



## **Abstract Volume**

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# VMSG Award lecture

## Living with volcanoes: past, present and future

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One critical challenge to volcanologists is that while the life cycle of most volcanoes is long, human memories are short. This has a number of consequences. The first is that since most of the world's active volcanoes are currently in repose, and most of these have been in repose for centuries or longer, our understanding of what might signal an impending eruption is incomplete. Indeed, even for volcanoes that have erupted in 'historical' times, there may be no formal scientific record of the sequence of events that led to the last eruption: the era of 'global' and distributed volcano monitoring has only just arrived. The second is that while many of the iconic eruptions of the past might still be well-known, at least by name, our understanding of those events probably still dates back to those scientific investigations and reports that helped to cement the status of those eruptions at the time. While the drive to develop better technologies (faster, better, cheaper) for detecting, measuring and analysing the volcanic activity of today and tomorrow is clearly both essential and valuable, will this ever be sufficient to advance our understanding of volcanic activity unless we also make parallel efforts to re-analyse eruptions of the past? In this talk I shall develop these themes, highlighting some recent work, emerging opportunities and new sources of 'data'.

## Session 1 - Processes at plate margins

### Oral Presentations

#### Magma processing in the lower oceanic crust

Lissenberg, C.J.<sup>1</sup>, MacLeod, C.J.<sup>1</sup>, Bennett, E.N.<sup>1</sup>, Loocke, M.<sup>1,2</sup>, Yang, A.Y.<sup>1,3</sup>, Lambart, S.<sup>1,4</sup>

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Mid-ocean ridges provide an excellent environment in which to study the evolution of magmatic systems. Geophysical data indicate that lower crustal magma reservoirs comprise crystal-rich and magma-rich portions, but their properties remain uncertain. Image analysis of glomerocrysts derived from crystal-rich parts of the magma plumbing system indicates that they contain a range of melt proportions, averaging ~5% [1]. Melt inclusions hosted in plagioclase antecrysts indicate that these mushy magma reservoirs may be vertically extensive, extending to >16 km depth [2].

Within the magma plumbing system, a number of processes operate which exert first-order controls on the compositions of extracted lavas. The first is reactive porous flow [3]. Experiments indicate that reactions between crystals and melts proceed rapidly, and that they operate through a dissolution-precipitation mechanism [4]. The second process is mixing. Recent data show that clinopyroxene and plagioclase contain nearly the full Nd isotopic heterogeneity observed along the northern Mid-Atlantic Ridge, including hotspots such as Iceland and the Azores, even though the associated lavas are isotopically homogeneous [5]. These data require efficient mixing, and indicate that lavas may mask mantle source signatures.

Efficient melt extraction from the lower crust is required to form mid-ocean ridge basalt, but this process is poorly understood. Data for fast-spreading lower crust suggest that extracted melts are in equilibrium with the deeper portion of the lower crust, but not with the plutonics that formed in the melt-rich body located at the base of the sheeted dykes [6]. This indicates that melt extraction from the lower crust occurs by episodic channeled flow that is rapid enough to prevent significant mixing or re-equilibration with high-level plutonic rocks. Together with the evidence for reactive flow, this suggests that melt transport in mid-ocean ridge magma reservoirs occurs both by continuous low-porosity porous flow and episodic, high-porosity focused flow.

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## **Bimodal volatile signatures in mid-to-lower crustal gabbros from the Oman Ophiolite**

Carter, E.<sup>1</sup>, O'Driscoll, B.<sup>1</sup>, Burgess, R.<sup>1</sup>, Clay, P.<sup>1</sup> and the Oman Drilling Project Phase 1 Science Party

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Formation of oceanic crust, its hydrothermal alteration and eventual subduction is of profound importance to our planet, supplying volatiles to explosive arc volcanism and contributing incompatible element-rich material to mantle heterogeneity. In order to model the subducted fluxes and volatile signatures transported to the deep mantle, it is important to understand the concentration, distribution and mineral controls on such elements through the full thickness of oceanic lithosphere.

While much may be learned from ocean drilling, recovered cores are limited to the upper 2 km of in-situ crust. A complementary approach is to consider ophiolites – sections of obducted oceanic crust and mantle. The middle and lower crust of the Oman Ophiolite was recently sampled (Winter 2016/17) by wireline diamond coring as part of the Oman Drilling Project (ICDP expedition 5057), yielding a unique sample set which is fresher and more complete than surface exposures.

A suite of 28 whole-rock gabbros and mineral separates were selected from holes GT3A (sheeted-dyke to gabbro transition) and GT1A (lower crustal gabbros). These were neutron-irradiated and their Ar-Ar ages, halogen and noble gas contents determined by laser-fusion using an ARGUS VI noble gas mass-spectrometer via neutron-produced noble gas proxy isotopes ( $^{38}\text{Ar}_{\text{Cl}}$ ,  $^{39}\text{Ar}_{\text{K}}$ ,  $^{80}\text{Kr}_{\text{Br}}$ ,  $^{128}\text{Xe}_{\text{I}}$ ).

Early results indicate pronounced variation between the two holes. The mid-crustal GT3A gabbros conform to an isochron approximately the age of the ophiolite (~96 Ma) suggesting a closed system since emplacement. In contrast, many of the lower-crustal GT1A gabbros show excesses of radiogenic  $^{40}\text{Ar}$ . Meanwhile, Br concentrations and Br/Cl ratios are systematically higher in the GT1A gabbros. Ongoing analyses aim to clarify to what extent the GT1 gabbros have been perturbed by fluid infiltration. However, if these bimodal signatures have not been disturbed, it would imply a marked break in the style of seafloor alteration from mid to lower oceanic crust.

## **Olivine reveals removal of mantle lithosphere, coincident with the onset of rhyolitic volcanism in the Taupo Volcanic Zone, NZ.**

Sally Law<sup>1</sup>, Geoffrey D. Bromiley<sup>1</sup>, Geoff N. Kilgour<sup>2</sup>, J. Godfrey Fitton<sup>1</sup>

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Understanding the driving forces behind shifts from normal andesitic arc-type eruptive style to hyper-productive silicic volcanism is one of the most fundamental aspects of geology. The central Taupo Volcanic Zone (TVZ) in New Zealand, the most productive of silicic volcanic centres, is flanked by younger andesitic stratovolcanoes to the south, which are regarded as precursory to rhyolitic volcanism, making the TVZ an ideal place to study driving forces behind the shift in eruptive style. Small basaltic scoria cones occur along the length of the TVZ, and compositions co-vary with the andesite-rhyolite shift. The most primitive of these basalts contain abundant xenocrysts, giving insight into the mantle feeding the TVZ.

Here, we find a shift in olivine xenocryst composition, from harzburgite-derived mantle xenocrysts in the south TVZ, to lherzolite-derived in the central TVZ, providing the first evidence for a shift in mantle fertility coincident with the shift from andesitic to rhyolitic activity. This implies a direct link between rifting, source composition and volcanic productivity. Diluted arc signatures in trace elements from the central TVZ, compared to enrichments in the north and south TVZ, show that subduction-derived fluids promote mantle melting, but it is ultimately the extent of rifting that controls mantle lithology, and therefore volcanic productivity. The central TVZ is testament to the effect that lithospheric thinning can have on volcanic activity, producing large-volume melts from flux melting and adiabatic decompression of fertile lherzolite mantle, driving the extraordinary productivity of the region.

# Systematics of Chalcophile Metals in Volcanic Arcs: A Global Perspective

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Arc volcanoes play an important but poorly understood role in supplying chalcophile metals (e.g. Cu, Mo, Sn) to the crust, ocean, and atmosphere [1,2]. Recent work has examined mantle wedge oxidation as an important control on an magma's ore potential, but whether this oxidation (high  $fO_2$ ) is due to slab dehydration [3] or a mineral-modulated process like garnet fractionation [4] is debated. Alternatively, other studies have indicated that  $fO_2$  might be irrelevant because of P/T effects on the sulfide stability field [3] and/or fractionation of magnetite [5]. Despite these debates, the ore potential of a given magma seems to be a function of crustal thickness, water content, sulphide saturation, and tectonics [3-6], and therefore is a function of processes spanning the full breadth of magma formation and differentiation. We integrated large datasets populated with geochemical [7] and geophysical [8-9] data with models of mantle melting [10] and fractionation to provide a framework for further investigation into parameters controlling arc metal enrichment.

Our results provide several key insights. Relative Cu enrichment in arc magmas is not correlated with the potential of that arc to contain a porphyry copper deposit (PCD) or other mineralized ores. Instead, factors like crustal thickness, fraction of melting, amphibole fractionation, and the timing of vapor vs. sulphide saturation seem to play the largest roles in metallic fertility. Our work also underscores the sensitivity of chalcophile elements to the user's choice of sulphide saturation model. Our results contribute to the growing body of work on Big Data and its role in informing igneous geochemistry. This work will serve as the basis of a comprehensive field campaign in March 2020 in Java, Indonesia. Models provided here will be tested against natural samples across and along-arc in Indonesia, which provides a natural laboratory for many of our insights.

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## Variations in the supply of fluids to the Lesser Antilles subduction zone

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Oceanic lithosphere carries volatiles, notably water, into the mantle at convergent plate boundaries. This water has long been proposed to exercise key controls upon the production of magma, earthquakes, the formation of continental crust and, potentially, mineral resources. However, determining the relationship between fluid release, fluid pathways and observed surface expressions has proved challenging. Only a few subduction zones currently subduct plates formed by slow spreading, which forms lithosphere with highly non-uniform hydration. Such subduction zones provide a unique end member for studying the deep water cycle, which motivated the recent VoiLA project, targeting the Lesser Antilles Arc. By studying boron trace element and isotopic fingerprints of melt inclusions, which are most likely to retain the signatures of the original fluids, we find that the supply of water to the central arc is likely greater than in the north or south. This region of elevated water supply (around the island of Dominica) is coincident with regions of higher rates of earthquakes, the location of historic interplate earthquakes, higher magma productivity and thicker arc crust, as well as prominent low shear velocities in the mantle below and behind the arc. Furthermore, boron isotopes reveal that the main source of the water in the central arc is serpentinite, i.e. hydrated mantle rather than crust or sediments. The source of the serpentinite derived water is most likely from two fracture zones and a boundary between two seafloor-spreading domains that have both been subducted in the central arc. These combined geochemical and geophysical data provide the clearest indication to date of a direct connection between structure and hydration of the downgoing plate and the evolution of the arc and its associated hazards.

### **The Explosive Volcanic History of Ilopango Caldera, El Salvador**

Sunyé-Puchol, I.<sup>1,2</sup>, Aguirre-Díaz, G.<sup>2</sup>, Pedrazzi, D.<sup>3</sup>, Dávila-Harris, P.<sup>4</sup>, Miggins, D.P.<sup>5</sup>, Costa, A.<sup>6</sup>, Smith, V.C.<sup>1</sup>, Ortega-Obregón, C.<sup>2</sup>, Pierre, L.<sup>2</sup>, Gutiérrez, E.<sup>7</sup> and Hernández, W.<sup>7</sup>.

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The Ilopango caldera (IC) is a large active volcano located along the El Salvador Volcanic Arc. Its magmatism is associated to the subduction of the Cocos plate under the Caribbean plate. Despite the surrounding regions being blanketed in thick and widespread pyroclastic deposits, little was known about the number of large eruptions produced by IC, their magnitude and their age. Here we present the results from field mapping, stratigraphic correlation and geochronological analyses, which provide insights into the magnitude and tempo of large explosive eruptions from IC. The results achieved during this investigation are key for future volcanic hazard assessment for the 3 million

inhabitants living in the San Salvador Metropolitan area, which is the most populated city in Central America.

Based on stratigraphic correlations, geochronologic constraints ( $^{40}\text{Ar}/^{39}\text{Ar}$  and U-Th-Pb ages) and regional tectonic deformation, the complete pyroclastic sequence of IC has been divided into three formations [1]: the Comalapa (1.78 – 1.34 Ma), Altavista (918 - 257 ka) and Tierras Blancas (<57 ka). Each eruption deposit identified was dated by techniques to reconstruct the volcanic history of IC. At least, IC has erupted explosively 13 times since its formation at 1.78 Ma ago. These high number of large eruptions from this volcano-tectonic caldera has been controlled by the El Salvador Fault Zone (ESFZ) [2]. The depth and the high slip-rate of the ESFZ structures assist magma ascent of large volumes of melt, and their eruption produces periodic caldera collapses.

The AD 6<sup>th</sup> century Tierra Blanca Joven (TBJ) was the last explosive eruption of IC, and occurred whilst Mayans populated the region. The TBJ erupted  $\sim 30 \text{ km}^3$  Dense Rock Equivalent (DRE) of magma [3], and dispersed volcanic ash over Honduras, Guatemala, Nicaragua and the Pacific Ocean. However, the TBJ was significantly smaller than the first eruptions from IC. For example, the pyroclastic density currents (PDC) of the Olocuilta ignimbrite (OI), a caldera forming event at 1.78 Ma, which covers an area of  $\sim 3000 \text{ km}^2$  with thick pyroclastic density currents (PDC) deposits. Based on the thickness of the deposits of OI (up to 120 m), it is possible that it may have been a supereruption with an erupted volume of  $\sim 350 \text{ km}^3$  DRE of magma [2].

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## Session 1 - Poster Presentations

### **Gateways through subducting slabs: a case of Pacific mantle ‘escape’ during the development and demise of the West Scotia Ridge in the South Atlantic**

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The Drake Passage between South America and Antarctica is one of the major gateways connecting the World’s major ocean basins. The opening of Drake Passage ( $\sim 32 \text{ Ma}$ ), and the subsequent creation of the West Scotia Ridge and Scotia Sea, did more than just connect seaways around Antarctica. The opening created a gap in an otherwise continuous curtain of subducted slab along the western margin of Pangaea (ie. South America and West Antarctica). Such a gap could allow shallow mantle to flow laterally, from the Pacific basin, towards the Atlantic, as predicted by Alvarez [1].

Using isotopic signatures, shallow mantle can be tracked in mid-ocean-ridge-basalt (MORB) chemistry; Pacific-, Indian- and southern Atlantic-MORB are distinct from one another in Nd-Pb-Hf isotope space. The isotopic differences point to long-lived mantle domains that do not homogenise. Using radiogenic isotopes, we find clear evidence that Pacific-MORB mantle was present beneath the West Scotia Ridge, prior to 6 Ma, when spreading stopped.

We speculate that conditions could have allowed Pacific mantle to reach as far east as the central segments of the actively spreading East Scotia Ridge. Published mantle flow studies suggest that eastward flow is currently weak beneath the Scotia Sea, but could have been stronger in the past; today, the mantle beneath the Scotia Sea is dominated by a deep (>200km) westward flow from the Atlantic, deflected to depths by the downgoing South Sandwich slab [2,3]. Other than the shallowmost mantle, the dominant westward flow pattern is likely to restrict mantle flow from the Pacific, and ultimately limit mixing and homogenisation of Pacific and Atlantic upper mantle. This suggests that even when subducted slabs do not form a physical barrier to lateral mixing of the upper mantle, they can exert an influence on mantle flow patterns to restrict homogenisation of the upper mantle.

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## **Tectonic control on episodic magmatic flare-up events revealed by AMS and U-Pb geochronology on the Antarctic Peninsula**

Burton-Johnson, A<sup>1</sup>, Riley, T.R.<sup>1</sup>, Harrison, R.J.<sup>2</sup>, Mac Niocaill, C.<sup>3</sup>, Muraszko, J.R.<sup>2</sup>, Rowley, P.D.<sup>4</sup>

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Significant improvements in the resolution and ubiquity of geochronological data can be used to demonstrate that continental arc magmatism (and consequently continental growth) is not a continuous process, but occurs in discrete flare up events. However, the cause of these magmatic flare-ups is disputed, with alternative hypotheses suggesting contributions from tectonic, mantle, and crustal processes.

New U-Pb zircon ages for the ~13,000 km<sup>2</sup> Lassiter Coast Intrusive Suite (LCIS) of West Antarctica show that it was emplaced during three discrete flare-up events: P1, 118.2±0.8-116.7±0.8 Ma; P2, 113.8±0.8-112.2±0.8 Ma; and P3, 110.0±0.8-109.3±0.7 Ma. These magmatic pulses occur during a longer period of mid-Cretaceous circum-Pacific continental arc magmatism and increased ocean-continent convergence along the West Antarctic subduction zone. Determining syn-magmatic deformation is challenging for intrusive rocks, but the magnetic mineral fabric (determined by anisotropy of magnetic susceptibility, AMS) of the LCIS records syn-magmatic tectonic strain under variable degrees of WNW-ESE oriented tectonic compression and extension. Combining the AMS and U-Pb data reveals that the pulses in LCIS

magmatism are coincident with periods of increased tectonic compression, whilst periods of reduced magmatic activity are associated with lower degrees of compression or crustal extension; despite a consistently high convergence rate for the whole suite.

We conclude that, as with seismic activity, whilst a high convergence rate is important for magmatism it is only during discrete periods of enhanced interplate coupling and consequent deformation that magmatic activity is increased and flare-ups are initiated.

## **Textural analysis of pumice deposits from Corbetti Caldera, Ethiopia**

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Corbetti is the southernmost and one of the largest calderas within the Main Ethiopian Rift (MER). It has undergone several large eruptions over the last 200 Ka and field surveys to date indicate it is likely to be one of the most active volcanoes in the MER during the recent past [1, 4]. However, like the vast majority of the 59 Holocene volcanoes in Ethiopia, very little is known about its eruptive and magmatic history. Since the caldera forming eruption at ~178 Ka [2], 3 intra-caldera edifices have developed: Artu, Urji and Chabbi. These volcanoes have erupted aphyric, geochemically homogenous, peralkaline magma, both explosively and effusively [1, 3].

Textural analysis of pumice from two explosive eruptions of Urji (Bedded Pumice and Wendo Koshe Younger Pumice [ $<2$  ka cal BP; 1, 3, 4]) have yielded insights into the dynamics of each eruption. Magma in both eruptions underwent multiple homogeneous bubble nucleation events prior to eruption, with varying degrees of bubble coalescence, driving fragmentation. Bubble number densities were calculated [5] and found to vary between  $\sim 1 \times 10^{13} - 3.5 \times 10^{14} \text{ m}^{-3}$ . From this, decompression rates between  $2 - 15 \text{ MPa s}^{-1}$  and  $\sim 11 - 23 \text{ MPa s}^{-1}$  were calculated for the Bedded Pumice and Wendo Koshe unit respectively. This demonstrates the potential for large sub-Plinian to Plinian eruptions to emanate from Corbetti and the need to conduct further research into the nature of the hazard faced by the ~260,000 people who live within 30 km of the volcano [4]. Further work will be conducted to accurately delimit the changes in eruption dynamics using both textural and geochemical techniques.

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## **Magma evolution at a mature subduction zone: Atitlán volcanic centre**

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The Atitlán volcanic complex comprises of three southward-younging overlapping calderas dated at 11, 7 and 0.084 Ma. Its age and volume make it ideal for studying the evolution of a mature volcanic system and how this may reflect the changing nature of the arc itself. The youngest caldera has two generations of stratovolcanoes on its rim, representing pre- and post-caldera-formation activity. Six stratovolcanoes are present, which in general young to the south. This shows that the southward migration of the system occurs on both long (14 Ma – present) and short (1 Ma – present) timescales.

Preliminary major and trace element results show similarities between the pre- and post-caldera stratovolcano construction phases. They have similar trace element profiles and plot in an overlapping area on a total-alkali-silica diagram, ranging from sub-alkaline basaltic andesites to rhyolites. However, some significant differences do appear in the differentiation trends of the stratovolcanoes. The older volcanoes form a liquid line of descent towards evolved compositions and potentially to the 300 km<sup>3</sup> of hornblende-rhyolite that formed the climatic caldera-forming Los Chocoyos eruption. This suggests a genetic link between the older stratovolcanoes and the magmas that were erupted to form Lake Atitlán and subsequent smaller rhyolite/dacite eruptions. This is particularly observed in the Yb and Er Harker plots, suggesting hornblende fractionation from andesitic melts. Younger phase four volcanics chemically overlap the earlier stratovolcano lavas but are more primitive, suggesting that processes that were ongoing at the older volcanoes are not proceeding to the same extent at the younger volcanoes. The older volcanoes also show lower REE abundances.

## **Fluid/rock reactions in lower oceanic crustal fault zones: Results from Oman Drilling Project Hole GT1A**

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Deciphering the signature of hydrothermal alteration and fluid circulation in the lower oceanic lithosphere is essential for unveiling mechanisms regulating crystallization and cooling of young ocean crust at fast-spreading mid-ocean ridges as well as its impact on global geochemical cycles. However, due to technical difficulties of recovering *in situ* samples of the fast-spreading lower ocean crust, fluid/rock interactions in the lowermost plutonic section remain poorly understood. Oman Drilling Project has recovered 3200 m of diamond drill core from key stratigraphic horizons within the Samail ophiolite. Hole GT1A revealed several fault zones potentially serving as conduits for channeled hydrothermal circulation. The highest density of faulting was documented at inferred original depths of 3650 to 3750 m bsf. Samples from that interval record alteration intensity varying from 10% to complete. Various textural and mineralogical patterns include prehnite-quartz-chlorite-dominated cataclasites, ubiquitous zoned epidote-group, prehnite, chlorite, anhydrite, and carbonate veins, and pervasive alteration to tremolite-epidote-prehnite-chlorite assemblages. Initial

geochemical results reveal slight depletion in  $\text{SiO}_2$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$ ,  $\text{P}_2\text{O}_5$ , and slight enrichment in  $\text{MgO}$ ,  $\text{Mn}_3\text{O}_4$ , and  $\text{Fe}_2\text{O}_3$ . These observations will be coupled with ICP-MS analysis of whole-rock samples and mineral separates from veins, as well as a strontium isotopes profile obtained by TIMS. The geochemical data aided with petrographic observations allows for correlation of the alteration features with chemical changes caused by hydrothermal alteration.

## The volcanics of a Neoproterozoic oceanic crust in North Wales

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Extending across Anglesey and Llŷn Peninsula in North Wales, the Mona Complex is a collection of Neoproterozoic-Cambrian units formed through the collision of an oceanic plate with the Avalonian microcontinent [1]. One of these units, the Gwna Complex, represents accreted ocean floor material that is largely characterised as a regional-scale tectonic mélange. Detrital zircon ages in terrigenous sediments suggest that subduction occurred around 600-540 Ma [2]. Accreted pillow basalts and associated volcanics can be used to help reconstruct the history, stratigraphy and origin of the ancient ocean floor, and also have a major influence on the structural controls of the accretionary complex.

In Newborough, Anglesey, the Gwna Complex is dominated by pillow basalts and associated hyaloclastites, peperites and massive basalts, whereas sea floor sediments tend to dominate the mélange elsewhere. The accretion of thick volcanic units that are overlain by carbonate rocks, and little preservation of terrigenous sediment, are all generally characteristic of the formation of an ocean island, however a geochemical study of the volcanics reveals a consistent mid-ocean ridge (MORB) signature for their origin. The basalts show a small yet systematic enrichment in immobile elements, suggesting a slightly more evolved magmatic source than expected for basalts of a typical mid-ocean ridge.

A small number of accreted dolerite sills have intruded sea floor sediments, providing evidence of a secondary magmatic event far away from the mid-ocean ridge. The sills have a geochemical signature more akin to an ocean island (OIB). Highly amygdaloidal hyaloclastites nearby may represent an external component to the magmatism responsible for these sills.

