysis of obsidian: An insight into collision related magmatism

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The geodynamic nature of the Lesser Caucasus region provides an ideal setting to study the occurrence of widespread young volcanism atop a complex history of subduction, obduction and collision [**1**]. Neogene-Quaternary volcanism in this region manifests as a number of volcanic arcs and represents a major area of terrestrial magmatism related to ongoing continental collision [**2**]. The Geghama volcanic highland is located in central Armenia; numerous monogenetic and polygenetic volcanoes make this an ideal site for the study of these young volcanics.

Obsidian is ubiquitous within the volcanic material of this region, yet there has been little work undertaken to determine its petrogenetic history. Quantitative measurements of microlite crystals in obsidian samples can provide significant insight into the eruptive dynamics and emplacement history [**3**]. In particular, microlite number density and orientation represent the summation of conduit flow, degassing and emplacement [**4**]. As such, there is great significance in the textural quantification of these parameters in obsidians collected from this region. Non-destructive microscopy techniques allow for direct measurement of microlites in the third dimension [**5**]. This provides a means of quantitatively comparing micro-textural variability between pyroclastic and effusive obsidians collected in deposits from two polygenetic rhyolitic centres (Hatis and Gutanasar). Analysis of these obsidians will establish patterns of textural heterogeneity as a signature for the distinction of volcanic glasses formed by different mechanisms (in-situ melting or effusive emplacement) and allow for identification of patterns in microlite alignment. Together these measurements will aid interpretation and improve understanding of this volcanic system, with applicability to the determination of the impact of these volcanic episodes on the distribution of early man in Armenia as well as assessment of the potential for future events.

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Fracturing related to granite emplacement in the Mourne Mountains

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The Mourne Mountains (MM), Northern Ireland, consists of five successively intruded granites, named Granite 1 to 5. The granites were emplaced as sheets or laccoliths at shallow crustal levels into Caledonian greywackes about 56 Ma ago. The host-rock greywackes are particularly hard due to zeolite facies metamorphism, generally steeply dipping, and isoclinally folded in the area [1]. In this study, we examine host-rock fracturing and the contact-proximal response to the granite intrusion to discern deformation of competent host-rock during magma intrusion at shallow crustal levels. We collected over 4000 fracture, dyke, and bedding measurements in the granites and the greywacke roof- and wall-rock in the MM to characterise fracture systematics related to the intrusion of the granites.

The host-rock in the eastern MM displays a minor set of semi-vertical fractures and larger aplitic dykes related to granite emplacement. In the western MM, pervasive semi-vertical fractures, parallel and perpendicular to the roof and wall contacts and sometimes intruded by aplitic dykes occur in the greywacke. Within 100 m from the contact, abundant mm to dm thick dykelets of granite intruded the bedding and fractures in the host-rock in the western MM. Our fracture analysis shows that granite emplacement generated Mode I tension fractures, which indicates that the granite intrusions were inflating. The differences in fracture patterns and intrusive brecciation between the eastern and western MM also suggest that the granite intrusion affected the host-rock more in the west. Variations in the orientation and deformation of the host-rock might have promoted differences in the response to the intrusion. Alternatively, the major boundary fault at the eastern border of the granites could have accommodated the intrusive uplift and consequently most of the strain caused by the granite intrusion in the east. Relatively higher stress would therefore have affected the roof rock in the west.

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Near-field monitoring of fault slip during the 2016 Central Italy seismic sequence

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Following the 24th August Central Italy earthquake (6.2 M_w), we have carried our detailed mapping of surface ruptures, collected terrestrial laser scan and Structure-from-Motion derived geospatial datasets and installed ten low-cost GNSS units as short baseline pairs across the causative Mt. Vettore normal fault in five different locations. The primary purpose of the datasets are to investigate repeat shallow coseismic and postseismic fault-slip process in relation to fault geometry, surface cover type and thickness, and along fault position. This combined approach to earthquake research will provide unprecedented insight into the temporal and spatial development of the 2016 Central Italy seismic sequence across a range of scales and depths. We are developing a low-cost Global Navigation Satellite System (GNSS) solution for the continual monitoring of active processes. The dataset covers the postseismic period of the 24th August 6.2 M_w, 26th October 5.5 M_w & 6.1 M_w earthquakes and the coseismic-postseismic period of the 30th October 6.6 M_w earthquake. The field datasets will be integrated with as coseismic and postseismic InSAR, body-wave seismology and coulomb stress modeling to provide insights into the co-seismic and post-seismic deformation associated with the sequence and understand the nature of stress modification on other faults in the region.

The North Scotia Ridge; A Plate Boundary?

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The boundary between the Scotia and the South American plates is defined by the North Scotia Ridge. The North Scotia Ridge stretches from offshore Terra Del Fuego to South Georgia and is composed of a series of small crustal blocks, largely characterised by active strike slip displacement.

Immediately south of the Falkland Islands the North Scotia Ridge is dominantly compressive in nature, whereby the Burdwood Bank, a crustal block, is thrust over the southern margin of the Falkland Plateau. This compression led to the development of a fold and thrust belt and foreland basin, as well as significant downwarping of the Falkland Plateau. This zone of compression is typically referred to as the Falklands Thrust, and is considered to represent the plate boundary. However, the southern margin of the Burdwood Bank is marked by a much simpler and dramatic continental-oceanic transition.

Using modern 2d and 3d seismic reflection data, as well as recent exploratory well data, this study will discuss the nature of this enigmatic plate boundary.

Geothermal Energy. The nexus between magmatics, tectonics, and geophysics.

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Geothermal energy uses the naturally occurring heat contained in the subsurface to drive turbines for power or to directly use in industrial or domestic settings. Even in mature geothermal settings (e.g. East African Rift, or the Paris Basin) there is significant exploration risk akin to hydrocarbon exploration.

This poster uses two examples, from vastly different geothermal exploration settings, to show how applied research in magmatics, tectonics, and geophysics identifies new potential geothermal resources and de-risks exploration.

The granites of the East Grampians of Scotland are currently in pre-exploration phase of resource development. Gamma-ray spectrometry surveys have found some of these granite plutons are enriched in the radioelements potassium, uranium, and thorium. The heat produced from radioactive decay significantly raises the geothermal gradient compared to surrounding rock. Temperatures high enough for direct usage (~80^{o}C) are estimated at depths of 2-3km, which would be economically feasible to use as part of a heating scheme of several MW size. However, there remains significant uncertainty over the permeability of these granites at depth. This is currently a barrier to development, as any scheme would need to tap into naturally occurring fracture networks and probably use stimulation methods in order to get required flow rates.

The East African Rift System (EARS) is an active exploration area where geothermal energy could allow emerging economies to develop without large consumption of fossil fuels. However traditional exploration techniques (e.g. using magnetotellurics to identify clay caps) do not work in all areas of the EARS, e.g. parts of Rwanda where relatively young active volcanoes rest on metamorphic basement rocks which are not conducive to hydrothermal clay development. Investigations using lower cost geochemical and geophysical surveys are helping identify new geothermal resource plays in hitherto underexplored areas, as well as de-risk exploration in mature plays by identifying active subsurface fluid networks. The EARS represents a high-enthalpy geothermal resource where water is tapped at ~200^{o}C which flashes to steam at surface driving turbines for power production.

Multi-sensor measurements of gas emissions from the volcanoes of Papua New Guinea

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Papua New Guinea is among the most active regions of volcanism in the Pacific, with around fifty volcanic centres having erupted in the Holocene. Large eruptions over the past few decades at Lamington, Rabaul, Manam, Karkar and others have resulted in significant loss of life, and destruction of infrastructure. More modest eruptions at these and other volcanoes pose threats to air traffic in the busy corridor linking Japan and Australia, and lava flows, lahars, ashfall and PDCs threaten growing local populations in often isolated settlements. The rugged terrain of Papua New Guinea and limited amounts of funding mean that the majority of the volcanoes receive only limited monitoring. In recent years, satellite observations have played an increasing role in tracking levels of activity, but these remain best suited to relatively limited range of activity types. Until more monitoring infrastructure is in place, hazard assessment of the volcanoes of Papua New Guinea will be best served by ground-based campaigns, complementary to longer term satellite observations.

In this contribution, we present early results from such a field campaign, undertaken in late summer 2016. Gas emissions from Papua New Guinea are relatively poorly constrained. The only data in the published literature pertain to sulfur dioxide (SO2) fluxes measured in one instance by airborne spectroscopic measurements, and another by satellite remote sensing. Focussing on volcanoes and geothermal fields in the regions of East and West New Britain and Bougainville, we performed: in situ measurements of gas composition using MultiGas instruments; remote spectroscopic measurements of SO2 flux; and direct sampling of plume and fumarolic emissions in Giggenbach-type bottles and copper tubing. We also deployed unmanned aerial vehicles carrying modified MultiGas-type sensors to make plume transits at high elevation volcanoes, and sampled recent lavas and tephras for geochemical analyses of magmatic volatile content.

Using SDRs to identify the mode of breakup along South America's magma-rich margin

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Seaward-dipping reflectors (SDRs) are thick packages of sub-aerial basalt that form during the final stages of magma-rich continental breakup. SDRs obscure the continent-ocean transition seen on conventional seismic profiles. Here, we use long-offset (10.2 km) 2D time & depth migrated seismic reflection data to document variations in SDR geometry offshore Argentina, Uruguay and Brazil. Detailed velocity analysis of high-quality pre-stack seismic gathers, along three seismic profiles, has been used to constrain the geological interpretation and has yielded novel insights into SDR formation. We recognise three types of SDRs that vary in distribution both across and along the margin.

Type I SDRs are fault-bounded and associated with anomalously high-velocity bodies (6.5-7 km/s) both beneath and at the down-dip end of their diverging wedges. *Type I* SDRs are identified along the entire margin. Outboard of the Type I, we observe a second set of SDRs (*Type II*) which are not fault-bounded and are not associated with high-velocity anomalies. In the south, the *Type II* SDRs are short (*IIa*) with average lengths of 2 ± 2 km. Conversely, closer to the Paraná flood basalt province, *Type II* SDRs are longer (*IIb*) with average lengths of 27 ± 23 km.

We interpret *Type I* SDRs as lava flows confined to continental rifts and sourced from point-source intrusive magmatic bodies while *Type II* SDRs are erupted from linear spreading centres. The difference in flow length between our two *Type II* SDRs is likely due to variations in source elevation along margin. Where the southern *Type IIa* lavas flow into standing bodies of water and the northern *Type IIb* do not. We suggest that the transition between *SDR Type I & II* marks the end of mechanical rifting and the onset of magmatic-controlled extension, and thus, represents a key point in the breakup of continental margins.

Using lake cores for tephrochronology in Ethiopia: an investigation into ash settling processes in lakes

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Ethiopia is home to 60 volcanoes fed from the Main Ethiopian Rift, a northern section of the East African Rift System. A recent report on volcanic hazard for the World Bank has classified many of these volcanoes at the highest level of uncertainty due to the deficit of data in this region. Many of the volcanoes are populated and therefore understanding their eruptive history is important for hazard mitigation.

One of the actively deforming volcanoes is Aluto. We are examining its Holocene tephra record preserved in lake beds (both in cores and now on land). To use these tephra records to constrain the frequency and style of Aluto's eruptions, it is necessary to understand how tephra is deposited and preserved in lakes. To address this question, and particularly to distinguish primary from secondary deposits, we are combining laboratory experiments with SEM analysis, density measurements and grain size information.

The tephras are typically normally graded, with large pumice clasts at the bottom. Laboratory experiments show, in contrast, that bulk tephra samples segregate in water, with small dense particles sinking and the large pumice clasts floating for hours to days eventually forming reverse-graded deposits. When the larger pumice samples are heated, however, the pumice clasts rapidly ingest water and sink relatively quickly. From these preliminary results, we suggest that the normally zoned deposits are primary, and were emplaced hot. We are extending these studies to explore the settling of heated bulk samples, as well as the possible influences of permeability and settling regimes. These experiments will inform our interpretations of lake records of eruptions, including the Holocene eruptions of Aluto.

Microstructural controls on the pressure-dependent permeability of Whitby Mudstone

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A combination of permeability and ultrasonic velocity measurements allied with image analysis is used to distinguish the primary microstructural controls on effective pressure dependent permeability. Permeabilities of cylindrical samples of Whitby Mudstone were measured using the oscillating pore pressure method at confining pressures ranging between 30-95 MPa and pore pressures ranging between 1-80 MPa. The permeability-effective pressure relationship is empirically described using a modified effective pressure law in terms of confining pressure, pore pressure and a Klinkenberg effect. Measured permeability ranges between 3×10^{-21} m^2 and 2×10^{-19} m^2 (3 and 200 nD), and decreases by ~1 order of magnitude across the applied effective stress range. Permeability is shown to be more sensitive to changes in pore pressure than changes in confining pressure, yielding effective pressure coefficient permeability effective pressure coefficients between 1.1 and 2.1. Based on a pore conductivity model which considers the measured changes in acoustic wave velocity and pore volume with pressure, the observed loss of permeability with increasing effective pressure is attributed dominantly to the progressive closure of bedding-parallel, crack-like pores associated with grain boundaries. Despite only constituting a fraction of the total porosity, these pores form an interconnected network that significantly enhances permeability at low effective pressures.

The Sorong Fault Zone, Indonesia: A Fresh Perspective

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The Sorong Fault Zone is widely believed to be a left-lateral strike-slip fault zone, located in Indonesia, extending westwards from the Bird's Head peninsula of West Papua towards Sulawesi. The fault zone is controlled by the interactions between the Pacific, Caroline, Philippine Sea, and Australian Plates.

Past research on the fault zone has been limited by the low resolution of available data, leading to ongoing debates over the extent, location, and timing of movements, and the evolution of eastern SE Asia on a broader scale. The fault zone is apparently currently inactive although it is possible that motion along the fault zone is cyclical.

High resolution multibeam bathymetry images of the seafloor, alongside onshore SRTM images, are being used in this study to revisit the structure and tectonics of the Sorong Fault Zone. This is complemented by field mapping. The data gathered during this project will be used for both kinematic analysis and estimation of timing of movements on the fault zone, and how these are associated with regional tectonics.

The fault zone's location has, over the years, remained in dispute; different studies have traced it north of the Sula Islands, truncating south of Halmahera, extending into Sulawesi, or splaying into a horsetail fan of smaller faults. This presentation offers a first-pass interpretation of the structure of the Sorong Fault Zone both on land and offshore at a resolution that has been unattainable prior to now. This preliminary interpretation of the new data suggests that, in the northern portion of the Bird's Head the fault zone is characterised by closely spaced E-W trending faults. To the west of the Bird's Head the fault zone diverges into multiple strands trending WSW, before reverting to an E-W trend close to the Sula Islands and Sulawesi. The strands have a horsetail character as the fault zone dies out. At their western ends the fault strands link to other faults and raise questions about the extent of the Sorong Fault zone and what may be regarded as independent fault zones.

Future work will include integrating a 2D seismic dataset to support analysis of the multibeam data. This will not only provide a new 3D interpretation of the fault zone at depth but will also allow better constraints on the fault zone's structure at the surface.

Strain localization in pseudotachylyte veins at lower crustal conditions

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Viscous shearing in the dry and strong lower crust often localizes on pseudotachylyte veins (i.e. quenched molten rocks formed by the frictional heat released during seismic slip), and it has been suggested that brittle (coseismic) grain-size reduction and fluid infiltration in the fractured domains are necessary to weaken the anhydrous granulitic lower crust and activate viscous creep mechanisms. However, the deformation mechanisms responsible for the associated strain weakening and viscous shear localization on pseudotachylyte veins are yet to be explored.

This study investigates the deformation microstructures of mylonitized pseudotachylytes in anorthosites from Nusfjord, northern Norway, where ductile shear zones invariably nucleate on pseudotachylyte veins. Thus, pseudotachylytes are weaker than the host rock during superposed ductile deformation. Geothermobarometry and thermodynamic modelling indicate that pristine pseudotachylytes and their mylonitized equivalents formed at ca. 700°C and 0.6-0.9 GPa. The stable mineral assemblage in the mylonitic foliation consists of plagioclase, hornblende, clinopyroxene ± quartz ± biotite ± orthoclase. Diffusion creep and grain boundary sliding were identified as the main deformation mechanisms in the mylonite on the basis of the lack of crystallographic preferred orientations, the high degree of phase mixing, and the nucleation of hornblende in dilatant sites. In contrast with common observations that fluid infiltration is required to trigger viscous deformation, thermodynamic modelling indicates that a very limited amount of fluid (0.4 wt%, similar to the bulk fluid content measured in the host rock and in the pristine pseudotachylytes) is sufficient to stabilize the mineral assemblage in the mylonite. This suggests that cosesimic grain size reduction resulted in a fluid redistribution into the fractured domain rather than in fluid infiltration. Recent experiments suggest that very small amount of water (tens of ppm) are very effective in facilitating mineral reactions if sufficient porosity in present. Coseismic fracturing and creep cavitation in the fine-grained mylonitized pseudotachylytes enhance the porosity of the shear zone and result in nucleation of new phases (mostly hornblende) in dilatant sites. This process keeps the grain size of the polymineralic aggregate in the grain-size sensitive creep field, thereby stabilizing strain localization in the mylonitized pseudotachylytes.

Acoustic characterization of crack damage evolution in rocks deformed under true triaxial loading

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Microcrack damage in rocks evolves in response to differential loading. However, the vast majority of experimental studies investigate damage evolution using conventional triaxial stress states ($\sigma_1 > \sigma_2 = \sigma_3$), whereas in nature the stress state is in general truly triaxial ($\sigma_1 > \sigma_2 > \sigma_3$). We present a comparative study of conventional triaxial vs. true triaxial stress conditions using results from measurements made on cubic samples of sandstone deformed in three orthogonal directions with independently controlled stress paths. We have measured, simultaneously with stress and strain, the changes in ultrasonic compressional and shear wave velocities in the three principal directions, together with the bulk acoustic emission (AE) output. Changes in acoustic wave velocities are associated with both elastic closure and opening of pre-existing cracks, and the formation of new, highly oriented, dilatant cracks by inelastic processes. By contrast, AE is associated only with the inelastic growth of new, dilatant cracks. Crack growth is shown to be a function of differential stress regardless of the mean stress. New dilatant cracks can form due to a decrease in the minimum principal stress, which reduces mean stress but increases the differential stress. We measure the AE, in both conventional triaxial and true triaxial tests and find an approximately fivefold decrease in the number of events in the true triaxial case. In essence, we create two end-member crack distributions; one displaying cylindrical transverse isotropy (conventional triaxial) and the other planar transverse isotropy (true triaxial). By measuring the acoustic wave velocities throughout each test we were able to model comparative crack densities and orientations. When taken together the AE data, the velocities and the crack density data indicate that the intermediate principal stress plays a key role in suppressing the total amount of dilatant crack growth and concentrates it in a single plane, but the size of individual cracks remains constant. Hence, the differential stress at which rocks fail (strength) will be significantly increased under true triaxial stress conditions than under the much more commonly applied condition of conventional triaxial stress.

Damage Recovery in Carrara Marble

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We investigate the effect of confining pressure on the recovery of elastic wave velocities after a deformation episode in Carrara Marble. Dry Carrara Marble cores were deformed in the ductile regime (Pc = 40 MPa) up to 3% axial strain. After deformation, the samples were held under constant stress conditions for extended periods of time (5-8 days) while continuously recording both strain and seismic wave velocities. During deformation, the elastic wave speeds decreased with increasing strain by more than 30% of the value for the intact rock due to the formation of distributed microcracks. Under constant hydrostatic pressure, the wave speeds progressively recovered between 12 and up to 60% of the initial drop depending on the applied confining pressure. The confining pressure appears to favour the recovery process. This recovery is interpreted as a progressive reduction in crack density in the sample. By contrast the strain recovery (deformation toward the initial shape of the sample) during the holding time is negligible (the order of 10^{-4}). We propose that one of the most important process in wave speeds recovery is the time-dependent formation of new contacts between microcrack surfaces altering the elastic properties of the sample but not its shape.

Estimating the brittle-ductile transition on Venus and exploring the disparate volcanic history of Earth's sibling (with a little help from Argon isotopes)

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The disparate evolution of sibling planets Earth and Venus has left them markedly different. Venus' hot (460 °C) surface is flat and dry, while Earth's temperate (15 °C) surface is mountainous and wet. Counterintuitively, despite the hot Venusian climate, the abundance of hot-spot volcanoes on Earth dwarfs those on Venus by more than an order of magnitude. Here we interrogate rock deformation and atmospheric argon isotope data to offer an explanation for the relative flatness and volcanic quiescence of present-day Venus. By collating high-temperature, high-pressure deformation data for basalt, we provide a failure mechanism map to assess the brittle-ductile transition (BDT) on Venus. Our approach suggests that the present-day Venusian BDT likely exists between 2-12 km depth (for a range of thermal gradients). The depth of the BDT on Earth is predicted to be at ~25 km using the same method. The implications for planetary evolution are twofold. First, tall structures will sink and spread due to the low flexural rigidity of the dominantly ductile Venusian lithosphere. This provides an explanation for the relative flatness of Venus. Second, magma delivery to the surface—the most efficient mechanism for which is flow along fractures (dykes)—will be inhibited on Venus. Instead, most magmas stall and pond in the ductile lithosphere. If true, magmatism on Venus should mostly result in plutonism, not volcanism. The relative quiescence of volcanism on Venus is supported by atmospheric argon isotope data. We argue here that the anomalously low present-day atmospheric $^{40}Ar/^{36}Ar$ ratio for Venus (compared to Earth) must reflect major differences in ^{40}Ar degassing (primarily volcanism) over 4.5 Ga. We conclude that the hot Venusian climate inhibits volcanism on Venus.

2D and 3D analysis of cataclastic deformation bands in poorly consolidated sandstones.

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Deformation bands are mm-cm scale tabular zones of localized strain mostly found in high porosity sand and sandstones. Deformation bands have been widely studied in field outcrops and boreholes across the world. Recently there have been an increasing number of studies on the formation of deformation bands in poorly and un-consolidated sands. Cataclastic deformation bands within a few hundred meters of the Earth's surface are of particular interest as it had been thought they required significant confining pressure to form.

Deformation band studies have often been motivated by the fact they can act as baffles to fluid flow. However, their identification has also been used to constrain burial history estimates, and as a potential indicator of past seismic activity.

We present both 2D and 3D analysis of deformation bands from outcrops of poorly consolidated Oligocene-Miocene aged sediments from northern Hungary, Pliocene aged sediments from the Upper Rhine Graben, France and Miocene aged sediments from Miri, Malaysia. We have characterised the physical properties (mineralogy, grain size, grain fracture, cementation, band density, band width) of the deformation bands to gain a clearer understanding of the micromechanics of deformation in poorly consolidated sandstones.

Lava flow reservoirs during burial: laboratory petrophysical and wireline geophysical results from two fully cored boreholes, Big Island, Hawai'i.

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Results from borehole logging and sampling operations within two fully cored c. 1.5 km deep boreholes, PTA2 and KMA1, from the Humu'ula saddle region on Hawai'i are presented. The boreholes were drilled as part of the Humu'ula Groundwater Research Project (HGRP) between 2013-2016. The boreholes encounter mixed sequences of 'a'ā, pāhoehoe and transitional lava flows along with subsidiary intrusions and sediments from the shield to post-shield phases of Mauna Kea. Borehole wireline data including sonic, spectral gamma and televiewer imagery were collected along with density, porosity, permeability and ultrasonic velocity laboratory measurements from core samples. A range of intra-facies were sampled for analysis from various depths within both boreholes. By comparison with core data, the potential for high resolution Televiewer imaging to reveal spectacular intra-facies features including individual vesicles, vesicle segregations, 'a'ā rubble zones, intrusive contacts, and intricate pāhoehoe lava flow lobe morphologies is demonstrated. Laboratory results record the ability of natural vesicular basalt samples to host very high porosity (>50%) and permeability (>10 darcies) within lava flow top facies which we demonstrate are associated with vesicle coalescence and not micro-fractures. These properties may be maintained to depths of c. 1.5 km in regions of limited alteration and secondary mineralization and, therefore, additional to fractures, may comprise important fluid pathways at depth. Alteration and porosity occlusion by secondary minerals is highly vertically compartmentalized and does not increase systematically with depth, implying a strong but heterogeneous lateral component in the migration and effects of hydrothermal fluids in these systems. The distribution and timing of dyke feeder zones coupled with the scale and spatial distribution of lava flows making up the lava pile form first order influences on the preservation potential of reservoir properties during burial. Our results demonstrate the complex relationship between the primary hydrogeology of lava flow fields and the resulting effects of hydrothermal fluid circulation on reservoir property evolution with burial.

Syn-eruptive hydration of a deep-submarine explosive eruption: Water speciation analysis of volatiles in rhyolitic glass

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Submarine volcanism accounts for the vast majority of global volcanic activity, yet we still have a very limited record and understanding of such eruptions. The 2012 eruption of Havre volcano, Kermadec Ridge, which produced >1.5 km^3 of rhyolite (VEI-5 equivalent), provides exciting new insight into deep-submarine eruptions. With no direct observations of the eruption at the 900m deep vent, the analysis and interpretation of volatile concentrations and speciation within glass is essential for constraining the eruption style and quenching mechanisms in this understudied environment. We present here the first detailed water speciation data for a large submarine explosive eruption. Water concentrations were measured in pumiceous clasts from known deposit localities across the Havre stratigraphic succession following ROV collection in 2015. Water speciation concentrations (molecular water (H_2O_m) and OH) were measured using high-spatial resolution Fourier-transform infrared (FTIR) spectroscopic imaging.