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## **Characterising hydrothermal alteration in the dike/gabbro transition zone: OmanDP Hole GT3A**

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The accretion of the lower crust at mid ocean ridge has two long standing end member models, the gabbro glacier and multiple sills models. These models differ primarily in the location and distribution of crystallisation of the lower crust and therefore heat release. Resolving the depth and magnitude of deep hydrothermal circulation would be a major step forward in understanding the formation of the ocean crust. Testing these models is one of the key objectives of the Oman Drilling Project. OmanDP has successfully cored three boreholes, each to 400 m depth, in the Samail ophiolite that sample key horizons in the lower crust and includes Hole GT3A that samples the dike/gabbro transition zone.

The dike/gabbro transition zone is a critical boundary within the ocean crust, representing the interface between the upper and lower crust and importantly separates the upper crustal hydrothermal system from the magmatically accreting lower crust. Hydrothermal alteration in Hole GT3A is extensive and is dominated by greenschist facies alteration assemblages. A combination of petrology and whole rock and hydrothermal mineral geochemistry are used to characterise and quantify the hydrothermal alteration recorded in Hole GT3A. Samples dominated by epidote and/or chlorite rich assemblages consistently show depletions in base metals relative to fresh samples indicating that the dike/gabbro transition zone is a source of base metals to the hydrothermal system. Major element chemical changes (e.g SiO<sub>2</sub>, CaO, MgO) can also be correlated with the alteration assemblage and extent of alteration.

## **Building an Accurate and Precise Chronological Framework for the British Palaeogene Igneous Province**

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Radioisotopic geochronology provides a means to interpret the temporal coincidences of Large Igneous Provinces (LIPs) with catastrophic global events, such as the K-Pg mass extinction and the Palaeocene-Eocene Thermal Maximum. However, in addition to establishing cause-and-effect relationships, which require precise and accurate ages for discrete events in time, advances in geochronology are now allowing for the dissection of LIPs on sub-100 ka timescales.

Here we demonstrate the temporal resolution that can be obtained using the <sup>40</sup>Ar/<sup>39</sup>Ar and ID-TIMS <sup>206</sup>Pb/<sup>238</sup>U zircon dating techniques available at the Scottish Universities Environmental Research Centre to construct a multi-chronometer framework for one of the

most intensely studied regions in the world, the British Palaeogene Igneous Province (BPIP). Despite numerous dating campaigns, the current geochronology for the BPIP is poor.

We leverage the ability to measure both  $^{40}\text{Ar}/^{39}\text{Ar}$  and  $^{206}\text{Pb}/^{238}\text{U}$  ages to a total precision of ca. 50 ka (tuffs and silicic-intrusive rocks), and also demonstrate the ability to produce reproducible ages from basaltic groundmass and plagioclase separates at similar levels of precision. The data challenges the regional paradigm of slow eruption of lavas and fast emplacement of central complexes [1]. The data shows that aurally extensive lava units as thick as 2200 m were erupted over relatively short periods of time (e.g., <800 ka) and central complexes were emplaced much slower, occupying as much as 3 Ma.

The temporal resolution achieved (1) reveals considerable hiatuses in activity for the region, (2) demonstrates the response of surrounding topography to the evolving magmatic system, and (3) has significance for the geodynamic setting of the margin. This contribution presents a revised time scale for the BPIP and highlights the potential of using a combination of  $^{40}\text{Ar}/^{39}\text{Ar}$  and  $^{206}\text{Pb}/^{238}\text{U}$  geochronology to dissect other LIPs.

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## Session 2 - Magma storage and transport

### Explosive or Effusive? Investigating the controls of volcano eruptive style'

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One of the biggest challenges in volcanic hazard assessment is to understand how and why eruptive style changes within the same eruptive period or even from one eruption to the next at a given volcano. Here I evaluate the competing processes that lead to explosive and effusive eruptions of silicic magmas. Eruptive style depends on a set of feedback involving interrelated magmatic properties and processes. Foremost of these are magma viscosity, gas loss and external properties such as conduit geometry. Ultimately, these parameters control the speed at which magmas ascend, decompress and outgas en route to the surface, and thus determine eruptive style and evolution. By compiling literature data, I show that explosive eruptions generally ascend faster and have shorter unrest periods prior to eruption, compared to effusive eruptions. I also look at specific volcano examples that illustrate the dichotomy of eruptive styles, including Kelud and Krakatau (Indonesia), and Quizapu (Chile) to show how these volcanoes may be used to understand factors that have not been explored in detail for instance, exsolved volatiles, oxidation state and overpressure.

### Crystal mush vs. magma chambers, the view from seismic tomography

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Conceptual models of magma storage and differentiation are converging towards a consensus that high-melt-fraction eruptible magma is stored in layers formed by segregation from large crystal mush zones: the Mush model [1]. According to the Mush model, most melt resides and evolves for long periods of time in crystal mush zones [2] and is rapidly extracted before eruption. The Mush model is increasingly popular, because it can explain the predominance of fractional crystallisation, the compositional bimodality in the volcanic record and the formation of layered plutons.

The lack of geophysical evidence for high-melt fraction bodies at active volcanoes is often put forward as an argument in support of the Mush model. I review the seismological evidence for and against the Mush model and conclude that most seismic tomography at arc volcanoes do not preclude the existence of large (tens of cubic kilometres in volume) melt-rich layers, which can go undetected because of limited resolution and wavefront healing [3]. Geophysics has provided strong evidence for partial melt [4-9] but has not yet provided accurate evidence for low-melt-fraction vs. high-melt-fraction storage. The main limitations are finite resolution of the imaging methods and large uncertainties in the sensitivity of physical properties to

melt. New imaging methods, particularly full waveform methods [10-12], and improvements in the quality of datasets can improve resolution, but the uncertainties in physical property relations remain a stumbling block. These uncertainties are usually ignored, but they are typically larger than a factor of 4 [7,9].

Constraining the size and distribution of melt-rich layers and their relations to crystal mush zones is one of the most important outstanding challenges in volcanology and requires bridging the gap between conceptual models of magma reservoirs and the geophysical imaging of such systems through integration of geophysics, rock physics, petrology and modelling.

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## The magmatic and eruptive evolution of the 1883 explosive, caldera-forming eruption of Krakatau

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Explosive, caldera-forming eruptions are exceptional and hazardous volcanic phenomena. Such eruptions have not occurred in recent times, and thus there has not been the opportunity to monitor the build-up to one of these events. Geochemical and petrological studies are therefore key to understanding caldera systems. The 1883 eruption of Krakatau is the only major, caldera-forming eruption for which there are detailed written accounts, allowing information on the eruptive progression to be integrated with the stratigraphy and geochemistry.

Fieldwork, conducted in August 2019, focussed on 1883 eruptive sequences freshly-exposed by the December 2018 tsunami. The stratigraphy has been established, with the identification of probable deposits from the May 1883 precursory eruptions at the base of the sequence.

Overlying this, there are two eruptive units associated with the cataclysmic phase of the eruption in August, separated by a lithic lag breccia. Lateral variations in the thicknesses of the two units support the hypothesis that the caldera collapsed in stages.

There are no systematic stratigraphic variations in whole-rock chemistry, suggesting the 1883 magma reservoir was not chemically zoned. However, the matrix glass chemistry of the May phase is distinct from, and more evolved than, the August tephra. The range in composition of August matrix glass shows small variations between samples. Chemical zoning in plagioclase varies greatly, from An<sub>32</sub> to An<sub>92</sub>. Approximately 15 % of crystals have cores of >An<sub>70</sub>, providing evidence for the existence of a more mafic reservoir feeding the shallow magmatic system.

The proposed model for the shallow system consists of a more evolved magma reservoir, excavated in May 1883. The associated unloading may have triggered the ascent of the magma erupted in August, likely from multiple reservoirs which coalesced and mixed. Decoupling and subsequent amalgamation of magma bodies may therefore play an important role in the progression of caldera cycles.

## **A revised magma system model for Sakurajima volcano, Japan**

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Sakurajima, the most active volcano in Japan, threatens the population of four large cities (800,000) and the Sendai nuclear power plant. The volcanic centre formed 26 ka ago in the southern part of Aira caldera and has a long and varied record of eruptions. The most recent (1914) Plinian eruption, the largest event of the 20th century in Japan, was complex, consisting of several eruptive stages lasting over 1.5 years. Increasing Vulcanian activity since 1955 may indicate a gradual transformation in magmatic processes. Recent ground deformation modelling indicates that the surface around the volcano has inflated to a similar level to that prior to the 1914 eruption.

The aim of this study is to determine whether geophysical observations can be linked to changes in magma geochemical composition for the different styles and volumes of eruption, within the framework of a trans-crustal magmatic system. Fifty five samples have been analysed, representative of Plinian, effusive and Vulcanian eruptions from the last 10 ka of Sakurajima activity. Seven rhyolitic samples from the Aira caldera-forming eruption (29 ka) have also been analysed to assess their geochemical relations to Sakurajima deposits. Interpretation of major and trace element and Pb isotopic data have allowed us to revise the magmatic system model for Sakurajima volcano to one where mantle-derived mafic magmas assimilated pyroxene-bearing crust. Subsequent evolution of the magma generated felsic mush zones at different crustal depths below Aira caldera. Reactive melt flow generated pockets of low-crystallinity, chemically differentiated magma, recorded as overgrowths on phenocrysts, which could ascent and trigger volcanic eruptions. Ongoing research is testing

this model by: (1) estimating the depths and temperatures of the magma sources for individual samples using geothermobarometry, (2) assessing magma residence times and ascent rates through diffusion studies on pyroxene, and (3) characterising melt inclusions and glass trapped in glomerocrysts.

## **Magma flow dynamics within growing and erupting dykes**

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Dykes are the dominant magma-transport structure in the crust which feed volcanic eruptions, and their dynamics of growth and potential eruption have significant influence on the entire volcanic plumbing system and volcanic hazards. Traditional approaches to the study of dykes only consider the deformation of the host-rock, and the role of magma rheology is critically underappreciated. For the first time, we have used scaled gelatine experiments injected by scaled magma analogues of different rheology to characterise the dynamics of magma flow during dyke growth and eruption. Magma rheology in nature is affected by factors including composition, pressure, temperature and strain rate. It is these key variables which control the relative proportions of melt, crystals and bubbles, and ultimately whether or not the magma behaves as a Newtonian (strain-rate independent) or non-Newtonian (strain-rate dependent) fluid. To investigate the influence of magma rheology on dyke propagation in the laboratory, an elastic gelatine solid (the crust analogue) was injected with water or a shear-thinning polymer (the magma analogue) to form an experimental dyke. The fluid was seeded with neutrally buoyant particles that fluoresced in a thin, vertical laser sheet. Particle image velocimetry (PIV) was used to measure the fluid velocity within the growing dyke and to produce a time-resolved map of flow. Different flow regimes were identified depending on the analogue magma rheology, with jet formation and focused flow inhibited by shear-thinning behaviour and high magma viscosities. The internal flow velocity relative to the dyke tip propagation velocity was also highly dependent on the fluid rheology. Our experiments demonstrate the importance of considering magma rheology in dyke propagation models, and that dyke flow dynamics could have significant impact on the interpretation of geophysical, geodetic and petrological signals of magma transport in a dyke.

## **Lateral offset of volcanic eruptions from melt sources: Field evidence from SE Iceland**

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Traditional representations of sub-volcanic magmatic plumbing systems typically assume a vertically dominated succession of interconnected intrusions where the eruption site directly overlies the melt source. However, a growing body of evidence indicates that extensive lateral magma transport can also occur through interconnected sills and inclined sheets that laterally offset eruptions from the melt source. Whilst, structures and flow patterns of lateral magma movement have previously been interpreted in sub-volcanic systems, geometrical and kinematic relationships with successive eruptive sites remains poorly understood which, is critical to volcanic hazard assessment.

Here, through anisotropy of magnetic susceptibility (AMS) measurements coupled with host rock structural data from the excellently exposed, sub-volcanic, silicic Reyðarártindur intrusion in SE Iceland, we demonstrate how the underlying mechanisms of lateral magma flow influenced the localisation of volcanic activity. AMS fabrics have constrained a lateral magma flow pattern predominantly oriented NE-SW throughout the intrusion. The distribution of prolate and oblate shaped AMS ellipsoids characterise the internal architecture of the intrusion as a series of incrementally emplaced coalesced magma lobes. Host rock deformation is broadly defined by a gently domed intrusion-induced forced fold geometry, reorienting the originally gently inclined lava piles to dip perpendicularly away from the contact. Both AMS fabric data and host rock structures also highlight the interference between competing local and regional stress fields in controlling the intrusion geometry.

Tensile stress along the forced folding guides upward propagation of the laterally flowing magma through inclined sheets. Imbricated AMS fabrics within these sheets suggest sub-vertical magma propagation which are locally traced to eruptive vent sites associated with an adjacent, extinct central volcano. These observations provide field evidence suggesting eruptive sites overlie lateral tips of subjacent intrusions supporting seismic observations that ground deformation preceding eruptions can be most prominent in areas adjacent to volcanism.

### **Three-Dimensional Outcrop Architecture of Flood Basalt Stratigraphy**

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A fundamental aspect of Earth Science is the realisation of rock strata in three dimensions (3D). Recent developments in photogrammetry have enabled the acquisition, processing and analysis of accurate, large scale 3D virtual outcrop models. Within this contribution we present results from virtual outcrop interpretation of lava flow stratigraphy from the Isle of Mull, Scotland, and the southern Etendeka, NW Namibia.

Large coastal cliff exposures (20 - >100 m high) of the Paleocene Mull Lava Group provide detailed insight into the structure of a heterogeneous extrusive sequence of the North Atlantic Igneous Province. Mull presents a wide range in volcanic and intra-volcanic deposits, lava flows exposed vary from <1 – 55 m thick, and intra-lava facies include epiclastic (conglomerates, sandstones and paleosols), autoclastic and minor pyroclastic deposits. Both syn- and post-magmatic faults are observed, adding to the complexity of the sequence. The Cretaceous Southern Etendeka of the Huab Basin represents a far larger, less heterogeneous lava sequence compared to the Mull Lava Group. Within the Namibian model's vast inland exposures (~600 m high) display basaltic small-scale and compositionally evolved large-scale flood basalts, and sub- and intra-basalt aeolian sediments (Fig. 1).

Analysis of large-scale virtual outcrop, collectively extending over 10s of kms, from both the Huab Basin and Mull Lava Group has supplemented detailed fieldwork and geochemical data to provide refined high-resolution models for both case studies. The models display the lithologies a georeferenced and scaled format, facilitating the generation of numerical data to quantify the range of lava geometries (horizontally and vertically). By comparing these contrasting case studies, it is possible to better constrain the variations in flood basalt architecture across several lava compositions, depositional environments and geological timescales.

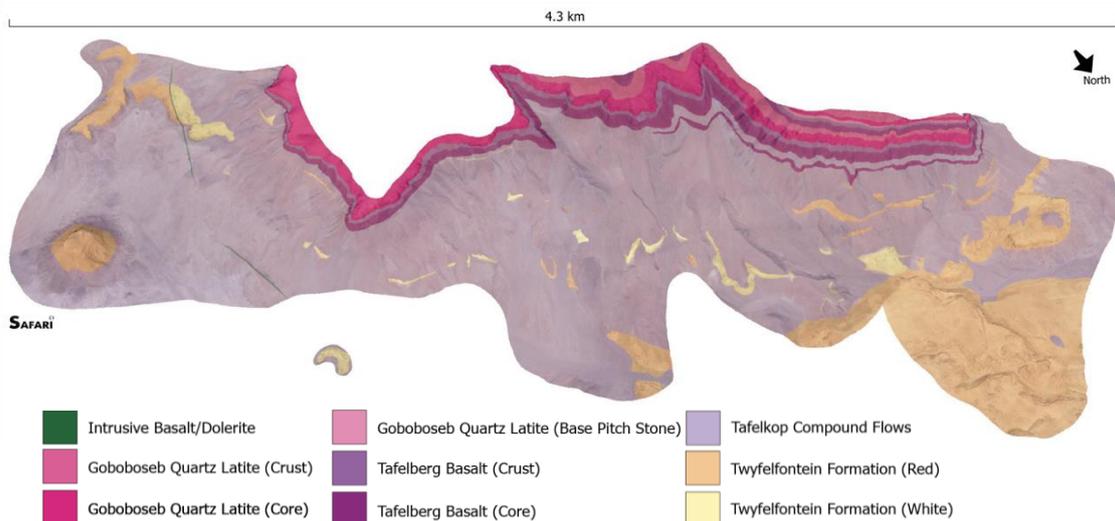


Figure 1. Example of virtual outcrop from Dune Valley, Huab Basin, Namibia, displayed in Lidar Interpretation and Manipulation Environments (LIME) software.

## **Crustal Influences on Neogene Arc Magmatism in Colombia and Panama**

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The Western margin of Colombia and eastern Panama are composed of a complex collage of oceanic terranes accreted since the mid-Cretaceous. These are a mixture of intra-oceanic arc and oceanic plateau rocks as in eastern Panama<sup>[1]</sup>, with related metamorphic and sedimentary components, which now form much of the basement of western Colombia<sup>[2]</sup>.

Today, these host some of the world's most dangerous volcanoes.

Recent advances in our understanding of arc magmatism highlight the role of fractionation and assimilation processes in the lower crust of arcs. We present new major and trace element and Sr-Nd-Hf isotopic data for Neogene magmatism across eastern Panama and western Colombia from the Miocene to the inception of the modern volcanic arc in Colombia. This is used to assess the role of accreted oceanic terranes in the formation of arc magmas across the region, compared to slab and mantle wedge components.

This is pertinent due to the presence and debated petrogenesis of "adakite-like" volcanic products and high-Mg# andesites in the region<sup>[3,4]</sup>, which are examined as part of this study.

These are compared to a large dataset of volcanic and hypabyssal rocks of comparable age from the region, and analyses of regional basement which is used to model fractionation trends and assess the role of crustal contamination and assimilation of oceanic basement.

This demonstrates a greater potential relationship between assimilation of lower and upper crustal material in the petrogenesis of arc magmas in the region than previously assumed, allowing us to test as yet unreconciled local models of andesite and adakite petrogenesis on a regional scale.

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## **Modelling the ascent and eruption of picritic lunar magmas**

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Quantifying the volatile content of the lunar interior is valuable for understanding the formation, thermal evolution, and magmatic evolution of the Earth and Moon [1]. Petrological modelling and geochemical measurements have been used to study the volatile composition of the lunar interior [2, 3]. Improvements to analytical instruments have facilitated more precise measurements of the volatile content of lunar samples and meteorites [4]. However,

several problems remain with these measurements, hence, the volatile content of lunar magmas has yet to be constrained with certainty. We propose a volcanological approach to infer volatile contents of different lunar magmas, and plan to ground truth our model using remote sensing datasets.

A terrestrial magma ascent model has been modified for lunar applications [5]. Numerous parameters were adjusted for lunar conditions, including: gravity, pressure, oxygen fugacity, H<sub>2</sub>O solubility, and CO solubility. The main parameters varied were: magma major element composition, from low-Ti (green and yellow glasses) to high-Ti (orange, red, and black glasses) [6, 7]; H<sub>2</sub>O content, from 4 to 745 ppm [4]; and CO content, from 50 to 500 ppm [8]. The model produced depth profiles for gas exsolution, viscosity, mass flow rate, and several other ascent conditions for 2 km and 10 km magma ascent profiles – Figure 1. Magma major element composition had the greatest effect on the viscosity of the ascending magma. Meanwhile, volatile content had the greatest effect on the depth at which volatile exsolution initiated, as well as magma velocity and gas/melt relative velocity. Finally, conduit radius was the key control on mass flow rate. Results will be used in a ballistic eruption model, which will be used to estimate the extent and thickness of pyroclastic deposits. Subsequently, these results will be compared with digital elevation models of the lunar surface, created using Lunar Reconnaissance Orbiter images.

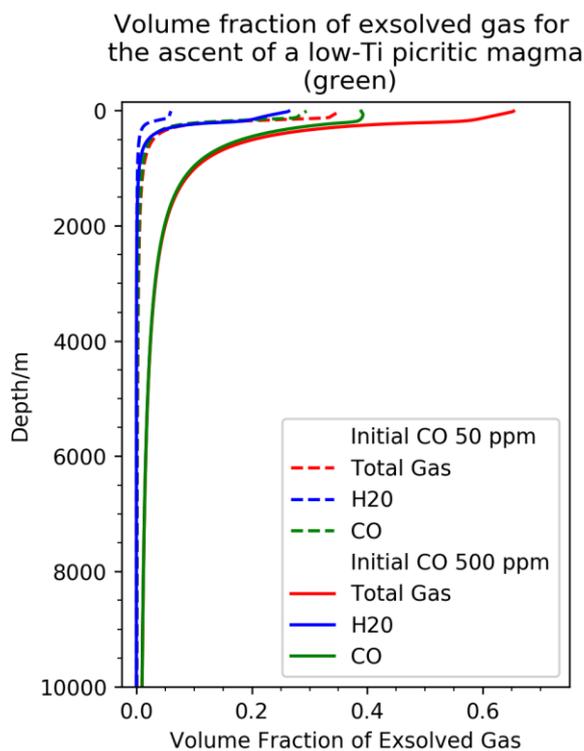


Figure 1: volume fraction of exsolved gas during ascent of a low-Ti, green picritic magma, with various initial volatile contents, assuming a conduit of 20 m diameter.

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## Session 2 - Posters

### **Monogenetic Volcanism and Magma Mixing at Slamet Volcano and Mount Loyang, Indonesia**

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Gunung Slamet is a polygenetic stratovolcano in Central Java with approximately 30 scoria cones on its flanks, the most distal of which is Mount Loyang to the East. Slamet is one of Java's most active volcanoes, having erupted last in September 2014. Slamet is surrounded by many population centres, the largest of which is Purwokerto, a city with 234,000 residents. A better understanding of the processes occurring at Slamet and other volcanoes across Java is imperative if we are to help mitigate this sizeable volcanic hazard. A small number of studies have investigated the processes occurring at the main Slamet edifice [1,2], and others have summarised the stratigraphy of the volcanic deposits at Loyang [3]. Examination of the distal components of the volcanic plumbing system, as represented by Loyang, has the potential to reveal the nature of the plumbing system at Slamet, and what role mixing of different magma populations may play in controlling this system.

Here we present an integrated petrological study, applying geochemical tools to samples from both the monogenetic and polygenetic cones in this complex. We have analysed mineral separates, with a focus on olivine, using an Electron Microprobe (EMPA) and Scanning Electron Microscopy (SEM). These data are combined with petrographic and QEMSCAN analysis of thin sections, as well as whole rock measurements using XRF. These results are tested against MELTS models [4,5] of magma fractionation to determine the likely depths of storage and principal controls on melt evolution at Slamet. Preliminary results indicate that Loyang erupts a less evolved magma than the main Slamet edifice and our fractional crystallisation models suggest Loyang is tapping a less evolved, deeper portion of the plumbing system. We find that there is significant geochemical variation in the erupted products from Loyang throughout its stratigraphy, suggesting a high degree of mixing and disequilibrium.

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### **Mapping crystal deformation in volcanic systems: An indicator of magma storage conditions**

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Crystal-plastic deformation occurs in magmatic settings as diverse as silicic lava domes [1] and basaltic cumulates and has been used as a strain marker in shallow parts of the volcanic system [2]. It has the potential to reveal information about magma storage conditions, including overpressure, at reservoir levels. Overpressure is a poorly-understood parameter which may influence magma ascent rate and therefore eruption style. This work uses high-angular resolution electron backscatter diffraction (HR-EBSD) to investigate whether crystal deformation can be used as an overpressure marker in a range of magmatic systems.

Crystal-plastic deformation within both natural and experimentally deformed samples is analysed using HR-EBSD, which measures angular distortions within a crystal lattice. We use volcanic rocks from a range of eruptions to quantify crystal deformation at the upper magma reservoir level. In addition, natural samples are experimentally deformed within cold-seal pressure vessels at a range of pressure-temperature conditions. These experimental samples are also analysed using HR-EBSD to determine whether there are systematic variations in crystal deformation as experimental pressure is increased. By doing this, it may be possible to calibrate the degree of crystal-plastic deformation to a set of pressure-temperature conditions, and use it as an overpressure marker in natural samples.

Preliminary HR-EBSD misorientation maps show that lattice distortions are concentrated around inclusions and along crystal edges. Overpressured experimental samples show greater distortion when compared to natural samples for some phases, whilst others show the reverse. Further analyses of crystals from a range of natural and experimental samples are required to map out the conditions under which crystal deformation occurs and to calibrate crystal deformation to magmatic overpressure. Analysis of crystal deformation may additionally provide insights in to eruption triggers and variations in magma compressibility.

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## **Unradiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ plagioclase crystals in cumulate xenoliths from Martinique and St. Vincent, Lesser Antilles.**

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Arc lavas from the central and southern Lesser Antilles (LA) show diverse radiogenic isotopic compositions and considerable variation at individual volcanic centres [1]. Debate centers on whether this variation represents addition of subducted sediment to the mantle source, or assimilation of arc crust by magma *en route* to the surface.

$^{87}\text{Sr}/^{86}\text{Sr}$  ratios of individual plagioclase crystals from cumulate xenoliths, entrained in erupting lavas, record the melt isotopic compositions during crystallization in crustal reservoirs so should track potential contamination of host magma. It may also be possible to determine  $^{87}\text{Sr}/^{86}\text{Sr}$  records of magmas at different crustal levels since thermobarometric and petrological data suggest cumulate formation over a range of depths ( $\leq 15$  km, pressures of  $\leq 4$  GPa) [2]. Cores of zoned plagioclase or deep formed cumulates enriched in radiogenic strontium would support a significant sedimentary input to mantle sources. However, increasing  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios from core to rim, and/or in progressively shallower cumulates, would indicate the presence of crustal contamination.

We have analysed unzoned plagioclase crystals from cumulate xenoliths found on Martinique and St Vincent. Martinique whole-rock (WR)  $^{87}\text{Sr}/^{86}\text{Sr}$  data from erupted lavas span the whole LA arc range, however, the isotopic composition of cumulate plagioclase is unradiogenic and restricted. Cumulate plagioclase compositions from St Vincent overlap with the unradiogenic Martinique cumulates, despite the differences in the isotopic compositions of the erupted lavas at both islands. Therefore, we provide strong evidence that the radiogenic Sr isotopic signature recorded in Martinique lavas is due to shallow level crustal assimilation rather than imparted by sediment recycling into the mantle source.

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## **The Origin of Fluidal Obsidian Pyroclasts from a Basaltic Fissure Eruption, Ascension Island, South Atlantic**

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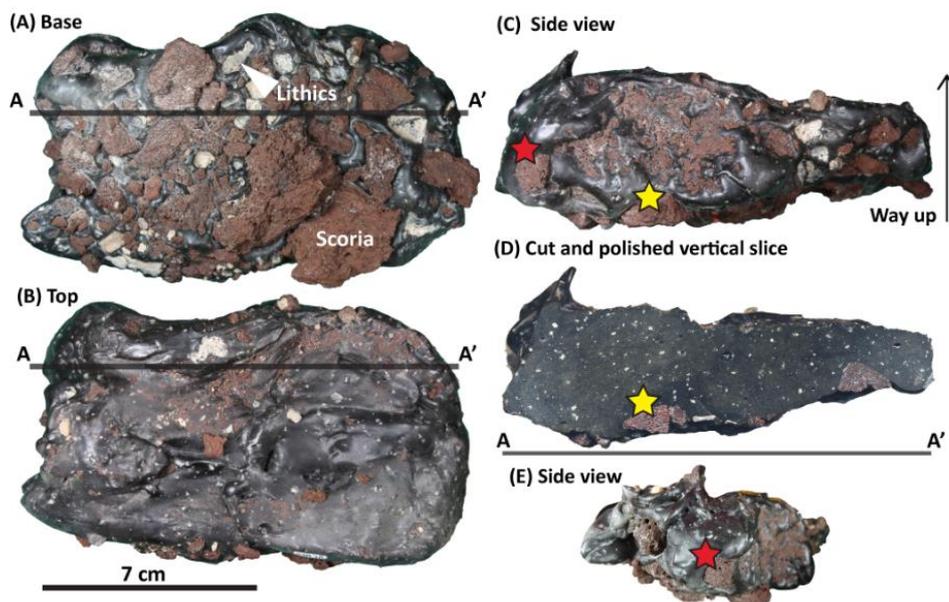
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Unusual, dense obsidian pyroclasts were co-erupted with scoria from a small-volume monogenetic fissure eruption on Ascension Island, South Atlantic. The obsidian pyroclasts vary from spherical/sub-spherical glass beads ( $< 1-5$  mm in diameter), resembling Pele's tears and spheres, to larger spatter-like bombs,  $> 40$  cm in diameter, found within scoria ramparts either side of the fissure. They account for  $\ll 0.005$  vol.% of the total ejected material. Fluidal morphologies imply that the clasts had unusually low melt viscosities on eruption and were therefore capable of flowing upon impact. Field relationships indicate the separate magmas did not mix during ascent but agglutinated on deposition to form an agglomerate composed of obsidian, scoria and lithic clasts.

In-situ geochemical analyses reveals two distinct magmas: the obsidian is rhyolitic (74 wt.%  $\text{SiO}_2$ ), while the scoria is intermediate, basaltic trachy-andesite to trachy-andesite (51-61 wt.%  $\text{SiO}_2$ ). Magmatic compositions are distinctly bimodal, with clear separation between obsidian and scoria components exemplified in macrocryst species present; the obsidian contains

anorthoclase while the scoria contains a continuum between andesine to labradorite. This implies that magma mixing did not occur within the crust or conduit. This is comparable to the wider Ascension Island magmatic suite where there is no evidence for magma mixing. Therefore, the storage of the two magmas and fragmentation remains ambiguous.

Here we present, field and textural observations and geochemical analyses to constrain the origins of the obsidian in this unusual eruption. Whilst a shallow pocket of degassed rhyolitic magma may have been intersected by ascending mafic magma in a dike, this is not in agreement with the low volume of obsidian clasts and absence of mixing textures. Instead (preferred hypothesis) their origin may be a result of assimilation of water-/gas-poor felsic country rock. Reheating to basaltic temperatures exceeded the glass-transition temperature, promoting remobilisation, thus invoking highly fluidal textures.



## Geochemical and temporal evolution of the St Kitts magmatic system, Lesser Antilles

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Detailed petrological and geochemical study of plutonic and cumulate xenoliths can provide insights into the inner workings of transcrustal magmatic systems [1,2]. This crustal architecture in turn influences the eruptive style, chemical diversity, thermal evolution and erupted volume at the associated volcanic system. Here we focus on the volcanic island of St. Kitts in the Lesser Antilles, an island with well exposed volcanic deposits and abundant erupted xenoliths.

Whole rock major and trace element analysis of volcanic and pyroclastic rocks show a well developed liquid line of descent. We use major element modelling to calculate the cumulate assemblages needed to generate this trend and compare them to natural samples. In-situ mineral trace element data for the cumulate and plutonic xenoliths are used to constrain the differentiation process as well as mineral reactions, particularly between clinopyroxene and amphibole. Thermodynamic modelling provides estimates of the equilibrium P-T (Pressure-Temperature) conditions for the xenoliths.

Collectively, these techniques allow us to develop a clearer picture of the magmatic system below St. Kitts.

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## **Stratigraphy of a mushy magma reservoir: insights from the 289 ka Fasnía eruption, Tenerife**

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Understanding the composition of, and relationships between, melt and crystals through the vertical extent of a magma reservoir is important in developing models of pre-eruptive magma assembly prior to large, explosive eruptions. A unique opportunity to examine such a system is present in the form of cumulate nodules ejected during a single event: the 289 ka Fasnía eruption on Tenerife. We have examined over 100 cumulate nodules from this event that span the complete crystallisation pathway of this alkaline magma system, ranging from ultramafic wehrlite and clinopyroxenite to felsic monzonites and syenites. Petrological and chemical analysis shows that these cumulates originate from a reservoir stratigraphy with three distinct domains: a deep ultra-mafic zone, a layered mafic sequence and a felsic zone in the upper crust.

Barometric estimates of the mafic and ultramafic cumulates, together with associated fragments of mantle peridotite, imply this part of the reservoir is at least partially located in the lithospheric mantle at 16-26 km depth. Magmas and cumulus phases from this deeper system indicate they mixed with a felsic magma characterised by a lower Mg# just prior to eruption [1]. This is likely to represent a catastrophic disaggregation of the deeper levels of the crystal-melt system followed by transport and mixing with the shallow (i.e. 6-8 km) felsic system.

Our cumulate nodules preserve between 1 and 60% melt in both the interstitial porosity and micro/macroscale interconnected pathways, which was quenched on eruption. Analysis of separated quenched melts reveal diverse chemical and isotopic compositions preserving a pre-eruption disequilibrium in the mush. This 'snapshot' is taken to record the amalgamation of melts from different crustal levels, with the disequilibrium reflecting the

brevity of mixing prior to the 13 km<sup>3</sup> DRE Fasnia event. This may represent the rapid pre-eruptive assembly of magma, thought to be a requirement for large-volume eruptions [2].

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## **Granite pluton emplacement mechanisms in a post-orogenic extensional tectonic regime – the Land’s End Granite, Cornwall**

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The timing and kinematics of regional deformation play a key role in granite pluton construction, and controlling the distribution of evolved melts as precursors to magmatic-hydrothermal mineralisation. The Permian Land’s End Granite pluton in the Cornubian Batholith, SW England is an excellent area to assess the role of regional tectonics on pluton construction and magmatic-hydrothermal evolution. The timing and association of regional tectonics with the batholith are well established, but the link between regional deformation and the construction and evolution of individual plutons is poorly constrained.

A comprehensive investigation of the roof zone of the Land’s End Granite and associated aureole has been completed. Field-based data collection was complemented by geometric and kinematic analysis of structures from the granite and host rock, analysis of LiDAR data, and mineralogical and geochronological studies.

Correlation with the orientation of host rock structures and granite sheets demonstrates emplacement utilised pre-existing, and active tectonic- ± magmatic-induced fracture networks. Magma ascent was primarily controlled by ENE-WSW-striking late-D3 faults. This was further enhanced by strike-slip movement along NW-SE-striking faults. Lateral magma migration occurred along crustal magma traps controlled by a major pre-existing sub-horizontal fault zone, and possibly lithological variations in the host rock. The pluton was accommodated in the crust by roof uplift and rotation of the host rock. This was promoted by the network of large-scale NW-SE and ENE-WSW-striking faults resulting in localised magma driving pressure > vertical stress.

This study provides a clear case for the incremental emplacement of a laccolith-type pluton in a post-orogenic extensional tectonic regime. The Land’s End Granite formed as a result of the amalgamation of three smaller plutons, constructed of discrete intrusive episodes over a complex c. 3 Ma magmatic history. The spatial and temporal distribution of late-stage granites have a strong correlation with areas of Sn-Cu mineralisation.

## Younger Giant Dykes in SW Greenland: Testing the Convection Hypothesis

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Igneous layering provides insight to processes inherent to the petrogenesis of igneous intrusions and their associated economic deposits. However, the origin of these important structures is debated as contrasting mineralogical, chemical and textural data are cited to invoke different dynamic and non-dynamic processes leading to their formation [1]. This study presents new field evidence and Anisotropy of Magnetic Susceptibility (AMS) analyses on the Younger Giant Dyke Complex (YGDC) in SW Greenland, as it presents an ideal opportunity to study the origin of layering in igneous intrusions and to test the rigour of the convection hypothesis in subvertical sheets [2].

The YGDC is a series of giant gabbroic dykes (up to 800 m wide) that can be traced for ~140 km. Many varieties of layering occur in isolated basins along the YGDC which systematically dip towards the centre of the intrusion defining concentric, oval shaped geometries. These layered basins have previously been interpreted as sites where convection cells developed [3].

Field observations identify two generations of mafic enclaves within the basins: the earliest aligning parallel to layering, and the latter mingling with no alignment to layering. This suggests a dynamic process is developing the layers, which ceased prior to complete crystallisation of the basin. New AMS analyses reveal that the long axis of the AMS ellipsoid plunge inwards towards a horizontal core of the basin whilst data from sections stratigraphically above basins show a more chaotic rock fabric pattern.

We evaluate two hypotheses; 1) that mineral layers and lineations reflect influx material from the dyke margins towards the centre during successive, turbidite-like flow events and 2) the laminated basin geometry records the process of a dyke-wide turbulent flow settling crystals out of suspension through a decrease in lateral velocities at the base of the flows.

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## **Petrogenesis and emplacement of the Ratagain Granite Complex, Western Scotland**

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Granites are the primary component of the upper continental crust. Determining how granitic magmas are generated and how they are structurally emplaced is key to understanding how the Earth's continental crust has grown throughout geological time.

Late Caledonian (c.447–383 Ma) granites in Scotland present an ideal opportunity to study the growth of continental crust by the emplacement of granitic bodies. Recent studies suggest that the granitoids show evidence of being generated through a combination of melting a compositionally heterogeneous mantle followed by crustal assimilation of local Lewisian and Moine rocks and fractional crystallisation (AFC) processes [1]. However, as yet, none of the numerous tectonomagmatic models proposed can fully explain how this diverse and enigmatic set of granitoids was generated and emplaced [2]. However, the recent development of trace-element and radiogenic isotope traverses across individual mineral grains to investigate granitic petrogenesis, enables us to further investigate the formation of the Scottish granites.

Here we undertake a combined geochemical and structural investigation of the Ratagain Complex, a c.17 km<sup>2</sup> pluton which outcrops along the shores of Loch Duich, western Highlands of Scotland. We review the current understanding of how the Late Caledonian granites were generated, geochemically enriched and emplaced following the subduction of the Iapetus oceanic crust beneath Laurentia between 447–383 Ma [3].

We subsequently present field relations from several of our field excursions, preliminary whole rock geochemical data and AMS structural analysis.

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## **Quantifying Magmatic Storage and Processing under Iceland and Hawai'i**

Maclennan, J.<sup>1</sup>, Wieser, P.E.<sup>1</sup>, Edmonds, M.<sup>1</sup>, Jenner, F.E.<sup>2</sup> and Kunz, B.E.<sup>2</sup>

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Interest in models of crustal magmatic architecture has seen a recent rejuvenation. Geological, petrological and geophysical observations have been used to test, develop and refine such models. While there is a broad consensus for a significant depth range of magma storage and evolution under volcanoes, and also agreement on the presence of mush in these systems, many crucial physical aspects of the physical behaviour of magmatic systems remain contentious. The shapes and sizes of liquid-dominated regions are not yet resolved, nor is the temporal evolution of the extent of mush on the crustal scale. The search for a generalised conceptual model of magmatic systems relies on detailed studies of the petrology and geology of selected sites. Different petrological techniques applied to different settings have, however, led to conflicting conceptual models [1].

To begin to resolve this mismatch, we provide a comparison of observations from the active volcanic systems of Kīlauea on Hawai'i and Krafla/Peistareykir in Iceland. These volcanoes have been the target of microanalytical investigation of crystal and melt inclusion compositions [1,2]. The systems show many similarities, with important variability in their erupted liquids, crystal cargo and melt inclusions over timescales of decades to millennia, and the development of unimodal or bimodal distributions of crystal cargo core compositions. The Icelandic observations have been interpreted to reflect mixing and millennial storage of melts in small sills with thin fringes of mush, stacked over a range of depths in the middle and lower crust [1,3]. In contrast, the magmatic system of Kīlauea is thought to be dominated by two storage zones, with mush thicknesses of hundreds of metres under the deeper zone [2]. We will explore how differences in the systematics of the microanalytical observations can be used to understand the development of focused magma storage zones.

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## **Magmatic Evolution of Holocene eruptive episodes at Mt. Taranaki, New Zealand**

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Mt. Taranaki is an unusually high-K, andesite cone volcano in the North Island, New Zealand. Taranaki has been active since 130 ka<sup>1</sup>, with a geological record replete with catastrophic cycles of dome growth, explosive eruptions and near-complete edifice collapse. With a population >100,000, and critical hydrocarbon and agricultural infrastructure located on the Taranaki Peninsula, a large eruption would cause extensive negative impacts. However, with limited seismometer coverage in comparison to other volcanic regions and a lack of recent activity (last eruption: 1780 A.D<sup>2</sup>), the key to understanding the sub-volcanic plumbing system, magma evolution and eruptive dynamics lies in the study of past events.

Taranaki lies 140 km behind the main focus of subduction-related activity, above a deeper section of the subducting slab. Volcanic deposits range from basalts to trachy-andesites, and generally contain clinopyroxene, plagioclase and amphibole phenocrysts, rare biotite and accessory magnetite and apatite. Bulk rock compositions are enriched in K<sub>2</sub>O and large ion lithophile elements (LILE). Abundant amphibole indicates relatively hydrous melts.

This study explores variations in bulk-rock, mineral and melt inclusion compositions from multiple eruptive episodes at Taranaki, focusing on the andesitic Upper Inglewood (3.3 ka)

and basaltic-andesitic Manganui (3.3–2.2 ka). Correlations in major element oxides are generally consistent with trends associated with fractional crystallisation. The occasional presence of cumulate and plutonic inclusions compliments this. However, more detailed examination of compositional variation highlights eruptive units which diverge from those dominant trends. For example, some intermediate compositions fall from the dominant  $\text{Al}_2\text{O}_3$  dog-legged trend, linked to plagioclase crystallisation. Additionally, least-squares/MELTS models fail to satisfy overall variations (especially  $\text{K}_2\text{O}$ ), suggesting that magmatic evolution is more complex. Zoning and resorption textures in phenocrysts and the presence of banded lavas and pumices are suggestive of magma mixing. Additionally, mineral and glass compositions are used to model magma storage (temperature and pressure).

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## **Bárðarbunga Caldera Collapse and Re-inflation in Iceland During 2014-2019**

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Bárðarbunga volcano is situated beneath the Vatnajökull ice cap in the Icelandic highlands. In August 2014, melt intruded 48 km from the caldera in a lateral dyke, before erupting at Holuhraun for 6 months until February 2015. During eruption, the caldera collapsed as melt flowed out from beneath it. Intense seismicity accompanied the process, both along the dyke path and within the caldera, recorded by a dense local network of seismometers deployed by the University of Cambridge and the Icelandic Meteorological Office (IMO). Since the eruption ceased, seismicity has continued in the caldera, and geodetic observations indicate that there has been significant re-inflation. Global Centroid Moment Tensor (GCMT) solutions for the largest earthquakes in the caldera show a corresponding reversal in polarity.

To investigate this further, automatic hypocentre locations for earthquakes detected since 2015 have been manually refined through picking phase arrivals and P-wave first motion polarities. These observations, recorded by a significantly denser seismic network than was operational in 2014, have been inverted to obtain tightly constrained focal mechanisms, providing further insight into the style of faulting and therefore the geometry of the caldera fault. Focal mechanisms for large magnitude events along the Northern rim of the caldera showed mostly normal faulting during the eruptive period as the caldera collapsed. However, from 2017 reverse faulting dominates. Most focal mechanisms in this study, including those for larger magnitude events, can be fitted by a double-couple moment tensor solution, in contrast to the CLVD solutions presented in global moment tensor catalogues. The fault plane orientation is similar for eruptive and post-eruptive events, with a steeply-inwards-dipping fault on the Northern rim, suggesting that the same faults are reactivated post-eruption in

the opposite sense. This can be attributed to re-intrusion of melt into the magma storage region beneath the caldera, thereby causing reinflation.

## **Dyke-hyaloclastite interaction within the Krafla geothermal system: a window on subsurface processes during the 1724-29 Mývatn Fires eruption**

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Borehole KH-6 was drilled close to the 1724-29 Mývatn Fires fissure, within the Krafla geothermal system, northern Iceland, and intersected a basaltic dyke at 557 m depth, which cuts basaltic hyaloclastite and has a thick (>1 cm) glassy margin. Here, we use textures and compositions (via EPMA, FTIR, and TGA-DSC-MS analysis) to interpret physical and chemical signatures of dyke-hyaloclastite interaction.

Glass textures reveal densely fractured sideromelane and tachylite bands. Alteration around fractures involved sideromelane replacement by palagonitic minerals including smectite and wairakite. Palagonitisation led to SiO<sub>2</sub>, Na<sub>2</sub>O, CaO and K<sub>2</sub>O depletion, but enrichment in MgO, FeO and MnO. Strong H<sub>2</sub>O enrichment across fractures in the glass indicates external water uptake. Characterisation of hyaloclastite thermal decomposition indicates that magmatic heat caused dehydration, dehydroxylation and smectite lattice collapse close to the dyke margin. Thermal decomposition drove rapid release, heating and expansion of pore fluids, driving fracturing of the dyke margin whilst it underwent viscous deformation, and mineral precipitation within pore space.

As the chemical composition of little-altered tachylitic bands most closely matches Mývatn Fires lavas, the dyke arguably represents part of its magmatic feeder system. The magma-geothermal fluid interactions recorded at the dyke margin therefore represent part of a spectrum of processes that included phreatic crater-forming explosions.

We propose that basaltic dyke intrusion destroys H<sub>2</sub>O-rich smectites within the hyaloclastite, promoting permeability and porosity via mineral breakdown. Liberated fluids enter the dyke margin via fractures, and consequently accelerate dyke margin quenching, increasing the glassy selvage thickness. Initially rapid palagonitisation of dyke margin glass, which slowed as the dyke cooled, was finally fuelled by the background reservoir geothermal heat. Such interactions between basaltic intrusions and water-rich basaltic hyaloclastites may be common within mid-ocean-ridge complexes and active geothermal systems such as Krafla, and play an important role in modulating magma ascent and geothermal reservoir characteristics.

## Fracking magma: Do tuffisites record a volcano's pressure levels?

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Hydrofracturing by magmatic fluids is a key process in the formation and evolution of dykes and volcanic conduits, generated when high pressure fluid overcomes the strength of the surrounding material. If pyroclastic material is injected into the fracture and deposited, a tuffisite forms, producing a fossil record for the hydrofracturing process.

A tuffisitic sill at Húsafell, associated with rhyolitic volcanism at a dissected Icelandic central volcano, is one such fossil. The sill, 60 cm thick and 50 m long, was injected between two ignimbrite units at 500 m depth and, where the fluid pressure was sufficiently high, fracked apart individual ignimbrite sheets. Grain-sizes in the fill detail variations in the injected fluid velocity, controlled by fluid pressure gradients along the length of the sill. Sedimentary structures such as slumping and cross-bedding indicate changes in the particle density of the injected fluid through time, and permit qualitative reconstruction of the fluid pressure history. Much of the sill comprises welded particles that were transported and deposited sufficiently rapidly to retain their heat and sinter. The degree of sintering of different particle sizes enables estimates of the timescale for transport and deposition, and hints at the temporal evolution of transient tuffisite permeability.