Concentrations range from 0.1 – 1.5 wt % total H_2O and 0.05 – 0.7 wt % OH over different stratigraphic units. Undersaturated OH concentrations for quenching at vent depth imply either: 1) much shallower quenching pressures from slower pyroclast cooling or 2) the presence of coupled-volatile solubility conditions during magma ascent. Comparison of water speciation data with speciation models suggests that Havre clasts experienced secondary, non-magmatic hydration. The variability of excess H_2O_m across units suggests a more complex glass-hydration mechanism instead of exclusively post-eruption, low-temperature secondary rehydration. The young sample ages are inconsistent with our current understanding of low-temperature H_2O-diffusivity timescales, implying faster secondary hydration in a higher-temperature submarine setting. We here explore potentially novel syn-eruptive, higher-temperature hydration mechanisms for deep-submarine pumice.

Controls on Fracture Healing in Fault Damage Zones.

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Off-fault coseismic fracture damage at depth can be inferred from reductions of crustal seismic velocity following large earthquakes. A growing body of geophysical evidence exists for 'healing' processes occurring in the crust following such earthquakes, inferred from time-dependent increases in seismic velocity lasting from days to years. This decrease in velocity has been attributed to coseismic fracturing, whereas the mechanisms that drive the recovery of velocities are poorly understood. If such velocity changes are due to fracture healing, little is known about the controls on co-seismic microfracture damage healing rates. While several experimental studies have focussed on crack healing that occurs at elevated temperatures and pressures (150-500 °C, 200-400 MPa), to date no work has focussed on healing processes occurring at pressures and temperatures commensurate with the shallow crust (i.e. < 150 MPa, <150 °C) where the majority of velocity recovery is measured in seismic studies. Here, we present experimental and microstructural observations on the rates of microfracture healing in terms of post-seismic recovery of seismic velocity, porosity and permeability, as a function of varying initial damage.

Westerly Granite samples were subjected to a thermal cracking procedure in order to induce a variety of of damage levels. Samples were then placed in a hydrostatic permeameter and 'cooked' at 130 °C at 80 MPa effective pressure (5 MPa pore fluid pressure) for 50 hours. Permeability evolution was monitored using the pore pressure oscillation tecnhqiue, and elastic wave velocities were measured before and after experiments. Thermal cracking induces increasing fracture damage with increasing thermal fracturing temperature, characterised by a decrease in P-wave velocities and an increase in permeability. Over 55 hours, significant P-wave velocity recovery is seen , but relatively minor changes in permeability. Microfracture analysis shows that shorter microcracks preferentially heal over these timescales, resulting in a significant increases in P-wave velocity. Permeability is controlled by longer connected cracks, which do not heal, and therefore shows little change in permeability. This suggests that reductions in seismic velocity and subsequent recovery following large earthquakes may be related to the healing of microscale damage, although we speculate that this may not be accompanied by any significant recovery of permeability controlled by larger fracture networks.

In search of the source of North Atlantic Ash Zone II and the Thórsmörk Ignimbrite

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North Atlantic Ash Zone (NAAZ) II is a complex ash zone found extensively in North Atlantic marine sediments and in the Greenland ice cores. The dominant (rhyolitic) tephra horizon within NAAZ II is a valuable chronostratigraphic marker that has been used to integrate palaeoclimatic and palaeoenvironmental information from across the North Atlantic region. This tephra has been identified in the terrestrial realm as the Thórsmörk Ignimbrite in southern Iceland. We aim to pinpoint the source of this significant explosive eruption that occurred during the middle of the last glacial period (55,380 ± 2368 a b2k).

Tindfjallajökull volcano, southern Iceland, has been accepted as the source of the Thórsmörk Ignimbrite for over 35 years. However, comparison of ignimbrite outcrops proximal (<6 km from summit) and more distal (9-13 km) to Tindfjallajökull has cast doubt on this. As close as 3.5 km from the summit, the ignimbrite is comparatively thin (~10 m thick), poorly welded, and devoid of non-juvenile clasts. Geochemical work in progress suggests that the ignimbrite, and NAAZ II, are instead derived from Torfajökull volcano, 20-40 km NE of the area of ignimbrite outcrop.

In particular, we have identified a major element correlation between the Thórsmörk Ignimbrite/NAAZ II and the Torfajökull Ring Fracture Rhyolites, a set of rhyolitic tuyas believed to have been emplaced englacially in one large-volume eruption (~18 km^3 DRE) during the last glacial period. This potential correlation is being more fully evaluated using geochronology ($^{40}Ar/^{39}Ar$) and trace element geochemistry (LA-ICP-MS).

If this correlation proves to be robust, it will lead to an improved understanding of the processes that can take place during large rhyolitic glaciovolcanic eruptions. For instance, it will confirm that these eruptions can produce sustained and large eruption columns following breaching of the ice, resulting in widespread tephra dispersal. It will also demonstrate that pyroclastic density currents can be produced by these eruptions, and can travel tens of kilometres over ice whilst retaining sufficient heat to weld.

The nature and emplacement of the rhyolitic lava-like Hruni Ignimbrite in the Hreppar Formation of southern Iceland

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Iceland is well known for its bimodal basaltic and rhyolitic volcanism, and explosive eruptions, which have been used widely for tephra correlation studies. However, there is little documentation of any pyroclastic density currents (PDCs) generated during these eruptions and their resultant deposits. Although ignimbrites have been described (e.g. Sólheimar and Thorsmörk ignimbrites), the behaviour of PDCs and deposition of ignimbrites in Iceland is relatively poorly understood. This study reports on an apparently newly discovered ignimbrite from the Hruni area of southern Iceland, and documents its nature and emplacement using field, UAV/“drone”, petrographic and geochemical techniques.

The Hreppar Formation, southern Iceland comprises basaltic lavas and interbasaltic sediments of Plio-Pleistocene age (3.3-0.7 Ma). In the Hruni area, basalt lavas are locally unconformably overlain by a distinctive ignimbrite that fills palaeo-topography in the lavas. The lowermost unit of the ignimbrite comprises a massive lapilli-tuff (non-welded) with distinctive blue spherulitic lapilli. This is overlain, although no direct contact is observed, by a black perlitic vitrophyre, locally with lithophysae horizons. This passes up into a grey/black to pink lithoidal ignimbrite with pervasive base-parallel flow banding and recumbent isoclinal folds. Locally, more complex open to curvilinear folds are preserved. Grey/black diapir-like lower units are locally “intruded” into upper pink units.

The lower massive lapilli-tuff records deposition from a fluid escape-dominated flow boundary zone in a granular fluid-based PDC, and indicates a more explosive Plinian-type eruption. The overlying vitrophyre and flow banded units may be the products of a later eruption, or different flow units and/or cooling units from a sustained, unsteady eruption. However, due to the absence of contact relationships this cannot be determined. We interpret the upper units as lava-like ignimbrite formed primarily by progressive aggradation of hot pyroclasts in an agglutinating layer, with rheomorphism imposed by non-coaxial ductile shear from the over-riding PDC (and gravity). Locally, some post-emplacement rheomorphism occurred due to downslope flow and gravity driven instabilities inside the deposit, which led to the formation of diapiric structures that locally rose through the deposit. The lava-like ignimbrites suggest a low fountaining “boil-over” type eruption.

Unravelling subduction and collision stages of the Mineiro Belt: the tectonic framework of a Paleoproterozoic orogeny

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Zircon U-Pb ages have been widely used to understand the evolution of continental crust. For example, the distribution of detrital zircon ages through an orogenic cycle can indicate the tectonic settings in which magmatic and associated sedimentary rocks were formed. In this study, we used zircon U-Pb geochronology and geochemical analysis of plutonic rocks and detrital zircon ages from sedimentary rocks from the Mineiro Belt, Brazil to study its orogenic evolution. The belt encompasses several granitoid suites (2.36 - 2.12 Ga) and metavolcano-sedimentary sequences (2.3 - 2.2 Ga). The Archaean crust (3.2 - 2.7 Ga) of the Southern São Francisco Craton acted as a stable foreland for the development of the Mineiro Belt, against which it was subsequently accreted. The geochemical data of the plutonic rocks indicate that they mostly belong to the calc-alkaline series, which are meta- to peraluminous and originally I-type in composition. These rocks have a continuous trend of being more evolved with time, and also represent a secular transition from Trondhjemite-Tonalite-Granodiorite (TTG) to sanukitoid-type magmatism (high Ba-Sr). This change in magmatic composition is recorded globally and has been inferred as the onset of modern-style subduction-driven plate tectonics (Martin et al, 2010). Samples dated in this study cover the orogenic evolution of the Mineiro Belt between 2.35 and 2.10 Ga. Our preliminary detrital zircon U-Pb data shows, from a tectonic perspective, that the sediments were sourced not only from eroded syn-orogenic magmatic rocks (i.e. 2.35 to 2.10 Ga) but also from Archaean basement (older than 2.7 Ga) in apparently higher quantities. The presence of substantial Archaean detritus could be associated with either the incipient nature of the arcs or the extended dimensions of the passive margin basins. Our new results, compiled with previous geochemical and geochronological data, confirm that the overall evolution of the Mineiro Belt occurred through successive accretion of younger magmatic arcs. The eventual collision of these arcs led to a subsequent amalgamation onto the margins of the Archaean core of the São Francisco craton by ca. 2.1 to 2.0 Ga. Hugo Moreira acknowledges CNPq Scholarship [234610/2014-0].

Volcanoes: Hot or Not? A neural network perspective.

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Satellite based remote-sensing has become an integral part of monitoring volcanoes. The ability to use satellites infrared capabilities have allowed us to constrain parameters such as eruption duration and size, effusion rates and cyclical thermal regimes, all vital information for hazard management. However, the ability to recognise thermal anomalies can not only be hindered by sensor capabilities, but the automated fixed algorithms that detect them. This is especially prevalent for transient and/or low intensity thermal anomalies, as well as subtle changes to eruption regime, which could potentially indicate larger eruptions.

To combat this, the research presented here utilises neural networks (NN), a form of artificial intelligence that uses an adaptive algorithm to classify images. The adaptive nature of the algorithm allows the constraints over whether a pixel is considered 'hot' or 'not' to be more flexible, whilst also providing robust rejection of false positives and cloudy pixels. Using datasets from the Moderate Resolution Imaging Spectroradiometer (MODIS) of Kilauea, USA and Vulcano, Italy, the algorithm worked with an accuracy of ~94% for both localities when compared to an independent data set. When compared to MODVOLC (a fixed-threshold algorithm) alerts over 31 days, the NN detected 31 days of thermal anomalies for Kilauea, the same as MODVOLC. However, the NN outperformed MODVOLC at Vulcano, detecting 7 days of thermal anomalies compared to MODVOLC's 0 days. These initial results are proving to be promising and showing the utility of NNs in volcano remote sensing, and their potential for further application to higher resolution sensors and over multiple platforms.

The Influence of Mantle Heterogeneity on Core Convection.

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Variations in seismic wave speeds at the base of the mantle arise due to a combination of thermal and chemical heterogeneity. Differences in the temperature or thermal conductivity of mantle material in contact with the core result in lateral variations in the heat flux extracted from the core. This uneven cooling of the core by the mantle can drive patterns of core flow that would not exist with a homogeneous boundary condition, but the extent to which the mantle organises core flow remains uncertain. Mantle control may account for observed features of the geomagnetic field and its secular variation, in particular high latitude patches of anomalously strong magnetic field and the relative lack of secular variation in the Pacific hemisphere may be linked to mantle-induced flow at the top of the core. Mantle influence on core flow may even extend across the entirety of the outer core. In some numerical models of the core large cold downwellings generated at the core-mantle boundary impinge upon the inner core boundary promoting localised freezing of the solid core, perhaps explaining the observed seismic heterogeneity at the top of the inner core. In this work we use numerical models of non-magnetic, rotating convection and impose a variety of patterns and amplitudes of thermal boundary heterogeneity. We consider global properties of convection, such as heat transport and characteristic velocity scales, as well as measures that characterise whether the outer boundary can indeed exert its influence across the entire region. We find that long wavelength and high amplitude patterns of thermal heterogeneity at the outer boundary are likely required to influence core convection throughout the shell and any effect at the inner boundary is very small for our lowest Ekman and highest Rayleigh models, which are most applicable to the Earth. However, Lorenz forces are not included in these models and the inclusion of a magnetic field may promote some large scale structures in core flow.

The role of the ancestral Yellowstone plume in the tectonic evolution of the western United States.

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Plate reconstructions indicate that if the Yellowstone plume existed prior to 50 Ma, then it would have been overlain by oceanic lithosphere located to the west of the North American Plate (NAP). Assuming long-lived easterly subduction beneath the NAP, the Yellowstone plume would have been progressively overridden by the NAP continental margin since that time, the effects of which should be apparent in the geological record.

Geodynamic models suggesting that the ascent of plumes is either stalled or destroyed at subduction zones have focused attention on the role of gaps or tears in the subducted slab that permit the flow of plume material from the lower to the upper plate during subduction. The ascent of plumes may be deflected as plume material migrates from the lower to the upper plate, so that the connection between the hot spot track and the manifestations of plume activity in the upper plate may be far more complex than precise relationships in the oceanic domain. Other geodynamic models support the hypothesis that subduction of oceanic plateau beneath the NAP correlate with the generation of a flat slab, which has long been held to have been a defining characteristic of the Laramide orogeny in the western United States, the dominant Late Mesozoic-Early Cenozoic orogenic episode affecting the NAP.

A growing body of evidence suggests that a plume existed from 70 -50 Ma within the oceanic realm close to the NAP margin with a similar location and vigour to the modern Yellowstone hot spot. Interaction of this plume with the margin would have been preceded by that of its buoyant swell and related oceanic plateau, a scenario which could have generated the flat slab subduction that characterizes the Laramide orogeny.

Unless this plume was destroyed by subduction, it would have gone into an incubation period when it was overridden by the North American margin, during which plume material could have migrated into the upper plate via slab windows or tears or around the lateral margins of the slab. The resulting magmatic activity may be located at considerable distance from the calculated hot spot track.

The current distribution of plumes and their buoyant swells suggests that their interaction with subduction zones should be common in the geological record.

Constraining the timescale of magmatic ascent prior to the Skuggafjöll eruption, Iceland

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Advances in the spatial resolution and precision of micro-analytical techniques has made diffusion chronometry a powerful technique for extracting timescale information about sub-volcanic processes that occur days to months before eruption. In contrast to most previous studies, we estimate timescales using multiple mineral phases from the same sample of erupted material that are expected to have undergone the same magmatic history. This approach allows for testing of diffusion models tailored for individual minerals. The ultra-phyric lavas of the Skuggafjöll eruption, part of the Bárðarbunga volcanic system in southern Iceland, contain primitive macrocrysts of plagioclase (An_{90}) and olivine (Fo_{86}) with homogeneous cores surrounded by rims of more evolved material ($An_{<79}$ and $Fo_{<82}$) that are separated by a sharp interface. Textural evidence suggests both phases shared a common magmatic history prior to entrainment in an evolved carrier liquid. We present a multi-phase and multi-element approach using a combination of BSE Imaging, EPMA and high-resolution SIMS data to quantify compositional profiles in plagioclase and olivine. Diffusive modification from step-like initial conditions was modelled using 1D and 2D finite-element code built upon recent experimental data on the spatial variability of the diffusivity of major and trace elements. The timescale of three distinct episodes were determined: the equilibration of plagioclase cores in a cold mush environment, the growth of olivine and plagioclase from a primitive depleted melt; and the entrainment of the phase assemblage into the evolved carrier liquid. Models indicate that the second event occurred over timescales of 100-300 days, whilst the timescale of the final event between mush disaggregation and eruption was on the order of 30-50 days; remarkably similar to ascent timescales and precursor activity retrieved from other Icelandic eruptions. If processes between melt injection and eruption in basaltic systems do indeed operate under a consistent temporal framework, this could offer a large breakthrough in eruption forecasting and hazard management.

Spatio-temporal variations in magmatism during continental breakup – insights from the 3D structure of Seaward Dipping Reflectors

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On volcanic rifted margins, continental breakup is accompanied by the emplacement of a thick succession of flood basalts. In seismic reflection data these are imaged as Seaward Dipping Reflectors (SDRs). Understanding the structural evolution of SDRs is crucial for understanding how continental rifting gives way to seafloor spreading. Several recent studies have focused on their 2D structural evolution, and it is clear that SDRs are erupted from an axial magmatic zone with the seaward dips forming from a combination of magmatic loading and normal faulting. However our understanding of their 3D structure is limited, despite its importance in determining the lateral variations of magma supply during breakup.

Here we use a closely spaced 2D seismic grid from the Orange Basin, offshore SW Africa, to separate the SDRs into packages and map them in 3D. We show that the location of the magmatic centres feeding the SDRs migrate through time via a series of abrupt jumps: During early SDR formation, magmatism was partitioned along-strike into a series of laterally offset segments. Each segment is approximately 30 km long, giving a similar configuration to the present day Main Ethiopian Rift. Following this initial stage of distributed magmatism, we observe the formation of a relatively continuous axial feeder zone. The formation of this continuous axial zone results in the abandonment of the now off-axis magmatic segments. This process requires rapid jumps in the location of magmatism, a process that has not been previously observed in the continent-ocean transition on volcanic rifted margins.

The signature of 'sharp sides' to the seismically slow regions at the base of the Earth's mantle

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Seismic tomography shows that there are two large regions of low velocities at the base of the Earth's mantle (known as 'LLSVPs'). However, there is no agreement on how they formed, how long they have been in their current form, or what they are made of.

Two endmember explanations for the LLSVPs are: (1) they are the sites of plume structures, which are hot and positively buoyant; or (2) they are 'piles' of chemically dense material which are negatively buoyant. Though some of the evidence for the 'dense pile' hypothesis has been questioned recently, observations of 'sharp sides' to the LLSVPs have been taken to mean they must be chemically distinct from the surrounding material.

These observations often consist of 'multipathing', a phenomenon which occurs when sharp changes in seismic velocity (~4–5%) occur over short distances (~200 km). In waves which experience this, multiple arrivals are present with different directions.

We test the ability of multipathing observations to discriminate between endmember hypotheses of LLSVP formation. We simulate mantle convection with and without dense piles, using Earth-like vigour, and incorporating temperature-dependent viscosity and compressibility. We assimilate information from the surface by incorporating plate velocities from the last 300 Myr. The simulations are converted to seismic velocities and we recreate observations of multipathing in seismic waves which traverse the LLSVPs.

We find that both classes of models yield gradients in seismic velocities which are strong enough to be considered 'sharp sides'. We test if the shape of the convective structures leads to multipathing in core-diffracted shear waves by using fully-3D, finite-frequency seismic simulations. Again, both classes of models reproduce the multipathed arrivals evident in the real Earth.

The argument that thermal convection cannot sustain sharp seismic contrasts is not supported by this work—and thus we look for a new way to tell 'piles' from 'plumes'.

Distributed deformation in the Zagros fold-and-thrust belt: insights from geomorphology

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The Zagros fold-and-thrust belt is part of the active Arabia-Eurasia collision zone, and is an excellent region to study the interactions of tectonics and landscape. In this work we present results of a geomorphic analysis covering the entire range, coupled with more detailed analysis of the Kirkuk Embayment, Iraq. This particular region is a low elevation, low relief region of the Zagros, important for the enormous oil and gas reserves held in late Cenozoic anticlinal traps.

Constraints from published earthquake focal mechanisms and hydrocarbon industry sub-surface data are combined with original fieldwork observations in northern Iraq, to produce a new regional cross-section and structural interpretation for the Kirkuk Embayment. We find that overall late Cenozoic shortening across the Embayment is on the order of 5%, representing only a few km. This deformation takes place on a series of anticlines, which are interpreted as overlying steep, planar, basement thrusts. These thrusts are further interpreted as reactivated normal faults, on the basis of (rare) published seismic data. The regional earthquake record confirms the basement involvement, although detachments within the sedimentary succession are also important, especially within the Middle Miocene Fat'ha Formation.

Overall, the Zagros is sometimes represented as having a few major thrusts each persistent for 100s of km along the strike of the range. However, these faults are very rarely associated with major structural relief and/or surface fault ruptures during earthquakes. We have analysed the hypsometry of the range and find only gradational changes in the hypsometric integral of drainage basins across strike. This contrasts with regions such as the eastern Tibetan Plateau, where published analysis has revealed abrupt changes, correlating with the surface traces of active thrusts. Our interpretation is that the hypsometry of the Zagros reflects distributed deformation on numerous smaller faults, rather than major uplift on a small number of laterally continuous nappes.

Volatiles in the Proto-Iceland Plume Source Mantle

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Melt inclusions in Baffin Island picrites preserve the highest (37-50Ra) 3He/4He ratios ever recorded in terrestrial lava samples (Stuart et al. 2003, Starkey et al. 2009). High 3He/4He ratios sampled in OIBs are indicative of a relatively less degassed and probably deep mantle (White 2015). However, the Baffin Island picrites also record a range of Sr-isotope compositions. The decoupling of volatile and radiogenic isotope systems leads to the possibility that volatiles behave differently during partial melting processes, magma transport and storage. We plan to use the halogens as tracers of volatile transport and storage in the mantle.

We have measured major and trace element compositions of olivine phenocrysts and melt inclusions from 4 BIWG picrite samples, and plan to determine the volatile (CO2, H20, S, F Cl, Br) inventory of the melt inclusions. This data will be used to determine the halogen inventory of the BIWG source mantle, and to test the hypothesis that the halogens are also decoupled from radiogenic isotopes and thus can be used to trace the behavior of volatiles in the mantle.

Elucidating structural uncertainty using seismic forward modelling.

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Complex structures are often poorly resolved in seismic reflection profiles. Using seismic forward modelling we demonstrate that additional data can be gleaned from the worst seismic reflection profiles.

After applying a traditional interpretation workflow, alternate potential interpretations are used to simulate a seismic acquisition. The resulting synthetic seismic data provides a tool to investigate the relative illumination of different structures and the geometric control on amplitude response.

Comparison between alternate geometries and the acquired data provides a useful reference to understand the relative likelihood of alternate geometries.

This approach highlights the significant uncertainty involved in estimating subsurface geometry at a range of scales. In application these results illustrate that uncertainty should be considered more widely in application to hydrocarbon trapping geometries and estimates of tectonic shortening.

Basal configuration of a mass-transport deposit influenced by subsurface magmatic plumbing: A 3D seismic case study from the Vøring Basin, offshore Norway.

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The influence of volcanic intrusions on the basal configuration of mass-transport deposits (MTDs) remains poorly resolved. In parallel, the origin and development of coves found at the basal shear surface of most MTDs remains an interesting subject of debate to the academic and petroleum industry.

In this study, we employed a high-resolution 3D seismic reflection data to assess the geometry of seven volcanic sills and study the growth of a kilometre-scale cove in the light of breakup volcanism. Our approach includes using the principles of volcanostratigraphy and seismic interpretation to characterize the influence of volcanic plumbing on the palaeo-topography of an identified inlet, which is a large-scale incision at the base of the MTD.

Our results show that shallow sills in the study area are tabular-shaped to transgressive sills fed from an interconnected sill complex comprised of variably shaped sills at depth of 5000 to 6000 ms TWTT. Interestingly, shallow sills mapped in the study area are favourably localized at the base of an inlet coincident with the basal shear surface of the interpreted MTD. On the other hand, the MTD spans more than 1,050 km^2 with an inferred direction of mass-transport northwestward of the study area. The inlet is apparently composed of debris flow deposits or chaotic to transparent seismic facies, as is identified on the high-resolution geophysical surveys. Sills in the area are point-sourced with general upward, outward and northwest migration of magma, parallel to the MTD direction.

Our work proves that the inlet formed on a paleo-high morphology, induced by the forceful emplacement of the volcanic sills during the Eocene in association with the opening of the Norwegian-Greenland Seas. Prior and during the mass-wasting event, the morphological high was subjected to erosion, deposition, sediment loading and differential compaction translating into the inlet interpreted on the present day seismic data.

Detailed fault damage zone characterisation and analysis of seismically active faults for improving estimations of the earthquake energy budget.

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The importance of the damage zone in the faulting and earthquake process is widely recognized, but our understanding of the evolution of damage zones, their characteristic properties, and how they feed back into the seismic cycle, are remarkably poorly known.
Our work will present field investigations of the damage zone profiles around various seismically active faults, including strands of the San Andreas Fault System (California, USA and Baja California, Mexico) and the Cittanova fault (Calabria, Italy). Characterising the extent, distribution, and density of the damage zone along faults of varying displacements will help develop our understanding of their evolution, and baseline kinematic energy of formation calculations should improve estimations of the earthquake energy budget.

The role of bubbles during the 1918 subglacial basalt eruption of Katla, south Iceland.

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Katla is one of Iceland's most dangerous volcanoes, owing to relatively frequent and particularly powerful subglacial eruptions…. But what is it that makes the eruptions of Katla so explosive?

We collected tephra samples from the last major eruption at Katla; K1918. The K1918 eruption produced a large flood (jökulhlaup) deposit (0.7-1.6 km^3) fuelled by the melting glacier[1] as well as substantial airborne tephra (~0.7 km^3) ejected after the overlying 400 m thick Myrdalsjökull glacier was breached[2]. Both jökulhlaup and air-fall tephra samples were collected.

Back-scattered electron (BSE) images of thin sections where collected at the University of Hawaii and then used as inputs into FOAMS[3] and imageJ to quantify bubble and crystal textures.