The strength and heterogeneity of the country rock control not only hydrofracture morphology but also fracture propagation and its associated fluid pressure fluctuations. To constrain the magnitude of fluid pressure fluctuations further, we plan to use the grain-size and deposition history of the tuffisitic sill to model the fluid velocity and fluid pressure gradient required for particle transport and deposition. The fracturing and reopening of sealed tuffisites has been proposed as the source of low frequency volcanic seismic events and understanding the magnitude and duration of fluid pressure variations could connect tuffisite evolution with geophysical signals at active volcanoes.

## What controlled the explosivity and sulphur release of one of the largest recent explosive eruptions on Earth?

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With a volcanic explosivity index of 7, the Samalas eruption of 1257 from the Rinjani-Samalas complex on Lombok Island, Indonesia was one of the most explosive eruptions of the Holocene<sup>[1]</sup>. This eruption is also responsible for the highest sulphur peaks of the past 7000 years that were measured in Greenlandic and Antarctic ice cores<sup>[2]</sup>. Such high explosivity and

sulphur yields to the atmosphere can be a threat to life on a local and global scale. Therefore, it is vital to understand the magmatic processes that lead to such eruptions to improve monitoring systems and surveillance data interpretation.

This PhD study aims to gain a better understanding of the magmatic reservoir conditions, as well as volatile storage and exsolution processes during magma ascent in the conduit for intermediate alkaline systems. Phase equilibrium experiments are performed to reconstruct the pressure and temperature conditions of the magma prior to the eruption. Natural trachydacite pumice from the 1257 Samalas eruption serves as starting material. The first set of experiments comprises systematic experiments at various pressures and temperatures with additional water as a volatile component. Results to date show that the magma chamber conditions before the eruption were above 900°C and 100 MPa for an oxygen fugacity of NNO +1 log units. First FTIR measurements of hydrous experiments at different P and T revealed that the magmatic water content of Trachydacite magma is relatively high (about 3.73 wt%) at pressures as low as 50 MPa.

Future experiments will include decompression at different rates to simulate magma ascent in the volcanic conduit. Further experiments will also involve sulphur as a volatile phase to evaluate the partition coefficients of sulphur from the melt into the fluid phase and the probability of crystallisation and breakdown of S-rich minerals as a contribution to excess sulphur in the system.

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- [2] Lavigne, F. Proceedings of the National Academy of Sciences, 110(42), 16742-16747

## **Magma shearing during lava dome eruptions: from flow to failure**

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Dome-building eruptions are commonly known for their ability to switch from effusive to explosive eruption style with little precursory warning. Such behaviour can be attributed to a complex interplay between deep and shallow magmatic processes, altering the magmas physico-chemical state and its propensity to erupt. Yet, the importance of shear during magma ascent remains elusive. Here, we assess the evidence, extent and role of magma shearing and strain localisation at active lava domes to investigate its impact on magma ascent dynamics. Strain localisation was investigated through a petrological survey of a marginal shear zone of the 1994–1995 lava spine at Unzen volcano, Japan [1]. We show that crystals can behave as strain gauges during magma ascent through the viscous–brittle transition, via rearrangement, crystal plasticity and comminution. Owing to a thermo-mechanical response, shear can trigger disequilibrium conditions leading to mineral reactions, alteration of rock magnetic properties and compaction of the porous network, thus influencing outgassing efficiency of the system. Strain localisation can also trigger seismogenic magma failure followed by faulting and slip along fracture planes. In particular, frictional sliding near the conduit margins can cause

localised melting, imposing important rheological controls on slip dynamics. Frictional melting is a non-equilibrium, selective mineral melting process. We experimentally demonstrate the importance of host-rock mineralogy on slip progression [2], notably that hydrous phases dramatically impact melt homogenisation and slip dynamics. Such shearing processes have been linked to regular small-to-moderate, gas-and-ash explosions at Santiaguito dome complex, Guatemala. However, in 2015–2016, activity shifted to larger, less frequent ash-rich explosions. We report petrological and geochemical vicissitudes of explosive tephra deposits, together with geophysical monitoring, that indicate a switch from shallow shear-driven fragmentation to a deeper fragmentation mechanism.

*References:*

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## **Thermochemical modelling of eruptible magma chemistry: Implications for the compositional diversity of igneous rocks**

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Most of the chemical diversity of magmas is acquired within the Earth crust and at times sampled by volcanic eruptions. As a consequence, the volcanic rock record holds valuable information about processes occurring within magmatic plumbing systems, which ultimately are of importance for volcanic hazard assessment, the genesis of economic resources and understanding of planetary dynamics. Detailed mapping, chemical analysis and dating of individual volcanic complexes has revealed that some volcanoes produce magmas of monotonous chemistry throughout their lifespan, while others tend to erupt magmas covering the entire spectrum from basalt to rhyolite, which is the focus of this contribution.

We present results from thermal modelling of magma injection in the mid- to lower crust (20-30 km depth) coupled with experimental petrology in order to calculate the compositional diversity and temporal evolution of eruptible magma geochemistry (i.e. magma with <50 % crystals and all interstitial melt) as a function of recharge rates and thermal conditions of the crust. The results show that low magma fluxes (<0.002 km<sup>3</sup> yr<sup>-1</sup>) at relatively hot or deep crustal conditions produce less geochemical diversity compared to large magma injection rates (>0.002 km<sup>3</sup> yr<sup>-1</sup>) into cooler or shallower crust. This indicates that the thermal structure of magma reservoirs, resulting from different injection rates and temperature variation within the surrounding crust is a primary control on the compositional diversity of magmas present within plumbing systems. We compared the modelling outcomes to various natural datasets, which show striking similarity. Our study demonstrates that basic heat transfer and phase equilibria considerations can be used in a probabilistic way to constrain otherwise inaccessible variables magma fluxes from analysis of volcanic rocks at the surface.

## **Focused Flow within Magmatic Sills: Insights from Analogue Experiments**

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Understanding how magma transport within sills contributes to volcanic plumbing systems could improve our understanding of volcano distributions and eruptible magma volumes. Recent geophysical observations of sills provide evidence of magma transport 100's of kilometres within these sheet-like magma bodies. However, existing magma flow models cannot explain how sills propagate so extensively. Scaled analogue experiments were conducted to explore the dynamics of magma flow in sills. Two gelatine layers with contrasting stiffness were prepared as the elastic crustal analogue with a weak interface, and Xanthan gum (a shear-thinning fluid used as the magma analogue) was injected through the base of the tank. This created a feeder dyke that transitioned into a sill at the interface. Evolving stress was imaged using polarising light, and flow within the injected fluid was visualised using passive tracer particles that fluoresce when interacting with a correctly orientated laser sheet. Particle Image Velocimetry (PIV) was used to create a velocity flow map. Prior to sill formation, flow within the experimental dyke is focused in a jet, with re-circulation of the fluid. The transition from feeder dyke to sill was manifested by additional fluid being drawn from the dyke to build the sill. This is reminiscent of flows observed in experimental dykes during eruption due to depressurisation. The jet within the feeder dyke transitioned into an area of focused flow within the sill (figure 1). These experiments suggest that focused flow may be common in shear-thinning fluids. If such focused flow were to occur in nature, this could explain how larger sills develop as magma would be predominantly transported through a localised region within a greater volume of potentially eruptible magma.

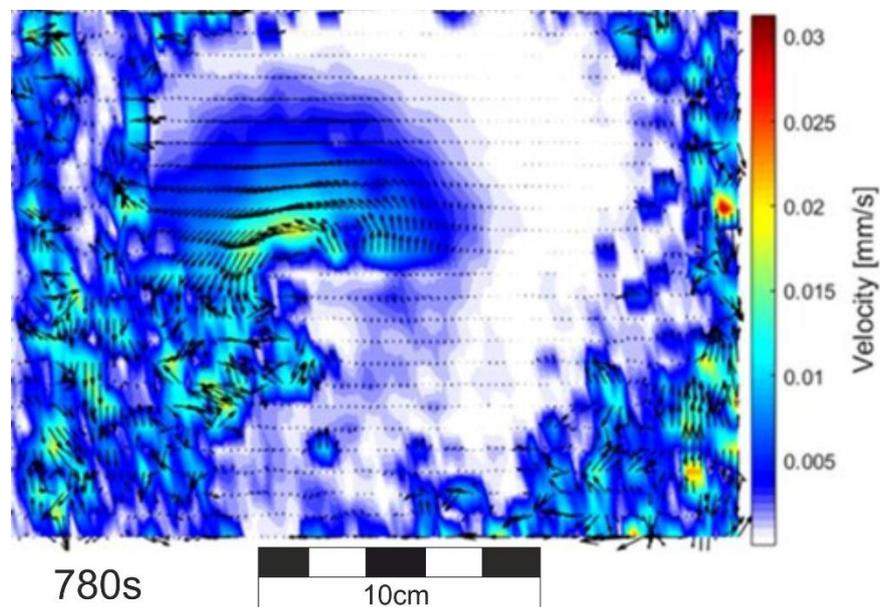


Figure 1: PIV image of an experimental Xanthan gum sill showing focused flow.

## **Basaltic volcanism in the Ethiopian Rift**

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The Ethiopian sector of the East African Rift (the Main Ethiopian Rift, or MER) showcases the interplay between active continental rifting and rift-induced magmatism during continental breakup. Ongoing research has attempted to constrain the role of mantle upwelling on MER magmatism, however further constraints on mantle properties, in particular temperature and composition, are necessary to resolve this conundrum. Furthermore, while many geophysical studies have unravelled the magmatic character of the MER through multiple methods, there remain fewer geochemical studies on magma generation and transport in comparison, with a distinct bias towards the larger central volcanoes of the Rift.

We present new geochemical data for several previously-unsampled monogenetic basaltic fields within the MER. Unlike materials sampled from the major volcanoes of the rift, scoria cones offer a glimpse into magmatic processes that may be overwritten during storage and fractionation. Our preliminary results highlight distinct along-rift differences in magma and olivine compositions, reflecting possible variability in the conditions of MER melt transport and storage as rift maturity develops. In addition, we present the first petrological estimates of olivine crystallisation temperatures from the MER and Afar. These temperatures will be used in conjunction with models of mantle melting to provide a new independent estimate of mantle temperature. Further work on these basaltic scoriae will be necessary to paint an overarching picture of magmatic character in the Ethiopian Rift.

## Session 3 - Timescales and rates of magmatic processes

### From magma storage to eruption: New questions for a new decade

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Fundamental to volcanology are questions related to volcanic eruptions: what initiates them? What controls their behaviour and evolution? What stops them? These questions have long been addressed from the perspective of pre-eruptive magma storage in upper crustal magma chambers, where eruptions can be driven by (1) recharge from below or (2) internal pressurisation via crystallisation and second boiling. The former mechanism associates recharge with eruption, while the latter requires recharge well before eruption. Eruption style is viewed primarily as a balance between volatile exsolution and gas escape, such that explosive eruptions occur when rates of vesiculation greatly exceed rates of gas loss. In the simplest case, eruptions tap a single pressurised magma batch and end when that overpressure is exhausted.

Simple conceptual models, however, often do a poor job of explaining observed patterns of eruptive activity. Here I review ways in which new views of magmatic systems as transc crustal offer new ways of addressing the questions raised above. For example, pre-eruptive magma recharge can be viewed as redistribution of vertically separated melt and/or fluid lenses within a larger magmatic system. Recharge can also be syn-eruptive if vertically or laterally distributed melt lenses are destabilised by pressure gradients created during eruptive activity. Alternatively, recharge may be post-eruptive, caused by downward-propagating decompression waves that extend into un-erupted parts of the magma storage region. Complex transc crustal magmatic systems also provide explanations for the variations in eruption style that often accompany long-lived eruptions, and suggest an origin of such protracted activity as driven and maintained, ultimately, by pressure gradients within the melt-connected portions of the system. Finally, a transc crustal view raises new questions about the nature and evolution of subvolcanic systems, questions that provide fertile ground for the next decade of volcanological research.

### Protracted assembly of the magmas feeding the 1783-84 Laki fissure eruption, Iceland

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The A.D. 1783-84 Laki eruption in Iceland was one of the largest basaltic fissure eruptions in historical times and serves as one of the best small scale modern analogues of a flood basalt

eruption. Significant quantities of SO<sub>2</sub> (~ 122 Mt), HF (~ 15 Mt) and HCl (~ 7 Mt) released throughout the 8-month long eruption have been linked to the death of nearly one quarter of Iceland's population. Approximately 14.7 km<sup>3</sup> of lava and ~0.4 km<sup>3</sup> dense rock equivalent of tephra were erupted from 10 en-echelon fissure segments that opened sequentially SW to NE. Understanding the timescales over which large volumes of eruptible magma are assembled before large basaltic fissure eruptions remains a key challenge in earth sciences and volcano monitoring.

Here we combine textural observations, microanalysis and diffusion chronometry of plagioclase crystals from eruptive episode VII of the Laki eruption to gain additional constraints on the conditions and timescales of magma storage underneath Grímsvötn. We have found that the plagioclase crystal cargo can be divided into 3 subpopulations based on crystal zoning pattern and trace element geochemistry (defined as Type I, II and III). All of the crystal populations have high-anorthite (An<sub>85-90</sub>) cores. Type I crystals have cores surrounded by oscillatory zoned mantles and sharp outer rims. Type II crystals have simple mantles and rims. Type III crystals just have a core and rim. Mg profiles measured by secondary ionisation mass spectrometry (SIMS) show that the mantles and cores of Type I plagioclases fully equilibrated with an evolved interstitial mush liquid at a temperature of 1120 °C. Bulk 3D diffusion modelling Mg in these crystals indicates that they had a minimum storage time in this environment of 2000 years. Type II and Type III plagioclase crystals exhibit major Mg disequilibrium in their cores. Diffusion modelling of Mg disequilibria in Type II plagioclase indicates that there was a melt replenishment event approximately 100 years before the Laki eruption. This corresponds well with a cyclical increase in eruptive activity at Grímsvötn central volcano. Diffusion modelling of Mg across Type III crystals reveals a mixing event approximately 150 days before the onset of the eruption, which is in agreement with pre-eruptive residence times estimated from primitive olivine crystals.

Combined, our observations and modelling results suggest that the magma reservoir that fed the Laki eruption incrementally grew over thousands of years with regular replenishment by new melts supplied under the Grímsvötn volcanic system. These replenishment events may have been closely associated with stress release events in southern Iceland. This creates an interesting framework in which monitoring strategies can be devised.

## **Mush cannibalism and disruption recorded by clinopyroxene phenocrysts at Stromboli volcano: new insights from recent 2003-2017 activity**

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The Present-day (<1.2 kyr) activity of Stromboli (Aeolian Islands, Southern Italy) is fed by a vertically-extended mush column with an open-conduit configuration. The eruptive products are the result of periodic supply of mafic magma (low porphyritic or *lp*-magma) from depth into a homogeneous shallow reservoir (highly porphyritic or *hp*-magma). Clinopyroxene phenocrysts from the 2003-2017 activity exhibit marked diopside-augite heterogeneities caused by continuous *lp-hp* magma mixing and antecryst recycling. Diopsidic bands record *lp*-recharges injected into the shallow *hp*-reservoir, whereas resorbed diopsidic cores testify to the continuous disruption and cannibalism of relic antecrysts from the mush. The transition between diopside (~1,175 °C) and augite (~1,130 °C) takes place at comparable *P* (~190 MPa) and H<sub>2</sub>O (0.5-2.4 wt.%) conditions. Shorter timescales (~1 year) for diopsidic bands from the 2003 paroxysm document restricted temporal intervals between mafic injection, magma mixing and homogenization in the *hp*-reservoir. Longer timescales (~4-182 years) for diopsidic cores indicate increasingly antecryst remobilization times. By comparing clinopyroxenes from the Present-day and Post-Pizzo eruptions, we argue a distinct phase in the life of Stromboli volcano commenced at least after the 2003 paroxysm. More efficient mechanisms of mush disruption and cannibalism involve diopsidic antecrysts remobilized and transported by *lp*-magmas permeating the mush, in concert with gravitational instability of the solidification front and melt migration within the shallow *hp*-reservoir. Magmatic injections feeding the persistent Present-day activity are more intensively mixed and homogenized prior to eruption, reflecting small recharge volumes and/or a more mafic system in which the mafic inputs are less evident.

## **Bubble Interactions in Basaltic Magma – Reducing the Timescale between Nucleation and Eruption**

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Bubble development within ascending magma affects eruption style and, thus, understanding how bubbles move and self-organise within volcanic systems improves understanding of eruption mechanisms and ultimately aids in mitigating volcanic hazard. While conduit models exist to describe the growth and motion of gas bubbles in basaltic systems, these do not sufficiently account for the effect of bubbles acting as groups. A series of analogue experiments were conducted to identify and quantify bubble grouping behaviour in a viscous liquid (silicone oil) and the effect of cylindrical constraining walls on a gas bubble-viscous liquid system.

The main experimental findings were that 1) bubbles tend to self-organise into groups of greater bubble number density, 2) these groups of bubbles act together such that their rise speed can be 2-5 times greater than the buoyant rise speed of individual bubbles, and 3) bubble interactions tend to promote vertical size stratification. For low viscosity magmatic systems, the timescale for bubbles to self-organise into groups of higher number density was estimated to be on the order of 10 to 100 hours, based on the mutual attraction of bubbles arising from the Bernoulli principle.

Experiments indicated that, in slow rising, low viscosity, magmas, bubble-bubble interactions may notably impact the gas mass transport, acting to shorten the timescale between bubble

nucleation and eruption to the surface. Additionally, bubble-bubble interactions could become an important component of future models of cyclical eruptive behaviour in low viscosity magmatic systems. For magma conduit models to account for the effects of group behaviour, additional experiments are required to generate a rigorous numerical model that can describe these effects across a broad parameter space.

## **Zircon in mingled magmas from Montserrat, Caribbean: insights into subduction magmatic plumbing**

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Soufrière Hills stratovolcano (SHV), Montserrat, is an active geological hazard. Recent activity, 1995-2010, includes dome growth, vulcanian explosions and pyroclastic density currents. Mafic magma remnants are ubiquitous, preserved as enclaves entrained in host andesites. How these coeval magmas interacted should shed light on eruptive processes.

Here mixed mafic-intermediate samples are investigated using field, petrological, geochemical and geochronological data.

Newly-discovered metre-scale blocks of medium-grained mafic rocks, from deep within the volcanic edifice, crop out in the most recent eruptive phase, 2009-2010, dome collapse block-and-ash deposits. These apparently represent an unerupted plutonic component of widespread centimetre-scale, fine-grained, erupted mafic enclaves.

Study of standard petrographic thin sections reveals, counter-intuitively, zircon is preferentially preserved in mafic enclaves and, particularly, their contact with the andesites. Moreover, zircons in mafic enclaves are predominantly euhedral-subhedral but typically subhedral-anhedral in andesite groundmass.

New andesite and enclave in-situ U-series zircon ages range from ca. 2-250 ka. These record evolved melts in the SHV magma plumbing system crystallizing zircon, an effective tracer of crystal cargo - mush -, over a prolonged period. Zircon compositions, e.g., U/Yb, Zr/Hf and <sup>176</sup>Hf/<sup>177</sup>Hf are similar in both andesites and enclaves: enriched mantle-crustal.

We propose zircon crystallized in the andesite, or, most likely a more SiO<sub>2</sub>-rich pre-mingling dacite-rhyolite, then was incorporated into the enclaves. So, the sub-SHV subduction magmatic plumbing system long-lived evolved host crystal cargo mingled into the mafic enclave magma.

The temperature contrast during mingling would have resulted in hotter mafic magma quenching and cooler evolved magma thermal reactivation. Corrosion of andesite zircons, consistent with plagioclase phenocrysts patchy-sieve textures, indicates the system was not in equilibrium. Furthermore, post-mingling incipient re-equilibration textures suggest the magmas were in contact for a considerable time. Therefore, neither magma replenishment by these mafic enclaves, nor volatiles derived from them, apparently triggered the 2009-2010 effusion-related collapse event.

## Session 3 Posters

### Changing eruption dynamics of Anak Krakatau in December 2018 inferred from physical and textural ash analyses

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Anak Krakatau experienced a lateral collapse in December 2018, which induced a tsunami causing devastation on surrounding Indonesian coastlines within the Sunda Strait. Here we analyse eruptive products spanning the time of the collapse to address whether there are any identifiable changes in magmatic activity associated with the collapse. If it can be demonstrated that these occurred prior to collapse, and may thus be implicated as a trigger for the event, this has important implications for identifying precursory signals to sector collapse. Alternatively, it is possible that the highly explosive eruption behaviour observed post-collapse was merely a consequence of unloading of the shallow plumbing system, and that non-eruptive processes initiated the event. To assess this, the physical and textural characteristics of tephra deposits from around the time of the collapse, post-collapse and from earlier stages of Anak Krakatau's development (1932-1997) is being examined. The textural characterisation includes particle morphometry, vesicularity and crystallinity (microlites and crystal size distribution). Initial results show negligible changes in bulk magma composition (basaltic andesite) before and after collapse, suggesting no significant deeper magmatic changes have occurred in the short-term [1]. Hence, unravelling various textural features will enable a reconstruction of magmatic processes within the shallow magma plumbing system. The 2018 phase of activity will also be placed in the context of longer-term development and growth at the volcano, since it first emerged subaerially in 1928 within the Krakatau volcanic complex [2]. The resulting textural insight into the eruption dynamics at Anak Krakatau, with constraints on the timing of changes from satellite observations, may highlight possible precursory signals, identifiable through monitoring, resulting in the potential revision of frameworks for recognising future collapse and tsunami hazards at island arc volcanoes. Moreover, the results will add further understanding to the short-term evolution of the volcanic system after sector collapse.

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## The effect of CaO on the partitioning behavior of REE, Y and Sc between olivine and melt: Implications for basalt-carbonate interaction processes

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The partitioning of REE, Y and Sc ( $R^{3+}$ ) between olivine and melt has been investigated experimentally during basalt-carbonate interaction. Three synthetic basalts ( $^{\text{melt}}\text{Mg}\#_{72}$ ,  $^{\text{melt}}\text{Mg}\#_{75}$ ,  $^{\text{melt}}\text{Mg}\#_{78}$ ) were doped with 0, 10 and 20 wt.%  $\text{CaCO}_3$  and then equilibrated for 72 h at 1 atm, 1,150, 1,200 and 1,250 °C, and the QFM oxygen buffer. Regular relationships are found between the ionic radius and the partition coefficient ( $D_{R^{3+}}$ ), showing typical near-parabolic patterns. From the point of view of the lattice strain theory,  $D_{R^{3+}}$  is described in terms of the radius of the crystal site ( $r_0$ ), Young Modulus ( $E$ ), and strain-free partition coefficient ( $D_0$ ). The value of  $r_0$  decreases as Ca cations are accommodated into the more distorted M2 site of olivine via progressive Ca-Fe substitutions. This mechanism is accompanied by a higher proportion of Mg cations entering into the smaller M1 site, making the optimum ionic radius smaller and favoring the crystallization of more forsteritic olivines from decarbonated melts. The enrichment of Ca in the crystal lattice is also proportional to the number of Si and Ca cations in the melt. This causes  $E$  to be anticorrelated either with Ca in olivine or the activity of CaO in the melt.  $R^{3+}$  cations behave as network modifiers and, during basalt-carbonate interaction, the increasing abundance of non-bridging oxygens enhances the solubility of REE, Y and Sc in the melt. As a consequence,  $D_0$  is negatively correlated with the degree of melt depolymerization. Additionally, the strain of the crystal lattice dominates the  $D_{R^{3+}}$  parabolic patterns and  $D_0$  is strongly controlled by forsterite and aluminum concentrations in olivine. The accommodation of REE, Y and Sc in the crystal lattice requires maintenance of local charge-balance by the generation of vacancies, in accord with a paired substitution of  $R^{3+}$  and a vacancy for Mg in octahedral sites.

## Morphometric evolution of volcanoes through analogue modelling: Volcano growth vs strike-slip fault deformation

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Volcanoes display diverse morphologies as a result of the complex interplay of several constructive and destructive processes. Scaled analogue models offer a tool to isolate and characterise the different processes. Here, we investigate the interplay between volcano growth and deformation caused by an underlying strike-slip fault through straightforward analogue models documented with photogrammetry. In particular, we analyse the morphometry of analogue volcanoes resulting from different growth-to-deformation ratios. Strike-slip deformation elongates the edifice at an angle of 10-45° from the fault trace along the extensional quadrants, generates a summit graben oriented perpendicular to the edifice elongation and decreases the overall cone steepness. Steep slopes are preserved or increased on the lower compressional flanks, commonly related to small avalanching. Growth by accumulation of additional material around the summit vent can partially to totally mask the features produced by strike-slip faulting, depending on the growth rate to strike-slip velocity ratio. The summit graben is easily masked even by low growth rates, whereas edifice elongation has the best preservation potential. Scaling of the experiments suggests that at volcanoes with growth rate (km<sup>3</sup>/yr) to strike-slip velocity (km/yr) ratios  $\leq 3.8$  km<sup>3</sup>/km, deformation features should be clearly preserved, whereas at volcanoes with ratios  $\geq 15$  km<sup>3</sup>/km, deformation features should be completely masked. The typical growth rates of volcanoes (0,01 to 1 km<sup>3</sup>/ka) and the typical velocities of strike-slip faults (1 to 20 mm/yr) suggest that in nature, growth rate to strike-slip velocity ratios can range over 3 orders of magnitude, spanning both types of end-members. Using examples of active and eroded volcanoes located on strike-slip faults with variable elongation, we highlight that our experimental results account for some of the morphometric variability observed at volcanoes in nature, although the role of vent distribution may complicate the observed morphologies.

### **How do you establish long-term eruption records for Mexico City?**

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<sup>5</sup> <https://www.icdp-online.org/projects/world/north-and-central-america/lake-chalco-mexico/details/>

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Eruption records are highly incomplete for most, if not all volcanoes around the world, particularly before the historical period. This limits our understanding of the range of past activity and makes it difficult to accurately assess eruption frequencies, variation in behaviour, and thus develop statistically robust hazard models. Heavily populated areas are even harder to obtain such a record of past activity due to a lack of exposure, yet in such areas it is particularly important to assess volcanic hazards. Being a megacity (home to nearly 20 million people), the Mexico City region is an exceptional example of a heavily populated area which is also home to several volcanoes. Surrounded by many large polygenetic centres, (e.g. *Popocatepetl*, *Iztaccíhuatl*, *Nevado de Toluca*), the city is also

partially built upon the *Sierra Chichinautzin Volcanic Field*, with larger caldera systems lying further afield.

Pyroclastic exposures within the Mexico City region are mostly limited to road cuttings and quarries. Whilst providing context of individual eruptions from a process-related approach, these typically only expose the most recent activity. We are therefore investigating these proximal exposures in conjunction with a deep sediment core from Lake Chalco within Mexico City, obtained in 2016 and part-funded by the International Continental Drilling Programme. This core is over 500 m in length and records around 200 fall deposits from local volcanic sources. These visible tephra layers range in thickness from millimetre to meter scale. By characterising the glass geochemistry of the proximal deposits we are able to define the compositional fields or ‘fingerprints’ of the source volcanoes and their eruptions. This allows us to correlate deposits in the core to particular volcanoes and deposits. These data will be combined with new geochronological data to establish the volcanic history of the region. By determining the eruption frequencies, magnitudes and styles of the eruptions that have affected the Mexico City region in the past it will allow us to better understand how these volcanoes may behave and what they could potentially do in the future.

## **Mixing modifies the crystal record of magmatic evolution**

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Near-fractional melting of the Earth’s geochemically and lithologically heterogeneous mantle produces diverse primary melt compositions. However, these diverse compositions are frequently homogenised by magma mixing during ascent. Unravelling disequilibrium within and between crystals and their carrier melts thus provides one way to evaluate the true complexity of melts supplied to the base of magmatic plumbing systems. Changes in magma temperature may trigger growth, resorption or diffusive re-equilibration depending on the degree of disequilibrium and kinetic considerations. Similarly, changes in magma composition induced by magma mixing also induce changes in crystal cargoes by changing phase equilibria relationships. However, the response of compositionally distinct basaltic magmas (i.e. crystal-melt mixtures) to magma mixing has yet to be quantified experimentally. To address this, we performed experiments on two primitive Icelandic magmas derived from distinct mantle sources, one depleted (ambient/lherzolitic) and one enriched (recycled/pyroxenitic). Synthesis experiments were performed at 300 MPa and 1190 °C, resulting in different phase assemblages. The depleted composition crystallised ol+plg+cpx (~50 wt.% crystals), whereas the enriched composition crystallised only ol+cpx (~20 wt.% crystals). Mixing experiments were then performed by placing pairs of quenched magma cylinders into new capsules and performing re-equilibration experiments for 1, 4, 8 and 96 hours. Transects across experimental products show that melt compositions underwent diffusive re-equilibration, with different elements showing responses commensurate with their different diffusivities.

The re-equilibration of melt compositions is largely unaffected by the presence of crystals yet exerts a dominant control on crystal stability, with a wave of plagioclase dissolution progressively invading the depleted portion of experimental samples. The ability of crystals to record magmatic processes is thus compromised by mixing-induced dissolution processes, meaning that mixing may modify records of magmatism in important but previously underappreciated ways.

### **Tracking degassing in rhyolite using lithium isotopes**

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Lithium (Li) is one of the most rapidly diffusing elements in melts and minerals at magmatic temperatures, making it a potentially powerful tool to estimate timescales of rapid geological processes such as syn-eruptive degassing. Here, we investigate these processes using the Mesa Falls Tuff (MFT, 1.30 Ma) of the Yellowstone volcanic field. MFT is a rhyolitic deposit containing an anhydrous mineral assemblage of sanidine, quartz, plagioclase, clinopyroxene, fayalite, orthopyroxene and accessory phases. Plagioclase crystals from MFT show core-to-rim Li depletion (from ~25 to ~5 ppm), reflecting magmatic degassing shortly prior to, or during, the eruption.  $\delta^7\text{Li}$  values measured by fs-LA-MC-ICPMS in the plagioclase crystals reveal that cores are about 5‰ lower than rims. The higher  $\delta^7\text{Li}$  in rims supports the interpretation that Li concentration gradients and  $\delta^7\text{Li}$  profiles are a result of diffusive fractionation during degassing that occurred within tens of minutes prior to quenching as resolved by diffusion modelling of Li abundances and isotopic ratios. This volatility of Li in silicic magmas is supported by Li concentrations measured in groundmass glass of MFT (35.6–54.8 ppm) being up to a factor of five lower than Li concentrations measured in quartz-hosted melt inclusions. The groundmass glass exhibits among the highest  $\delta^7\text{Li}$  values (6.5–6.9‰) compared to the mineral assemblage of MFT apart from quartz (5.7–7.2‰). In contrast, quartz-hosted melt inclusions measured by SIMS exhibit  $\delta^7\text{Li}$  values as low as –15.3‰. This indicates a large isotopic fractionation between the entrapment of the melt inclusions (MI) and the deposition of the groundmass glass. The over 20‰ difference can partly be explained by the loss of  $^6\text{Li}$  (the lighter isotope) to the vapour phase during degassing. Our data show that despite the widely-held belief that isotopic fractionation is minimal at high-temperatures the kinetic effects occurring during volcanic degassing are significant.

### **Reconstruction of the intensive variables and magmatic architecture of Vulcano island (Aeolian Arc, Italy)**

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In this study, we present new mineralogical and petrological data on olivine, clinopyroxene, plagioclase and titanomagnetite phenocrysts from sixteen eruptive products (i.e., lava flows and pyroclastic deposits) collected at Vulcano island (Aeolian Arc, Italy) and representative of a relatively wide time period, from Epoch 5 (70-42 ka) to Epoch 8 (< 8 ka). These rocks show shoshonitic (SHO) to high-K calc-alkaline (HKCA) affinity, with compositions evolving from basalt (Mg#<sub>60-57</sub>) to basaltic trachyandesite (Mg#<sub>41-35</sub>) to trachyandesite (Mg#<sub>32-54</sub>) to trachyte (Mg#<sub>30-40</sub>) to rhyolite (Mg#<sub>23-28</sub>). The intensive variables driving the crystallization of magma were reconstructed by employing mineral-melt equilibrium and thermodynamic models, as well as barometers, thermometers, hygrometers and oxygen barometers. The stability of olivine (Fo<sub>61-91</sub>), as first phase on liquidus, is restricted to 100-300 MPa and 1080-1180 °C. Afterwards, the melt is co-saturated with clinopyroxene (Mg#<sub>92</sub>, diopside), which composition progressively evolves (Mg#<sub>64</sub>, augite) as the temperature decreases to 1090 °C. The jadeite exchange between clinopyroxene and melt indicates that the overall decompression path of magmas ranges from 900 to 0.1 MPa. The maximum crystallization pressure decreases from basalt/basaltic trachyandesite (900 MPa) to trachyandesite (650 MPa) to trachyte/rhyolite (250 MPa). The melt-water content (0.5-6.5 wt.%) is sensitive to either pressure or melt composition, thus controlling the plagioclase stability and chemistry (An<sub>30-80</sub>). Titanomagnetite (Usp<sub>11-29</sub>) equilibrates with progressively more evolved and oxidized melts, from  $\Delta$ QFM+1.5 to  $\Delta$ QFM+3. We conclude that the architecture of the plumbing system at Vulcano island is characterized by multiple reservoirs in which compositionally distinct magmas stall and undergo polybaric-polythermal differentiation, before eruption to the surface.

## Session 4 – Intraplate Magmatism

### Enigmatic high He isotope around the Fiji Triple Junction: Does high $^3\text{He}/^4\text{He}$ always track mantle plumes?

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The convecting upper mantle (away from the influence of mantle plumes) is widely held to produce largely uniform  $^3\text{He}/^4\text{He}$  with a canonical value of  $8 \pm 0.5 R_a$ . The prevailing view that large volume melts beneath ridges smear out subtle chemical heterogeneities has been called into question lately. High density sampling of mid-ocean ridge basalts (MORB) reveal long-wavelength  $^3\text{He}/^4\text{He}$  variations that identify large regions of compositionally-distinct mantle that is not evident in incompatible trace elements. Significant  $^3\text{He}/^4\text{He}$  ranges are observed locally on ridges that cannot be linked to an obvious intra-plate volcanic source, e.g. [1], that is consistent with upwelling material polluting the upper mantle without generating hotspot volcanism [2]. We will show that basalts dredged from along the Red Sea reveal close coupling of  $^3\text{He}/^4\text{He}$  with trace elements which trace mixing of the present day Afar mantle plume with ambient upper mantle. In contrast new analysis of basalts ( $n=45$ ) dredged from between  $16^\circ$  and  $21^\circ\text{S}$  around the Fiji Triple Junction (FTJ) in the North Fiji Basin record high  $^3\text{He}/^4\text{He}$  that are seemingly unrelated to mantle heterogeneity. South and north of the FTJ  $^3\text{He}/^4\text{He}$  display a narrow range (8.8 to 9.3  $R_a$ ) that is at the upper end of the MORB range upper mantle. For a few 10's km around the FTJ  $^3\text{He}/^4\text{He}$  increase to a maximum of 12.8  $R_a$  on the topographic high that marks the triple junction. The mean  $^3\text{He}/^4\text{He}$  of FTJ basalts (10.6  $R_a$ ) is markedly higher than the surrounding ridges (9.0  $R_a$ ) and has been missed by several earlier low-density sampling. The high  $^3\text{He}/^4\text{He}$  FTJ basalts are indistinguishable in trace element and Sr-Nd-Pb isotope composition from adjacent ridges and is inconsistent with the presence of blobs of deep mantle that is upwelling beneath Raratonga or Samoa.

### Coupled Trace Element and Helium Isotope Analysis of Mantle Xenoliths Reveal the Dynamic Evolution of the Sub-Continental Lithospheric Mantle

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The sub-continental lithospheric mantle (SCLM) is widely understood to have initially formed as a residue during melt extraction from the convecting upper mantle. Subsequently, it has

been enriched by multi-phase metasomatism by volatile-rich melts and/or fluids. While there are several sources for the metasomatizing fluids (e.g. subducting slabs, convecting upper mantle, deep mantle) the extent and mechanisms of SCLM enrichment remains enigmatic. Here, we combine incompatible trace elements and helium isotope ( $^3\text{He}/^4\text{He}$ ) composition of  $\text{CO}_2$ -rich fluids in mantle xenoliths ( $n=60$ ) from a broad range of tectonic and metasomatic settings. This investigation aims to illuminate which reservoirs are dominantly evolving the SCLM and the influence this has on He (and therefore  $\text{CO}_2$ ) enrichment.

Our new determinations of  $^3\text{He}/^4\text{He}$  ratios for peridotite and pyroxenite xenoliths range from 5.5–8.4  $R_a$  and 5.3–7.3  $R_a$ , respectively. Peridotite and pyroxenite xenoliths from the same eruptions have overlapping  $^3\text{He}/^4\text{He}$  suggesting similar metasomatic origins.  $^3\text{He}/^4\text{He}$ -HFSE-HREE-LILE systematics of peridotite and pyroxenite show a clear mixture between asthenospheric mantle and crustal signatures suggesting SCLM interaction with subduction- and mantle-derived melts. However, the strongly hyperbolic nature of mixing the radiogenic He component shows the subduction-derived melts have a low He concentration consistent with volatile loss to the fore-arc during subduction. Furthermore, clinopyroxenites have 1-2 orders of magnitude higher He concentrations (and therefore  $\text{CO}_2$ ) than peridotite.  $^3\text{He}$  concentrations vary positively with MREE/HREE ratios, which implies that the magmatic  $\text{CO}_2$  accumulation in the SCLM is controlled by interaction with the most evolved mantle melts.

Overall, our results show the SCLM is evolving due to variable interaction with different crustal and mantle reservoirs. However, volatiles influencing the SCLM are dominantly sourced from the upper mantle and the degree to this enrichment is controlled by the nature of the metasomatizing agent.

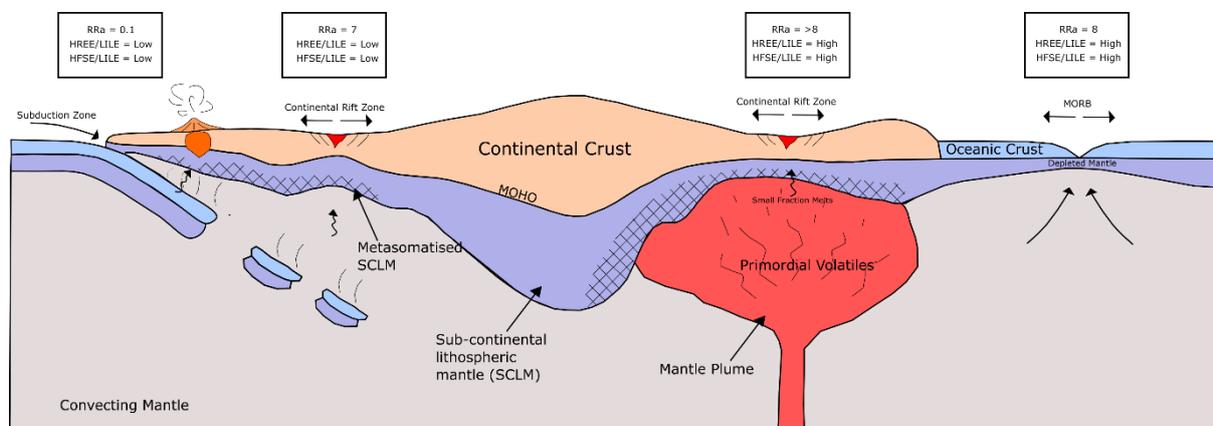


Figure 2 Showing metasomatic evolution of the SCLM due to interaction with different reservoirs of Earth as inferred from this study.

## The Heterogeneity of the Miocene Iceland Mantle Plume

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The oldest basalts (15-16 Ma) on Iceland are preserved in several ~1 km thick sequences in Vestfirðir in NW Iceland. Each sequence contains a hiatus in volcanism, marked by a laterite-lignite horizon, that is likely the result of the relocation of a spreading axis [1]. The basalt geochemistry provides an insight into the heterogeneity of the Iceland mantle plume in the mid-Miocene. A suite of 605 basalt samples have been collected from 21 profiles. A preliminary study demonstrated that the sequence contains an enriched mantle component and a depleted mantle component that is present only in the basalts from below the volcanic hiatus (Hardarson et al, 1997). They are characterised by high  $^3\text{He}/^4\text{He}$  ( $37 R_a$ ) requiring the involvement of deep mantle [2].

Incompatible trace element and Nd-Sr-Pb isotope data indicate that there are two enriched mantle components within the Miocene mantle. Both have low  $^{143}\text{Nd}/^{144}\text{Nd}$  and high  $^{87}\text{Sr}/^{86}\text{Sr}$ , that are comparable with the most enriched modern Iceland basalts. The two components are differentiated by the relative enrichment in the more incompatible trace elements and Pb isotopes. Component NWE1 is similar to the enriched plume derived component in the neovolcanic rift zone basalts. The higher Nb/Zr, La/Sm and Pb isotope composition of NWE2 is more comparable to modern off-axis magmatism present at 15 - 16 Ma. The depleted component (NWD1) identified in the Vestfirðir basalts is distinct from modern North Atlantic N-MORB and the depleted component in the neovolcanic rift zones by, for instance, higher incompatible trace element concentrations and their Sr-Nd isotope compositions. These observations provide new evidence for a distinct compositional change in the Icelandic mantle over the last 15-16 Myr.

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## **Aillikite Diatremes and the Early Stages of the Gardar Rift System**

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The Mesoproterozoic Gardar Province of South Greenland has been integral in developing our understanding of alkaline magmatism and continental rifting. In this investigation we explore the area north of Narsarsuaq, in which suites of diatreme structures were reported [1]. We produce a detailed geological map using modern classification schemes for lithological units, and present geochemical and petrological information for the intrusions examined.

The area is split into four components; a series of NE-SW dykes parallel to and with compositions correlating with the region's Main Late-Gardar Dyke Swarm; a syenitic intrusion; SE-NW trending dykes showing physical and geochemical characteristics similar to the Brown Dykes (BD) of the Gardar; and an array of diatremes composed primarily of ultramafic lamprophyre (UML). Petrography of UML revealed mineralogy most accurately resembles that

of aillikite [2], contradicting previous studies referring to the structures as “carbonatite”. Crosscutting relationships show the diatremes are older than the BDs, and U-Pb dating of baddeleyite from BDs in previous studies gives ages of ~1.28 Ga [3]. Thus, we propose the diatremes belong to the Early-Gardar (1.30-1.25 Ga), representing low degree partial melts produced in the earliest stages of rifting.

Calcite ocelli within aillikite outcrops display textures reminiscent of liquid-liquid contacts, with  $\delta^{13}\text{C}_{(\text{VPDB})}$  and  $\delta^{18}\text{O}_{(\text{VPDB})}$  data consistent with mantle values and suggesting ocelli represent primary magmatic carbonate. The field evidence and petrography are consistent with a model whereby carbonatite and UML melts originated through liquid immiscibility of a common parent, however trace element chemistry does not show simple cogenetic relationships suggesting a more complicated relationship exists between the two lithologies. Nevertheless, our findings place the various structures into regional context within the Gardar and give insight into the early stages of the rifting event.

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## **Using iron isotopes to trace mineralogical heterogeneity in the Samoan mantle plume**

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Iron isotope compositions in the global ocean island basalt (OIB) dataset extend to heavier values (higher  $\delta^{57}\text{Fe}$ ) than observed in mid-ocean ridge basalts (MORB), which is often ascribed to mineralogical heterogeneity, namely recycled components, in mantle plume source regions [1,2]. Inter-mineral fractionation effects couple iron isotope compositions to source mineralogy, allowing heavy stable isotopes to complement radiogenic isotopic systems as a source tracer [3,4].

Rejuvenated lavas from Samoa record the heaviest iron isotopic composition in the global OIB dataset, which has been suggested to be the result of pyroxene-rich source lithologies [1]. Here, we utilise a suite of new iron isotope data from Samoan shield lavas combined with a model of expected melt isotopic composition for different lithologies to investigate iron isotope variability along the Samoan chain, and any underlying mineralogical heterogeneity in the mantle source. We find that shield lavas, which show separate geographical and radiogenic isotopic trends, record isotopic compositions within error of MORB ( $\delta^{57}\text{Fe} = 0.15\text{‰}$ ) but are distinct from previously measured rejuvenated lava samples ( $\delta^{57}\text{Fe} = 0.32\text{–}0.50\text{‰}$ ).

After correcting for fractional crystallisation, the remaining Samoan iron isotope variability correlates with lead isotopes, suggesting a source control on iron isotopic composition. However, our combined phase equilibria and isotope fractionation model shows that a peridotite source modified by reaction-zone pyroxenite formation [5] cannot plausibly produce the sufficiently isotopically heavy liquids required for some shield and all rejuvenated lavas. This result means the interpretation of heavy iron isotopic compositions in OIB as a recycled pyroxenite signature must be explored further.

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## **Session 4 Posters**

### **Early evolution of an intraplate magmatic system before initial eruptions of the long-lived Dunedin Volcano, New Zealand.**

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Investigating magmatic processes that precede and accompany initiation of long-lived composite volcanoes is challenging as early products are buried by those of subsequent eruptions. Since cessation of activity 10 Ma, erosion of the Dunedin Volcano in southern New Zealand has exposed the old core of the volcano at Otapahi, which formed at 16 Ma. Otapahi exposures offer a window into early stages of an evolving magmatic system concomitant with the initiation of a long-lived volcano. Otapahi preserves the oldest and stratigraphically lowest known volcanic rocks of the Dunedin Volcano, a bedded pumice unit which transitions from phenocryst-poor phonolitic pumice at its base, to beds of pumice containing abundant phenocrysts of olivine, augite, plagioclase, orthoclase, and kaersutite. This unit is crosscut by multiple diatremes and a diverse array of dikes. Complex, peperitic contacts between mingled dikes, diatremes, and the pumice beds, indicate near-contemporaneous emplacement of multiple dikes soon after the eruption that produced the zoned pumice. Cross-cutting diatremes contain lithic fragments from the basement schist, but no lithic clasts from any older magmatic activity preceding formation of the pumice unit. Whole-rock XRF, EMPA glass analysis, and petrography confirms the wide compositional range of rocks, from basanite and alkali basalt to trachyte and phonolite. Analysis of major and trace elements, petrographic textures, and EMPA mineral data reveal that the range of compositions at Otapahi were generated by mixing of different magmas. The rapid shift from explosive eruptions and

subsequent intrusion of compositionally diverse, mixed, magmas during early development of the volcano suggests that a complex magmatic system and highly evolved magmas, of the sort typically attributed to "mature" magmatic systems, had already developed before the first surface eruptions.