Jökulhlaup samples have high bubble number densities (BNDs) and vesicularities relative to air-fall samples, suggestive of high decompression rates and rapid volatile exsolution. The relatively vesicle-poor air fall samples have a small number of large bubbles in the clast interiors suggestive of post-fragmentation vesiculation and bubble coalescence. This is supported by higher microlite contents, indicative of relatively slow cooling rates. By comparison, the nearly aphyric sideromelane in the jökulhlaup samples suggests very rapid quenching.

These insights into the relative roles of degassing and phreatomagmatic fragmentation during the K1918 eruption could be useful for predicting the eruptive behavior and likely clast type produced during future Katla eruptions, which could have important implications for ash dispersal and the aviation industry.

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Using trace elements to constrain gas pathways at Cordón Caulle, Chile

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The style of a volcanic eruption can be influenced by magmatic outgassing, with efficient outgassing being key to effusive behaviour. Obsidian flows and domes are evidence this process can happen at rhyolitic centres. The recent rhyolitic eruptions at Chaitén and Cordon Caulle in Chile, the first in half a century, offer excellent opportunities to better understand the complex outgassing processes occurring in more silicic eruptions. Highly permeable bubble and fracture networks, sometimes preserved as tuffisite veins, have been proposed as degassing mechanisms for such highly silicic centres, by acting as transient pathways for volatiles to the surface. Major volatiles species (e.g. H_2O and CO_2) can also act as carrier gases for many trace elements, as evidenced by their enrichment at fumaroles and in volcanic plumes. The 2011–2012 rhyolitic eruption of Cordón Caulle produced largely aphyric bombs from the explosive and hybrid phases of activity, preserving textures suggestive of a multi-stage degassing history. Here we assess the efficiency of vein networks as outgassing pathways in rhyolites using trace-element variations associated with these features.

Preliminary data indicate that these tuffisite veins have elevated semi-volatile trace metal concentrations with respect to their hosts (e.g. As, Pb), while bubble-rich zones within the hosts show depletions (e.g. Cu, Tl). This suggests both reabsorption of metals by contact with a fluxing vapour and loss of metals to a vapour phase. Cross-cutting textural features related to successive degassing events exhibit differences in the elements enriched or depleted suggesting compositional change of the gas with time and/or space during the eruption. These early results support the concept of using chemical heterogeneity in volcanic rocks to study degassing processes at depth.

Retrieval and validation of volcanic SO_2 injection height and eruption time from satellite maps.

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A large body of work has reported detection and retrieval of volcanic gas emissions from space. However, quantitative integration of the volcanic processes that drive eruptions with both the resulting three-dimensional distribution of gas and ash in the atmosphere and ground-based volcano monitoring data, poses a greater challenge. Overcoming this challenge would open a new frontier in the investigation of volcanological processes using satellite data, which would be of particular value for poorly monitored volcanoes.

A key prerequisite for such studies is the determination of plume age and height, as these are required to improve the quality of SO_2 retrievals and to determine gas emission rate time series. Here, we use satellite imagery and a numerical procedure based on back-trajectory analysis to calculate plume heights at the satellite measurement time together with injection plume height and time. Three different Etna eruptions have been analysed and results validated using independent satellite and ground based estimations. We compare retrieved injection heights with measurements of volcanic tremor, which reflects the eruption intensity, in order to perform an initial proof of concept analysis demonstrating the potential of combining satellite-retrieved plume parameters and ground-based observations.

A model based characterisation of passive degassing in basaltic magmas.

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A key characteristic of basaltic magmas is their ability to allow bubbles to ascend and burst independently at the magma surface. This enables an efficient degassing mechanism which enables large quantities of gas to be emitted passively on a per second basis, on the order of ≈ 1 – 1000 kg s^{-1}. Currently, knowledge of bubble dimensions which contribute to passive emissions is limited to bubble populations in lavas and from analysis of material ejected during explosive activity, while estimates of conduit dimensions are often broad.

Here, we detail a new model aimed at characterising passive degassing dynamics, incorporating knowledge of total gas fluxes, ascent velocities of bubbles, and a convecting magma. Using known gas fluxes and magma ascent rates, appropriate bubble and conduit dimensions can be estimated for a range of gas volume fractions. We demonstrate our model in detail, using a relatively well constrained example: the North-East Crater of Mt Etna. Here, by using an average gas flux of ≈ 50 kg s^{-1} (Aiuppa et al. 2008), we show that with a gas volume fraction of ≈ 20%, a 10 m conduit radius and average bubble radii of ≈ 0.01 m are able to facilitate observed fluxes. In addition, the model can be used in reverse to estimate maximum gas flux which could be supported for a conduit and magma with known dimensions and properties respectively, over a range of gas volume fractions and bubble radii.

Used in combination with gas flux measurements our model could provide vital information on sub-surface flow dynamics, important for understanding transitions between passive and explosive degassing styles.

Timescale of effusive to Plinian eruptions at Popocatépetl (Mexico).

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The timescales over which an explosive stratovolcano switches from low-to-moderate explosive activity to cataclysmic Plinian eruption are fundamental in understanding the eruptive behavior and thus contributing to volcanic hazard assessment. Popocatépetl volcano in Mexico ranks high both in term of explosivity and threatened population (> 20 million, including Mexico City). It has had at least five major Plinian eruptions in the last 23 ky. These highly explosive events punctuate periods of quiescence and interplininan activity with effusive and Vulcanian eruptions – a pattern shown by many arc volcanoes.

El Fraile lavas erupted between 23 and 14 ky BP, prior to the Pumice with Andesite (PwA) Plinian eruption, the most powerful eruption at Popocatépetl. Macroscopic evidence of magma mingling are abundant both at El Fraile, with red and black lavas, and in the PwA, which shows mingled deposits and banded pumices. However, each eruptive sequence is very homogenous in term of whole rock major and trace elements and isotope signature. El Fraile lavas are andesites and dacites with a narrow range of Sr and Nd isotope compositions. The PwA sequence is more mafic (basalt-andesite) with more variable Sr isotope ratios and lower εNd. All samples have similar paragenesis (phenocrysts of plagioclase, ortho- and clinopyroxene ± amphibole). A complex population of pyroxenes textures is found in both eruptive events, namely: (i) Type 1 pyroxene with evolved cores ± inclusions of Fe-Ti-oxide and mafic bands (El Fraile Mg# 64-86, PwA Mg# 73-86), and (ii) Type 2 pyroxene with mafic cores (Mg#>81) ± Cr-spinel surrounded by evolved rims. Type 1 pyroxene can be further subdivided in Type 1a and 1b, with the former associate with inclusion of apatite in the evolved core. These pyroxene textures testify pulsatory intrusion of new mafic magma carrying mafic crystals and/or antecrysts in a steady-state magmatic system. The NIDIS chronometry (Petrone et al., Nat Comms 7, 12946, 2016) has been applied to suitable ortho- and clinopyroxene to constrain the timescale of refilling events at El Fraile and PwA. An order of magnitude difference in timescales between interplinian and Plinian events is evident. El Fraile interplinian activity points to a rapid/short magma resident time (days/months) similar to the present-day activity, whereas the building up of the PwA Plinian eruption occurred over longer magma storage timescales (decades to hundreds of years).

Oblique rifting above a lower crustal lineament: What can upper crustal faults tell us about deeper structures?

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Many complex rift systems experience multiple phases of tectonic activity, with their development potentially influenced by the presence and reactivation of pre-existing structures at depth. Obtaining direct constraints on the geometry and reactivation of such deep structures is often problematic due to the typically non-unique and low-resolution nature of geophysical imaging methods. Understanding the geometric and kinematic evolution of complex fault networks at shallow levels may offer insights into the formative mechanisms of rift systems, including the geometry and potential reactivation of structures at deeper levels.

Here, we use borehole-constrained 3D seismic reflection data to examine the structural evolution of the southern margin of the E-trending Farsund Basin, offshore southern Norway. The basin is characterised by N-S- and E-W-striking non-colinear fault sets and is proposed to overlie a lower crustal lineament, the Sorgenfrei-Tornquist Zone (STZ). Using quantitative fault analysis, including throw-length plots and fault displacement backstripping, we analyse the structural evolution of the major E-W striking Fjerritslev North and South Faults, with respect to the minor N-S faults.

Permian-Carboniferous activity along the E-W-striking Fjerritslev North and South faults was succeeded by Triassic activity along predominately N-S faults. During Late-Jurassic extension the Fjerritslev North Fault was obliquely reactivated in response to dextral transtension, resulting in its vertical propagation and upwards bifurcation into a series of left-stepping en-echelon fault segments. At the same time, the Fjerritslev South Fault propagated laterally westwards, cross-cutting pre-existing N-S striking faults. As a result of the oblique reactivation of these E-W faults, localised inversion and oblique motion occurred along linking N-S faults. Collectively, oblique reactivation in this interval is interpreted to represent the formation of a transtensional pull-apart basin.

Through deciphering the evolution of a complex upper crustal fault network, we find that the geometry and reactivation of E-W faults was controlled by reactivation of the underlying STZ. Furthermore, Early Cretaceous pull-apart formation suggests that the Farsund Basin is situated above a releasing bend in the STZ.

Conduit processes in basaltic systems by quantitative analysis of X-ray microtomographic images of volcanic rocks

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Basaltic volcanism is the most widespread volcanic activity on Earth. Basaltic eruptions can manifest different types of eruptive styles, from quiet lava emissions, to mild/moderate Strombolian explosions, to more violent fire fountaining events and paroxysmal activity. Understanding basaltic volcanism and its eruptive styles is therefore key to forecasting the impacts of eruptions. In this view, a series of X-ray computed microtomographic experiments, using both synchrotron and conventional light sources, have been performed to investigate the textures of volcanic rocks in 3D with the aim to link such textures to the rheological and fluid dynamics processes that have generated them in the conduit. In this contribution, I will illustrate how vesicle and crystal textures in scoria and pumice products interact between each other to develop and increase magma permeability, promote non-explosive degassing of magmatic volatiles, and generally dictate the style of eruptive activity at basaltic volcanoes.

Crustal Imaging of Haiti's Transpressional Fault System through Seismicity and Tomography

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Haiti's transpressional fault system is dominated by two strike-slip fault zones that bisect the island from east to west, the Enriquillo-Plantain Garden fault (EPGF) in the south and Septentrional-Oriente fault zone (SOFZ) in the north. Much of the fault system has no clear surface expression with its geometry and slip style still relatively poorly understood despite the 12th January 2010, Mw7.0 earthquake. It is widely accepted that the initial rupture of the 2010 earthquake occurred on a blind thrust fault before partitioning stress and causing unclamping on the EPGF. This highlights the importance of understanding the subsurface aspects of any fault system when assessing hazards potential. In 2013 a network of 27 broadband seismic stations were deployed on Haiti for an 18-month period as part of the Trans-Haiti Project, which is supplemented by up to four permanent stations active during this time. To date 678 local earthquakes have been recorded during the first 7 months of the data with a spatial coverage of seismicity that is greatly improved over previous studies. Well located earthquakes are used for a 2D tomographic inversion for crustal Vp and Vp/Vs ratios to improve earthquake relocations and image crustal structure. The seismicity has shown a previously unrecorded zone of activity along a mapped fault north of Lake Enriquillo, 100km east of the 2010 rupture zone. This cluster suggests that stress-transfer following the 2010 earthquake may have loaded fault segments in the Lake Enriquillo region. In addition, continued activity was observed along the EPGF near to the 2010 rupture and aftershocks. Here we present the earthquake locations recorded with the Trans-Haiti seismic network along with the modelled Vp and Vp/Vs tomographic inversions.

Extension along a 60,000 km^2 detachment fault opened the 7 km Weber Deep in eastern Indonesia

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The Weber Deep forearc basin, at 7.2-km depth, is the deepest point of the Earth's oceans not within a trench. How the Weber Deep achieved its anomalous depth within the tightly-curved Banda Arc in Eastern Indonesia has puzzled geologists for decades. Several models have been proposed to explain the tectonic evolution of the region in the context of the ongoing (*c.* 23 Ma–present) Australia–Southeast Asia collision, but no model explicitly accounts for how the Weber Deep achieved its anomalous depth. Here propose the Weber Deep formed by forearc extension driven by eastward subduction rollback of the Banda Arc. Substantial lithospheric extension in the upper plate was accommodated by a major, previously unidentified, low-angle normal fault system we name the Banda Detachment (Pownall *et al.*, 2016). High-resolution bathymetry data reveal that the Banda detachment is exposed underwater over much of its 120 km down-dip and 450 km lateral extent, having produced the largest bathymetric expression of any fault discernable in the world's oceans. We propose the Banda arc is analogous to other highly extended terranes that may similarly have "rolled open" behind migrating subduction zones. For instance, the Banda detachment's listric geometry and vast scale are analogous to detachment faults characterizing the Basin and Range province in the western United States.

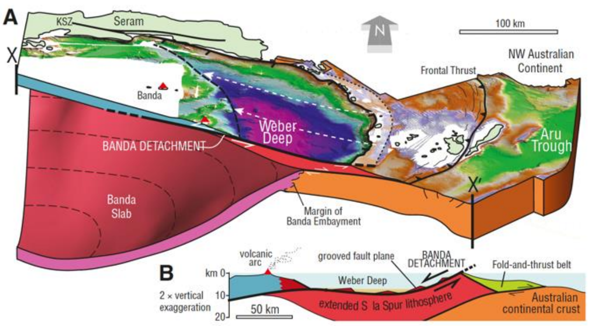

Fig. 1: Extension of the Weber Deep along the Banda Detachment, eastern Indonesia (from Pownall *et al.*, 2016)

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Viscous Flow Causes Weakening in Calcite Gouges Sheared at Seismic Velocity

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Despite viscous flow at thigh strain rates is a well known deformation mechanism occurring in metals, only recently it has been associated to the behaviour of natural fault materials during earthquakes. Microstructures attributed to grain boundary sliding have been described in high velocity shear experiments on carbonates where the recrystallized materials commonly have a submicrometric grainsize.

We designed and performed a set of friction experiments on a rotary shear apparatus on fine grained calcite gouges. Experiments are run at different velocities, from subseismic (<10 cm/s) to seismic (up to 1.4m/s), and stopped at different amounts of slip in order to document the evolution of microstructures coupled with mechanical data.

Experiments show a characteristic four stage evolution of the friction coefficient when the material is sheared at seismic velocities (v>10 cm/s): SI) increase from initial Byerlee's values, f = 0.6-0.7, up to peak values, f = 0.8-0.9; SII) sudden decrease to low values, f < 0.4; SIII) attainment of low steady-state values, f = 0.15-0.3; and SIV) sudden increase to final value, f < 0.6, during sample deceleration.

Microstructural analysis of samples that experienced weakening to steady state conditions (SIII) shows the development of a thin discrete slip zone with thickness < 200μ m composed by a low-porosity aggregate of equigranular recrystallized crystals (< 1μ m) displaying triple junctions. The slip zone is sharply bonded by smooth surfaces marked by a granulometric decoupling.

Prior to the onset of weakening (SI), deformation localises in a horizontal Y-shear band, precursor of the principal slip zone, which shows extreme comminution (<< 1μ m).

Microstructures in the slip zone are strikingly similar to those observed during experiments on metals and fine-grained carbonates deformed at T > 900 °C, where superplastic behaviour due to GBS has been inferred.

These evidences raise the critical role that extreme comminution and localisation play in the onset of seismic weakening in carbonate gouges, possibly dominated by viscous flow of high strain rate ultramylonites.

A 1 million year eruption history of Ascension Island

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Ascension is an ocean island volcano located in the South Atlantic, ~ 90 km west of the Mid-Atlantic Ridge axis. The volcanic rocks of Ascension define a transitional to mildly alkaline basalt-hawaiite-mugearite-benmoreite-trachyte-rhyolite sequence that spans a wide range of eruptive styles across only ~ 98 km^2 of land. The central and eastern sectors of the island are predominantly composed of pyroclastic deposits, trachyte and rhyolite lava flows and domes. The northern, southern and western regions comprise mafic lava flows punctuated by scoria cones [1]. The oldest rocks exposed at the surface outcrop in the centre of the island and have been dated at ~ 1 Ma [2].

Here we present a new pyroclastic stratigraphy and $^{40}Ar/^{39}Ar$ ages for Ascension, revealing that more than 75 explosive eruptions have occurred during the last 1 Ma. Throughout this period, sub-Plinian and phreatomagmatic eruptions have been common, with at least 12 eruptions producing pyroclastic density currents (PDCs). In addition, felsic lava flows and domes, as well as basaltic lava flows have been dated to shed light on timescales of effusive volcanism on Ascension, revealing a new record of Holocene activity.

These data form part of a larger project, which aims to integrate the timing and style of volcanic activity on Ascension with the timescales over which magmatic processes occur. The project is allowing us to examine the control that magmatic processes exert over eruption duration, style and magnitude.

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The stratigraphy and emplacement of lava-like and welded ignimbrites on the southern flank of Las Cañadas Caldera, Tenerife, Canary Islands

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Lava-like ignimbrites are the highest grade deposits of pyroclastic density currents, representing products of extremely hazardous volcanic eruptions. Similarities between lava-like ignimbrites and lavas (e.g. flow banding and columnar jointing) have resulted in misinterpretation of deposits historically, which poses a threat at active/dormant volcanoes, potentially leading to underestimations of the hazards of future volcanic activity.

The extra-caldera deposits of the southern flank of the Las Canadas Caldera, Tenerife, belong to the Uncanca Formation, the oldest of the Las Canadas Upper Group. They extend for ~16 km, and form prominent rusty orange, terraced mountains in the landscape. There is very limited understanding and documentation of these units, which are briefly and loosely referred to in the literature as “lavas” (Ridley, 1969) and later as “welded fall deposits” (Soriano et al, 2002; 2006). However, the units are poorly described with very limited evidence of the suggested emplacement model.

A reassessment of the stratigraphy, structure and emplacement of the extra-caldera deposits is presented. We interpret them as lava-like ignimbrites, exhibiting a range of welding and rheomorphic textures. A series of thick, stacked, predominantly lava-like tuff units have been identified, punctuated by lenses of stratified, pumiceous-rich tuffs, lapilli tuffs and breccias with various degrees of welding. The uppermost units in the sequence are highly welded, locally lava-like, flow-banded tuffs and lapilli tuffs, with an abundance of crystal fragments, mafic enclaves and breccia horizons, indicating proximity to the vent. Possible vent structures (plugs and inclined strata) have been identified on the caldera rim (Soriano et al 2006).

These deposits represent a significant period of eruptive history on Tenerife currently absent from the stratigraphy of the island and their interpretation as lava-like ignimbrites is crucial to understanding the potential hazards posed by active volcanism on the island, and in the wider Canary Islands.

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Preliminary investigation of a complex plumbing system at Ritter Island volcano (PNG) using LA-ICP-MS mapping

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We present preliminary LA-ICP-MS mapping results on clinopyroxene from subaerial lavas and feeder dykes from Ritter Island volcano in the Bismarck Arc, Papua New Guinea. The goal of the study was to elucidate the source and growth history of the complex crystal populations found in the samples, and gain first insights into the volcano plumbing system.

LA-ICP-MS maps were constructed to show trace element distribution on selected clinopyroxene crystals. These maps were compared with electron microprobe major element analyses in the cores and rims of the mapped crystals, and mineralogy and XRF bulk chemistry of the sample. Crystal aggregates, xenolithic crystal aggregates, xenocrysts, phenocrysts, and groundmass clinopyroxene crystals were all mapped in samples from both the north and south coves of Ritter Island, that correspond to older and younger units in the volcanic sequence erupted before the 1888 AD collapse of Ritter Island.

Microscale, concentric variations in trace element concentrations of compatible and incompatible elements, most noticeably Cr, Ni and Nd, were observed in samples from the north and south of the island. We interpret these as growth episodes in magmas of changing composition, related to complex magma histories. Crystal populations within one sample share the most recent growth episodes, indicating residence in the same magma for some time before eruption. Larger crystal aggregates display more episodes of mafic enrichment than phenocrysts in the same magma, suggesting longer residence times and repeated recharge events. The north cove crystals show evidence of late mafic recharge, which we interpret to have triggered the eruption, whereas the south cove crystals do not have a mafic trace element rim, suggesting a different eruption trigger for that magma.

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Lava lakes and persistent degassing at Masaya volcano, Nicaragua

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Situated in western Nicaragua, Masaya is a persistently active basaltic shield volcano and caldera complex. Within the caldera lies a basaltic edifice formed by eruptions from a 2 km long chain of vents. The vast majority of edifice development resulted in the construction of Masaya and Nindiri cones; however multiple occurrences of pit crater collapse also took place, forming Masaya, Santiago, Nindiri and San Pedro pit craters. The currently active Santiago pit crater exhibits alternating periods of prolonged volcanic degassing and lava lake formation. Gas emissions have been known to reach crisis levels, triggering chronic ailments, crop failures and the contamination of water sources downwind of the crater.

The most recent lava lake episode began in December 2015 and is still active today, vigorously convecting and expelling juvenile Pele's hair and scoria. The lava lake resulted in temporary closure of the volcanic park to tourists earlier in the year. Microgravity, levelling and gas emission measurements before and after the lava lake was established allow the role of a lava lake on Masaya's activity to be investigated.

Microgravity monitoring across the volcanic complex indicates very minimal changes in subsurface mass between 2014 and 2016. Precision levelling surveys performed in 1994 and 2015 demonstrate a net deflation.

Volcanic gas studies conducted in February-March of 2015 and 2016 entailed measurements of SO_2 emission rate by ultraviolet spectrometry (FLYSPEC) traverses below the plume, 5.5 km downwind of the active vent. Additionally, ground level gas monitoring was conducted using a network of SO_2 and acid gas diffusion tubes spanning from the periphery of Santiago crater to the Pacific coast.

In 2015 SO_2 downwind exposure levels averaged 4309 $\mu g/m^3$ inside the caldera and 155 $\mu g/m^3$ outside of the caldera and daily SO_2 fluxes averaged 56 t/d. In 2016, following the development of the lava lake, SO_2 downwind exposure levels averaged 1014 $\mu g/m^3$ inside the caldera and 163 $\mu g/m^3$ outside of the caldera and daily SO_2 fluxes averaged 136 t/d. The work presented will address the significance of these variations and factors that may have influenced them.

Fault displacement and seal analysis in space and time

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Quantitative fault analysis is based on the principal that faults develop in a predictable manner in three-dimensional space. Understanding this development allows us to model fault displacement distributions in time as well as space, while evaluating the results of these analyses can rapidly highlight interpretation errors and complexities related to fault evolution; both of which can have important implications when considering the economic significance of a fault (e.g. sealing capacity). The techniques and theories associated with fault analysis are primarily derived from detailed coal-mine mapping in the mid-1980s but today are most frequently applied to geological models built from high-resolution 3D seismic reflection data. Despite the prevalence of detailed structural models, most previous work has focused on static models with limited integration of established restoration techniques and displacement-based fault analysis. While enabling definition of present day geometries and across-fault relationships, static analysis provides minimal insight into the characteristics of a fault during its evolution. Here we demonstrate how sequential backstripping and fault restoration using industry standard compaction curves, allows implementation of palaeo-fault analysis within Midland Valley's Move suite. By accounting for compaction and displacement, the true development of faults can be quantified allowing across-fault relationships and geometries to be defined at key time-steps, for instance at the time of hydrocarbon migration and trapping. Case studies are presented from New Zealand's Taranaki Basin where the growth histories and palaeo-sealing capacities of two major normal faults, the Parihaka and Cape Egmont Faults, are examined. The Cape Egmont Fault bounds the Maui gas-condensate field, New Zealand's largest hydrocarbon discovery and has been previously assumed to act as a barrier to cross-fault fluid flow. This work shows that the nature of fault seal has varied since the onset of expulsion and that the fault may have facilitated cross-fault hydrocarbon migration to charge to the Maui field.

3D Seismic Constraints on the Morphology and Emplacement of Mafic Laccoliths: Implications for Surface Folding and Shallow Magma Transport

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Sills play an important role in transporting magma through the crust and to the surface. However, the role of mafic laccoliths in feeding small volume basaltic eruptions has until now been unknown. In this study we use exceptionally high resolution 3D seismic data to provide the first evidence of a mafic laccolith feeding multiple small volume (<1 km^3) lava flow fields. The laccolith was emplaced at <300 m beneath the paleo-surface as a series of interconnected lobes, and magma was accommodated by formation of a multi-lobed forced fold. The fold is characterised by collapse faults, inferred to result from drainage of magma from the intrusion through to the lava flow fields. The volume of the laccolith far exceeds the volume of lava erupted, indicating that the magnitude of folding associated with magma intrusion does not provide accurate constraint on the magnitude of ensuing eruptions. This study highlights the importance of concordant mafic intrusions in feeding small volume eruptions and suggests that other mafic volcanic provinces may similarly contain laccolith-like intrusions, particularly where magma is emplaced at shallow levels in unconsolidated sediments.

Determining the chronology of Holocene earthquake clustering on the Garlock fault, California.

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Earthquake clustering is important as it has implications for probabilistic seismic hazard assessment, as well as for the ways in which the crust distributes and releases elastic strain. Understanding the magnitude, location and timing of past earthquake events within clusters will help in the development of physical models of fault behaviour. Finding contexts to recover this information is challenging, but new developments in luminescence dating are providing new possibilities.