## **Generation of the Mt Kinabalu granite by crustal contamination of intraplate magma modelled by Equilibrated Major Element Assimilation with Fractional Crystallisation (EME-AFC)**

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We present new geochemical data for the composite units of the Mount Kinabalu granitoid intrusion of Borneo, to explore the discrimination between crustal- and mantle-derived granitic magmas, and present a new methodology for modelling geochemical differentiation by AFC. This work was published this year in *Journal of Petrology* [1].

The geochemical data demonstrate that the units making up this composite intrusion became more potassic through time. This was accompanied by an evolution of isotope ratios from a continental-affinity towards a slightly more mantle-affinity ( $^{87}\text{Sr}/^{86}\text{Sr}_i \sim 0.7078$ ;  $^{143}\text{Nd}/^{144}\text{Nd}_i \sim 0.51245$ ;  $^{206}\text{Pb}/^{204}\text{Pb}_i \sim 18.756$  for the oldest unit compared to  $^{87}\text{Sr}/^{86}\text{Sr}_i \sim 0.7065$ ,  $^{143}\text{Nd}/^{144}\text{Nd}_i \sim 0.51250$  and  $^{206}\text{Pb}/^{204}\text{Pb}_i \sim 18.721$  for the younger units). Oxygen isotope ratios (calculated whole rock  $\delta^{18}\text{O}$  of +6.5–9.3‰) do not show a clear trend with time. The isotopic data indicate that the magma cannot be the result only from fractional crystallisation of a mantle-derived magma. Alkali metal compositions show that crustal anatexis is also an unsuitable process for genesis of the intrusion. The data indicate that the high-K units were generated by fractional crystallisation of a primary, mafic magma followed by assimilation of the partially melted sedimentary overburden.

We present a new, Equilibrated Major Element – Assimilation with Fractional Crystallisation (EME-AFC) approach for simultaneously modelling the major element, trace element, and radiogenic and oxygen isotope compositions during such magmatic differentiation; addressing the lack of current AFC modelling approaches for felsic, amphibole- or biotite-bearing systems. We propose that Mt Kinabalu was generated through low degree melting of upwelling fertile metasomatised mantle driven by regional crustal extension in the Late Miocene.

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## Fataga volcanism on Gran Canaria

Ellis, B.S.<sup>1</sup>, Cortes-Calderon E.A.<sup>1</sup>, Neukampf, J.<sup>1</sup>, Mark, D.F.<sup>2</sup>, Wolff, J.A.<sup>3</sup>, Harris, C.<sup>4</sup>, Bachmann, O.<sup>1</sup>

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The ocean island volcano of Gran Canaria experienced a period of intense explosive volcanism in the Miocene. While the older portions of this activity (the Mogán Group) have been well-studied, the overlying Fataga deposits remain poorly known. Based on a new map (15 km<sup>2</sup> at 1:22,000) of the Fataga deposits we define a succession of 14 ignimbrites with 4 intercalated lavas. Utilising this strong stratigraphic framework we combine bulk rock and mineral geochemistry to document a shift through time from silica-oversaturated compositions (the Mogán Group) to silica-undersaturated compositions (the Fataga Group). Coincident with this change in silica-saturation,  $\delta^{18}\text{O}$  values decrease from the older Mogán deposits to the younger, more mantle-like, Fataga rocks. Together these observations are consistent with a decreasing role for the assimilation of sedimentary lithologies during the transition from Mogán to Fataga time. While these temporal compositional trends describe the evolution of the system in broad strokes, on a closer scale compositional variability within individual units also demonstrates the operation of processes internal to the magmatic system. Fataga ignimbrites commonly contain both crystal-poor phonolitic compositions and crystal-rich trachytic compositions, the latter thought to result from melting or entrainment of a cumulate pile dominated by alkali feldspar. Melting alkali-feldspar-dominated cumulates acts to push compositions away from the respective minimum (in this case the phonolitic minimum) and towards the feldspar join in the petrogeny's residua system and has been termed a 'trachyte attractor'. While the Mogán suite of rocks (thought to contain at least 14 ignimbrites) was emplaced relatively rapidly (on the order of 1 Ma), new high-precision <sup>40</sup>Ar/<sup>39</sup>Ar geochronology reveals that Fataga volcanism spanned at least 3 Ma.

## Earth's lithospheric mantle as a source for volatiles in magmas erupted in Large Igneous Provinces and continental rift zones

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Throughout Earth's history, the break-up of supercontinents has been accompanied by the largest volcanic eruptions (flood basalts) and millions of Mt of CO<sub>2</sub>, H<sub>2</sub>O and HF are believed to have been emitted to the atmosphere. In some cases, this contributed to mass extinction events. But where in the solid Earth are CO<sub>2</sub>, H<sub>2</sub>O and F that are emitted from volcanoes sourced? The global quantification of the flux of these highly volatile elements from the solid Earth to the exosphere is in its infancy. Most recent studies have focused on crustal processing and degassing by arc magmas but, over much larger areas, the flux of volatiles

from our planet's deep interior to its surface is modulated by the sub-continental lithospheric mantle; the layer that separates Earth's convecting mantle from its crust. Our work explores if this, the second largest and one of the most long-lived chemical reservoirs in the solid Earth, acts as a long-term source or sink for CO<sub>2</sub>, H<sub>2</sub>O and F. We combine geochemical analyses of minerals found in fragments of mantle material and geophysical data to provide internally consistent estimates of the quantities of these elements that are 'trapped' within the lithospheric mantle.

The subcontinental lithospheric mantle represents one of Earth's most long-lived and ancient chemical reservoirs. It potentially acts as both 'sink' and 'source' for volatiles (CO<sub>2</sub>, H<sub>2</sub>O, S, F, Cl, Li) and thereby plays a critical role in modulating their flux from our planet's deep interior to its atmosphere (via volcanism). Nevertheless, the volatile inventories of this major reservoir, and their variability beneath the continents and oceans, are poorly constrained. Geophysical studies have revealed large differences in the thickness and thermal structure of the lithosphere whereas mantle peridotites -- found as xenoliths, in orogenic massifs or dredged from the ocean floor -- show systematic variations in composition between oceanic, continental on- and off-craton settings. We combine high-precision *in-situ* analyses of volatiles in the most abundant, nominally volatile-free phases (olivine & pyroxenes) with their respective modal proportions to estimate concentrations of H<sub>2</sub>O, F and Li in lithospheric mantle from oceanic, continental on- and off-craton settings. We use these analyses together with new estimates of global volumes of lithospheric mantle (from surface wave tomography) to calculate volatile inventories at different tectonic settings.

Our findings reveal, for the first time, that the H<sub>2</sub>O, F, Li (and CO<sub>2</sub>) budgets of the lithospheric mantle at each major tectonic setting are all on the order of 10<sup>7</sup> to 10<sup>9</sup> Mt. For mantle with only nominally volatile-free phases these amounts vary according to incompatibility of the volatiles in percolating metasomatic melts, i.e. CO<sub>2</sub>>H<sub>2</sub>O>F>Li. When modal estimates of phlogopite and amphibole are included the volatile inventory of H<sub>2</sub>O and F increases by an order of magnitude. Our calculations show that the volume of lithospheric mantle beneath the global cratons exceeds that beneath continental off-craton and oceanic regions and is the greatest repository for H<sub>2</sub>O (8.55 x 10<sup>9</sup> Mt), CO<sub>2</sub> (3.53 x 10<sup>8</sup>), F (1.77 x 10<sup>9</sup>) and Li (8.13 x 10<sup>7</sup> Mt). Our internally-consistent estimates for volatile inventories provide important constraints on the potential of different regions of Earth's lithospheric mantle to act as a source of H<sub>2</sub>O, F, Li and CO<sub>2</sub> for melts generated during major rifting and heating events (e.g. Large Igneous Provinces).

## **Long-lived mantle metasomatism under the Kaapvaal Craton: The utility of large sample sizes in zircon U-Pb analysis of mantle xenoliths**

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Understanding the timing of metasomatic events is critical for understanding the evolution of the continental lithosphere and formation of its mineral deposits, but this is challenging in most mantle rocks due to a lack of suitable proxies. Zircon U-Pb is one of the few applicable systems used to date mantle metasomatism[1], as zircon growth can occur in metasomatic lithospheric peridotites. Small grain sample sizes are usually employed, yet mantle zircon from single hand samples often provide a wide range of dates. These data imply either long-lasting or episodic metasomatism, but typical sample sizes are insufficient to discriminate between these metasomatic styles. We have analysed zircon from mantle xenoliths hosted in kimberlite from the Kimberley region of the Kaapvaal Craton, South Africa, and have employed zircon sample sizes more typical of detrital provenance studies ( $n > 100$ ). Our larger sample sizes permit the elucidation of the metasomatic history of individual xenoliths.

Zircon dates are dispersed over the period 140 to 85 Ma (the age of kimberlite emplacement), with a modal peak at c. 100 Ma. Crystallisation is continuous over this time period, indicating long-lasting disequilibrium. The modal zircon age peak immediately precedes Group I kimberlite magmatism, which demonstrates that lithospheric mantle metasomatism was pervasive before kimberlite emplacement had begun. The initiation of melt extraction coincides with a marked decrease in metasomatic activity, at least as recorded by zircon. Whilst these data come from a limited number of xenoliths, they can be used to construct a relatively simple metasomatic model, which can be sensed only using large sample sizes. We propose a model, in which the continental lithosphere undergoes increasingly pervasive metasomatism until the initiation of Group I kimberlite melt extraction below the wider Kaapvaal Craton limits further metasomatic activity.

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## **Diamonds illuminate the nature of Earth's deep and dynamic carbon cycle**

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Carbon is omnipresent yet very mobile within the Earth system. The predominant mechanisms driving exchange between Earth's layers are diffusion, volcanism, and chemomechanical mixing (i.e., plate tectonics). A minor technical issue is that >90% of Earth's carbon is stored within the inaccessible interior (mantle + core). This means that tracing Earth's planet-wide carbon cycle is challenging, to say the least. However, there are windows into Earth's mysterious interior, and they're made of diamonds. Diamond is a chemically simple mineral comprised largely of carbon with trace amounts of nitrogen (~0.025%). The formation of these crystals sometimes traps fluid and solid inclusions (metasomatic fluids and mantle minerals,

respectively). Decades of diamond geoscience has shown us that the carbon cycle is dynamic with evidence for the interaction of subducted volatiles with indigenous mantle carbon during complex tectonothermal events, such as the subduction of crustal material and/or plume-lithosphere interaction [1].

Three main diamond types are recognised; monocrystalline, fibrous and polycrystalline. The latter, also known as diamondites, are a mixture of diamond intergrown with silicates and oxides [2]. We present major and trace element geochemistry alongside He-C-N-O stable isotope analysis from a suite of garnets and diamonds from diamondites sourced from the Orapa mine in Botswana. These data show that diamondites provide evidence for remobilisation of existing mantle carbon by subducted volatiles, ultimately resulting in a hybridised fluid [3]. Furthermore, the fluid rock interaction, modelled using the Deep Earth Water model [4], shows that metasomatism during diamond-formation can produce silicate-inclusions which do not reflect the geochemistry of the country rock in which diamonds form. Instead, the inclusions strongly reflect the initial, metasomatic, diamond-forming fluid. This diamondite-forming media is indistinguishable from the fluids which precipitate gem-quality diamonds in terms of major and trace element geochemistry. However, while the nature of the parental fluid(s) share a common lithophile element geochemical affinity, the origin(s) of diamond-forming carbon-rich mantle fluids do not always share a common origin.

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## **Ultramafic Lamprophyre on Tuttutooq Island, Gardar Province, S Greenland**

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The island of Tuttutooq lies within the Gardar province of Southern Greenland, adjacent to the settlement of Narsaq. The island is particularly known for two giant dyke complexes (the Older & Younger Giant Dyke Complexes, OGDC & YGDC), a central complex (the Tugtutooq central Complex) and expressions of the main Late Gardar dyke swarm [1]. Less frequently described are Ultramafic Lamprophyre (UML) bodies which are associated with Tuttutooq magmatism [2].

UML occurs as minor components of the magmatism of the Gardar province of Southern Greenland and are thought to be sourced from lithospheric mantle metasomites [3]. They

have been noted often to precede more voluminous magmatism; however, the bodies on Tuttutooq are thought to diverge from this trend [2]. Mapping of the two UML bodies on Tuttutooq Island has allowed for an investigation of their emplacement timings with implications for the rest of the Rift Province.

One of the UML bodies is crosscut by the younger members of the Late Gardar dyke swarm but not the older dykes, demonstrating that emplacement was broadly synchronous with the Late Gardar swarm. Field evidence from the other has led to the interpretation that it is a xenolith within the YGDC. Both interpretations differ from previous opinion and suggest that the number of UML occurrences of distinct age in the Gardar is broader than formerly thought.

We consider the UML as important components of the magmatic history of the region, representing low degree partial melts of sub-Gardar mantle. As such they provide insights into mantle composition and evolution. An extended catalogue of UML bodies including their field evidence and petrography, such as those described here, will allow for greater insights into the evolution of the mantle source for the entirety of the Gardar period.

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## **Intraplate Cenozoic magmatism in Mongolia: A legacy from the past?**

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Intraplate volcanic activity in Mongolia, East Asia, has occurred intermittently since the Late Cretaceous, until the present day. Mesozoic basaltic volcanism was widespread throughout much of the southern and eastern parts of Mongolia. It is thought that the volcanism was caused by widespread but patchy removal of lithospheric mantle from beneath parts of Mongolia, East China and Russia [1, 2]. In contrast, Cenozoic magmatism in Mongolia largely extends through the central parts of the country, from north to south; small plateaus are diffusely dispersed and are relatively small volumes (<30 km<sup>3</sup>) [3]. The exception to this is Dariganga plateau in the southeast where volcanic activity is represented by >200 volcanic cones, covering an area of >10,000 km<sup>2</sup>. The only area known to exhibit both Mesozoic and Cenozoic volcanism is the Gobi Altai, in the far south.

Although several models have tried to explain the Cenozoic magmatism in Mongolia, there is no clear evidence of what causes the volcanic activity. Here, we examine the possibility of a direct link between the late Mesozoic and Cenozoic volcanic events in Mongolia by assessing the melt sources of the magmatism, focusing on three contrasting regions. (1) In central Mongolia, Cenozoic basalts occur on the flanks of an uplifted dome (Hangai Dome), which is thought to have been uplifted in the Mesozoic [4] but did not experience any volcanism at

the time. (2) The Gobi Altai area experienced both Mesozoic and Cenozoic magmatism, separated by ~40-50 Ma gap, but did not undergo any Mesozoic uplift. And finally, (3) the Dariganga plateau, which has experienced extensive volcanism during the late Cenozoic but not during the Mesozoic and in contrast to Hangai, underwent Mesozoic basin development rather than uplift. We will compare and contrast mantle sources of these regions to determine whether Mesozoic events have influenced the composition of the Cenozoic magmatism.

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## **Highly oxidised magmas from El Hierro (Canary Islands) link volatile enrichment, mantle metasomatism and melt generation at low melt flux ocean islands.**

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El Hierro, Western Canary Islands, has been fed by exceptionally volatile-rich magmas over the last 20 ka [1,2]. The source of volatile enrichment is not yet fully understood, with both undegassed primitive mantle and recycled lithosphere in the melting region being possible explanations.

Here we present oxygen fugacity ( $fO_2$ ) data estimated using olivine-spinel pairs and glasses, together with temperature estimates for various stages of magma evolution. Spinel record  $fO_2$  of  $\Delta FMQ = 2.5 \pm 0.5$ , which is 1-2 log units higher when compared with melt inclusions and matrix glasses ( $\Delta FMQ = 0.5$  to 1.3). This indicates that primary melts at El Hierro are as oxidised as island arc basalts, and that the  $fO_2$  recorded by glasses is strongly affected by crystallisation and degassing. Oxidising conditions are coupled with spinel-olivine equilibrium temperatures of  $1300 \pm 20$  °C, which is 30°C higher than equivalent temperatures for MORB [3]. Olivine-melt and clinopyroxene-melt thermometers indicate temperatures of 1100-1250 °C. Rhyolite-MELTS modelling confirm that the spinels record near-liquidus temperatures, while olivine-melt and clinopyroxene-melt thermometers record the main crystallisation phase. Mantle potential temperatures for El Hierro, the Canary Islands and mid-Atlantic MORB are  $1346 \pm 49$  °C,  $1351 \pm 71$  °C and  $1426 \pm 33$  °C ( $1\sigma$ ), respectively. These estimates provide no evidence for excess temperature beneath the Canary Islands compared to closest oceanic ridge sections.

We propose that melting at El Hierro is driven by the upwelling of volatile-rich metasomatised mantle and recycled lithosphere from the transition zone. Melts rich in oxidised C and S originating from this material cause volatile enrichment, a decrease in solidus temperature, and oxidation of the silicate assemblage in the upper asthenosphere. Highly oxidised, low-degree melts from this metasomatised asthenosphere, possibly enriched in  $^{238}\text{U}$ , are the likely source of magmatism at El Hierro. A similar melting process

could explain magmatism at other low melt flux ocean islands with a HIMU isotope signature.

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## **Welding and Degassing of Peralkaline Ignimbrites, Main Ethiopian Rift**

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The Main Ethiopian Rift (MER) contains a number of central volcanoes that offer exceptional insight into the dynamic of peralkaline magmatism, yet the majority of them remain understudied. Understanding eruption dynamics of these volcanic centres is vital to volcanic risk assessment in the surrounding areas [1]. Ignimbrite deposits associated with the most explosive eruptions provide an important window to study these events.

Here we examine the petrography and geochemistry of ignimbrite samples associated with the caldera-forming eruptions of the MER volcanoes Aluto, Fentale, and Kone (collected by F. Iddon and K. Fontijn during the RiftVolc project). The samples were sourced from thin (<10 m) deposits that paradoxically contain features of intense welding throughout. Previous workers [2] have interpreted this as the result of extremely heterogenous eruptive processes, during which both degassed pumice fragments and undegassed magma were erupted, entrained, and deposited.

We present quantitative textural characteristics of these samples using Back-Scatter Electron imaging and light microscopy, with glass compositions determined using Electron Probe Microanalysis. Fiamme from these samples are consistently oblate and strongly aligned, while containing two distinct types of vesicle populations: (1) elongate and strongly aligned; (2) circular and randomly oriented (i.e. no apparent deformation). We find that fiamme with type-2 (commonly interpreted as 'revesiculated [3]') vesicle populations are compositionally distinct from their surrounding glassy matrix, notably in Cl (in which the fiamme is elevated by ~0.25 wt%). We used a coupled cooling-degassing model to explore the interplay between compaction, cooling, and composition during emplacement of the deposit to gain insights into the dynamics of peralkaline magmatism.

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## Session 5 – Monitoring and Forecasting

### **A new dataset of eruption source parameters devoted to eruptive column model evaluation.**

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Eruptive column models are crucial to the management of volcanic crises, to the forecasting of future events and to the reconstruction of past eruptions. Given their central role and the large uncertainties undermining their predictions, the evaluation and improvement of these models is critical. Such evaluation is challenging as it requires independent estimates of the main model inputs (e.g. mass eruption rate) and outputs (e.g. “the” column height). Despite recent efforts to extend compilations of independently estimated eruption source parameters (ESP), there is no standard, community-based ESP database devoted to the evaluation of eruptive column models.

We will present a new ESP dataset designed specifically for evaluating these models and aimed to become an online database open to the community. Data for over 120 eruptive events are gathered in the dataset with independent estimates of: i) the mass eruption rate; ii) the height reached by the column; and iii) atmospheric conditions during the eruption. In contrast with previous ESP datasets, we distinguish estimates of column height that relate to different phases (ash and SO<sub>2</sub>) and part of the column (plume top or umbrella). For all events for which they are available, we additionally provide the total grain size distribution, uncertainties on eruption parameters, and multiple sources for atmospheric profiles. The dataset includes a wealth of additional information, such as the morphology of the plume (weak/transitional/strong), enabling modelers to distinguish different eruptions when evaluating or calibrating models.

We will show preliminary results derived from this dataset. In particular, we will revisit empirical scaling relationships between the mass eruption rate and “plume height”, and how they depend on the type of event and plume height considered.

## Improving inverse model estimates of volcanic ash source characteristics using an ensemble of meteorological forecasts

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In the event of a volcanic eruption airlines need to make fast decisions about which routes are safe to operate and to ensure airborne aircraft land safely. Keeping passengers safe is of paramount importance but grounding and re-routing of aircraft comes with a large economic cost. As does increased maintenance and checks that need to be performed if an aircraft is deemed to have potentially encountered ash.

Currently these high-impact decisions are made using qualitative forecasts produced without any indication of uncertainty. Their deterministic nature means flight operators have incomplete information on the risk of flying following an eruption, resulting in overly conservative decisions being made. For instance, the eruption of the Icelandic volcano Eyjafjallajökull in April 2010 disrupted European airspace for thirteen days, grounded over 95,000 flights and is estimated to have cost the airline industry over £1 billion.

These qualitative forecasts are produced using dispersion models which rely heavily on estimates of the source term characteristics, including the plume height, mass release rate and the vertical distribution of ash, along with numerical weather prediction data. One method of determining a description of the source is to use inversion modelling to combine information from dispersion modelling and satellite retrievals. This gives an estimate of the source which varies in time and height which optimally fits both the ash concentrations from dispersion modelling and satellite observations of ash column loading. In the operational setting forecasts are produced using a single realisation of meteorological situation. This can lead to large discrepancies between the dispersion forecasts and the observed location of the ash.

In this presentation, the impact of using an ensemble of meteorological conditions to produce time varying emissions rate estimates using InTEM (Inversion Technique for Emissions Modelling), the UK Met Office inversion model, on forecasts of the location of ash following Grimsvotn 2011 eruption will be shown. Also presented will be initial work on determining which is the “best” source term estimate to use to produce the most representative ash forecast and how to communicate a large volume of uncertainty information in a clear and concise way to end users of the forecasts.

## OpenSO<sub>2</sub>: An open access approach to volcanic SO<sub>2</sub> flux measurements

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Quantitative measurements of volcanic SO<sub>2</sub> flux are important for understanding the role of volatile species in eruptive processes and monitoring active volcanoes for risk mitigation. SO<sub>2</sub> fluxes are also used to determine total volcanic emission budgets through a combination of measured in-plume molar ratios with other volcanic gases (such as CO<sub>2</sub>) and so are essential in understanding the impact of volcanic emissions on the climate [1, 2].

SO<sub>2</sub> fluxes are commonly measured from the ground using scanning UV spectrometer networks which allow high temporal frequency flux measurements to be collected automatically (approximately every 5 minutes). Many such networks have been installed at volcanoes worldwide [3, 4], but are often associated with large uncertainties from various sources including the plume geometry, speed and direction of the plume vector, and the spectral analysis process. These uncertainties can mask true patterns in the SO<sub>2</sub> flux and can lead to incorrect interpretations of volcanic processes if left unaccounted for.

We have designed a new platform, called OpenSO<sub>2</sub>, with which we aim to improve the future quality of SO<sub>2</sub> flux measurements by making the process as open and accessible as possible. OpenSO<sub>2</sub> has two components: hardware and software. The hardware is based on a Raspberry Pi single board computer and is designed to utilise commercially available components and pre-existing scanner technology. The software is entirely open source and freely available, making the system affordable, adaptable and accessible for all.

We will present the initial data from an OpenSO<sub>2</sub> scanner installed in March 2019 on Soufrière Hills Volcano, Montserrat, and discuss the performance and results so far.

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## Application of back trajectory modelling to TROPOMI SO<sub>2</sub> observations to retrieve sub-daily volcanic fluxes

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The use of polar-orbiting satellite instruments to monitor volcanoes has been an established technique for decades. However, a major limitation is the temporal resolution provided by these satellite platforms. For UV instruments, one or occasionally two observations per day are possible for tropical latitudes, though an improved temporal resolution is seen at high latitudes. The SO<sub>2</sub> altitude within the atmospheric column is usually highly unconstrained and is one of the largest sources of uncertainty within the SO<sub>2</sub> retrieval. This method assigns a best-fit altitude to each pixel, instead of using a single value for the whole plume.

TROPOMI is an UV spectrometer, launched on the Sentinel-5P platform in October 2017. The instrument has a swath of 2600 km and a spatial resolution of 5.5x7.5 km (improving to 3.5x7.5 km from August 2019). Sentinel-5P flies with the A-Train constellation, with an equatorial overpass time of 13:30 local time.

Applying the NOAA HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) back trajectory model, the injection time, injection and measurement altitudes of the SO<sub>2</sub> in each pixel within the satellite image is derived. Back trajectories are run for each pixel at a range of altitudes. The natural variability in the wind field at different altitudes (wind shear) means that only some of those trajectories will return to the volcano, constraining the measurement altitude to those trajectories. The SO<sub>2</sub> concentration is interpolated to this altitude. Finding the point in the trajectory when it most closely approaches the volcano provides the time and altitude of injection.

Combining the corrected SO<sub>2</sub> concentrations with the injection time produces the SO<sub>2</sub> flux that generated the observed SO<sub>2</sub> cloud, and with the injection altitude to calculate the mass eruption rate. These parameters can also be used to improve eruption plume modelling by improving the constraints on the eruption column characteristics.

## **How does a temperature-dependent viscoelastic regime affect spatiotemporal volcano deformation patterns?**

Head, M.<sup>1</sup>, Hickey, J.<sup>1</sup>, Gottsmann, J.<sup>2</sup>, Fournier, N.<sup>3</sup>

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Episodes of ground deformation, relating to the unrest of a volcanic system, are often readily identifiable within geodetic timeseries (e.g. GPS, InSAR). However, the underlying processes facilitating this deformation are more enigmatic. By modelling the observed deformation signals, the ultimate aim is to infer characteristics of the deforming reservoir; namely the size and time-dependent evolution of the system and, potentially, the fluxes of magma involved. These parameters can be estimated using simple elastic models, however the presence of shallow or long-lived magmatic systems can significantly perturb the geothermal gradient and invalidate the elastic approximation. Inelastic rheological effects are increasingly utilised to account for elevated thermal regimes, where a component of viscous behaviour is expected to characterise the observed spatiotemporal deformation field.

Here, our investigations are concentrated on Taupo volcano, New Zealand, the site of several catastrophic caldera-forming eruptions. We use 3D thermomechanical models of the Lake Taupo region, featuring thermal constraints and heterogeneous crustal properties, to compare the Maxwell and Standard Linear Solid (SLS) viscoelastic configurations under contrasting deformation mechanisms; a pressure condition (stress-based) and a volume change (strain-based). By referring to models allocated a single viscosity value, we investigate the influence of a temperature-dependent viscosity distribution on the predicted spatiotemporal deformation patterns. These models highlight the importance of the viscosity structure with regard to deformation timescales; enabling the SLS rheology to account for both abrupt and long-term deformation signals. We also examine the behaviour of the commonly-used Maxwell model, resulting from changes in viscosity, and query the suitability of this rheology in other model setups. Ultimately, we demonstrate that crustal viscosity variations greatly influence spatiotemporal deformation patterns, more so than heterogeneous mechanical parameters alone, impacting the inferences of the underlying processes. The inclusion of a viscosity distribution is therefore an important consideration when modelling volcanic deformation signals.

## **Repeating long-period earthquakes during November 2015 at Tungurahua Volcano, Ecuador**

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In November 2015 an episode of periodic, repetitive long period (LP) earthquakes occurred at Tungurahua Volcano, Ecuador, in a phenomenon known as ‘drumbeats’. Previously drumbeat seismicity has been attributed to ascent of degassed magmas in the conduit and plays a key role in understanding plug processes at Tungurahua. Unlike in previous observations, however, this episode did not culminate in eruption and appeared to be a more passive, decelerating process. Following a week of minor explosions, ash and magma extrusion and then seven days of quiescence, these drumbeats persisted for five days with minimal implications at the surface.

This study examines the emergence and decay of over 900 LP earthquakes, using quantitative and statistical tools to analyse individual events and broad trends across several hours. A cross correlation analysis is conducted to extract similar families of events throughout the sequence. Spectral analysis highlights 2 persistent fundamental frequencies common to over 50% of events in the sequence. Whilst periodicity of the binned event rates remains high, the temporal rate of decay is modelled with modified Omori’s Law. Despite this decay, amplitudes and Q values of individual events, and families remain constant through the sequence.

Using daily records of surface observations and additional radial tilt data we place the episode in the broader context of 2015 activity, relating this sequence to the April 2015 drumbeat episode and final explosions in March 2016. An integrated interpretation of the data suggests this drumbeat sequence represents a sealing process in the conduit plug following magma ascent and degassing. The persistent periodicity and amplitude of the

events, implies repeated loading and failure from a source, where the failure strength remains constant. Yet, the decaying rate suggests the source is slowing. This seismic observation therefore presents an interesting insight into magma ascent dynamics at Tungurahua. This assessment also has implications in volcanic hazard assessment as a key case study where heightened seismicity leads to an overall decreased state of activity.

## **Electric self-potential from strain-induced groundwater flow and its role in volcanic unrest monitoring**

Arens F.<sup>1</sup>, Gottsmann J.<sup>1</sup>, Hickey J.<sup>2</sup> and Kilgour G.<sup>3</sup>

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A pressurized magmatic intrusion will strongly interact with its surrounding by provoking changes in the subsurface stress and strain fields. As a result, nearby aquifers can experience pore pressure variations which in turn drive fluid motion. Induced subsurface flow can cause variations in the electrical self-potential (SP). The SP method has been widely used to map preferential fluid pathways, faults, feeder dykes and morphological features on many volcanoes. While studies highlight changes in groundwater flow and well water levels by poroelastic responses in volcanic environments, resultant SP signals have not been explored in detail.

SP measurements are inexpensive, non-intrusive and efficient and could be a valuable contribution to monitoring efforts if the link between subsurface stressing, induced fluid flow and resultant potential field anomalies is better understood. This study investigates SP anomalies resulting from shallow fluid flow driven by a dyke intrusion. Specifically, we use the Finite Element Analysis (FEA) method to generate coupled fluid and solid mechanics time-dependent multiphysics models to investigate the SP signal resulting from subsurface stressing. We perform a parameter space analysis to isolate the dominant parameters and material properties controlling subsurface strain, water level changes and resultant SP signals. As expected, preliminary results demonstrate that the magnitude, spatial pattern and temporal evolution of the SP signature varies as a function of elastic, fluid and electric properties of the subsurface. However, predicted magnitudes of SP signals at the ground surface range between mV and V in early-stage simulations, and match the range of values measured in volcanic areas. This provides an important proof of concept for our numerical approach; contributing new insights into subsurface processes associated with volcanic unrest and their quantification.

## Episodic volcanism recorded in coral skeletons

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The aragonite skeleton that is precipitated by a coral polyp provides a record of the chemistry of the water column in which it resides. For example, elements such as Sr have long been used as proxies for sea surface temperature and hence used to infer the state of the climatic system. Corals are commonly found on the submarine flanks of volcanic islands located within the tropics. Here, we investigate the ability of corals to record disturbances to the water column due to volcanic eruptions. We focus on corals located in distal locations, as corals located proximally to a volcanic centres are likely to be destroyed or significantly damaged by intense ash fall, gravitational collapses of the volcanic edifice or pyroclastic flows that enter the ocean. Analysing a coral sample that is located approximately 100km from a volcanic centre, we systematically measure the geochemical profile along the growth axis of the coral skeleton using LA-ICP-MS. We show that the coral skeleton records the eruptive activity as elevated levels in incompatible elements. Episodic explosive activity is also observed as spikes in Mg and Al in the coral skeleton. The prevalence of these signals varies along the skeleton reflecting changes in the modal mineralogy of ash clouds belonging to different explosive events.

## Session 5 - Posters

### Numerical modelling of volcanic deformation associated with time-dependent magma injection into a mush zone: A parametric study

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The melt dominated magma chamber has always been central to conceptual models of volcanic systems. Recently, however, this paradigm has been questioned and a new model suggested based on a trans-crustal magmatic system (TCMS), consisting of multiple lenses of high melt magmas within a larger mush zone. To test this, numerically, we will move beyond the widely used static, kinematic simulations for volcano deformation to a new dynamic approach. We introduce a novel model that addresses the process of injecting melt dominated magma into an existing mush-dominated magma reservoir (defined as a porous media) in a well-constrained physics-based finite element (FE) model. Using the fluid-structure interaction (FSI) module in the FE COMSOL Multiphysics software, we couple magma flow and deformation in the surrounding solid rock. Moreover, FE techniques are also capable of accounting for additional aspects of the subsurface and magmatic system that we will consider, including crustal rheological heterogeneities and temperature-dependent viscoelastic deformation. In this study, we focus on modelling the geodetic observations generated by magma of different viscosities ascending into an existing mush-dominated

reservoir from a deeper source. Our model consists of a Newtonian fluid ascending through a vertical conduit into a porous chamber; the fluid dynamics of the magma drive the time-dependent displacement observed at the surface. Preliminary results suggest that the flow recharge rate, as well as the dynamic properties of the magma, have a significant impact on the magnitude and the deformation rate observed at the surface. This study is the first step towards incorporating a full TCMS approach into volcano deformation modelling.

## **Multiple Pressure Source Numerical Modelling of the Sakurajima Volcano and Aira Caldera Magmatic System**

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Sakurajima, situated on the southern rim of Aira caldera, is one of the most active volcanoes in Japan. Long term deformation data suggests the caldera is approaching the inferred level before the 1914 VEI 4 Plinian eruption, increasing the need for a better understanding of the magmatic system.

Most geodetic modelling of the magmatic system feeding Sakurajima has thus far been conducted using analytical methods, primarily using the Mogi model. However, using analytical approaches has introduced limitations, such as using a homogeneous crust and spherical deformation sources, producing crude representations of the subsurface. Numerical modelling techniques can account for material heterogeneity, and given the wealth of multi-disciplinary data available around Sakurajima, can produce more robust models.

Whilst analytical modelling has suggested multiple deformation sources may be present beneath Aira caldera and Sakurajima volcano, the only numerical study suggested a single source. Using continuous geodetic data from Sakurajima and Finite Element (FE) modelling, this study will assess the validity of a multiple deformation source model using FE techniques, and constrain source parameters.

Preliminary work will analyse a series of stacked, isolated sources of varying shapes and depths to test the effects on predicted vertical and horizontal surface deformation patterns. We will simultaneously examine the effect in both homogeneous and heterogeneous model domains, to account for the effect of differing material properties with depth

A better understanding of the plumbing system of Sakurajima is imperative to improve interpretations of deformation data in the build-up to eruptions, with similar methods being applicable to volcanoes world-wide.

## **Using GPS and EDM to investigate the shallow magmatic system at Soufrière Hills Volcano**

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Ground deformation patterns offer vital insights into the activity of volcanoes, as well as the characteristics of the magmatic systems that feed them. The Soufrière Hills Volcano (SHV), a stratovolcano located on the Caribbean island of Montserrat, started erupting in July 1995, alternating phases of eruption and pauses in activity. Pauses have been marked by the absence of magma extrusion, but with a minimum daily SO<sub>2</sub> output average of 200t/day, and by continuous inflation of the island. The SHV is currently undergoing an extended 'pause' state in its anomalously long eruptive cycle, and it is unclear whether reactivation of the volcano will occur. The extended eruption has allowed for the installation of a comprehensive multi-disciplinary monitoring network, which has aided extensive research into the magmatic system underlying the volcano. However, the island's Electronic Distance Measurement (EDM) network has been underutilised in research, to date only being used for monitoring purposes. Utilising co-analysis of Global Positioning System (GPS) and EDM data, this MSc by Research study aims to delineate the modern shallow magmatic system conditions in order to investigate the status of the volcano.

Previous modelling studies on the SHV often assumed a homogenous or simplified heterogeneous elastic crust due to computational limitations. However, due to high heat flow associated with the Lesser Antilles volcanic arc, the crust (rheological medium) is likely to show viscoelastic behaviour. This study will examine the differences in how GPS and EDM data record deformation events, by experimenting with a range of shallow magma storage conditions and geometries in a simplified 2D viscoelastic medium representing SHV. Following this, the study will transition to 3D Finite Element modelling that incorporates SHV present topography, in order to delineate the shallow magmatic system in greater detail, and provide insight into how the shallow magma system has evolved.

## **Towards Imaging Cracking prior to Caldera Collapse with Seismic Anisotropy**

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Seismic anisotropy is the variation of seismic wave speed with direction and is most frequently observed using shear-wave splitting (SWS). Seismic anisotropy in the crust arises when microcracks in subsurface rocks are aligned, for example when the rock is under differential stress. When this occurs, the rock displays a directional variation in seismic velocity that may be used as a proxy for maximum compressive stress and it is also affected by the type of fluid filling the microcracks. Therefore, SWS analysis can be used to detect changes in stress and pore-fluid movement during volcanic activity.

Between April and August 2018, Kilauea Volcano produced lava eruptions in its Lower East Rift Zone (LERZ) and collapse events with phreatic explosions at its summit caldera. The rate at which the summit lava lake and shallow magma reservoir drained caused incremental

caldera collapse with unprecedented rates of seismicity and deformation. Even though similar activity has been seen before, it has never been captured with modern equipment and so this activity has provided a completely new data set and presents a unique opportunity to learn about the subsurface processes at Kilauea.

Using over 16,000 located events >M3 in four months in the Kilauea region, we have calculated SWS parameters. We observe changes in SWS throughout the eruption correlating with caldera collapse. We have inverted the SWS data to obtain 2D tomographic models of anisotropy at snapshots throughout the eruption and find that SWS can be used to indicate the development of cracks prior to collapse. In addition, we have mapped regions in which the anisotropy has not previously been investigated due to lack of data and find that, despite the apparent high stress and fluid flow associated with the eruption, anisotropy did not change significantly during the course of this eruption along the LERZ.

## **Working towards a multi-parameter machine learning approach to understanding the timing of eruption end**

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The timing and processes that govern the end of volcanic eruptions are not yet fully understood, and there currently exists no systematic definition for the end of a volcanic eruption. Currently, end of eruption is established by either generic criteria (typically 90 days after the end of visual signals of eruption) or volcano-specific criteria.

Machine learning can be applied as a tool to determine the timing of transitions in large and noisy datasets. Furthermore, machine learning approaches have been used, in the fields such as healthcare, finance and meteorology, to recognise non-linear patterns in data that traditional analyses failed to detect. Machine learning represents a tool for detecting when the pattern of seismic activity significantly changes, potentially signalling the onset or end of volcanic activity. Our previous work has involved successful classification of time series derived from single-station seismic data for two volcanoes displaying contrasting eruptive styles, which yields end-dates in agreement with previous, non-physical definitions of eruption end.

We are now expanding on this work to include a variety of datasets in the classification study, in addition to the time-series of seismicity. The 2006 eruption of Augustine Volcano, Alaska, represents an excellent case study due to the large number of datasets associated with the eruption and related phenomena. We shall present a status report on this ongoing work.

## Volcanic gas chemistry and flux from Bagana: a major “known unknown” deep carbon source?

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Bagana (Papua New Guinea) is among Earth’s youngest and most active volcanoes. Its activity comprises multi-year episodes of lava extrusion interspersed with pauses characterised by strong passive degassing. Based on satellite observations over the last 15 years, Bagana is the third ranked global source of volcanic sulfur dioxide. Recent work—based on global correlations between volcanic gas composition and magma trace element chemistry—has predicted that it may be the fifth ranked global volcanic deep carbon source. To date no direct measurements exist to validate this suggestion.

Bagana is remote, steep, and highly active. Measuring the composition of its summit gas plume poses a formidable challenge. We present the first measurements of gas chemistry from Bagana, achieved by unoccupied aerial system (UAS) flights through the plume, with a miniaturized MultiGAS payload. Our UASs fly beyond visual line of sight at ~6 km distance and ~2 km altitude. We also present simultaneously acquired SO<sub>2</sub> flux measurements made by UV camera and DOAS traverses made under the plume using a vertical take-off UAS. These two datasets allow us to calculate the first volatile budget (H<sub>2</sub>O, CO<sub>2</sub>, SO<sub>2</sub>) for Bagana volcano. We find, overall, that Bagana’s emissions are on the order of 400 td<sup>-1</sup> SO<sub>2</sub> and 1300 td<sup>-1</sup> CO<sub>2</sub>. We interpret these low emissions to be a consequence of low magmatic unrest and high shallow scrubbing, and caution that assumptions of persistent high gas flux from variably active volcanoes may need to be revised globally.

We also present highlights from recent and continuing work on Bagana, drawing on satellite observations of SO<sub>2</sub> emissions and lava extrusion, as well as chemical and textural analyses of erupted lavas. We discuss the potential pre-eruptive processes and source reservoir conditions that influence the overall high fluxes of magma and volatiles from depth at Bagana.

## Generating long period and tremor-like seismicity without fluids in volcanic materials

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Volcano seismicity is routinely used in the remote monitoring and forecasting of activity at volcanoes around the world. The nature of this seismicity varies, but long period (LP) seismicity is generally interpreted as an indicator of fluid migration, and as a potential precursor of increased activity at the surface. We employ acoustic-emission to monitor rock deformation experiments using weak volcanoclastic sediments at a range of strain rates. These produce microseismic events which are spectrally indistinguishable from long-period and tremor seismicity observed in natural volcanic settings, with the effect most noticeable at low (visco-elastic creep) strain rates.

Given the ubiquitous nature of slow edifice deformation, and the frequent occurrence of such low cohesion materials in the upper edifice of volcanoes, we suggest low frequency seismicity in volcanic settings does not require fluid movement; It may also be an indicator that strain is being accommodated by weak material within the edifice.

## Effect of light dilution on passive UV spectroscopy of volcanic SO<sub>2</sub>

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Monitoring of SO<sub>2</sub> flux is regarded as a key function of most volcano observatories, as magmatic gas flux and magma dynamics that control eruptive activity and unrest are strongly coupled. Such monitoring therefore aims to detect any pre-eruptive changes in SO<sub>2</sub> emissions. SO<sub>2</sub> flux is also used in combination with gas ratios such as CO<sub>2</sub>/SO<sub>2</sub>, allowing quantification of CO<sub>2</sub> fluxes from volcanoes. Studies of CO<sub>2</sub> flux from volcanoes worldwide help inform our understanding of the global geological carbon cycles. High precision and accuracy in SO<sub>2</sub> flux quantification is therefore critical.

Here, we show that current methods to analyse the UV spectra collected by routine volcano SO<sub>2</sub> flux monitoring are potentially flawed, particularly during critical pre-eruptive and eruptive periods where high quality data are most important. We focus on the impact of light dilution, where light scatters into the field of view of the spectrometer in front of the plume, reducing the measured SO<sub>2</sub> densities. Further, we find that when this effect is present there

is an effective upper limit on how much SO<sub>2</sub> can be detected, meaning that large pre-eruptive peaks in SO<sub>2</sub> emissions may be missed. We highlight that monitoring of many of the world's most active volcanoes are likely to be greatly affected by this process, as the distance from plume to sensor is greater than several km.

Our analysis shows that analysing two wavebands, similar to [1], provides a simple and easily deployed method to detect the presence of light dilution and to correct it. The effect of light dilution always produces underestimates in SO<sub>2</sub>, potentially greater than an order of magnitude, and that this implies that our current understanding of global volcanic fluxes may be significantly underestimated.

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## **Small flank failure of Anak Krakatau Volcano caused catastrophic December 2018 Indonesian tsunami**

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On 22 December 2018, flank failure of the Anak Krakatau volcano in Indonesia generated a tsunami that killed more than 400 people. This event is the first volcanic island flank collapse to be captured by a complete suite of satellite remote sensing, eyewitness accounts, seismic and infrasound monitoring stations. These observational data have allowed for multiple studies to try to reconstruct the events that led to the tsunami, and to investigate its impact. Volcanogenic tsunamis are one of the deadliest volcanic phenomena and this event represents a unique opportunity to improve our understanding of their triggering processes to help develop appropriate monitoring and mitigation strategies.

In this study, we combine historic observations with satellite data and anecdotal reports to interpret the internal architecture of Anak Krakatau, and reconstruct the failure, tsunamigenesis, and regrowth processes. Importantly, our study uses SAR (synthetic aperture radar) data from 8 hours after the tsunami to constrain the volume of material involved in the initial tsunamigenic flank failure and find that it was relatively small (~0.1 km<sup>3</sup>). Despite the small size, the flank failure was able to generate rapid tsunami waves with devastating impacts and changed the eruption to an explosive phreatomagmatic style. These eruptions destroyed the summit, as seen on the later SAR and true-colour satellite images, before partially rebuilding the lost flank. The findings demonstrate that hazard assessments at ocean islands must consider that even small flank failures, during unexceptional eruptions, can have catastrophic consequences. This work demonstrates the rapid first analyses that can be done

with remote sensing to inform hazard analyses and risk mitigation strategies in the short-term with low-latency freely available satellite remote sensing observations.

## Session 6 – Hazard Risk and Communication

### **Integrating hazard, exposure and vulnerability for risk assessment and management: the case study of Vulcano island, Italy**

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Risk assessments in volcanic contexts are complicated by the multi-hazard nature of both unrest and eruption, which can occur over a wide range of spatial and temporal scales. The contribution of various dimensions of vulnerability (e.g. physical, systemic, social, economic) evolve throughout phases of preparedness, emergency and recovery and dictate how exposed communities will be affected and whether they can return to a certain degree of normalcy and if so, under what conditions and timeframe. Although several risk assessment methodologies have been proposed, none is currently able to comprehensively capture the multi-dimensional and dynamic nature of vulnerability and risk towards volcanic hazards and, instead, tend to focus on individual aspects of hazards whilst considering a static vulnerability framework. As an attempt to capture the multi-dimensional and dynamic nature of volcanic risk, we developed a conceptual approach that focuses on two temporal dimensions that authorities address in a volcanic context: short-term emergency management and long-term risk management. In most volcanic crises, the first objective is to minimize fatalities or injuries by evacuating people from hazardous areas. In contrast, long-term risk management is based on a risk analysis that identifies key areas where mitigation actions could and should be implemented in order to reduce the consequences triggered by a volcanic event. The proposed approach has evolved over a decade of study on Vulcano island (Italy). Recent signs of volcanic unrest there combined with uncontrolled urban development, including commercial businesses and critical facilities, and significant seasonal variation of exposed populations result in significant variations in volcanic risk.