One of these new contexts is the central Garlock fault, CA, USA. This WSW-ENE trending left-lateral strike slip fault sits within the Mojave Desert, where occasional high magnitude storm events lead to the deposition and subsequent erosion of small gravel terrace units on alluvial fans. By carefully selecting different targets in the form of terrace risers that display different offsets, and determining firm age control using single grain post-IR IRSL (Infra-Red Stimulated Luminescence) of potassium feldspars, we are able to determine fault slip-rate and cumulative slip over different periods. By combining the slip history with a, existing nearby high quality palaeoseismic record, we are able to construct a slip-per-event record of relatively high resolution through the last (and possibly on-going) late Holocene earthquake cluster, covering 5 earthquake cycles. We are now attempting to extend this approach to the last 12,000 years, and assess the potential to reconstruct slip history over even longer periods.

Revealing the internal flow of salt structures using anisotropy of magnetic susceptibility

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The mobilisation and intrusion of salt plays a major role in the evolution of basins. Although the geometry and distribution of salt structures can be easily examined, the internal dynamics of salt intrusion are only partially understood. Collecting detailed structural data from outcrop is difficult due to limited exposure, inaccessibility and poorly preserved visible fabrics. To overcome this crucial impasse in salt tectonics, detailed and high quality strain data is required from salt outcrops. To obtain structural strain data we have used anisotropy of magnetic susceptibility (AMS) measurements on oriented samples collected from mine and coastal exposures of evaporites in Nova Scotia, Canada.

It is unusual to find diapiric structures so well exposed as they are on the west coast of Cape Breton, Nova Scotia. These evaporites form as part of the carapace overlying a predominantly halite core surrounded by Carboniferous sediments. Deformation within the structural carapace reflects deformation of the underlying halite core of the diapir and the overall structure. Both brittle and ductile deformation fabrics have been recorded within the surrounding sediments and we have observed them imprinted within the evaporite facies. To understand the AMS measurements these must first be fully understood. Pugwash mine offers a perfect opportunity to study diapiric growth structures at a much larger scale. Using 5 maps at different depths we can better understand the deformation of the deposit and the 3D geometries formed.

Magma storage of the Monte Amarelo dikes, Fogo, Cape Verde

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The volcanic island of Fogo is situated in the Cape Verde archipelago, 600 km west of Africa. The volcano is regarded as one of the most active in the world recording at least 8 eruptions since the 18^{th} century. During a large landslide that occurred between 132 ka and 86 ka, the eastern flank of the 3500 m Monte Amarelo volcano collapsed into the Atlantic Ocean. We collected samples from the radial dikes in the Bordeira cliffs, left by the landslide. Previous work on magma storage for the volcanics, shows clinopyroxene rim crystallization pressures between 0.25 and 0.68 GPa[1,2]. Our study aims to constrain the magmatic plumbing system for the Bordeira dikes.

The dikes are basanitic to nephelinitic in composition with 1.82 to 11.5 MgO wt%. The main mineral constituents are clinopyroxene ± amphibole with minor olivine, titanomagnetite, and interstitial apatite, plagioclase, alkali feldspar, nepheline and biotite. Clinopyroxene shows a large variation in Mg#, with cores ranging from Mg# 58 to 85, with a mean Mg# of 74±7, 2s.d. (n=110). For rims and microcrysts, Mg# varies from 26 to 78, with a mean Mg# of 70±11, 2s.d. (n=411). Interstitial feldspars form two groups, one with An# from 15 to 79, with a mean of 63±28, 2s.d. (n=134) and the other group has Or# of 19 to 100 with a mean of 69±43, 2s.d. (n=72).

Preliminary clinopyroxene-melt thermobarometry shows crystallization pressures for cores of 0.28 to 0.95 GPa, with a mean of 0.64 ±0.22 GPa, 2s.d. (n=105) whilst rims and microcrysts have pressures of 0.02 to 0.74 GPa, with a mean of 0.45±0.27 GPa, 2s.d. (n=336).

The Moho at Fogo is 0.34 to 0.39 GPa[3]. This indicates the main crystallization initiates in the lithospheric mantle, however 20% of the rims and microcrysts crystallize in the crust.

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Riding the right wavelet: Detecting scale transitions in fracture and fault orientations using Morlet wavelets.

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Fractures, joints and faults are ubiquitous in the brittle crust of the Earth, occurring at all scales. In well-developed networks, fractures can create highly anisotropic permeability within rocks, providing hugely important conduits for fluids (e.g. water, geothermal fluids, gas, oil). Considerable uncertainty exists regarding the organization of fractures at different scales, but there are persuasive indications that many features of fracture systems are scale dependent.

The analysis of images through two-dimensional (2D) continuous wavelet transforms makes it possible to acquire information at different scales of resolution. This allows us to use wavelet analysis to quantify anisotropic networks of fractures. Previous studies [1] have used 2D anisotropic 'Mexican hat' wavelets to analyse the organisation of fracture networks from cm- to km-scales. However, Antoine et al. [2] explained that this wavelet has a relatively poor directional selectivity. This suggests the use of a wavelet whose transform is more sensitive to directions of linear features, i.e. 2D Morlet wavelets [3]. In this work, we use a fully-anisotropic Morlet wavelet to analyse fracture networks, as implemented by Neupauer & Powell [4] for their analysis of permeability variations.

We demonstrate the validity of this technique by application to both synthetic – i.e. artificially generated with known distributions of orientations and lengths - and experimentally produced fracture networks. We have analysed SEM-BSE images of thin sections of Hopeman Sandstone (Scotland, UK) deformed under triaxial conditions. We find that the Morlet wavelet, compared to the Mexican hat, is more precise in detecting dominant orientations in fracture scale transitions at every scale from intra-grain fractures (μm-scale) up to the faults cutting the whole thin section (cm-scale). Through this analysis we can determine the relationship between the initial orientation of tensile microcracks and the final geometry of the through-going shear fault, exploiting the total areal coverage of the analysed image.

This technique, easily applicable to bigger scales compared to those analysed in this study, e.g. satellite images and aerial photographs, provides useful data for interpreting the mechanical behaviour of brittle deformation and for unravelling the geometrical complexity of faulted areas.

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Constraining the timing of fault-zone evolution using LA-ICP-MS U-Pb geochronology of calcite

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There is a lack of readily available techniques for providing absolute chronological data on brittle fault zone evolution. Calcite is an abundant fracture-filling mineral in many geological settings, and has the potential to be dated by U-Pb geochronology. Calcite mineralisation can often be linked directly to fault displacement/opening events, or to bracketing such events; it can also provide a record of fluid flow and the associated fluid composition through a fault/fracture system. Thus, the absolute dating of calcite formation has the potential to provide a widely accessible technique to enhance our understanding of fault evolution and upper crustal deformation.

Previous attempts at dating hydrothermal calcite have been unsuccessful due to unfavourable U/Pb ratios. So far no physical criteria have been identified that would help to distinguish the best samples for geochronology. It is clear that the source fluid must be able to transport U in solution, requiring it to be oxygenated because U is immobilized with reducing fluids. The incorporation of common Pb during precipitation of calcite hampers it's use for U-Pb geochronology. Here we present a methodology for the dating of calcite with the U-Pb isotopic system using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), and we discuss the benefits and pitfalls of applying this technique to calcite and brittle fault zone evolution. This approach is applied to a case study of rift-related fault-zone evolution in the Faroe Islands, NE Atlantic margin.

Using surface geochemistry to identify and map fluid and gas conduits in high enthalpy geothermal systems in East Africa.

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Three years ago, it was estimated that less than around 23% of Kenyans had access to reliable, cheap, clean electricity. Although that has increased, dramatic climatic changes that affect the region means the current choice of electricity generation methods cannot cope with even the base load demand; thus forcing the Kenyan government to introduce energy rationing.

East African nations from Eritrea in the north to Mozambique in the south are in a prime location along the East African Rift System (EARS) to explore, exploit and develop the huge resource of geothermal energy. The geology and processes associated with the early stages of continental break up has given rise to a very high temperature, shallow resource that could bring many of the East African nations out of fuel poverty by 2030.

In Kenya’s Gregory Rift, nine separate locations have currently been identified for exploration and development, with a further nine in Ethiopia. Current estimates suggest a potential energy output for the region due to geothermal developments at around 15 GW. One of the locations is the Menengai summit caldera in the Gregory Rift, Kenya.

The development in the caldera is almost at the end of phase one, when connected to the grid, this location will provide 105 MW. Recent work here has been looking in to whether simple, quick, low cost surface exploration methods associated more with monitoring volcanic unrest, could be applied to exploration for geothermal resources. Using the method allows for the locating of buried fault and fracture networks that are act as conduits for fluid and gas movement, by measuring CO_2 degassing at the surface and sampling for $\delta^{13}C/\delta^{12}C$ analysis to further identify where the deep seated structures are likely to be. The use and further development of these methods in an area already developed allows for a compare and contrast of results.

Such surveys could be used to further advance detailed and targeted geophysical, geochemical and hydrogeological surveys and reduce the risk of drilling “blind” by guiding the development of logistically complex drilling programs.

Using the data that has been collected from three field campaigns to Menengai caldera, the potential of these methods will be demonstrated here.

Magma intrusion in viscoelastic media: laboratory model of coeval brittle and ductile deformation

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Crustal rocks are complex materials that exhibit contrasting rheological behaviour in different settings. Magma intrusion morphology is linked to this complexity, where end member elastic and visco-plastic conditions are understood to produce blade-like dykes and rounded, mushroom-shaped diapirs respectively. However, the form of magma bodies intruding into intermediate, viscoelastic hosts is poorly constrained.

Here we present a laboratory model of magma emplacement in visco-elasto-plastic materials which aims to bridge this gap in magma intrusion theory. Our model consists of a Hele-Shaw cell (figure 1) in which oil and water (magma analogues) are injected into laponite (a crustal analogue), a viscoelastic and photoelastic gel. The experiments are recorded using a polariscope such that the local stress-strain patterns are highlighted as birefringence. Digital image correlation is then used to quantify the stress-strain relationships in the host matrix and map the distribution of the visco-elasto-plastic deformation accommodating magma emplacement (Bertelsen 2014).

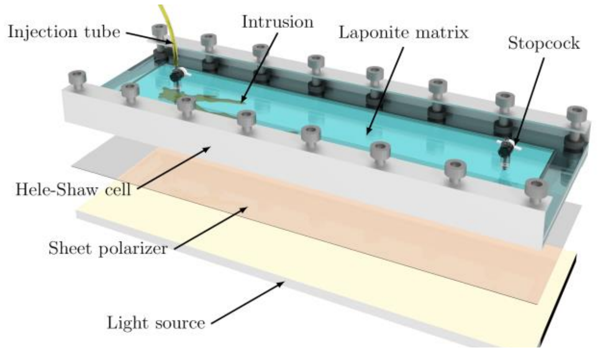

Figure 1 - Hele-Shaw cell

The intrusions formed broad, lobe-like Rayleigh-Taylor fingers and narrow, magma-filled fractures in viscous and elastic host materials respectively, while more complex intrusion geometries were formed in intermediate visco-elasto-plastic host conditions.

This method allows for the observation of intrusion morphology in association with carefully controlled host rheology, but also to link the intrusion to the form of deformation present in the host material. One major implication of the experiments is that intrusions that appear to propagate through dominantly viscous processes in fact exhibit elastic stress patterns and fracturing. These experiments therefore provide valuable insight into the complex mechanics of magma intrusion in viscoelastic settings.

The deformation-fracturing during the intermittent dome growth at SHV

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Long-term research on the relationships between ground deformation and fracturing (Kilburn, 2003; 2012) developed a model for self-accelerating processes. Here we report a test of this model against seismic precursors recorded before the outbreak of andesite lava at Soufriere Hills Volcano (SHV) on Montserrat in 1995. The aim is to apply the Model, which was developed for volcanoes reawakening after a long period of repose, to the fluctuations in eruptive conditions during a continuous eruption at SHV. The rationale behind this approach was that SHV's long-lived eruption was intermittent in nature, characterised by five distinct dome building phases of lava extrusion, separated by pauses in activity. Precursory signals occurring prior to its 'restart' events closely resembled the type of activity normally associated with dormant volcanoes, thus potentially applicable. The results revealed that the volcano-tectonic (VT) and deformation signals analysed were not very useful in forecasting extrusion events during this type of eruption. However, these can indicate changes in stress across Montserrat and therefore aid in the reconstruction of the 'stress-strain' history for the study period. In addition, phases of relaxation could be identified for some extrusion events but inconsistencies were observed in connection to the expected behaviour. The correlation between the deformation relative movement and the change in volcanic activity could not be validated with confidence due to major uncertainties and suggested two alternative interpretations. Firstly, one that implied that stress is dropping and the north side of the island is relaxing in respect to the south; secondly, that there was a build-up of stress on the south side of the island, which appeared to be more valid in relation to the volcanic activity. These results could potentially be solely explained by the fact that SHV is an open-system with different sets of conditions, in comparison to volcanoes reawakening for the first time, following a long period of dormancy. However, the limitations of the present research lie in the analysis of partially complete data available and the limited number of open-system volcanoes the Model was tested on. Therefore, further research is needed in order to apply the Model to a wider range of similar volcanoes and validate the present findings.

Porosity-Velocity relationship in volcanic rocks: An example from the Parana-Etendeka LIP

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The presence of volcanic rocks in many sedimentary basins presents a range of challenges for hydrocarbon exploration, development and production (e.g. both North and South Atlantic Margins). The volcanic rocks from the Parana-Etendeka Igneous Province (PEIP) preceded rifting of the South Atlantic Ocean and represent a direct analogue for similar aged volcanic rocks present within prolific hydrocarbon bearing basins offshore Brazil. Predicting porosity-velocity relationships is vital when correlating well data with lithofacies distributions and geometries. In this study we present a detailed integration of outcrop analogues with laboratory measurements of porosity, permeability, density, and ultrasonic acoustic velocities (P- and S-waves). The analyses were carried out on 166 unsaturated samples from the lava flows of the PEIP under ambient P and T conditions and represent the first of its kind in the area. Within this study the lava flows were grouped in: 1) compound braided facies; and 2) classic tabular facies. Flow cores are typically massive with P-wave velocities ranging from 4.5 to 6 kms^{-1}, and S-wave velocities from 2.5 to 3.5 kms^{-1}, and porosities < 5%. Lava upper crusts are usually highly vesicular or rubbly and have porosities as high as 28.3%. The initial porosity is rarely preserved, being in many cases filled by secondary minerals (clays + zeolites). Velocities in the upper crusts of lavas are scattered from 3 to 5 kms^{-1} (Vp) and 1.8 to 3 kms^{-1} (Vs). Derived elastic rock properties are scattered along the lower elastic Reuss bound calculated for typical basalt compositions (ol, plag, cpx). Variations in rock mineralogy, such as addition of olivine/oxides, can increase velocities by ~1 kms^{-1} while alteration (substitution of mafic phases by clay minerals) can decrease original velocity values in ~0.5 km^{-1}. These variations are more significant for low porosity samples (<5%). Fluid substitution equations were used to predict fluid saturation effects. In samples with porosity < 5% the effects of fluid saturation are minimum. Higher porosity samples present velocities up to 5% higher when saturated with water. Our data shows that the porosity/velocity relationship within lava facies is primarily controlled by the lava flow structure and mineralogy and is modified on a smaller scale by alteration process and fluid saturation. Future modelling will compare unaltered samples with the existing data to define the modification path of primary porosity during burial/diagenesis.

Capture of shear mixing in pyroclastic density currents at Mount St. Helens

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Flume experiments have previously demonstrated that deposits from granular currents can exhibit reworking and erosion features which are generated by by shear instabilities. These are driven by a velocity profile between the substrate and active flow region, and result in forms strongly reminiscent of Kelvin-Helmholtz instabilities in traditional Newtonian liquids and gases. Due to the material uniformity within pyroclastic deposits it was expected that signs of these features in the field would be difficult if not impossible to observe.

A recent field campaign to Mt St Helens explored deposits of the 1980 eruption which have been subject to severe and ongoing erosion, exposing new fresh surfaces. Within these faces a range of wave-like features have been identified which closely resemble shear-derived instability forms. Dimensions of the features are used to explore the likely flow conditions during deposition, and how these tally with existing observations of the 1980 event.

Hydraulic conductivity of thin, planar cracks in shale and sandstone as a function of shear and normal stress.

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Conductivity of fluids along fractures in rocks is known to be reduced by increasing normal stress across the crack, but the conventional view that the onset of shear failure along planar cracks enhances fluid flow owing to a small amount of dilatancy has not been ambiguously demonstrated. Fluid flow in cracks is usually modelled beginning with the ‘cubic law’ relating flow rate along a parallel-sided channel to its width, then adding complexity due to crack roughness and tortuosity of flow paths. Here we determine experimentally how increasing normal and shear stress affects fluid flow along cracks treating the crack as being replaced by a thin slab of homogeneous material of greater permeability. This greatly simplifies the problem.

We used argon gas to measure conductivity of planar cracks in Bowland shale and a higher viscosity synthetic oil for the much more conductive Pennant sandstone. In both cases conductivity is reduced by increasing normal stress (over a range of 80 MPa), and is recoverable during pressure cycling. Shear stress was increased at constant resolved normal stress until the onset of frictional sliding. In both cases, at this point the conductivity decreases markedly and permanently, due to the formation of a very thin layer of very fine-grained (10 μm) fault gouge as crack surface asperities are broken through and granulated. The positive normal stress sensitivity of friction stress indicates that there is local dilatancy, but from the point of view of conductivity, this is clearly swamped by the formation of the fine, low conductivity gouge matrix and its compaction. The combination of increasing normal stress and shearing can reduce conductivity by up to 5 orders of magnitude.

These results can impact greatly on approaches to the modelling of fluid flow through rock masses containing crack arrays, necessary for the design of hydraulic fracture treatments, geothermal energy extraction, the design of waste repositories in a range of rock types and the flow of reservoir fluids.

Aligning petrology with geophysics: the Father's Day intrusion and eruption, Kīlauea Volcano, Hawai'i

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The Father's Day 2007 eruption at Kīlauea Volcano, Hawai'i, is an unprecedented opportunity to align geochemical techniques with the exceptionally detailed volcano monitoring data collected by the Hawaiian Volcano Observatory (HVO). Increased CO_2 emissions were measured during a period of inflation at the summit of Kilauea in 2003-2007, suggesting that the rate of magma supply to the summit had increased [Poland et al., 2012]. The June 2007 Father's Day eruption in the East Rift Zone (ERZ) occurred at the peak of summit inflation. It offers the potential to sample magmas that have ascended on short timescales prior to 2007 from the lower crust, and perhaps mantle, with limited fractionation in the summit reservoir. The bulk rock composition of the lavas erupted are certainly consistent with this idea, with >8.5 wt% MgO compared to a typical 7.0-7.5 wt% for contemporaneous Pu'u'O'o ERZ lavas. However, our analysis of the major and trace element chemistry of olivine-hosted melt inclusions shows that the melts are in fact relatively evolved, with Mg# <53, compared to up to 63 for some high fountaining eruptions, e.g. Kīlauea Iki. The magma evidently entrained a crystal cargo of more primitive olivines, compositionally typical of summit eruption magma (with 81-84 mol% Fo). The melt inclusion chemistry shows homogenized and narrowly distributed trace element ratios, medium/low CO_2 abundances and high concentrations of sulfur (unlike typical ERZ magmas). Dissolved volatile contents along profiles in embayments ("open" melt inclusions) were measured and compared to diffusion models to predict timescales of magma decompression prior to eruption. These are compared to timescales of lateral dike intrusion measured using tilt, GPS and seismology to refine our understanding of horizontal and vertical magma flow in dikes between the summit reservoir and ERZ.

The role of the Ad Damm Shear Zone during Red Sea rifting: western Saudi Arabian Margin.

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Reactivation of continental basement structures during later rifting is commonly invoked as controlling fault patterns, and basin architecture. Here we investigate the role of the Ad Damm Shear Zone (ADSZ), Saudi Arabian margin, during Cenozoic Red Sea related rifting. The ADSZ is a major Neoproterizoic right-lateral strike slip fault, which separates the Jeddah terrane to the north from the Asir terrane to the south. South of the ADSZ, the Red Sea oceanic basement exhibits well-developed linear magnetic anomalies; to the north, they are not present. Onshore, and within continental crust, the ADSZ bounds a large topographic escarpment perpendicular to the rift margin, with higher elevations to the south. In addition, recent studies show active strike slip seismicity within the Jeddah terrane bounded by the ADSZ, suggesting reactivation. Focal mechanism solutions indicate reactivation of primary fault planes striking N30±05°E within the ADSZ during NE-SW extension associated with Red Sea. Initial structural characterization of the ADSZ shows high temperature deformations (e.g., dynamic recrystallization and grain size reduction) are dominant, with only minor upper crustal brittle deformation observed. Rift-related faults and dikes cut ADSZ mylonitic fabrics at a high angle (~65°); dikes show varying strikes in the north (N45W) and south (N15E-N53W), across the ADSZ, suggesting a basement control on structure geometry. Future work will use a combination of remote sensing and field-based structural characterization, and geochemical analysis, to determine phases of reactivation of the ADSZ.

Challenges with Seismic Imaging in Volcanic Margins

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Volcanism associated with continental breakup and the formation of the North Atlantic covers much of the Faroe-Shetland Basin, causing a major problem in geophysical exploration of margin basins. The extrusive basalt sequences on the Atlantic margins can be in excess of 3 km thick, and are highly heterogeneous, which causes complex scattering and attenuation of the seismic wavefield during exploration surveys, resulting in poor intra-basalt and sub-basalt seismic imaging. Sequences contain a range of lavas, intra-basaltic siliciclastic and volcaniclastic sediments, and the high acoustic impedance contrasts between units results in the generation of multiples and mode conversions. In addition, lavas exhibit a high impedance contrast between the dense flow cores and the lower density unit crusts, as well as rough interfaces, which leads to further wave scattering. Wide-angle seismic data has typically been used to develop crustal velocity models, using a common technique known as ray-tracing tomography. This method, based on the ray-theory approximation to seismic wave propagation, may lead to unreliable velocity model estimates due to it not being able to accurately model the heterogeneity seen in basalt sequences, in particular, the presence of lower velocity material. An important issue that arises is that the thickness of the extrusive basalt layer can be significantly underestimated. Using a synthetic wide-angle seismic dataset, we compare and contrast the ray-tracing technique with more appropriate full-wavefield seismic modelling methods.

Further to this, we apply the full-wavefield technique to the imaging of intrusive igneous bodies, such as sills. Igneous sills typically have a high velocity and density relative to the surrounding sedimentary country rock, resulting in strong seismic reflections. This becomes problematic in stacked sill networks, where thick sills mask the appearance of thinner sills below. Recent studies that compare seismic imaging of sills with well data that penetrates the network [1] show that ~88% of sills in the North Atlantic are below the level of the vertical seismic resolution, meaning they are missed during the interpretation of seismic data. Here we use synthetic seismograms for field analogues from the San Rafael Sub-Volcanic Field in Utah, USA, to highlight the issues with imaging sills.

[1] Schofield, N. *et al.* (2015). Basin Research.

Differentiation processes of Sumatran Andesites

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Arc volcanism in Sumatra is characterised by a chain of dominantly andesite volcanoes that run the length of the island. Recent explosive eruptions at Sinabung have demonstrated the potential hazard that andesites volcanoes pose to local and regional communities, but only limited data if any exist for many of these volcanoes.

The genesis of andesites is a contentious topic with the debate surrounding whether melts are contaminated within the mantle or the overriding crust. Here we report major, minor and trace element, Sr-Nd-Pb-O isotopes of whole rock and mineral separates of 14 volcanoes along the Sumatra arc segment (from north to south Sinabung, Sibayak, Toba, Bual Buali, Sorik Marapi, Marapi, Talang, Kerici, Berang, Kaba, Dempo, Sekincau, Ratai and Rajabasa) to provide insights into andesite magma genesis and thereby gain insights into the magmatic processes in the region.

Erupted lavas are generally porphyritic with plagioclase and pyroxene crystals as the dominant phases. Differences in degree of differentiation can be observed at each volcanic centre. Combined with the crystal rich nature of the majority of the samples, this indicates that fractional crystallisation was an important processes in the genesis of these andesites.

Little along arc bulk rock geochemical variation is observed. However, whole rock and mineral specific geochemistry reveals two groups of andesites 1) a central and southern grouping and; 2) a northern volcano group that commences north of Bual Buali. Andesites in the central and south of Sumatra region show dominantly mantle-like geochemical signatures. In contrast, andesites in the northern group, show dominantly crustal geochemical signatures, indicating that additional crustal processes are relevant in the genesis of andesites in northern Sumatra.

Morphology of the Katla SILK tephra and implications for volcanic ash dispersion modelling

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Complex magmatic and eruptive processes result in significant variations in the physical properties of volcanic ash particles, including size, density, and shape. The shape of volcanic ash particles in an eruption column can significantly impact particle terminal velocity and therefore maximum travel distance, making morphology an important parameter to accurately quantify in atmospheric dispersion modelling. Most models approximate ash as spherical or adjust drag coefficients based on a single shape factor, most commonly sphericity, the ratio of a particle's surface area to that of an equivalent-volume sphere. However, due to difficulties in characterising fine volcanic particles in three dimensions, a two-dimensional measure of circularity, based on particle perimeter, is often used as a substitute. This study analyses the sensitivity of the Met Office's dispersion model NAME to both shape parameters when shapes are extremely non-spherical. A detailed morphological analysis of the SILK tephra layers UN, MN and LN (Upper, Middle and Lower Needle layers, respectively) formed by silicic eruptions of Katla volcano in Iceland reveals particles with an average sphericity of around 0.2, far lower than found in the majority of studied volcanic ash deposits. Parameterising this shape in NAME results in particles travelling significantly further than when spherical particle defaults are used. Discrepancies between modelled eruptions using sphericity and circularity as shape factors suggest that when particle shape is extreme, a 2D approximation may not be sufficient to accurately model particle fall velocity and therefore atmospheric dispersion. The results have significant implications for ash hazard to the UK in the case of a potential future silicic eruption from Katla volcano.

Volcanic risk through the ages: social factors influencing volcanic risk on St Vincent, Lesser Antilles from a historical perspective

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Our research has been focused on how societies come to co-exist in a volcanically active environment. Here we explore the concept that volcanoes are not only agents of change, but also impact on the environment and society, encouraging the society to continuously adapt to volcanic eruptions through identified responses, coping strategies, hazard mitigation and recovery methods. St Vincent is an appropriate location to demonstrate this, as three eruptions have occurred at distinct periods of societal development: during slavery, post-emancipation and, on the eve of Independence.

The complexity of volcanic risk lies in understanding various environmental, social, cultural, economic and political factors, the volcanic hazard phenomena and the interconnectivity between vulnerability and resilience. It also requires the acknowledgement that these factors can and will change through time. However, how an island's volcanic risk has evolved in conjunction with societal development is not well understood.

Here, we show the impact of volcanic eruptions on St Vincent's agriculture, the country's most important industry, and how social, political and economic development influenced the impacts. We found that the agricultural sector was influenced by the topography of the island, conflict between the indigenous population and colonists, peasants and large estate owners, and fluctuations in the global market demand. The volcanic eruptions caused temporary disruption to the industry, and in the instance of one eruption, changed the focus from one commodity to another. Recovery and reconstruction were influenced by existing social capital and political pressure on the national government. Assistance was more favourable towards the white elite due to political pressures on the national and British government, whilst for the rest of the society, recovery relied on existing and fostered social capital.

We anticipate that our research will open up discussion on how investigating the impacts of historical eruptions can inform us of present day and future volcanic risk and, the different ways in which volcanic eruptions have influenced societal change.

Inelastic deformation during sill and laccolith emplacement: insights from an analytic elasto-plastic model

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Numerous geological observations evidence that inelastic deformation occurs during sills and laccoliths emplacement. However, most models of sill and laccolith emplacement neglect inelastic processes by assuming purely elastic deformation of the host rock. This assumption has never been tested, so that the role of inelastic deformation on the growth dynamics of magma intrusions remains poorly understood. In this contribution, we introduce the first analytical model of shallow sill and laccolith emplacement that accounts for elasto-plastic deformation of the host rock. It considers the intrusion's overburden as a thin elastic bending plate attached to an elastic-perfectly-plastic foundation. We find that, for geologically realistic values of the model parameters, the horizontal extent of the plastic zone l_p is much smaller than the radius of the intrusion *a*. By modeling the quasi-static growth of a sill, we find that the ratio l_p/a decreases during propagation, as $(a^4 \Delta P)^{-1/2}$, with ΔP the magma overpressure. The model also shows that the extent of the plastic zone decreases with the intrusion's depth, while it increases if the host rock is weaker. Comparison between our elasto-plastic model and existing purely elastic models shows that plasticity can have a significant effect on intrusion propagation dynamics, with *e.g.* up to a factor two for the overpressure necessary for the sill to grow. Our results suggest that plasticity effects might be small for large sills, but conversely that they might be substantial for early sill propagation.

Nature of crust in the central Red Sea

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Determining the nature of crust in the central Red Sea is essential to a full understanding of the development of young oceanic basins, for instance, how the seafloor spreading takes the place of continental rifting. Whether the crust in the central Red Sea is continental or oceanic is a controversial subject. To determine the crust type, the basement subsidence across the ridge-axis and the rugosity intensity parallel to the spreading ridge were calculated to be analysed. In this study, the basement subsidence in the central Red Sea is compatible with an oceanic crust. Moreover, the root mean square (RMS) values show that the basement relief around the spreading center is consistent with the crust being oceanic. The variations in basement depth were derived from free-air anomaly data using slab formula under the assumptions of oceanic and continental crust. After that, the basement depths were derived from the variations under the constraint of seismic reflection data. A map of basement topography was then constructed from the gravity-derived basement depths. Werner deconvolution was used to derive the magnetic source depths along the seismic lines. The clustering of Werner solutions gives confidence in the seismic-derived basement depths. Additionally, the RMS values and the depth-age curve indicate the type of underlying crust around the axial trough is different from that near the coast.

Investigation of Rift Evolution through Examining Scaling Properties of Fault Populations within the Central Kenya Rift

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Fault scaling relations for three different fault populations within the central Kenya rift have been quantitatively analysed and compared in order to characterize the behaviour of fault growth and distribution of strain accommodation, and therefore inform our understanding of the evolution of this part of the rift. 500 surface faults were mapped from digital Elevation Model data, and three fault population zones (zone1, zone2& zone3) were defined based upon their average fault orientations as NNE, NNE to NNW and NNW respectively. Estimations of extensional strain obtained from three different methods revealed a general increase of strain from the south to the north. Relationship between fault lengths and their throws for the picked faults fit reasonably to a power-law distribution. Fault length populations in the three zones showed similar power-law exponent, hence fault throw populations were used to examine deformation in this region. the Power-law exponents for throw populations in the three zones decrease with increasing strain, which implies that the strain is increasingly localised onto larger faults as the fault system becomes more evolved as we move from south to north along the rift, this decrease of power law exponent could indicate different stages of fault evolution, which may suggest that faults in zone3 in the south are in a less mature stage of growth than zone2 faults in the centre, and zone2 fault population is in a less developed phase of growth than faults in zone1 in the northern part of the study area. Analysis of the spatial distribution of fault throw populations exhibits three domains of deformation in the three zones; distributed faulting in zone3 and localized faulting deformation in zone1, with the transition between the two occurs in zone2. Isolated faults in zone3 seemed larger in displacement comparing to that of zone2 but fault trace length appear to be to some extent comparable in the two zones, which may suggest a rapid propagation of fault length at an early stage of fault growth. The results showed that this part of the central Kenya rift displays a range of variations, not only in fault orientation, but also in the total amount of strain, strain accommodation and fault evolution along the axis of the rift. These results also underline that the processes of progressive fault system maturity and strain localization onto large faults could occur even at relatively small scale of fault populations within the rift system.

Tectono-magmatic evolution of the Boset-Bericha Volcanic Complex in the Main Ethiopian Rift

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Tectono-magmatic interactions are an intrinsic feature of continental rifting and break up in the Main Ethiopian Rift (MER). The Boset-Bericha volcanic complex (BBVC) is one of the largest stratovolcanoes in the MER (with a total area of ~870 km^2), with the main volcanic activity estimated to have occurred over the last ~2 Myr. Despite the fact that 4 million people live within 100 km of the volcano, little is known about its eruptive history and how the volcanic system interacts with rift valley tectonics. Here, we present a detailed relative eruption chronology with morphometric analyses of lava flows and a characterisation of tectonic activity for the BBVC, based on field work observations, and mapping using high-resolution elevation data, including NERC ARSF LiDAR data. The BBVC consists of the Gudda Volcano and the younger Bericha Volcano, two silicic eruption centres located along the NNE-SSW trending rift axis. Overall the fracture system predominantly comprises rift-related distributed extensional faults, as well as localised discrete faults showing displacement of up to 50 m in the rift centre, and at the NE-SW trending border faults. Multiple cones, craters and fissure systems are oriented perpendicular to the minimum compressive stress. Petrographical and whole rock analyses provide further constraints on magmatic evolution at the BBVC. The eruption history of BBVC can be differentiated into 5 main eruption stages, subdivided into at least 12 eruptive phases. Crosscutting relationships of lava flows provide a relative chronology of the eruptive history of the BBVC, starting with pre-BBVC rift floor basalts, pre-caldera and caldera activity, three post-caldera phases at the Gudda Volcano and two phases formed Bericha Volcano. At least four fissure eruption phases occurred along the rift axis temporally in between the main eruptive phases. Morphometric analyses indicate a total corrected volume of eruptive material at the BBVC of ~36 km^3. The magmatic and morphometric evolution of the BBVC is spatially and temporally complex, showing a bimodal distribution of effusive basalts towards explosive peralkaline trachytic and rhyolitic lavas for the Gudda and Bericha Volcano, respectively, with rare intermediate lavas from fissure eruptions. Preliminary geochemical data suggest that fractional crystallisation may have played an important role in magmatic evolution the BBVC.

Quantifying the sedimentation of ignimbrites: understanding pyroclastic density currents through experimental modelling

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Pyroclastic Density Currents (PDCs) are hot, density driven mixtures of gas and volcanic particles formed during explosive volcanic eruptions. They are capable of depositing large ignimbrite sheets, which can exhibit a variety of sedimentary structures.

Due to their inherent nature, the direct observation of the deposition of ignimbrites by PDCs is incredibly challenging, and our knowledge of the internal processes of PDCs comes largely from physical and numerical modelling. Following significant advances in recent decades, laboratory experiments have great potential to provide a step change in our understanding of emplacement processes within ignimbrites.

The aim of this work is to experimentally generate the wide range of structures and bedforms seen in ignimbrites and in turn quantify the process controls on depositional character. The experiments will be conducted in a novel flume facility at the University of Portsmouth. The laboratory modelling will take into account the fact that PDCs are aerated and highly mobile, with high pore pressures. We will investigate how both flow and sedimentation processes respond to complex topographies across a range of conditions.

By comparing the laboratory modelling to real ignimbrite structures in the field, the aim is to achieve an improved, quantitative interpretation of ignimbrites. This will ultimately improve our understanding of the behavior of PDCs in the interests of consistent, predictable hazard assessment.

The onshore Cenozoic basin development of the UK and its relation to present-day vertical surface motions

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Historical long wavelength uplift and subsidence patterns in the UK have been assumed to reflect glacial isostatic adjustment. Shorter wavelength variations are generally neglected, and do not fit with glacial rebound models, hence they may give important clues to other processes driving vertical motions. Present day vertical surface motions are based on one generation of observed data and do not necessarily represent the long-term stress and tectonic configuration of the UK. Cenozoic strata can provide a record of long-term changes and potentially can indicate the drivers of present day short wavelength variations. Understanding the dominant controls on UK tectonics may have implications for petroleum systems, geotechnical assessments and anthropogenic impact factors.

Here we apply stratigraphic backstripping techniques to determine Cenozoic vertical surface motions. To complete the dataset, we also backstripped the Pleistocene Crag formations of East Anglia which post-dated the substantial Miocene hiatus most likely caused by the main phase of Alpine orogenic development. These deposits, the youngest being 2.1 Ma pre-date the glacial maximum of the UK helping to bridge the gap between the early Cenozoic and recent events. Subsidence analysis of the sequence indicates larger subsidence rates and sediment accumulation in the Hampshire basin than in the rest of southeast England. Reactivation of Variscan faults during the deposition of Cenozoic sediments appears to have taken place concomitantly with tectonic shortening and suggests phases of compression affected the UK throughout the Paleogene and Neogene not dissimilar to the current stress state and earthquake record.

From our data we may be able to understand the major tectonic controls influencing southern England during the Cenozoic and assess the nature of the transition to the vertical surface motion observed from CGPS (Continuous Global Positioning Stations) at the present day. The Cenozoic could be a good analogue for the present day and for projecting into the future.

Hypocentral Event Location within the Groningen Gas Reservoir, NE Netherlands.

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The Groningen gas field, situated in the North-East of the Netherlands, is Europe's largest producing gas field. Prior to gas extraction, starting in 1963, the region was considered aseismic, with no historical evidence of past events. However, in 1986 small magnitude earthquakes, at estimated depths of 2.6-3.km started within the region. These events lead to large peak ground acceleration and short signal pulses, causing surface damage and public concern. The seismic network within the Groningen region was extended in 2014 from 8 to 59 passive borehole seismic strings, each consisting of 4 three-channel 3C geophones spaced from 50-200m at 50m intervals. We discuss the use of the complete shallow borehole array in conjunction with detailed 3D velocity model to determine accurate hypocentral event locations and error, for the period of 2015-2016. Full waveform modelling has been used to further constrain event locations, and improve the uncertainty in the first arrival pick estimates. Full Moment Tensor solutions are investigated for each event and compared with mapped subsurface fault structures. Most event locations appear to lie on pre-existing fault planes within the lower anhydrite or Slochtern sandstone reservoir levels. A smaller subset lies outside the reservoir levels within the upper anhydrite floaters.

Transient deformation in the Asal-Ghoubbet Rift (Djibouti) since the 1978 diking event: Is deformation controlled by magma supply rates?

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In November 1978, an exceptional rifting event occurred in the Asal-Ghoubbet Rift (AG Rift) in Djibouti. The AG Rift lies in the subaerial continuation of the Aden ridge system. This segment constitutes a natural laboratory to study rifting processes and mechanisms involved in continental breakup and oceanic spreading. Continually upgraded and expanded geodetic technology has been used to record the 1978 Asal rifting event and postdiking deformation. In light of recent results obtained for the Manda Hararo-Dabbahu rifting event (2005–2010), we propose that the horizontal and vertical geodetic data can be modeled with a double source, involving a dike-like inflation component aligned along the rift axis and a spherical pressure source located at midsegment below the Fieale caldera. By revisiting the codiking data, we propose that the reservoir below Fieale could have fed, at least partially, the 1978 injection and the contemporaneous Ardoukoba eruption and potentially induced local subsidence due to magma draining out of the central reservoir. As an alternative to previously proposed viscoelastic relaxation models, we reinterpret postdiking observations using a purely elastic rheology. We determine the relative contribution of a midsegment reservoir inflation and a dike-like opening component, together with their respective time evolutions. Our results suggest that interactions between steadily accumulating tectonic strain and temporal variations in melt supply to the shallow magma plumbing system below the AG Rift may entirely explain the geodetic observations and that viscoelastic deformation processes played a minor role in the 30 years following the 1978 rifting event.

Petrogenesis of the volcano-plutonic Tezhsar Alkaline Complex in a collision zone setting (Armenia)

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The significance of alkaline igneous rocks in continental collision zone settings is still a subject of intense discussion. This study is a petrological and geochemical characterisation of the Eocene Tezhsar Alkaline Complex (TAC) in Armenia. The entire region is characterised by collisional geodynamics as the South Armenian Block and Arabia collided with the Eurasian Plate in the Late Cretaceous and Oligocene, respectively. The aim of this study is to improve our understanding of the formation of alkaline rocks in collisional settings.

The TAC is subdivided into an outer volcanic unit, an inner plutonic unit and a central volcanic vent that have been juxtaposed by ring faulting. The volcanic rocks predominantly comprise trachyandesites, trachytes and phonolites. The plutonic unit consists of syenites and nepheline syenites. Subordinate nepheline syenite pegmatites contain large (up to 3 cm), black andradite garnets.

Whole-rock geochemical data show that the TAC rocks can be classified as metaluminous, alkalic and silica-undersaturated. The general trace element enrichment and the strong fractionation of rare earth elements (La_N/Yb_N values up to ~70) point to an enriched magma source and low degrees of partial melting. Prominent negative Eu anomalies in syenites point to significant fractionation of plagioclase. Negative Nb-Ta anomalies in mantle-normalized trace element diagrams of all rock units demonstrate a typical subduction-zone signature. Initial $^{87}Sr/^{86}Sr$ isotope ratios show only small variations between 0.704 and 0.705 whereas εNd values vary from +3 to +5, indicating no crustal influence and derivation from a somewhat enriched mantle source compared to the depleted MORB mantle.

In summary, the geochemical data of the TAC show a subduction signature from ancient subduction beneath the Eurasian continental margin. The occurrence of the TAC in a setting of continued overall plate convergence can be explained by the metasomatic processes in the mantle lithosphere accompanying subduction of the Tethyan oceanic plate.

Crystal cargoes of Kilauean eruptions.

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Melts generated within the Hawaiian mantle plume are erupted through the Kilauean edifice at a mean rate of ~0.15 km^3 per year. Lavas are basaltic and contain phenocrysts of olivine, with plagioclase and augite in the groundmass. The cores of olivine crystals erupted in Kilauea lavas are typically out of equilibrium with their carrier liquids (melts). Lavas may be assembled in the crust by batches of fresh magma entering magma reservoirs at various depths through the mantle and crust, fractionating, mixing with resident melts, and perhaps entraining crystals from an olivine mush. We examine the crystal cargo of two eruptions that occurred very close together in time, yet separated laterally: the December 1959 Kilauea Iki eruption at the summit and the January 1960 Kapoho eruption 25 km downrift. It has been proposed that these two eruptions tapped the same magma source at the summit based on their whole rock geochemistry.

Olivines from tephra from both eruptions are categorized in terms of their morphology, size, shape and compositions using SEM and EDS in order to a) examine the relationship between olivine size, composition and zoning profile and b) look for systematic differences between the crystal populations of the two eruptions that might indicate crystal loss (via settling) or gain (via mixing with rift-stored magmas and due to cooling). We find that the Kilaeua Iki lavas have a higher crystallinity, with a higher proportion of large (>0.5 mm effective radii), primitive olivines ($Fo_{>80}$). The Kapoho lavas are cooler and contain higher proportions of plagioclase and clinopyroxene. A small fraction of olivine crystals have Fo>80 mol%, but most are >80 mol%, with effective radii < 0.5 mm. We construct a thermal and mixing history for the Kapoho magma during transit along the East Rift.

Seismic Tomography to illuminate crust and mantle structure beneath the East African Rift System

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The East African Rift System (EARS) is a region of significant tectonic interest; in the north exhibiting extensive rifting leading to the formation of new oceanic crust and to the south displaying marked changes in surface expression in comparison to the north, both regions hosting complexities relating to the broader influence of dynamic topography. As such, there have been numerous temporary broadband seismic deployments over the previous 20 years. In this study we focus on the structure of the central and southern parts of the system, using regional group velocity tomography to illuminate crustal structure. The initial results presented here, utilise FTAN group velocity measurements from earthquakes to illustrate the variations of group velocity from 20s-70s, with a particular emphasis on structures at the continental margin. Additionally, we investigate the effect(s) that a better resolved crustal structure has upon previous mantle tomographic models.

Pre-eruptive unrest at Campi Flegrei Caldera, Southern Italy

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Campi Flegrei in Southern Italy is among the most populated volcanoes on Earth. Post-caldera eruptions are located along the volcano’s margin, within the zone of ring faults produced during collapse. The most recent eruption in 1538 occurred after 100 years of caldera-wide uplift, which raised the town of Pozzuoli, near the centre of the caldera, by 15 m. Uplift recommenced in 1950, elevating Pozzuoli by more than 3 m. Crucial for emergency management is determining whether 15 m of uplift must again be achieved before an eruption can occur.

The amounts of uplift and volcano-tectonic seismicity since 1950 are consistent with the repeated intrusion of magma about 3 km beneath Pozzuoli and an accumulation of strain in the overlying crust. A sill-geometry is the preferred shape for the intrusion, either as a single sill that is episodically replenished, or as a succession of independent bodies. Analytical and numerical models for a homogeneous, elastic-brittle crust show that bulk failure around a single sill at 3 km depth will occur once uplift has reached ~ 5 m but that additional uplift can be accommodated if (1) the crust can slip along subhorizontal discontinuities between the sill and the surface, (2) magma is intruded as a succession of sills, each solidifying before its successor is emplaced, or (3) there is a significant expansion of fluids due to pressure changes in the hydrothermal system. The latter can potentially increase uplift by a factor of 2-3.5. In all cases, conditions for eruption also require that an intrusion enters the ring fault zone. The probability of an eruption thus depends not only on the mode of sill development, but also on the location of the intrusion with respect to the caldera’s margins. It is therefore possible to achieve conditions for eruption before 15 m of total uplift is reached.

Seismic slip on clay nanofoliation

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Deformation processes active at seismic slip rates (ca. 1 m/s) on smectite-rich gouges are not well understood, though they control the mechanics of tsunamogenic earthquakes, seismic surface rupturing and landslides.

Here we present a set of rotary experiments performed on water-dampened 2 mm thick clay-rich (70% wt. smectite + 30% wt. opal) gouge layers sheared at slip rates V from 0.01 to 1.5 m/s, for 3 m of displacement under 5 MPa normal stress. Microstructural analyses were conducted on pre- and post-sheared gouges with Focused Ion Beam Scanning Electron and Transmission Electron Microscopes. Gouges were slip strengthening (the friction coefficient increased from 0.15-0.17 to 0.5-0.4 with slip) when sheared at V= 0.01 and 0.1 m/s and slip weakening (friction decreased from 0.43 to 0.12) when sheared at V = 1.5 m/s. Despite the large difference in the imposed slip rate and frictional behaviour, the slipping zone always consisted of a nanofoliation with S/C' fabric made of smectite nanocrystals wrapping opal grains. The microstructural differences were (1) the thickness of the slipping zone (1.5 mm at V = 0.01 m/s and 0.15 mm at V=1 m/s), and (2) the deformation mechanism operating in opal grains (diffusive mass transfer at $V \leq 0.1$ m/s and cataclasis at V= 1.5 m/s). The presence of an identical nano-foliation in all smectite-rich wet gouges suggests the activation of similar frictional processes, probably grain boundary and interlayer frictional sliding aided by water films, operating at seismic strain rates ($10\text{-}10^{4}\ s^{-1}$).

Remote stress state control on igneous sill geometry

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Igneous sills can play an important role in upper crustal magma transport networks in rifted passive margins and continental basins. Natural sills are commonly bedding parallel at the local-scale (cm-m) but typically have a low-angle transgressive geometry at the basin-scale (km). Close spatial association between sills and dykes in layered (sedimentary) host rocks, has led to a number of sill emplacement mechanisms that involve stress rotation related to layering: from horizontal extension and dyke emplacement, to horizontal compression and sill emplacement. The associated switch in principal stress orientations – from horizontal to vertical σ_3 – is inferred to reflect a near-hydrostatic ambient stress state, facilitating intrusion of pre-existing discontinuities such as bedding or faults. Here we present a case study in which host layering cannot be invoked as the control on sill intrusion: the Loch Scridain Sill Complex, Isle of Mull, UK. The Loch Scridain sills are gently transgressive (average 29° dip), and cut sub-vertically layered Moine basement metasediments, sub-horizontal Mesozoic sediments and Paleogene lava cover sequences. Sills dip consistently towards the NW and SE regardless of the country rock foliation attitude. No dyke to sill transitions are observed. The country rock hosts sub-horizontal and sub-vertical fracture networks that pre-date sill emplacement. Observations indicate that magma was able to dilate and intrude sub-horizontal fractures as Mode I (opening mode) and Mixed-Mode (extensional-shear) fractures. Steps occur at contacts with sub-vertical fractures and foliation, but neither is intruded to form dykes. This geometric reactivation is consistent with sub-horizontal compression and vertical extension during sill emplacement. Based on these field relationships, we envisage an anisotropic poroelastic response of the host material on the approach to reactivation and failure. From this we infer the remote stress state leading up to and during sill intrusion. Mechanical modelling of slip tendency, dilation tendency, and fracture susceptibility for the country rock suggests that radial horizontal compression (i.e. a stress ratio, $R \neq 0$) is required to prevent opening of vertical fractures. This condition is required in the basement and the cover, hence layering is not a primary control on sill emplacement. We suggest that by considering sill complexes as a record of the regional stress, it may be possible to gain a better understanding of the changeable nature of stress along passive margins during rifting and within basin systems.

Interpreting apatite volatile compositions using thermodynamic models: new insights into pre-eruptive processes at Campi Flegrei

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Volatile elements play an important role in almost every aspect of the physiochemical architecture of sub-volcanic plumbing systems, from the liquid line of descent to the dynamics of magma storage and eruption. A variety of petrologic methods has been employed to decipher the volatile histories of past eruptions, giving access to records of melt volatile contents over variable pre-eruptive timescales. However, in many cases it is difficult to constrain the behaviour of the magmatic volatiles on short timescales before eruption (e.g. using melt inclusions): specifically, in the final days-to-months of magma storage and the early stages of ascent. Apatite is a common igneous accessory mineral, which has recently received attention as an alternative magmatic volatile 'probe' that may give new insights into volatile systematics in the build-up to eruption.

Here, we present thermodynamic models that predict the theoretical compositional evolution of apatite during fractional crystallisation in the presence/absence of different fluid phases and changing magma chamber conditions (i.e. pressure, temperature). We compare the model outputs with texturally-constrained apatite analyses from eight eruptions of the Campi Flegrei system (Italy). Clinopyroxene- and biotite-hosted apatite inclusions consistently record volatile-undersaturated conditions. For apatite microphenocrysts, we identify three different compositional trends, which we interpret as resulting from (i) volatile-undersaturated conditions, (ii) high pressure crystallisation, in the presence of a supercritical fluid, and (iii) low pressure, vapour-saturated crystallisation. These data are used to construct a model of pre-eruptive volatile behaviour in Campi Flegrei and demonstrate the wealth of novel information about sub-volcanic systems that can be accessed through apatite. These apatite analyses reveal that Campi Flegrei magmas consistently undergo protracted volatile-undersaturated crystallisation, before becoming H_2O-saturated at depth and stalling at shallow crustal levels during ascent.

Dante's Maximum Likelihood: Exploring a machine-learning approach to detecting changes in volcanic activity

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In recent decades the explosion in development of machine learning approaches has revolutionized the ability to make inferences based on datasets. The development of such methods for volcanic applications is in its infancy. As demonstrated with other applications (e.g., analysis of healthcare data and other high-integrity systems), there is potential for these approaches to recognize patterns in data, that either take time to present themselves, or are not present at all, during more traditional analyses. This pilot study applies three key techniques to seismic datasets from the persistently restless Telica volcano in Nicaragua and the more sporadically active (but explosive) Nevado del Ruiz volcano in Colombia. Feature extraction is the process of taking the raw datasets received from observatories and then deriving time series such as event rates, frequency ratios and multiplet information, from which we then extract statistics such as mean, variance and percentiles. Principal component analysis is then combined with both univariate and bivariate graphical analysis, by means of histogram visualization and clustering, to evaluate the diagnostic utility of each of the extracted features of the data. We describe initial extraction of these various features, and then explore techniques such as logistic regression (with sparsity), spatial clustering, and the support vector machine. As well as identifying key statistics to extract from the raw data, the algorithms characterized different stages of the volcanoes' eruptive activity. The agreement of the algorithms against the known eruption histories, on untrained data, demonstrates the worth of further research in this area. In particular, we found remarkable consistency in the eruption end-dates suggested by the algorithms, suggesting they could be used to give objective identification of end-points of eruptions.

The role of fluids in the subduction-intraplate geochemical transition

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Active continental collision zones are one of the most enigmatic tectonic settings for volcanic activity on earth. In arc settings, volcanism is driven by the supply of fluids during subduction. These fluids hydrate the mantle, creating fusible hydrous phases which lower the solidus temperature of mantle peridotite. Following the end of subduction, one would expect the rate of volcanic activity to rapidly decay as the fluid supply is switched off.

Despite the end of fluid supply once subduction ceases, volcanic activity has been observed in several collision zones. The Arabia-Eurasia collision zone is one example of collision-related volcanism, and this study focusses on the Armenian sector of the collision zone.

Broadly, the style of volcanism transitions from high volume, silicic, explosive volcanic activity; to low volume, relatively primitive, effusive activity. The complete compositional range observed (basanite to rhyolite) can be generated by fractional crystallisation of a mantle-derived primitive parental melt.

All volcanic rocks display a subduction signature on a normalised trace element diagram, indicating that fluids have been retained to some extent in the mantle source. Furthermore, this source appears to have been metasomatised by a slab derived silicate melt component. As such the story of igneous petrogenesis in Armenia appears to have been influenced by several components of a former subduction zone. Initial Sr-Nd isotope ratio determinations allow us to quantify the mixing of these components following the end of subduction.

Following on from this work, it is hoped that B isotope analysis and Ar-Ar age determinations will provide a way to investigate the spatio-temporal variability in the fluid budget of the mantle source in Armenia, and to see how this relates to variations in geochemistry and the style of volcanism.

Outcrop analysis of the Upper Benue Trough, NE Nigeria; Insights into the Tectono-Stratigraphic Development of the Subsurface Bornu Basin

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The Bornu Basin is an intra-continental rift basin located in NE Nigeria. This potentially petroliferous basin is entirely contained in the subsurface, being imaged in sparse, variable-quality seismic reflection data and penetrated by only a few wells. As such, there is a relatively poor understanding of the basins structure and stratigraphy and, therefore, its petroleum systems. We here present structural and stratigraphic field data from the Gongola Arm of the Upper Benue Trough, Onshore NE Nigeria in this study with the aim of helping better constrain the seismic sub-surface geology and tectono-stratigraphic development of the Bornu Basin.

We show that NE-striking, moderately dipping (40˚ - 60˚) normal faults occur in the basin, which presumably accommodated Early Cretaceous extension. Latest Cretaceous (Maastrichtian) shortening is also inferred based on folding of Upper Cretaceous Gombe Sandstone. This particular tectonic event is not established from the sub-surface studies of the Bornu Basin. Strike-slip flower structures are observed in crystalline (biotite-granite) basement, with similar structures only seismically imaged in the Bornu Basin in shallower, Cretaceous strata due to poor data quality at deep burial depths. The top 50 m of the crystalline basement is intensely weathered suggesting a potential occurrence of basement reservoir system in the Bornu Basin. Furthermore, evidence of magma emplacement and extrusion (e.g., monogenetic volcanoes) were observed during the fieldwork. Our outcrop analysis suggests that both Upper Benue Trough and Bornu Basin may have evolved in response to the same regional tectonics associated with Gondwanaland break-up.

Melt generation in a dynamic melting column and its application to the genesis of intracontinental basalts

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Basaltic melts are typically formed by partial melting of upwelling mantle material over a pressure interval (i.e. a melting column), often in a heterogeneous source containing peridotites and pyroxenites/eclogites. However, previous trace element based models were unable to calculate accumulated melt composition from a melting column with lithological changes.

To address this, we suggest a step-by-step trace element based dynamic melting column model that can model decompression melting realistically in intraplate settings. This model makes it possible to assume a heterogeneous mantle source by adding melting cells with different chemistry and mineralogy into the regime as the mantle upwells, and can handle changes in bulk distribution coefficients caused by phase transitions, e.g. the spinel-garnet transition in the upper mantle.

In the case of a mixed spinel-garnet bearing source, the model is able to give constrain the melting depth of basalts (due to the sharp change of partitioning of REEs), if the potential mantle temperature is known, as it controls how deep the spinel-garnet transition occurs. In the case of intraplate basalts, the final melting pressure most likely represents the LAB (lithosphere-asthenosphere boundary), hence lithospheric thickness can be estimated.

The model's ability to estimate melting was tested by using published whole-rock data from volcanic fields located in the Carpathian-Pannonian Region (CPR), and from the northern part of the Lunar Crater Volcanic Field (LCVF), Basin and Range, USA. The obtained melting pressures are within error (± 5km) for the CPR basalts when compared with previous major element based modelling data. In two cases a larger difference is present (~30 km); however, the trace element based model data is in accordance with geophysical observations. In the case of the LCFV, the older eruption centres have lower melting pressure (p_f=1.7-2 GPa), while more recent basalts have somewhat deeper source (p_f=2-2.2 GPa). This could indicate that lithospheric extension in the region has been replaced by thermal subsidence, causing a deeper LAB.

Sustained Deformation at the Tendaho Geothermal Prospect, Ethiopia

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In complex tectonic settings, numerous active natural and anthropogenic processes can cause surface deformation. We focus on the Tendaho graben, in Central Afar, Ethiopia, which is tectonically and volcanically active with normal faults, eruptive fissures, hydrothermal vents and central volcanoes and contains towns with large populations such as the capital of Afar, Semera and recently built infrastructure such as the Tendaho Dam. We use Interferometric Synthetic Aperture Radar (InSAR) to study surface deformation in Tendaho graben. The InSAR data was collected by the Envisat satellite in 2004-2010. The line-of-site (LOS), and two-dimensional rates of displacement and time-series are calculated using Poly Interferometric Rate And Time-series Estimation (PI-RATE) and Multi-dimensional Small Baseline Subset (MSBAS) methods. The cumulative displacement is compared to data from a continuous GPS station projected in to the satellite's LOS. We observe a 20km diameter circular deformation located NE of Semera, in the area of a geothermal prospect site. The displacement rate is 5cm/yr of range increase along the satellite LOS, corresponding to subsidence. The time-series from both InSAR and GPS shows ongoing deformation, starting, at the end of 2008. The 1D InSAR displacements and the 3D GPS projected into satellite's LOS show a consistent pattern. We use a Markov Chain Monte Carlo Inversion (MCMC) to find the best fitting source and compare this to locations of seismicity. The pattern of deformation is consistent with either magmatic or geothermal processes. Understanding this sporadic deformation is vital for unveiling the tectonic of the region and for assessing the seismic and volcanic hazard to development and identifying resources.

The role of lava domes in controlling volcanic eruptions.

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Many volcanoes exhibit persistent effusive activity forming lava domes (e.g. Merapi, Indonesia, Unzen, Japan; Santiaguito, Guatemala and Mount St. Helens, USA). These domes, which can reach volumes of more than 200 Mm^3 are often inferred to be positioned directly above the conduit vent. The resulting overburden pressure caused by these massive structures is significant and acts in the opposite direction to forces promoting magma extrusion. However, the role that these large structures may play in suppressing volcanic eruptions has received little consideration. Here we show that if a large enough dome grows as a coherent mass, the resulting pressure from the weight of the dome may be larger than the magma over pressure driving the eruption, and sufficient to stop or at the very least alter activity. When assessing changes in the behaviour of a volcanic system, most studies focus on deep processes in the magma chamber or conduit system for possible explanations. In contrast, the dome overburden pressure may explain why some eruptions stop with a large dome situated at the summit of the volcanic edifice (e.g. La Soufrière, Guadeloupe). What is more, for many domes, prior to collapse, explosive activity, or a change in behaviour, the maximum height reached during recorded extrusive phases appears to be broadly consistent (e.g. Montserrat ~ 950m, Merapi ~ 100m, Colima ~40m), suggesting that the magma over pressure in the system is exceeded, and any potential new activity needs to overcome these restrictive conditions. Unless the driving force within the volcanic system has increased, whether a new eruptive period commences will depend on the magma finding a new route to the surface or if the dome has become weak or unstable. We use numerical magma flow modelling to study conditions under which a dome could suffocate magma ascent and stop eruptive activity.

A detailed snapshot of Cyprus Slab Interaction with the Mantle Transition Zone Beneath Turkey

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The geodynamics of the eastern Mediterranean are dominated by northward motion of the Arabian/African continents and subduction of the oldest oceanic crust on the planet along the Aegean and Cyprean trenches. These slabs have previously been imaged using seismic tomography on a continental scale, but detailed information regarding their descent from upper to lower mantle and how they interact with the mantle transition zone have been severely lacking.

The Dense Array for North Anatolia (DANA) was a 73 station passive seismic deployment active between 2012-2013 with the primary aim of imaging shallow structure beneath the North Anatolian Fault. However, we exploit the exceptional dataset recorded by DANA to characterise a region where the Cyprus Slab impinges upon the mantle transition zone beneath northern Turkey, providing arguably the most detailed view of slab penetration into the lower mantle ever obtained.

We map varying positions and amplitudes of the transition zone seismic discontinuities ('410', '520' and '660') in 3D using >1500 high quality receiver functions over an area of approximately 200km x 300km. The '660' is depressed to >670 km across the entirety of the study region, consistent with an accumulation of cold subducted material at the base of the upper mantle. Anomalous low velocity layers above, within and below the transition zone are constrained and may indicate ongoing mass/fluid flux between upper and lower mantle in the presence of subduction.

The results of the study have implications not only for the regional geodynamics of Anatolia, but also for how subducted slabs penetrate into the lower mantle globally.

Influence of water on the strength of olivine dislocation slip systems

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In order to quantify the influence of hydrogen (i.e., from water) on the activity of dislocation slip systems in olivine, we performed a series of deformation experiments on olivine single crystals under either hydrous or anhydrous conditions using a direct shear geometry. The direct shear geometry allows for the isolation of both the slip plane and slip direction and, thus, the strength of the dominant dislocation slip systems in olivine. Deformation experiments were performed at shear stresses of 24 to 171 MPa, resultant shear strain rates of 2.0×10^{-6} to 3.9×10^{-4} s^{-1}, temperatures of 1200° to 1300°C, and a confining pressure of 300 MPa in a gas-medium (Paterson) apparatus. Hydrogen from the dehydration of brucite was supplied to the crystals via diffusion through a thin nickel sleeve placed around each crystal and shear piston assembly. Fourier transform infrared spectroscopy analyses reveal that infrared absorbance at wavenumbers typical of O-H stretching bands in olivine are present in crystals deformed under hydrous conditions but absent in crystals deformed under anhydrous conditions. Results from experiments performed under hydrous conditions reveal values of stress exponents ranging from 2.7 to 3.2, which are consistent with deformation that is rate-limited by climb of dislocations via volume diffusion. In contrast, experiments performed under anhydrous conditions indicate values of stress exponents ranging from 3.5 to 5.0, consistent with deformation rate-limited by climb of dislocations via diffusion through the cores of dislocations. For a given stress, crystals oriented to activate slip on either the (001)[100] or (100)[001] slip systems deform at strain rates a factor of ~7 or ~5 faster under hydrous conditions compared to anhydrous conditions, respectively. At the conditions used in this study, crystals oriented for slip on (001)[100] are weaker than those oriented for slip on (100)[001] regardless of hydrogen content, although the opposite has been observed for anhydrous crystals deformed at conditions of higher stress and lower temperature.

Experimental approach to Gypsum's Dehydration reaction and associated acoustic emission

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Non-volcanic tremor has been described in several active fault zones, particularly in subduction zones, where they were first recorded. In subduction zones they usually occur at the bottom of the seismogenic zone, in the transition between brittle-ductile behaviour. The location of the tremors is also associated to areas of low Vp/Vs ratios, which is an indicator of high pore-fluid pressure. It has been widely postulated that these high pore-fluid pressures are the result of dehydration reactions in the subducted slab, which generate seismicity as they move rapidly to the surface, or via local effective pressure changes.

To improve our knowledge of what occurs in this complex system, we report data from a set of experiments using Voltera gypsum as analogue material. This material was chosen due to its low dehydration temperature (~100^{o}C). Experiments were performed in a conventional, externally heated triaxial cell, with samples encapsulated in a rubber jacket fitted with mounting points for an array of 12 P-wave and S-wave Acoustic Emission (AE) sensors (6 each). These record both passive fracture events and elastic wave velocities.

Preliminary results from our pilot experiments, in which we measured pore-fluid volume, AE, elastic wave velocity, and permeability as a function of temperature and confining pressure, indicate that the dehydration reaction rate starts to pick up after ~120 ^{o}C, and is dependent on pore and confining pressure. An increase of liberated pore fluid accompanies the reaction, with swarms of AE events simultaneously measured, in addition to significant changes in P-wave and S-wave elastic velocity at the same stage in the experiment.

Fluid flow, feeders and fault zone structure – controls on metal distributions in Irish-type deposits.

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The term feeder is used in mineral deposits to refer to locations where metal bearing fluids enter the site of mineralisation. Metals typically precipitate in an order determined by their solubilities in response to physio-chemical changes (i.e. reduced temperature and\or pressure, fluid mixing and host-rock interactions). This differential precipitation results in zonations characterised by changes in concentrations and relative metal proportions.

We use metal distribution patterns at two Irish-type deposits, Lisheen and Silvermines to gain insights into the local controls on mineralisation, locate the position of feeder zones and track fluid pathways along faults and through the host lithology. In Irish-type deposits, concentrations of metals are highest closest to feeders while relative proportions of metals increase from minor metals (i.e. Ni, Cu, As) proximal to feeder zones through to Pb and finally to Zn distally.

Tonnage maps of Lisheen show that: (1) the distribution of early-stage Fe mineralisation is governed by early, E-NE-trending structures, (2) Zn and Pb mineralise later and follow both the early Fe trends as well as an additional NW-trending structure, (3) no significant Pb or Zn occurs within relay ramps, (4) Cu, Ni and As follow similar trends and show high concentrations proximal to feeder zones but die out quickly distally, and (5) Zn/Pb ratios increase away from feeder zones evolving from ratios of 3:1 proximally to ratios of 12:1 distally. This zonation is due to the increased mobility of Zn over Pb.

Grade distribution maps for Silvermines show that: (1) Zn/Pb ratios evolve from 2:1 proximal to feeder zones, to 4:1 distally, (2) low Zn/Pb ratios occur along fault planes and high ratios occur at the base of the host lithology then steadily increase NNE-wards away from the fault, (3) elevated Ag values occur close to, and along the faults, (4) Zn mineralisation occuring on the ramp, is a distal expression of mineralisation and is not sourced from the ramp itself while Pb mineralisation is distinctly absent, (5) moderate metal concentrations occur in breccias associated with breach points.

Finally, we conclude that ramp relay zones are only mineralised at local scales (fault separation < 300m) where the ramps are fully breached. Metal zonations originate from points along fault planes that are not necessarily at the point of maximum displacement. Feeders occur along fault planes in places where a) favourable units are brought into juxtaposition with the host lithology and/or b) where relay ramps are fully breached. The insights in this study highlight the fundamental structural controls of segmented fault arrays on the formation of these Irish-type deposits.

Linkage and imbrication of fold-thrust structures, offshore Northwest Borneo

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Fold and thrust belts are a fundamental mechanism to accommodate shortening in the crust. Those contractional structures are best described in three dimensions, so that their structural geometries and kinematic evolutions can be well understood. But such successful characterization of fold-thrust structures is commonly challenging. Fault exposures are usually sparse and hangingwall cutoffs are easily eroded in nature. Seismic images often display wipeout zones at forelimbs and in footwalls due to steeply dipping beds and seismic signal loss through popped-up hangingwalls. These issues form the background of limited studies on structural variation along fold-thrust structures, and largely unresolved mechanism of fold-thrust structure development. This contribution aims (1) to present quantitative descriptions of fold-thrust arrays imaged by a high-resolution 3D seismic data, and (2) to assess a kinematic scenario produced along-strike variation of the structures.

We use a high-resolution 3D seismic data acquired by multi-azimuth acquisition technique in the slope of offshore Northwest Borneo, Malaysia, to constrain structural geometry of fold-thrust arrays. Within the seismic data coverage, Late Miocene-to-recent deepwater sediments have been deformed into three trends of fold-thrust structure that largely trend NNE-SSW and verge NW-ward. These fold-thrust structures are commonly associated with imbricate thrusts and crest erosions at central sections. Deformation degree increases from south to north in general. We map top of pre-kinematic sequence, and measure fault heaves to quantify structural variation along folds and thrusts.

The fault heave plots against distance along strike indicate that the imbricate thrusts occur at deficits in fault heave of structurally the lowest, longest thrust fault in each structural trend. Thrust-related foldings are significant and associated with crest erosions where fault heave minima are located. Aggregate of all faults' heave shows largely smooth, linearly increasing pattern toward north whilst individual structural trend showing major minima in fault heave.

These features imply: (i) the imbricate thrusts were developed above former linkage of fold-thrust structures where diminished fault displacement was accommodated by significant folding, and (ii) the fold-thrust structure trends interact and are kinematically linked.

Bulk melting not an option: Assimilation and remelting in the Yellowstone volcanic field

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In the Yellowstone volcanic field, low-$\delta^{18}O$ rhyolite lavas (+0.1 to +5.8‰) erupted following caldera collapse are thought to be the consequence of bulk melting of previously deposited and hydrothermally altered rhyolite in the down-dropping caldera roof. The "self-cannibalisation bulk melting" theory relies on the assumption that hydrothermally altered materials are near-cotectic and hydrous (>3 wt% H_2O) and will thus rapidly melt at temperatures below 850°C (Bindeman et al. 2008, Bindeman & Valley 2001).

We examined three drillcores from a 1960s USGS drilling campaign in Yellowstone in order to characterise the hydrothermally altered material in terms of mineralogy, major and trace elements, oxygen isotopes and water contents via Karl-Fischer titration, and compare them to fresh unaltered rhyolites sampled at the surface. Our results indicate that rhyolite $\delta^{18}O$ values can shift from "normal" (+5.8 to 6.1‰) to as low as -5‰ at depths of 100 to 160 m. While being variably altered and silicified, the drillcores do not show any systematic compositional changes in major and trace elements with depth. Alteration is not associated with significant uptake of water and >75% of the drillcore samples have <0.5 wt% H_2O, thus water is the main limiting factor during remelting and assimilation. Modelled melting curves via rhyolite-MELTS suggest that at 850°C, a maximum of 35% melt could be created and that bulk melting would require extremely high temperatures >1100°C.

Our findings indicate that bulk melting is not a realistic scenario and that low-$\delta^{18}O$ rhyolite lavas are more likely the result of mixing between a low-$\delta^{18}O$ crustal partial melt and a normal-$\delta^{18}O$ fractionation-derived melt component from the main reservoir, as supported by isotopic mass-balance models and thermal and volumetric constraints.

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The structural geology of Foula, Shetland: an onshore analogue for the top of the Clair Ridge, west of Shetland.

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The Clair Field, situated to the west of Shetland, represents the largest hydrocarbon resource in the UKCS and Europe. It is comprised of fractured Devonian-Carboniferous sandstones that overlie an up-faulted ridge of fractured Precambrian metamorphic basement.

Foula, a 13km^2 island situated 25km SW of the Shetland Isles is possibly the best onshore analogue to the Clair Ridge, which is the second phase development area for the Clair Field. Despite being only ~70km from the Clair Field, the island is relatively poorly studied with regards to its structural evolution. Some 1600m of Middle Devonian sandstones are spectacularly exposed in continuous, kilometre-long cliff sections up to 376m high. These rocks unconformably overlie likely Precambrian-age amphibolite facies basement gneisses and schists intruded by sheeted granites of uncertain age and affinity.

Building on earlier studies carried out in the 1980's, the initial results of an ongoing reappraisal of the structure, stratigraphy and tectonic evolution of the island and surrounding area will be presented. This is being achieved through detailed land-, sea- and aerial-(drone) based studies of exposed basement-cover contacts, and the structure and broad stratigraphic architecture of the overlying sandstone dominated sequences exposed in the continuous coastal sections. Samples of the basement have also been collected for radiometric dating using U-Pb geochronology.

Fieldwork data will be presented, supplemented by the use of photogrammetry to capture the geology of key localities and analyse structures in difficult to access areas. 3D models of the stratigraphy and structure are being created for later use in modelling of stratigraphic architecture, fracture networks, numerical simulations of fluid flow, up-scaling and reservoir quality studies. These findings will be compared to previous analogue studies and applied to the current concepts and models which underpin the stratigraphic and structural architecture of the Clair field and the wider regional tectonic setting.

The structure of the Sorbas Basin (S.E. Spain) from geological mapping and regional gravity surveying.

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The internal zone of the Betic Cordilleras (S. Spain) forms a wedge-shaped region of back-arc extension of Miocene through Recent age through westward rollback of the subduction zone beneath the Gibraltar arc. The tectonics can be compared to the Tyrrhenian basin extension and the Aegean stretching. In the stretched wedge metamorphic basement rocks have been brought to the surface in a series of E-W elongate metamorphic core complexes, bounded by fault-bounded upper Miocene intramontane basins. The stretched wedge is bounded to the north by the right-lateral Internal-External zone boundary fault, and to the south by the left-lateral Trans-Alborán shear zone, extending from offshore Alicante, through the province of Almería as the Carboneras fault zone, and across the Alborán sea to Morocco (Jebha fault). These fault zones are stretching continental transforms accommodating U-Mantle velocity discontinuities.

This study focuses on the faulting and sedimentation within the Sorbas basin, lying north of the Carboneras fault in Almería province. Detailed geological mapping was carried out to discover the main fault systems accommodating extension and their relationships to sedimentation, and the shape of the sediment fill. This was augmented by a regional gravity survey to determine the shape of the basin floor.

The early evolution (Serravallian–Tortonian) of the basin fill is partially obscured by unconformably overlying Messinian through Recent sediments. The early, much more extensive, shape of the basin has been modified through emergence of the basement massifs of the Sierra Cabrera and Sierra Alhamilla, locally (and helpfully) deflecting the lowermost part of the basin fill and its basal faults to the surface. The gravity survey, coupled with forward modelling, allowed for the shape of the basin's base to be determined. Combining this with the detail from the surface geology and the early basin fill, inferences have been made on the geometry of buried intrabasinal faults, leading to an interpretation of the early evolution of the Sorbas basin.

Continuous volcanic monitoring using the SO_2 camera.

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Volcanic activity is driven through the exsolution, expansion and release of gas from ascending magma, and measuring gas fluxes from volcanoes is key in understanding the dynamics of such systems. A powerful technique for observing SO2 is through UV imaging. SO2 is an ideal target gas due to its strong UV absorption, high volcanic gas concentration, and crucially, unlike like the most abundant constituents of volcanic gas (CO2 and H2O), it has a low background atmospheric concentration. The development of the SO2 camera is creating significant improvements in the temporal resolution of SO2 flux measurement, allowing the changes in volcanic plume SO2 to be observed during short-lived explosive events.

Higher temporal resolution opens the possibility of improved integration with geophysical monitoring techniques, such as seismic and deformation, which further enhances our ability to forecast and track eruptions. Previous studies using the SO2 camera have mostly been limited to several short-term deployments, for example at Stromboli, Sakurajima and Kīlauea, but provided significant insights into individual explosive events. Mt. Etna, in Sicily, is one of the first volcanoes to be routinely observed by the SO2 camera, so presents a wealth of data for further understanding volcanic gas processes, alongside an opportunity to develop SO2 camera.

Geomechanical Modelling of Seismicity Induced by Coal Mining

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In 2014, the village of New Ollerton was declared to be the U.K.'s "Earthquake Capital". Between December 2013 – January 2014, over 40 seismic events were recorded in this area, the largest of which had a magnitude of M_L = 1.7. It was rapidly established that these events were associated with longwall coal mining in the nearby Thoresby Colliery. In response to the seismicity, the British Geological Survey deployed a local array of 7 seismometers. Between February – October 2014 a further 300 events were identified. The precise locations afforded by the local network showed that the seismicity generally occurred at the similar depths to the longwall mining, and that event epicentres shifted laterally in the same direction as the mining orientation.

In order to better understand induced seismicity created by a range of energy technologies, it is vital that we develop the capacity to build geomechanical models that are able to simulate the deformation induced by subsurface activities, thereby anticipating when and where seismicity may occur, and what are the controls on the event size. In this paper we develop a numerical geomechanical model to simulate the seismicity induced by coal mining at New Ollerton. We begin by identifying the *in situ* stress conditions by combining measurements of shear-wave splitting (SWS) and earthquake source mechanisms, inverting for the stress field.

We use this information to develop a simple geomechanical model to simulate the stress changes and deformation that result from the longwall mining process. This model is constructed using the commercially-available COMSOL finite element modelling code. To simulate the induced seismicity that results from this deformation, we resolve these stress changes onto a stochastically-defined fault/fracture population. By identifying when and where such fractures exceed Mohr-Coulomb criteria, we simulate when and where seismic events occur. Using the orientations of such fractures, and the orientation of the shear stress vector along these planes, we determine the source mechanism. By combining the modelled stress drop and rupture length, we model event magnitudes.

The result is a population of modelled events, including position, time, source mechanism and magnitude, that we compare with the observed event population at New Ollerton.

The 1257 Samalas eruption: the single greatest gas release of the Common Era.

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Large explosive eruptions inject volcanic gases and fine ash to stratospheric altitudes, contributing to global cooling at the Earth's surface and occasionally to ozone depletion. The modelling of the climate response to these strong injections of volatiles commonly relies on ice-core records of volcanic sulphate aerosols. Here we use an independent geochemical approach which demonstrates that the great 1257 eruption of Samalas (Lombok, Indonesia) released enough sulphur and halogen gases into the stratosphere to produce the reported global cooling during the second half of the 13th century, as well as potential substantial ozone destruction. Major, trace and volatile element compositions of melt inclusions, whole-rocks and matrix glasses recording the magmatic differentiation processes leading to the 1257 eruption were analysed. They indicate that Mt Samalas evacuated 40 km^3 of trachydacite magma which released 158 ± 12 Tg of sulphur dioxide, 227 ± 18 Tg of chlorine and a maximum of 1.3 ± 0.3 Tg of bromine. These emissions stand as the greatest volcanogenic gas injection of the Common Era. Furthermore, the calculated SO_2 yield matches the estimates based on ice-core records and climate modelling, indicating efficient transport of volatiles in the plume up to the stratosphere. Our findings not only provide robust constraints for the modelling of the combined impact of sulphur and halogens on stratosphere chemistry of the largest eruption of the last millennium, but also develop a new methodology to better quantify the degassing budgets of explosive eruptions of all magnitudes.

Hydration of Silicate Glasses below the Glass Transition Temperature.

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Water exsolution provides the buoyancy that drives volcanic eruptions. However, water solubility at low eruptive water vapour pressures and temperatures is poorly constrained. Yet preliminary data and published results suggest that mechanism, rate and quantity of water solution and exsolution in magma near the glass transition temperature are fundamentally different compared to established processes at high temperatures and pressures. Identifying the conditions for water exsolution and dissolution in magma could allow us to determine the origin of water in volcanic glasses, and to quantify the extent of magma degassing during ascent and its control on eruption dynamics.

We investigate the impact of a water rich argon atmosphere on soda lime silicate glasses at temperatures close to the glass transition. Synthetic spherical glass beads of well confined grain size of 125-250 µm (produced by Spheriglass) were heated in simultaneous thermal analyses of both differential scanning calorimetry and thermogravimetry. Initial glass transition temperatures and mass stayed constant under an argon atmosphere at the heating rates of 10 ºCmin^{-1} used in our experiments. Preliminary results show that when closely packed and heated in a hydrous argon atmosphere (1) there is a measurable water uptake during timescales as short as 2 hours even below the glass transition temperature, (2) the temperature of the glass transition is significantly shifted even by hydration below the glass transition temperature, and (3) sintering is more efficient and densification takes place at lower temperatures and/or within shorter timescales.

Hydration below the glass transition temperature has previously been considered to have only a minor impact on the silicate glass structure and its physico-chemical properties, respectively. However, our preliminary data suggest a significant alteration of the glass despite the evidence from others that no speciation reaction occurs below the glass transition, implying that the dominant solution is molecular water rather than hydroxyl groups. A structural impact of low temperature hydration and a fast rate of such hydration could pose a significant paradigm shift and we hope to quantify and characterise the hydration and its impact in future studies.

Conjugate dykes and sills: a record of differential stress?

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Dykes and sills are commonly treated as opening mode (i.e. Mode I) magma-filled fractures, in which the fracture walls display no shear offset. This assumption is used to constrain the stress axes: the intrusion plane is considered to form parallel to the principal stress σ1-σ2 plane, and normal to the axis of σ3 (where σ1 > σ2 > σ3). This implies intrusion is during low differential stress (σ1 − σ3), and has led to the development of numerous models that involve switching from dykes to sills during near-hydrostatic stress conditions. Sills, and in particular, dykes that display shear offset across the intrusion plane are inferred to reactivate pre-existing faults (e.g., ring dykes and cone sheets), or are cut by later faults. Here we present mechanical models and field examples of intrusions to show that there is no requirement that the intrusion plane form parallel to the σ1-σ2 plane, and that extensional-shear opening can be a primary feature of sheet intrusions. Our case study area – the San Rafael Sub-Volcanic Field (SRSVF) in Utah – is host to ~200 Pliocene-age segmented dykes and sills that were emplaced into lithified Jurassic sediments. The intrusions crop out within an observable elevation range of ~500 m, emplaced within the upper 1 km of the crust. Dyke segments dip steeply (>80°) to the east or west and show a range of strikes; dominantly NW-SE and NNE-SSW, intersecting at a low angle, with the acute bisector oriented NNW-SSE. Sills in the SRSVF form complex networks of horizontal to inclined sheets (<25°) that gently cut across the host stratigraphy. Inclined sills consistently dip NW and SE in the north of the area, and NE-SW in the south of the area; host layering shows vertical offset across the sills in all cases, and oppositely-dipping sills show mutual cross cutting relationships. We propose that the intrusions formed originally at an acute angle to the σ1-σ2 plane, with σ3 lying in the obtuse angle between sheets (i.e. vertical for sills; horizontal and trending ENE-WSW for dykes). We suggest that sheet intrusion geometry is a function of the remote applied stress: discontinuities will be reactivated at low differential stress, or if discontinuities are favourably oriented with respect to the tectonic stress. Notably, this model does not require instantaneous switching of the principal stress axes, nor the presence of local magma chambers and associated stress perturbation.

Chemical hysteresis during frictional melting: Rheological implications for slip dynamics in volcanic systems

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Seismogenic faulting may lead to frictional melting of adjacent fault rocks, imposing rheological controls on slip dynamics. The eruption of highly viscous magma provides the ideal opportunity for strain localisation and frictional heating as a consequence of slip along shallow conduit margins, akin to tectonic fault zones. Heating during deformation can lead to chemical changes occurring out of thermodynamic equilibrium, causing complexities such as bypassing the formation of eutectoid melts. Although this initial slip will promote disequilibrium melting and mixing in the melt zone, further slip could generate a chemical hysteresis that would facilitate homogenisation between the melt and bulk composition of the magma.

In order to understand melt homogenisation during frictional melting, high-velocity rotary shear experiments were performed at a constant coseismic slip rate (1 m/s) under controlled axial stress (1 MPa). Two sample sets of amphibole-bearing and pyroxene-bearing andesites (Soufrière Hills, Montserrat and Volcán de Colima, Mexico, respectively) were used to investigate the mineralogical effects on melting dynamics upon fault slip. For each sample 5 experiments were performed, stopping (1) at the onset of melting; (2) after a full melt layer had formed; (3) after 5 m of slip; (4) after 10 m of slip; (5) after 15 m of slip. The proto-melts were analysed using X-ray spectroscopy at the synchrotron Diamond Light Source, UK, focusing on concentrations of REE. Complementary EPMA measurements were performed on bulk glass, bulk crystals, proto-melt and remnant proto-melt crystals to quantify the degree and timescales of chemical homogenisation during melting.

The preferential melting of mineral phases (in order of melting point) near the slip zone plays a clear role in frictional melt composition via decomposing during flash heating rather than disequilibrium chemical diffusion breakdown. However, due to time-dependence of melt homogenisation, slip behaviour can be related to chemical diffusion once steady state conditions are achieved. These changes during dynamic friction have important rheological implications, with melt chemistry and mineral comminution having fundamental controls on the mechanical forces associated with slip.

The impact of water on dislocation content and slip system activity in olivine constrained by HR-EBSD maps and VPSC simulations

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Changes in concentration of H^+ ions in olivine have impacts on its rheological behaviour and therefore on tectonic processes involving mantle deformation, but the details of how these effects manifest remain poorly constrained. We use high angular-resolution electron backscatter diffraction (HR-EBSD) to map densities of different types of geometrically necessary dislocations (GND) in polycrystalline olivine deformed experimentally under wet and dry conditions and also in nature. HR-EBSD provides unprecedented angular resolution, resolving misorientations <0.01°. We also employ visco-plastic self-consistent (VPSC) simulations to investigate changes in slip-system activity. HR-EBSD maps from experimental samples of Fo_{90} and Fo_{50} demonstrate that olivine deformed under hydrous conditions contains higher proportions of (001)[100] and (100)[001] edge dislocations than olivine deformed under anhydrous conditions. Furthermore, maps of wet olivine exhibit more polygonal subgrain boundaries indicative of enhanced recovery by dislocation climb. VPSC simulations with low critical resolved shear stresses of the (001)[100] and (100)[001] slip systems reproduce an unusual CPO, with bimodal maxima of both [100] and [001], observed in wet olivine aggregates. Analysis of a mylonitic lherzolite xenolith from Lesotho, with 104 ± 17 ppm H/Si in olivine (Paterson calibration), reveals the same unusual CPO and similar proportions of dislocation types to 'wet' experimental samples, supporting the applicability of these findings to natural deformation conditions. These results support suggestions that H^+ impacts the flow properties of olivine by altering dislocation activity and climb, while also providing full quantification of GND content. In particular, the relative proportions of dislocation types may provide a basis for identifying olivine deformed under wet and dry conditions.

The evolution of the 2016 Central Italy seismic sequence from geodesy, seismology and field investigation

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The destructive 2016 Central Italy earthquake sequence constitutes the largest release of seismic energy in Italy since the 1980 Irpinia earthquake. The sequence started on 24th August with a M_W 6.2 earthquake, which was followed on the 26th October and 30th October by M_W 6.1 and M_W 6.6 events respectively, as well as by hundreds of smaller aftershocks.

Here we use geodesy and bodywave seismology to estimate source mechanisms for each of the major earthquakes, and to estimate the spatio-temporal distribution of seismic and aseismic slip throughout the sequence. Our field measurements of extensive metre and decimetre-scale surface ruptures are used to constrain and to validate our source models. We use our slip estimates to calculate the evolution of Coulomb stress on the causative and surrounding faults throughout the sequence.

We find that each of the M_W>6 events involved slip on the Vettore fault, a structure that had not produced earthquakes in the historical record, despite being known to be active over the Holocene. Slip in all events was also largely restricted to shallow (<8 km) depths, possibly related to structural segmentation of the Vettore fault with depth.

We show that these earthquakes have stressed the down-dip extent of the Vettore fault. As this portion of the fault has not failed in the recent seismic sequence or in historical earthquakes, we suggest there is still a potential for large earthquakes on the Vettore fault within a relatively short interval, an occurrence that has precedent in other tectonic regions worldwide.

Seismic observations of mid-mantle reflectors linked to significant compositional heterogeneity in the deep Earth

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Recent tomographical studies have found that both up and downwelling mantle flow is commonly deflected in the mid-mantle at around 1000 km depth [Fukao and Obayashi, 2013; French and Romanowicz, 2015]. This deflection shows some relationship to seismic reflectors. However, there are no candidate mineral phase changes below approximately 800 km to explain either the reflectors or deflection. Although some recent publications suggest that the transition is a viscosity jump or a compositional difference [Rudolph et al., 2015; Ballmer et al., 2015], the causative mechanisms of deflection and relationship to seismic features is unclear.

Here, we perform a comprehensive global scale interrogation of mid-mantle seismic reflectors in the depth range 800 – 1300 km, using a large high quality global dataset of SS precursors. Reflectors are detected globally, with variable depths and polarities. Regions with an absence of reflectors are also detected globally. Interpreting our observations in the context of global geodynamical models, we find that the reflectors may be grouped regionally into three categories, associated with seismic velocity:

1. Dominantly absent reflectors in seismically fast regions beneath Europe and the Philippines, correlated with sub-vertical heterogeneous slab material;
2. Abundant reflections from areas of slow upwelling, corresponding to the top of the thermochemical pile beneath the Pacific Ocean;
3. Laterally extensive and coherence reflectors at variable depths in seismically average/neutral regions, possibly indicative of a transition in composition or rock texture, and linked to long term slab stagnation.

The diversity of these reflectors indicates distinct and varied origins, and reveals widespread compositional heterogeneity in the mid-mantle.

Using laterally compatible cross sections to infer fault growth and linkage models in foreland thrust belts

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We investigate changes in shortening, displacement and fold geometry to understand the detailed along-strike structural variation within fold-thrust belts, and infer thrust growth and linkage mechanisms. Field observations from the Vercors in SE France are used to characterise deformation style in the region. Parallel cross sections are constructed, analysed and used to create shortening and thrust displacement profiles from the northern to southern Vercors. Cross sections show changes in structural style and shortening accommodation from thrust-dominated in the north to fold-dominated in the south. The total shortening distance in the main Vercors region does not change significantly along strike (3400-4650 m), however displacements along individual thrust zones do vary significantly and displacement profiles show a range in displacement gradients (16-107 m/km). Despite relatively simple shortening patterns in the Vercors, cross sections show a more complex 3D internal structure of the fold-thrust belt. Thrust displacements and geometries suggest both large-scale thrust zones and small-scale thrusts are soft linked, transferring displacement along strike through transfer zones. Short, soft-linked thrust segments indicate an intermediate stage of thrust growth and linkage, well documented for normal fault systems, which form prior to the formation of thrust branches and hard-linked displacement transfer.

Young arc magmas are found along the length of New Guinea

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New Guinea has a long, complicated history of arc magmatism and accretion. The present day shape of the coastline resembles the shape of a bird in flight, this shape has ultimately resulted from a long history of oblique convergence between the Australian plate and the Pacific/Caroline/Philippine. This convergence led to multiple episodes of collision between continental crust and island arcs.

These multiple events make it difficult to decipher the tectonic history of New Guinea. However, this can be simplified by dividing New Guinea into four major tectonic belts; (1) accreted Palaeogene island arcs, (2) the New Guinea Mobile Belt, (3) the New Guinea Fold Belt and (4) a southern stable platform. These tectonic belts have been correlated along most of New Guinea in major review papers. Yet, such reviews largely ignore New Guinea's western most peninsula ("the Bird's Head"). This is due in part because of a relative scarcity of data in western New Guinea (Papua/Irian Jaya) vs. eastern New Guinea (Papua New Guinea).

Continental magmatic arc rocks of Miocene to Pleistocene age within the New Guinea Mobile Belt and Fold Belt, have been extensively studied throughout central and eastern New Guinea (e.g. the Maramuni Arc, Frieda River porphyry deposit) and occur in a near continuous arc that until now has not been correlated with coeval volcanic rocks in the Bird's Head.

New U-Pb zircon geochronology, geochemical analyses and field studies in the Bird's Head indicate the presence of Middle to Late Miocene intermediate to felsic volcanic rocks with associated granitoid intrusives, formed in an active continental margin along the entirety of New Guinea.

The magmatic arcs of central and eastern New Guinea indicate collision of magmatic arcs with the northern margin of the Australian continental crust during the Middle Miocene. These arcs are typified by associated porphyry Cu-Au deposits (Frieda River, Ok Tedi, and Grasberg). There has been little focus on Cu-Au exploration in the Bird's Head up until very recently. The discovery of young intermediate rocks in this region, together with other data implies that there is perhaps some likelihood of ore-bearing rocks associated with these arc volcanics in the Bird's Head.

Stress triggering and field observations of the 2016 central Italy earthquake sequence

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Three M≥6 earthquakes struck central Italy between August and October in 2016. The earthquake sequence ruptured the Mt Vettore and Laga faults and culminated in a M6.6 event that re-ruptured parts of the Mt Vettore fault that broke in the first two events. We present initial field observations made in the aftermath of each event including structural measurements of fault offsets in addition to photogrammetry and terrestrial laser scans of the fault ruptures that document the co-seismic and immediate post-seismic evolution of the surface ruptures. Surface observations showed visible ruptures on the Mt Vettore fault for all three events with different surface rupture lengths and surface offsets recorded in each event

We use slip inversion models derived from InSAR and seismology observations to calculate the stress changes caused by each event on both the Laga and Mt Vettore faults and also the surrounding faults in the central Apennines. We show the changes in Coulomb stress on the Mt Vettore fault caused by the fault two events prior to the M=6.6 event on 30th October.

Prediction of slip tendency with uncertain stress data

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Previous work has suggested that fracture stability can be predicted from stress data (Barton et al. 1995; Ferrill et al. 1999; Zoback 2007). However, the input stress data are always uncertain. We show variabilities of predicted stress values for vertical stress (S_v), horizontal stresses (S_{hmin}, S_{Hmax}) and pore pressure (P_p) from wells in the Australian North Perth Basin (NPB) and calculate slip tendency (T_s) for an arbitrary set of fractures to show the impact of uncertainty in stress data on T_s prediction.

We use reported stress and pressure data for S_{hmin} and S_{Hmax} from leak-off tests and stress polygons (Zoback 2007), as well as our own predictions for S_v after Tingay et al. (2003). P_p estimation after Eaton (1969) is applied to several wells in the NPB, and the data are used to calculate stress gradients and determine their variations. Monte Carlo simulation allows us to explore the full range of possible stress states (within the observed variations) necessary for T_s determination.

We find that all predicted stress gradients of the NPB are highly variable with greatest variability in S_{hmin} (>20%). All predicted stress gradients are non-normally distributed, although in some cases the number of available data is small ($n < 10$). Deviations from the mean are highest in S_{hmin} and S_v, with the latter showing great degrees of data skewness. Analysis of T_s for a set of artificial fractures oriented in direction of S_{hmax} at a determined depth shows that predicted T_s strongly varies with the (un)certainty of the predicted in-situ stresses.

Results suggest that:

+ The NPB is a strike-slip regime with S_{Hmax} > Sv > S_{hmin}

+ Variation in NPB stress gradients can be as large as 20%

+ Allowance for uncertain measurements must be incorporated in fracture stability analyses for more reliable results

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ISC-EHB: Reinventing the EHB Earthquake Database

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The EHB database was originally developed with procedures described by Engdahl, Van der Hilst & Buland (1998), and currently ends in 2008. Our aim is to expand and recreate the EHB database, in collaboration with the International Seismological Centre (ISC), to produce the ISC-EHB. We begin with events in the modern period (2000-2014) and apply new and more rigorous procedures for event selection, data preparation, processing, and relocation.

The ISC-EHB criteria selects events from the ISC Bulletin which have more than 15 teleseismic (> 28^0) time defining stations, with a secondary teleseismic azimuth gap of < 180^0, and a defining prime magnitude > 3.75 (Di Giacomo & Storchak, 2016). These criteria minimize the location bias produced by 3D Earth structure, and result in the selection of many events that are relatively well located in any given region.

There are several processing steps; (1) EHB software relocates all the events using ISC starting depths; (2) Near station and secondary phase arrival residuals are reviewed and a depth is adopted or assigned according to best fit, and in some instances depths may be reassigned based on other sources (e.g., USGS broadband depths); (3) All events are relocated with their new depths and plotted in subduction zone cross sections, along with events from the ISC-GEM catalogue for comparison; (4) These plots are used to confirm or modify weakly constrained depths; (5) The "ISCloc" (Bondar & Storchak, 2011) uses the final EHB depths to relocate the events.

The new ISC-EHB database will be useful for regional and global seismicity studies, as well as tomographic inversions. This will be facilitated by online access to the ISC-EHB Catalogue and Bulletin via the ISC, and will include maps and cross sections of the seismicity in subduction zones. Example maps and cross sections for events in years 2000-2003 will be presented.

Things you didn't know you didn't know about diffusion creep

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It is commonly asserted that diffusion creep is characterised by equant grains, and that it destroys crystallographic preferred orientations. The flow law contains grain size but no mechanical anisotropy. Numerical models show that none of these things apply in general, and several experiments interpreted as involving diffusion creep don't support these assertions either.

Grain shapes in numerical models are shown to become elongate, though they do not track overall strain because of neighbour switching and grain boundary sliding. Grain shapes in experiments on calcite become slightly elongate and in perovskite more so. Olivine is *unusual* in that it appears to maintain equant grain shapes in diffusion creep. This may be due to grain growth and work is in progress to model this.

Because grain shapes become inequant, grain rotations – although they do occur – are not random, and tend to slow down as strain accumulates. Consequently crystallographic preferred orientations, if present initially, may be weakened but are not destroyed.

Again perhaps because of assumptions that grains remain equant, mechanical anisotropy is never considered in flow laws for diffusion creep, even though it is found in experiments on superplasticity in metals. However numerical models show that it is not only a part of the flow law, but that the mechanical anisotropy can be huge, with implications yet to be explored.

Caught in the Act: Rifting and Melt Injection from the Faroes Margin to the Icelandic Rift Zones.

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Seismic reflection and refraction profiles across the Faroes continental margin show one of the best examples in the world of intrusive melts frozen as sills in the lower crust and extrusive lavas forming seaward dipping reflectors and landward propagating flows above sediments in the upper crust. On the Eastern Rift Zone (ERZ) of Iceland we have caught the processes of melt intrusion and eruption in the act by tracking melt movement using microseismicity.

The ERZ is a good analogue of the original continental breakup above a mantle plume. The ERZ sits above the present Iceland mantle plume and is a young (c. 3-6 Ma) rift formed by an eastward jump into crust 30-35 km thick in this region. We have imaged melt injection using seismicity in two dykes, Upptyppingar (2007) inclined at 50° and Holuhraun (2014) travelling horizontally c. 45 km before eruption. Elsewhere persistent micro-seismicity in discrete mid-crustal patches along the Askja segment records melt intruding between crustal sills at different depths. Locations of melt in the crust are imaged by seismic tomography around the Askja central volcano and show regions in the mid-crust of melt residence in addition to shallow (c. 6 km depth) large melt storage regions.

The work reported here derives from more than a decade of fieldwork and research both on the Faroes margin and in Iceland in collaboration with Bryndís Brandsdóttir, Phil Christie, Alan Roberts and Nick Kusznir and a large group of graduate students and field workers too numerous to list individually here. I am grateful to them all for their contributions and their friendship. Some key references are listed below:

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Skarn-Forming Processes in Calc-Silicate Xenoliths from Merapi Volcano, Indonesia

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Merapi exhibits near continuous activity, characterised by basaltic andesite lava dome growth, interrupted by gravitational or explosive dome collapse and associated pyroclastic density currents. Abundant calc-silicate xenoliths are found at Merapi, with recent work focussing on the role of crustal contamination by assimilation of carbonate lithologies in influencing eruption dynamics via volatile exsolution. This study aims to explore the reactions, mechanisms and chemical transfers occurring during magma-carbonate interaction.

The characteristic mineralogy of calc-silicate xenoliths collected from deposits of recent eruptions, including the paroxysmal 2010 eruption, can be subdivided into three types based on the typical skarn-type mineral associations observed: 1) wollastonite ± diopside, 2) grossular-andradite garnet + Ca-Tschermak clinopyroxene + wollastonite + anorthite, 3) Ca-Tschermak clinopyroxene + gehlenite + grossular garnet + spinel. Wollastonite and diopside commonly host abundant dacitic to trachydacite-rhyolitic melt inclusions, moderately Ca-enriched relative to lava phenocryst hosted glasses. The xenolith cores are commonly surrounded by distinct rims of moderately Ca-enriched rhyolitic glass, and granular diopside+plagioclase+Fe-Ti oxides closer to the lava contact. CaO-enriched glasses testify to the crystallisation from a contaminated silicate melt for many of the xenoliths, which can be classified as magmatic skarns, and an exoskarn origin for other samples.

Our petrographical and mineral chemical data suggest shallow level, high temperature carbonate assimilation-skarnification below Merapi involving localised enrichment of Ca in adjacent magmatic melt, driving clinopyroxene, plagioclase and wollastonite precipitation. Oxygen fugacity exceeding the magnetite-hematite buffer within many of the xenoliths is suggested as a result of carbonate breakdown, driving strong Ca-Tschermak substitution within xenolith core clinopyroxene, high stoichiometric Fe^{3+}/Fe_{tot} within clinopyroxene and garnets, and formation of accessory phases that indicate oxidizing conditions. Accessory metal and Cl-F-S-bearing phases show evidence for a volatile-rich, shallow level magmatic-hydrothermal fluid phase within the Merapi system.

Whole-rock and olivine chemistry of Don Casimiro and associated rear-arc volcanism: An insight into geochemical variations along the Andean Southern Volcanic Zone.

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The Southern Volcanic Zone (33°S-46°S) is one of several volcanically active segments within the Andes. This arc segment is subdivided into north, transitional and southern zones (NSVZ, TSVZ and SSVZ respectively). This region shows extensive geochemical variability, previously explained by:

a) a mixing, assimilation, storage and homogenization (MASH) zone at the base of the crust

b) source region contamination by subducted sediment, lithospheric mantle, or subduction erosion of the upper plate

c) variations in the degree of mantle melting along the arc

d) variations in slab fluid input.

Most previous studies have focused on the TSVZ and the SSVZ to solve this debate, due to a scarcity of primitive magmas in the NSVZ. However, we focus on 15 mafic lavas from the arc-front Don Casimiro volcano; an extinct Pleistocene centre located on the rim of the Maipo Volcano Complex (34.164 °S). This occurrence of olivine-rich (and therefore, presumable more primitive) lavas within the NSVZ should avoid the complications encountered when working with more evolved rocks. In particular, this should allow the mantle source region geochemical variation to be separated from that caused by crustal contamination.

To the east of the arc-front lies a rear-arc province with intraplate basalts of debated origin. To fully isolate the contribution to the geochemistry along the arc-front from source variations, we also analyse 7 scoria samples from monogenetic centers in the Argentinian rear-arc. We hypothesise that these analyses will allow access to the mantle composition before slab inputs are added.

Whole rock and trace element chemistry will be analyzed with XRF and ICP-MS. LA-ICP-MS and EPMA melt inclusion data on individual olivines, along with whole-rock Sr and Nd isotope data, may be collected. This work is essential to constrain the processes occurring in continental margin settings, and should help to resolve a 30+ year controversy.

The development of a low-cost UV camera and its application to the quantification of volcanic SO_2 fluxes

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Monitoring volcanic emissions of SO_2 with scientific grade UV cameras has now been practiced for approximately a decade. The high spatial and temporal resolutions provided by such systems have enabled detailed investigations into a range of degassing phenomena; furthermore, SO_2 cameras are now an important component of monitoring networks at a number of volcanoes. Although nominally cheap (≈ USD 1000s), the cost of these systems is still a limiting factor when considering widespread proliferation to augment the assessment of global volcanic hazard; since a large proportion of active volcanoes are located in developing countries, where funds are limited, the price becomes ever more pertinent.

Here, we present on the development of a low-cost SO_2 (UV) camera by modifying a Raspberry Pi camera module (≈ USD 25), which comprises a cheap sensor designed primarily for the smartphone market. By removing the sensor's Bayer filter and rebuilding the optical system for optimized UV throughput, we produce a camera system with greatly heightened UV sensitivity, relative to the original off-the-shelf product. We compare the performance of this system to that of a scientific grade camera (JAI CM-140 GE-UV) which is routinely deployed for volcanic SO_2 retrievals. The results show that our new low-cost SO_2 camera can perform comparably to an expensive system, exhibiting similar signal-to-noise characteristics once pixels are binned to a resolution of 648 x 486. Furthermore, the SO_2 flux time series generated by our camera shows remarkably good agreement with that of the JAI system (r^2 = 0.92). Our findings suggest that these new units could greatly benefit volcano monitoring and research groups worldwide, by providing a lower price point solution to measurements of SO_2 emissions.

Stress drops for earthquakes M ≥ 4.0 across the Blanco Oceanic Transform Fault

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We present initial results in estimating stress drops of M ≥ 4.0 earthquakes on the Blanco Oceanic Transform Fault, off the coast of Oregon. From these stress drops, we plan to examine how stress drops vary spatially and temporally, particularly in foreshocks, aftershocks, and swarms. We estimate stress drops on the Blanco fault using a phase coherence method that evaluates phase differences between station records for two colocated earthquakes. These phase differences depend on the spatial extents of the two collocated earthquakes. If the energy of an earthquake is generated over a large rupture, then different stations will see different source time functions dependent on the rupture history of the two earthquakes. The phase difference is frequency dependent and most pronounced at frequencies higher than the reciprocal of the seismic travel time across the earthquake rupture length. By cross correlating between station records for colocated earthquakes, we isolate frequency-domain phase differences between earthquake source time functions, giving us a falloff in the phase coherence. The falloff frequency corresponds to the rupture length of the larger earthquake in the pair and thus the stress drop. We present falloff frequency results for several pairs of earthquakes and demonstrate the reliability of the phase coherence method using multiple collocated pairs for one earthquake. We present phase coherence results for several pairs of earthquakes finding realistic rupture lengths. We demonstrate the reliability of this method for the Blanco fault using multiple collocated pairs with one common earthquake finding consistent rupture lengths across most pairs.

Understanding conduit processes with InSAR at Turrialba, Costa Rica

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Deformation associated with conduit processes is often detected by tiltmeters and GPS stations close to the vent. One caveat of these methods is that the observations are made at a sparse network of instruments, often just one or two points. As a result, we cannot determine the spatial pattern or extent of the deformation. However, by using InSAR it is possible to observe the full spatial pattern of the deformation over the volcano. This could enable us to distinguish between the three conduit processes that may be causing the deformation: a standard Modi model, a shear flow model, or a gas slug model. Our research initially uses COSMO-SkyMed data for Turrialba, Costa Rica, focusing on the periods of explosive activity in 2016. Seismic and SO2 data indicate key periods of activity between March and July, and in September. Future research will also focus on Irazú, which is located 10 km SW of Turrialba. ALOS-2 and Sentinel data will be used to determine the deformation associated with the deeper magmatic system beneath Turrialba and Irazú.

The strong influence of weak heterogeneities on strain distribution

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Thin viscous sheet models of lithospheric deformation can show significant changes in strain distribution across a model but the development of large scale shear-zones requires specific conditions. Prior work has shown how viscous heterogeneities of higher strength than a background region influence strain distribution. This study examines how a single weak viscous heterogeneity affects strain distribution in a simple shear context and promotes strain localisation.

A layer of viscous fluid containing a single weak inclusion is subject to simple shear under a plane-stress condition. A strain-weakening process is included in the calculations. With increasing shear, the initially circular weak zone focuses the deformation and narrow zones of enhanced shear develop either side of the inclusion due to the strain weakening. We measure velocity changes across the layer and consider the temporal and spatial dependence of viscosity and strain rate in the shear zones adjacent to the weak inclusion.

We use the velocity gradients as a measure of the degree of strain localisation in these 2D numerical experiments. For a given initial strength of the inclusion the strain localises with time at a rate that increases faster than exponential; outside the shear-zone, strain rates decrease rapidly. For an initially weaker inclusion strain localises within a shorter time and develops at greater distances from the inclusion. Thus, time, distance from the weak inclusion and the relative viscosity of the inclusion are all important controls on strain localisation.

Convergent plate boundaries that show diffuse deformation, such as the on-going India-Asia collision, contain regions of highly localised strain expressed as large-scale shear zones. These simple experiments inform thin viscous sheet models of continental convergence and suggest one possible mechanism for the genesis and evolution of these shear-zones. Insights from these models provide a greater understanding of global variations in lithospheric deformation.

Small-scale en-echelon dyke segmentation beneath the 2014-15 Holuhraun eruption fissure recorded by microseismicity

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The 2014 Bárðarbunga-Holuhraun dyke intrusion was tracked by laterally migrating seismicity between 16th-27th August 2014, before the main eruption began on 31st August. We study in detail the seismicity observed beneath the eruption fissure between 25th August and 2nd September. Relative relocations of refined hypocentral locations reveal that the final 3 km of the dyke was intruded along two small-scale en-echelon segments in two distinct episodes of intrusion on the 25th and 27th August. Tightly constrained moment tensor solutions show that the seismicity produced during the propagation episodes is dominated by left-lateral strike-slip faulting at the dyke-tip. This failure mechanism is consistent along the whole 15 km length of the northernmost segment of the dyke and facilitates plate spreading. Between 27th August and 2nd September a cluster of entirely right-lateral seismicity is observed at the junction between the two small-scale en-echelon dyke segments, adjacent to the southernmost end of the eruption fissure. At the termination of the dyke, north of the eruption fissure, further persistent seismicity is observed between 29th-31st August including several earthquakes that do not fit a double-couple moment tensor solution. These are best fit by an oblique-normal focal mechanism with a small opening-crack volumetric component. All recorded seismicity in the final 3 km of the dyke is confined to a depth range of 4.5-6.5 km despite geodetic evidence for significant opening at shallower depths and melt breaching the surface.

Freeze-thaw effects on the mechanical and microstructural properties of bentonite

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Geological disposal has been recommended as the best available long-term approach to safely manage radioactive waste and spent fuel. Argillaceous media within Geological Disposal Facilities (GDFs) are being considered by many countries as a potential host rock or engineered barrier for radioactive waste. The long-term safety of utilising GDFs needs to span at least 1 million years, and therefore the evolution of our climate must be considered. Despite climate models showing an overall rise in global temperatures of at least 2 ºC as an immediate response to anthropogenic emissions of CO_2, evidence from palaeoclimate studies predict that glacial periods are inevitable. The potential detrimental effects of permafrost to GDF integrity have not yet been fully researched. These processes could include freeze-thaw weathering of the GDF, a variation in regional and local groundwater flow patterns, increased salinity at depth, or even the formation and destabilisation of gas hydrates beneath the frozen layer. The GDF multi-barrier approach uses engineered barriers, for example swelling clays such as bentonite, to ensure harmful radioactive isotopes can never reach the biosphere. The long-term thermo-mechanical properties of these clays must be thoroughly researched in order for their use to remain feasible. The moisture content of bentonite may affect its response to freeze-thaw cycles. Cylindrical samples of MX-80 bentonite were compressed at 63 MPa as used in the KBS-3 disposal concept. These samples had a moisture content of 22.7%, porosity of 39%, dry density of 1.68 $g.cm^{-3}$, and therefore a degree of saturation over 95%. The effects of persistent freeze-thaw cycles on the uniaxial compressive strength of MX-80 bentonite has been investigated in addition to porosity, pore shape, and pore size using SEM analyses. Future research will concentrate on the tri-axial and shear deformation of freeze-thawed bentonite, and the role of dry density on the hydro-mechanical properties. In addition, the degree of salinity and type of salinity (NaCl, $MgSO_4$, KNO_3 etc.) will be examined to assess the suitability of using bentonite as an engineered barrier.

Persistent outgassing of open vent basaltic volcanoes

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Basaltic open vent volcanoes produce >50 % of the global volcanic outgassing flux of volatiles to our atmosphere and are often characterised by persistent outgassing between as well as during eruptions. This style of volcanic eruption is largely responsible for shaping our atmosphere over geological time. Previous experiments focusing on the fluid mechanics of persistently outgassing basaltic volcanoes have been based on exploring the modes of gas flow through a liquid, and this has led to understanding of some of the modes of eruption and gas release, in particular relating to slug flow in the conduit, and also the generation of foam in the magma reservoir. Instability in the foam can lead to periodic release of large gas bubbles, while in other systems the mode of eruption involves the continuous release of small bubbles. However, much of this understanding has been developed with little account for the presence of crystals, even though magma chambers contain abundant crystals which are predicted to have a fundamental influence on development of porosity, movement of gas slugs and gas segregation. We report on a series of new 3-phase (solid-liquid-gas) analogue laboratory experiment in which we have investigated the role of crystals in the magma in a volcanic conduit and explore how the crystals influence the formation and dynamics of gas bubbles rising through the system. Data from these experiments will be combined with *in situ* gas composition and flux, geophysical and petrological studies, including crystal stratigraphy and inclusion geochemistry, to reconstruct melt degassing and geophysical processes in basaltic open vent volcanic plumbing systems.

The Fault Damage Zone; Implications of slip displacement on damage zone width

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Geological faults are perhaps one of the most studied and arguably fundamental features of the dynamic earth system. However, with over a century of studies on fault systems, one aspect of the modern fault model which is still somewhat poorly constrained is the fault damage zone. While fault zones only account for a relatively small volume of the earth’s crust, they play a fundamental role in the transportation of fluids, the mechanical behaviour and the structural strength of the crust. Therefore, it is essential to have a detailed understanding of the spatial relationship of the surrounding damage zone in a fault zone to fully appreciate its control and implications on fault growth processes.

A fault zone consists of two primary components, the **fault core**; which is where the majority of displacement is accommodated, and the **fault damage zone**; a region of damaged host rock represented by deformation occurring on a range of scales from the macroscopic to the microscale. Existing theorem suggests that the spatial width of this damage zone should be greatest towards the fault tips, where displacement along a fault is typically lowest. Few studies have however successfully characterised the fault damage zone and its spatial relationship to fault slip as such efforts are hampered by faults having occurred through different lithologies or having crossed into different tectonic settings. This in part appears to be due to the difficulty in studying recently exhumed fault zones which are hindered by poor exposure, especially as fault rocks are usually friable in nature.

This study focuses on the damage zone associated with a single strike slip fault found within the Mesozoic Atacama fault zone (Northern Chile) within a homogenous lithology of granodiorite. It presents a rare opportunity to characterise and study the spatial extent of the damage zone through the length of the fault and test it against existing damage zone models. The damage zone width is quantified by performing a microfracture analysis which measures fluid inclusion planes (FIPs) in quartz at several points along the length of the fault. Petrographic images are processed in image analysis software (ImageJ) to produce a quantifiable microfracture density. This microfracture density value is compared with known slip displacement measurements to assess the relationship between the spatial extent of the damage zone and fault slip.

The microtextural and petrochronological record for the rapid tectonic exhumation of Himalayan lower crust

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When rapid tectonic processes are coupled with relatively sluggish reaction rates, detailed information on the tectonic and metamorphic evolution of a mountain belt can be encapsulated in a single rock. High-grade gneisses and mafic granulites found in NW Bhutan, eastern Himalaya demonstrate this, since they comprise complex microstructures that record multi-stage metamorphic histories[1&2].

There is strong petrological evidence for an eclogitic precursor (20-24 Ma[3]) and high-pressure granulite facies overprint occurring at c. 14 Ma[2] in mafic boudins found in NW Bhutan. The geochronological data from the boudins is corroborated by coincident growth of monazite in the host gneiss (15.4-13.4 Ma[3]). These observations indicate that the rocks were rapidly exhumed from depths of >50km to ~20km in a relatively short ~5 Myr period of time.

By comparison, geochronological and microtextural data from another tectonic unit, only 5 km to the south, yield older ages (21-17 Ma[2]) and a lower grade, shallower metamorphic history. This implies the presence of an out-of-sequence tectonometamorphic discontinuity in the upper GHS of NW Bhutan[2&4]. The tectonic driving mechanism that exhumed the upper tectonic unit is still unclear.

Detailed and accurate geochronology coupled with fine-scale petrographic modelling will allow us to constrain the tectonic processes that caused the metamorphic changes in NW Bhutan. This project aims to link geochronology and petrology via novel geochemical fingerprints to allow “age” and “stage” to be precisely linked.

1. Grujic, D. et al. (2011) *Lithosphere,* 3(5), pp.346-366. **2.** Warren, C. J., et al. (2011). *Tectonics, 30*(2). **3.** Warren, C. J. et al. (2012). *J. Met Geol*., *30*(2), 113-130. **4.** Montomoli, C. et al. (2014) *Geol. Soc., London, Special Publications,* 412, p.SP412.3

InSAR observations of focused interseismic strain along the entire North Anatolian Fault: implications for seismic hazard assessment and the rheology of the lower crust

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Earthquakes are caused by the release of tectonic strain accumulated in the interseismic period. Recent advances in satellite geodesy mean we can now measure this interseismic strain accumulation with sufficient accuracy such that strain data can be useful for seismic hazard assessment. However, it remains unclear whether these short-term (decadal) geodetic observations can be useful when assessing the seismic hazard of faults that accumulate strain over centuries to millenia. Here we show that interseismic strain around a major continental transform fault reaches a near-steady state within a few years after major earthquakes.

We use InSAR observations acquired by Envisat between 2002 and 2010 to measure the rates of tectonic strain accumulation along the entire North Anatolian Fault, where the time period since the last earthquake varies from ~7 years to ~70 years. When combined with GNSS observations collected prior to two major earthquakes in 1999, we show that the shear strain rate is independent of the time since the last earthquake, once a rapid postseismic transient has decayed. Short-term geodetic strain observations can therefore usefully contribute to seismic hazard assessment. Geodetic observations for an entire earthquake cycle can only be explained if a weak shear zone is embedded within a strong lower crust (viscosity >~10^{20} Pa s).

Kinematics of polygonal faulting in the northern North Sea

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Polygonal fault systems have been documented from over 100 basins worldwide and comprise large numbers of layer-bound (fine-grained), low-displacement (<100 m throw) normal faults, which in plan-view have a polygonal arrangement and cover areas of up to 2,000,000 km^2. Polygonal faults play a key role during compaction and drainage of fine-grained sedimentary sequences, yet we still know surprisingly little about their development. A variety of hypotheses, including overpressure, gravitational sliding, syneresis, diagenesis, yielding (i.e. ductile failure) and low coefficients of residual friction, have been put forward to explain the nucleation and growth of polygonal fault systems. This study tests existing hypotheses for polygonal fault nucleation and growth by conducting a quantitative analysis of the geometry, displacement patterns and kinematics of 137 polygonal faults imaged by 3-D seismic reflection data in the Cenozoic of the northern North Sea. We find that the majority of the faults nucleated in sediments that were undergoing silica diagenesis (i.e. opal-A/CT transformation). Although diagenesis may explain polygonal fault nucleation as a result of horizontal stress reduction, alternative explanations invoking syneresis or yielding are difficult to dismiss based on fault kinematics alone. While polygonal fault growth or more precisely, the accumulation of displacement, can generally be explained by low coefficients of residual friction of the host strata, the preferential accumulation of displacement below the point of fault nucleation appears to require: (1) variations in the coefficient of residual friction; (2) a reduction of horizontal stresses due to opal-A/CT transformation; and/or (3) multiple stages of fault growth. This study highlights that the kinematics of polygonal fault systems derived from 3-D seismic reflection data provide key information that help us understand the development of these enigmatic systems.

Accretion of the upper crust of the Troodos ophiolite (Cyprus)

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Introduction

This field-based and geochemical study of the Troodos ophiolite aims to link the processes of volcanic accretion and tectonic stretching during seafloor spreading. The Troodos ophiolite is a 90 km across-axis slice of oceanic crust exposing original spreading structures in two or three dimensions, allowing detailed reconstruction of the relative timing of tectonism and volcanism throughout its spreading history. Previous work on Troodos has recognised that tectonic stretching caused rotation of the Sheeted Dyke Complex to form three grabens. But how has that extension effected the mechanism of accretion of the volcanic layers?

Observations

By mapping the geochemical variation of lavas across the extrusive section it is possible to identify the geometry of those lava flows and to constrain the relative timing of different syn-tectonic eruptive events in relation to episodes of tectonic activity. Two geochemical groups of the lavas have been redefined and traced laterally across the entire width of the ophiolite. The lower lava unit is compositionally uniform, more evolved, and more viscous. In contrast, the upper lava unit is more primitive, more heterogeneous in composition, and is less viscous. It was found that thickness variations were predominantly within the upper unit, and that lavas at depth have been tilted while lavas near the surface are undisturbed.

Conclusions

It is suggested here that the lower lava unit was erupted at an on-axis setting. However, the upper lava unit probably erupted at a slightly off-axis position, and these flows were ponded on the seafloor against exposed normal faults in active half-grabens. Simultaneous on- and slightly off-axis eruption of lavas could be an integral part of thickening of the oceanic crust at other slow-rate and intermediate-rate spreading centres.

Comparison of fracture features at different scales for laminites

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In order to gain insight into geomechanical behaviour of heterogeneous rocks, it is important to run laboratory deformation experiments under known boundary conditions, to test a variety of samples and then compare the results with large-scale observations. This is useful in order to a) validate that laboratory conditions can achieve observed deformation features and b) to understand which characteristics can or cannot be scaled. This study compares a set of laminated carbonates (from outcrops in NE Brazil) deformed under laboratory conditions with outcrop observations. Laminites from the Crato Formation have been identified as possible analogues for some Brazilian pre-salt carbonate facies. Core plugs (Ø 38mm) have been deformed in axi-symmetric compression at 20, 30 and 40MPa confining pressures to a little beyond the peak stress and are then unloaded so that only early stage early deformation features are formed. The plugs were photographed and x-ray tomography (XRT) was performed to characterise surface fractures and any deformation features occurring within the plug. During a field trip to the outcrop area fractures similar to the ones observed on the core plug surfaces were observed (Figure 1A, 1B).

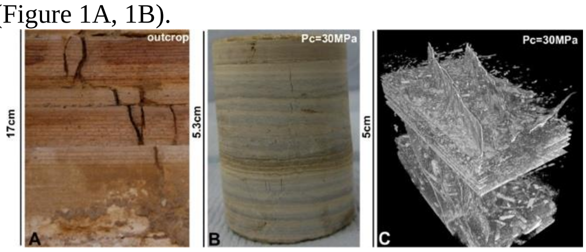

Fig 1. Laminite deformation A: outcrop B: core plug C: 3D reconstruction from XRT

Fractures observed in the laminite core plugs are not affected by size or edge effects and overall characteristics can be scaled up to outcrop scale quite easily. However, fracture aperture and possibly fracture length are not as easily scaled and a more detailed understanding of these relationships is necessary. Due to the correlation between surface fractures it is very likely that internal fracture network characteristics (Figure 1C) will also be present at the outcrop scale. Further investigations are required to fully understand the links between laboratory and outcrop scale for laminites.

Workshops

Workshop 1 - Experimental methods in Earth science

Date: Saturday, 7th January, from 10:00 to 16:30

Organizers: Prof. Yan Lavallée, Dr. Jackie Kendrick, Dr. Felix von Aulock (University of Liverpool)

In this workshop we will introduce diverse experimental methods developed in rock mechanics and magma rheology, helpful to constrain a spectrum of geological processes related to volcanoes, fault zones and geothermal systems. The course will first review some key concepts related to the rheology of silicate liquids (e.g., viscosity, diffusivity) and the mechanical properties of rocks (e.g., strength, frictional properties, permeability). We will also introduce the design, use and limitation of a few key apparatus and monitoring devices, demonstrate their use, and discuss how to plan successful high-temperature experimental programs.

Workshop 2 - Quantitative scanning electron microscopy (SEM) techniques in the Earth Sciences: an introduction to Electron backscatter diffraction (EBSD) and Quantitative Evaluation of Minerals (QEMSCAN)

Date: *Saturday, 7th January, from 10:00 to 16:30*

Organizers: Dr. Elisabetta Mariani, Prof. Richard Worden (University of Liverpool)

This workshop will be divided in two parts and will first introduce the basic physics of EBSD analyses as well as data acquisition procedures in a SEM, methods of data processing after acquisition is completed and how EBSD can be used in combination with other techniques such as energy dispersive spectroscopy (EDS). This will be followed by an overview of the latest technological and software advances. A discussion of current applications of EBSD to different branches of Earth Sciences and the potential for future cutting edge research in the field of quantitative microstructure analysis will conclude the workshop. In the afternoon, the workshop will focus on the use of QEMSCAN to determine the distribution of mineral phases in rocks.

Workshop 3 - Digital elevation models (DEM) in Earth sciences

Dates: *Saturday, 7th January, from 10:00 to 16:30*

Organizers: Dr. Felix Von Aulock, Dr. Pablo Jose Gonzalez, Dr. Mike James

Digital Elevation Models (DEMs) have become increasingly accessible and cheaper, and their extent now covers large areas of the Earth at high spatial resolution. In this workshop we will present different methods (satellite-, airborne-, or ground based) to acquire spatial data and generate DEM; this will include an introduction to the use of drones and structure-from-motion algorithms, satellite data and LiDAR analysis. A portion of the workshop will be dedicated to introduce how to employ these methods. We will conclude with a discussion where attendees are invited to present their applications.

Workshop 4 - Reconstructing geomaterials in 3D using X-ray tomography

Date: *Saturday, 7th January, from 10:00 to 13:00*

Organizer: Dr. Kate Dobson (Durham University)

X-ray computed tomography (XCT) allows the non-destructive imaging of the internal textures inside our samples. From porosity and fracture, to mineralogy and crystal orientations there is a wealth of qualitative and quantitative information that we can extract, before we even have to section our samples. The latest advances also mean we can perform experiments inside the imaging systems so we can capture the textural evolution of the samples as it changes in response to temperature or load or flow. Many geoscientists are not yet fully exploiting the potential of these methods. This course aims to give a general introduction to the theory and application, capabilities and limitations of 3D and 4D (3D + time) XCT as applied to geological materials. We will also cover the basics of data processing and outline the various simple methods that can be applied to get quantitative textural information from the image data.

Workshop 5 - NERC Advanced Training Workshop: Python solutions for management of continuous seismic data and ambient noise interferometry

Date: *Monday-Wednesday, 9-11th January 2017, from 10:00 to 16:30*

Organizers: Dr. Silvio De Angelis, Dr. Thomas Lecocq, Dr. Corentin Caudron, Prof. Florent Brenguier

Recent advances in the understanding of the seismic ambient noise field, using interferometry hold potential for applications ranging from exploration geophysics to deep Earth seismology. This workshop will introduce standards and practices for the management and processing of large volumes of seismic data with applications in ambient noise interferometry. Participants will receive training on the principles of seismic interferometry and ambient noise seismology, and their application to a range of seismic data at different scales. The objectives of the workshop are to enable participants to evaluate the potential of seismic interferometry, and to provide them with a working knowledge of this technique. The workshop will use open-source Python-based software packages. The team of organizers includes international leaders in the fields of ambient noise interferometry, and experts in management and processing of large volume seismic databases.

Workshop 6: 3D model building, fault displacement and seal analysis, and restoration in Move

Date: *Tuesday, 3rd January, from 09:30 to 16:30*

Organizers: Dr. Cathal Reilly, Dr. Hugh Anderson, Dr. Roddy Muir (Midland Valley Exploration)

In this hands-on workshop we will use many of the tools available in the Move structural modelling and analysis software, giving attendees a working knowledge of the toolkit. Throughout the course of the day, we will use a dataset from the Taranaki Basin, offshore New Zealand's west coast in order to: build a 3D structural model; analyse fault displacement distributions to understand timing and nature of faulting; quantitatively assess fault seal; and carry out a 3D restoration to understand the temporal variability in displacement and seal associated with faults through time. The course will review some of the theory behind the algorithms used in Move's restoration and Fault Analysis tools and is a great introduction to new users of the software and those interested in constrained 3D model building, displacement analysis, fault seal and restoration.