### **Trace element emissions during the 2018 Kīlauea Lower East Rift Zone eruption**

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The 2018 eruption on the Lower East Rift Zone of Kīlauea, Hawai'i released unprecedented fluxes of gases (>200 kt/d SO<sub>2</sub>) and aerosol into the troposphere [1,2]. The eruption affected air quality across the island and lava flows reached the ocean, forming a halogen-rich plume as lava rapidly boiled and evaporated seawater.

We present the at-source composition – gas and size-segregated aerosol – of both the magmatic plume (emitted from 'Fissure 8', F8) and the lava-seawater interaction plume (ocean entry, OE), including major gas species, and major and trace elements in non-silicate aerosol. Trace metal and metalloid (TMM) emissions during the 2018 eruption were the highest recorded for Kīlauea, and the magmatic 'fingerprint' of TMMs (X/SO<sub>2</sub> ratios) in the 2018 plume is consistent with measurements made at the summit lava lake in 2008 [3], and with other rift and hotspot volcanoes [4,5].

We show that the OE plume composition predominantly reflects seawater composition with a small contribution from plagioclase +/- ash. However, elevated concentrations of some TMMs (Bi, Cd, Cu, Zn, Ag) with affinity for Cl-speciation in the gas phase cannot be accounted for by the silicate correction and therefore may derive from degassing of lava in the presence of elevated Cl<sup>-</sup>. In the case of silver and copper, concentrations in the OE plume are elevated above both the F8 plume and seawater.

At-vent speciation of TMMs in the F8 plume during oxidation (following a correction for ash contributions) was assessed using a Gibbs Energy Minimization algorithm (HSC chemistry, Outotec Research). We also demonstrate the sensitivity of speciation in the plume to the concentration of common ligand-forming elements, chlorine and sulfur. These results could be used as initial conditions in atmospheric reaction models to investigate how plume composition evolves as low-temperature chemistry takes over.

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## **Analogue experiments on the effect of shear on sedimentation from volcanic clouds**

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The dispersal and sedimentation of ash from volcanic clouds presents a hazard both proximally (e.g. human respiratory health, roof collapse) and distally (e.g. aviation traffic). This creates a need for accurate parameterisations of ash sedimentation processes. Recent studies have demonstrated that sedimentation can occur through downward-propagating columns of ash (ash-fingers) that form from settling-driven gravitational instabilities at the base of the volcanic cloud. Whilst the precise conditions that allow their formation are yet to be determined, these fingers are thought to enhance sedimentation of fine particles and have been witnessed at eruptions from numerous volcanoes such as Eyjafjallajökull (Iceland) and Mt. Etna (Italy). Recent studies have started to characterise ash-fingers through field studies and analogue experiments, though thus far there has been no consideration of how finger formation and the resultant sedimentation rate are affected by shear.

We present results from analogue experiments where a buoyant, particle-bearing, fresh-water gravity current propagates above a denser, sugar-solution environment. The propagation speed increases with the density difference between the two fluids and by varying the initial density ratio, we observe different behaviours depending on the relative timescales of spreading and settling. For fast spreading, shear inhibits sedimentation as particles remain suspended in the current. In contrast, slow spreading allows sufficient time for sedimentation, forming visible fingers produced by the settling-driven gravitational instability. In an intermediate regime, shear instabilities modulate the gravitational instability, grouping fingers into larger-wavelength downwellings.

We systematically characterise the observed behaviour according to the occurrence and interaction of gravitational and shear instabilities and present our results in terms of dimensionless quantities including the ratio of spreading and settling timescales. These parameters can then be used to scale and compare our results to the natural system.

## **The buildup of molten volcanic ash in jet engines; simulating the role of magma composition, ash particle size and thermal barrier coatings.**

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Volcanic ash can cause major disruption to commercial aviation. The primary concern is the build-up of ash deposits which can interfere with the flow regimes within jet engines leading to loss of thrust [1]. Limits are placed on the acceptable ash exposure for commercial aircraft flying in and around eruptive events [2]. The role of ash composition is known to be an

important variable but the rate of deposit build-up, the nature of the deposits and how this is affected by interaction with ceramic thermal barrier coatings is not well understood.

We discuss experiments using ash from seven compositionally diverse volcanoes (Figure 1a). The ash is heated and deposited onto coated and uncoated Nickel alloy targets at temperatures matching those of modern engines. Measurements of the mass and volume of the ash deposits are used to calculate parameters that influence reduction in the most critical flow passage area within the engine.

For the realistic range of fine ash sizes tested we find a clear trend of increasing deposition rate with particle diameter. After correcting for particle size, there is no clear influence of ash composition on the rate of build-up of deposit in terms of mass. However, an important finding from our study is that ash from more silicic volcanoes forms a relatively low density deposit, with significant vesicularity implying an increased level of reduction of flow area for a given mass of ash deposited. It is also clear that ash remains adhered to ceramic coatings more efficiently than bare metal.

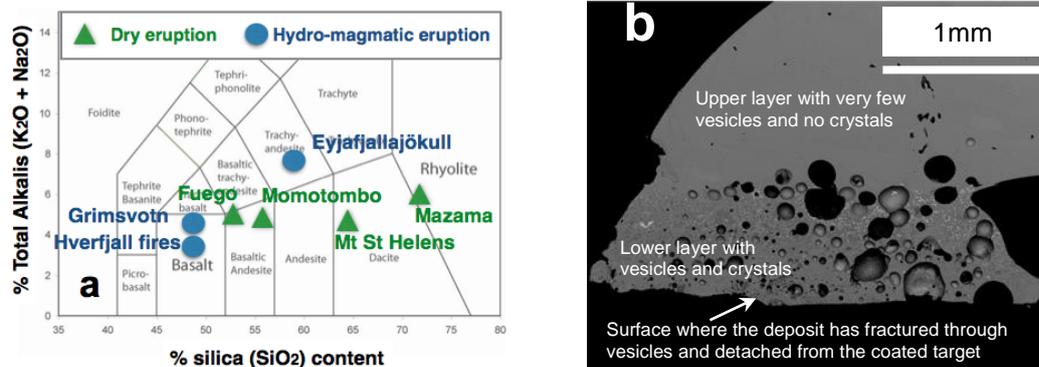


Figure 1. a: The volcanoes used in the study b: Hverfjall Fires ash deposit.

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## **Fireside tales: Local experiences of the recent eruptive activity of Volcán de Fuego, Guatemala, and factors affecting the decision to evacuate**

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The danger of Volcán de Fuego was demonstrated in the eruption of 3<sup>rd</sup> June 2018, when a series of pyroclastic flows descended Barranca Las Lajas and buried the community of San Miguel Los Lotes, resulting in hundreds of deaths.

Since 2015, Fuego has entered a new eruptive regime, consisting of explosive paroxysmal eruptions occurring every 30 – 45 days and preceded by lava effusion [1]. The 3<sup>rd</sup> June eruption is only one of the most recent of a persistently active volcano and illustrates that a typical paroxysmal eruption of Fuego can rapidly develop into a greater hazard. Therefore, making the decision to evacuate from a paroxysm may mitigate the exposure of local people to volcanic risk [2]. However, there is a lack of recent<sup>1</sup> information available about locals' experiences of Fuego's activity. Neither do we know what factors are important to them in their responses to volcanic activity. Both areas have critical implications for understanding local responses to future eruptive crises at Fuego.

There are approximately 30 communities within 15 km of Fuego's summit. In early 2019 we conducted an investigation among 10 of these communities on locals' experiences of eruptive activity and factors affecting their decision to evacuate or not during eruptive crisis. The investigation consisted of semi-structured interviews and participant observation and was supplemented by interviews with INSIVUMEH scientists and CONRED staff.

We discovered significant differences between the observations illustrated in [1] and local experiences of Fuego's activity. Furthermore, a clear dichotomy emerged between communities on Fuego's west and east flanks in terms of lived experience of 20<sup>th</sup>-century eruptions and in communication with INSIVUMEH and CONRED.

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Within the last five years: The most recent studies on volcanic risk at Fuego are the PhD theses of Kate Graves (2007) and Rüdiger Escobar-Wolf (2013), both of Michigan Technological University (MTU).

## **The use of social media in volcano science communication - challenges and opportunities**

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Volcano eruptions have always received considerable attention in the print, online, TV and radio news. These tools are also used by authorities to communicate to the public during a volcanic crisis. Recently, social media are tools that give members of the public unprecedented access to volcanologists, volcano observatories and institutions and amateur volcanologists. There are over 3 billion internet users using social media sites, and these numbers are expected to grow. Thus, social media is a powerful tool that can be used by volcanologists, volcano observatories and disaster management authorities to engage the public, particularly during times of volcanic crises.

During a volcanic crisis, effective communication between the institution responsible for monitoring the volcano, local government, civil defence authorities, the media and ultimately the public is essential to ensuring safe management of the crisis. The rapidity in which news can be posted and then disseminated through social media can allow for quickly disseminating information, sharing official sources of information, seeing rumours forming in real time and addressing them, and having a two-way conversation (answering questions) with the public. However, incorrect information can be spread just as rapidly.

Here we summarise the opportunities and challenges that a volcano-community presence on social media brings to crisis management based on our experiences, discussions with colleagues and observations during recent events. We identify a clear and urgent need for research on the effectiveness of social media channels which are increasingly becoming the dominant line of both official and unofficial communication during a volcanic crisis. This research should provide the evidence-base required to update the 'Professional conduct of scientists during volcanic crises' for a social media context and ultimately improve communication during a crisis with the aim of reducing the impacts of volcanic eruptions.

## Session 6 – Posters

### **Volcanic Unrest as the Crucible of Disaster: lessons from 20<sup>th</sup> Century Caribbean ‘undisasters’**

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The uncertainty that pervades volcanic unrest compromises clarity in decision-making processes which can prevent effective actions to mitigate the impacts of imminent activity. Dissecting volcanic events that escalate into eruption and disaster then represent only half the story.

We address that here by examining de-classified materials from episodes of unrest that did not escalate at two Caribbean volcanoes. This time series of correspondence from politicians, civil servants, scientists and community members are related to observed unrest signals, providing multiple perspectives on volcanic unrest. The examined episodes occurred on Montserrat in 1897-1899, 1933-38, and 1966-67 and we include the 1971-72 eruption on St. Vincent, where activity did not escalate into an eruption with significant physical impacts.

The particularity of volcanic unrest crises, their uncertain timescales and outcomes pose strong challenges for decision-making. Volcanologists need to be engaged on long time-scales in a proactive rather than responsive mode: and this is not always done. Once there, scientists can be agents for confusion, particularly when they focus on the deployment of new or cutting edge instrumentation to an audience eager to interpret this as a means to lower scientific uncertainty. Finally, the difficulties in declaring the end of volcanic activity contribute to the maelstrom of uncertainty-driven inertia. The ‘sigh of relief’ during effusive stages overwhelms the need for preparedness for future escalations, and creates problems in emergency response systems.

This analysis points to important lessons at the interface between volcanology and disaster management: a need to identify and communicate the length and implications of unrest episodes and to consider synergies and divergences with other hazard contexts; the need for volcanologists to focus on the outcomes of new techniques and instrumentation from the perspective of decision-makers when communicating their deployment; and the need to understand, forecast and communicate the end of eruptions, and changing eruptive activity.

### **Counting currents: correlating flow units to understand how pyroclastic density currents wax and wane in time and space**

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The number of pyroclastic density currents (PDCs) generated during an eruption is typically interpreted using stratigraphic evidence for a hiatus in flow that defines discrete “flow-units”. However, PDCs are unsteady and non-uniform, potentially complicating interpretation of flow units with distance from the vent. Full understanding of the number and behaviour of PDCs during an eruption can be important for hazard assessment but is generally lacking due to a paucity of proximal ignimbrite exposures.

This study interrogates PDC behaviour in time and space by correlating well-exposed proximal and distal counterparts of the 273 Ka Poris ignimbrite on Tenerife. Previous work has shown that only one flow hiatus is recorded in the proximal succession [1], whereas the distal succession, 15-20 km away, records at least three [2,3].

Correlation was undertaken by identifying temporal correlatives in lithofacies architecture, known as entrachrons [4], and verified with XRF analyses. Entrachrons include (1) green obsidian fragments in the proximal Plinian fallout and the lowermost distal Plinian unit (Hidalga M.), (2) distinctive accretionary lapilli with grey cores in a proximal discontinuous ash layer and a distal lapilli tuff (Magua M.), (3) a lithic-block layer marking caldera collapse in the proximal and distal successions, and (4) an abundance of mafic and banded pumices above the lithic-block layer. A proximal hybrid unit and an upper distal Plinian fallout unit (Caballos M.) both contain distinctive pale green pumice clasts and are linked geochemically by their relatively low Zr content.

The distal Poris succession records the passage of at least four density currents, whereas the proximal succession records just two. The correlation and lithofacies analyses show that the first PDC was relatively short-lived and is recorded similarly in proximal and distal locations. The second PDC evidently was highly energetic, sustained and unsteady. Periodic waning of this later current formed two widespread hiatuses in the distal zone, recorded in an ash bed and a second Plinian unit, while deposition continued proximally. During these waning events, proximal deposition was particularly unsteady, creating stratification and localised hiatus. This work highlights caveats of flow unit interpretation and identifies potential for future experimental work modelling deposition from highly unsteady pyroclastic density currents.

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## **Global mapping of citizen science projects for disaster risk reduction**

Hicks, A<sup>1</sup>, Barclay, J<sup>2</sup>, Chilvers, J<sup>2</sup>, Armijos, T<sup>3</sup>, Oven, K<sup>4</sup>, Simmons, P<sup>2</sup>, Haklay, M<sup>5</sup>

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Citizen science for disaster risk reduction (DRR) holds huge promise and has demonstrated success in advancing scientific knowledge, providing early warning of hazards, and contributed to the assessment and management of impacts. While many existing studies focus on the performance of specific citizen science examples, our study goes beyond this approach to conduct a systematic global mapping of citizen science used for DRR in order to draw out broader insights across diverse methods, initiatives, hazards and country contexts. Our systematic mapping enabled us to analyze a total of 106 cases of citizen science applied to DRR across all continents. Unlike many existing reviews of citizen science initiatives, relevance to the disaster risk context led us to ‘open up’ our mapping to a broader definition of what might constitute citizen science, including participatory research and narrative-based approaches. By taking a wider view of citizen science and opening up to other disciplinary practices as valid ways of knowing risks and hazards, we also capture these alternative examples and discuss their relevance for aiding effective decision-making around risk reduction. Based on this analysis we draw out lessons for future research and practice of citizen science for DRR including the need to: build interconnections between disparate citizen science methods and practitioners; address multi-dimensionality within and across hazard cycles; and develop principles and frameworks for evaluating citizen science initiatives that not only ensure scientific competence but also attend to questions of equity, responsibility and the empowerment of those most vulnerable to disaster risk.

### **FLOW: Unlocking the potential of the arts in volcano communication**

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Communicating scientific insight into volcanoes and associated hazards to the public is a key component of volcanic risk reduction that the volcanological community is becoming increasingly involved in. Public engagement is about sparking curiosity and starting a dialogue with the audience, therefore it needs to be intuitive and collaborative in nature. This prescribes a need to translate challenging research and complex scientific language into more accessible forms. One avenue to achieve this is the use of artworks, as art can speak to people new and interesting ways, particularly in engaging with and addressing the emotions associated with volcanic activity.

Here, we present ‘FLOW’, a 3m tall, freestanding LED column visualising magmatic processes in the volcanic conduit at Soufrière Hills volcano, Montserrat. The artwork is the centrepiece of an exhibit showcasing the history of the Soufriere Hills volcanic crisis and the cultural

response of Montserratians, which was developed for and in collaboration with Montserratian communities. The current iteration of FLOW shows a 1.5D representation of magma ascent, bubble growth and degassing, linked to recordings of corresponding seismic events. This magmatic sequence alternates with ash fall animations and lightning effects accompanying audio recordings of calypsos written by Montserratians in response to the eruptive activity. The model is currently being modified to use physical models in order to recreate scientifically accurate magma ascent patterns and even eruption cycles tailored towards Soufrière Hills.

FLOW had an exceptional reception at UK-based science festivals and art exhibitions as well as in Montserrat. The strong audio-visual appeal of FLOW naturally draws people in and creates a space of curiosity and dialogue. The versatility of the artwork offers various opportunities for further use in Montserrat and at other volcanoes, and its success shows the great potential of art as collaborative tool in volcano risk reduction.

### **Using serious games to raise awareness on geological hazards and risk management – lessons learned from applications in Central Africa**

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Improving the risk perception and understanding of risk reduction strategies of population and DRR managers exposed to natural hazards is essential to reach the objectives of the Sendai Framework. This is especially crucial in contexts where the risk governance remains rudimentary and hazards are infrequent. Being highly interactive, serious games are an engaging sensibilization method that offer the opportunity to expose players to a complex risk situation. It gives space for training problem-solving and decision-making skills, testing different strategies, observing and exchanging information with others, while experiencing the consequences of disasters in a safe and entertaining environment.

In this contribution, we report on the use of the serious game *Hazagora* in different countries in Africa, especially in the city of Goma, D.R.Congo, in the Virunga Volcanic Province. *Hazagora* is an educational board game during which the players have to develop their livelihoods on an island regularly exposed to a range of natural hazards (lava flow, tephra fall, flood, landslide and earthquake). Each player aims at fulfilling the basic needs of its community while strengthening their resilience to disaster with preparedness measures. The game was extensively tested in secondary schools as well as with risk managers. The learning outcomes of the game were tested using a pre-post questionnaire approach. Feedback from participants also highlights the advantages and limitations of such serious games relative to more traditional educational methods. *Hazagora* game appears to positively enhance the players' insights into processes involved in disasters, while being fun to play and generating the active engagement of the player. As such, the game is an efficient fun learning tool to introduce participants to the concepts of natural hazards, risk and disasters. It also proved to be a

suitable tool to generate discussions among risk managers, enhancing horizontal communication, emotional engagement and cooperation among players.

## **Identification of Holocene tephra in the Northern Pennines, UK**

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The effects of volcanic eruptions can be felt on inter-continental scales, and the UK remains at risk of ash (tephra) inundation from Iceland. Airborne volcanic ash represents a major hazard for the aviation industry. Detailed records of Holocene eruptions that provide information on how frequently ashfall affects the UK and which parts of the UK are most affected, are required for planning and mitigation. Spatial gaps exist within the tephrostratigraphical record in the UK, and the North of England remains sparsely studied. This study aimed to address this by quantifying tephra inundation frequency at Walton Moss peatland, Cumbria. Two boreholes, comprised of three peat cores each were extracted, spanning a depth interval of 150cm. Samples were prepared using the combustion method, mounted onto glass slides, and viewed under a light microscope to identify particle abundance and morphology. 16 cryptotephra layers were identified, with 5 showing particle counts >200. Age-depth models indicate each borehole represented the period 838CE-597BCE (1450 years). A high degree of variation in the ash-particle morphology of individual layers emphasizes the stochastic nature of pyroclastic dispersal in this region, and volcanic products appear in the geological record of this region at a recurrence of approximately twice per century throughout the Holocene. The findings of this study support prior research indicating a high-frequency of ash-fall events over the UK. Future work in this location should conduct geochemical analysis to confirm the sources of these tephra layers.

## **An integrated approach to understanding volcanic hazards on Saint Kitts and Nevis**

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Saint Kitts and Nevis lie in the northern part of the Lesser Antilles island arc, an archipelago formed by the subduction of the North American plate beneath the Caribbean plate. These volcanic islands are all examples of Small Island Developing States (SIDS); social and economic development has been significantly influenced by a range of natural hazards.

To understand the potential hazards posed by Mt Liamuiga, and the other volcanic centres on St Kitts and Nevis, it is important to characterise their past activity. Published literature that draws on the historical record implies that there may have been activity on St Kitts as recently as 1690 and 1843 coincident with significant earthquakes, while volcanic activity at Nevis is thought to be significantly older, based on radiometric dating.

Here we present a re-examination of historical disaster events on Saint Kitts and Nevis, compiled directly from archival investigations, alongside the preliminary findings from fieldwork on the islands. This field campaign has sampled deposits that represent the most recent eruptions on each island. Petrological and geochemical techniques will be combined with our field observations of deposit character and heterogeneity to unravel the nature of the magmatic systems and the conditions that led up to the triggering of the youngest eruptions on both islands. This information, combined with modelling of the runout and impact of the inferred volcanic phenomena generated during future eruptions, will lead to an improved understanding of the hazard and associated risks posed by further volcanic activity on these islands.

## **Assessing long-range volcanic ash impacts: effects of regional volcanic eruptions on UK infrastructure**

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Volcanic ash layers have been found across northern Europe and the recent eruptions of Eyjafjallajökull (2010) and Grímsvötn (2011) in Iceland deposited ash in the UK. In addition to Icelandic eruptions, it is feasible that in the right wind conditions and with a large enough eruption, ash from Italy, the Azores, Canaries or Greece may reach the UK. In this study, we assess the potential for volcanic ash impacts on UK infrastructure, and present a probabilistic assessment for likelihood of volcanic ash hazard to UK from multiple potential volcanic sources.

We identified volcanoes within 3000 km of the UK as capable of producing ash that could reach the UK, clustered volcanoes into regional sources, and developed frequency-magnitude relationships for each source that account for the time-limited quantity and quality of historical eruption data. We then analysed meteorological conditions over Europe through the use of synoptic (1000 km scale) weather patterns and determined their probability of occurrence. These were used as forcing for dynamic ash dispersal modelling using Fall-3D to simulate the dispersal and deposition of volcanic ash from each source, eruption size and for each meteorological condition.

Model simulations suggest that all synoptic weather patterns and eruption sources can result in ash reaching the UK. The annual probability of ash from a volcanic eruption exceeding a ground level concentration of 0.5 mg/m<sup>3</sup> at a UK location is about 1 in 300, and the majority of ash particles will be smaller than 10 microns (respirable; PM<sub>10</sub>). We found that Iceland is the dominant source for ash hazard for the UK because of its relative proximity, frequency of eruptions and often favourable wind conditions, but larger eruptions of volcanoes in Italy, the Canaries and the Azores could also result in ash deposition on the UK.

## **Mapping Spatter Ramparts from the 1944 Eruption of Mount Vesuvius**

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Spatter ramparts are a common volcanic feature and are present around the rim of Mount Vesuvius, Italy from the eruption in 1944. They can build up and result in rootless lava flows down the flanks of the volcano which can be a risk to the local population. Mapping these features allows for more accurate hazard maps to be created for the area, better preparing those who live in the areas at risk. Observations were carried out at the crater rim, with detailed sketches being drawn of each of the protruding spatter ramparts, as well as observing their progression down the flank of the volcano. Results showed that protruding features around the crater rim are indeed spatter ramparts, having been formed during the lava fountaining phase of the eruption from the Grand Cone with deposition locations being influenced by the wind direction. This spatter, being predominantly from phase two of the eruption, is well vesiculated with an average of 48% vesiculation within these deposits. At a number of sites around the crater rim these formations agglutinated and remobilised, resulting in a rootless lava flow down the flank of Mount Vesuvius. The end of these flows is difficult to distinguish due to the presence of vegetation covering the landscape. Depending on the size of these rootless lava flows, which hinges on the size of the eruption itself, buildings and infrastructure on the flanks of the volcano may be at risk which were previously thought to be safe. Hazard maps should take into account the increased risk from the possibility of rootless lava flows caused by remobilised spatter ramparts in order to best protect the local residents.

## **Volcanic Video Games: How accurate is volcanism portrayed in mainstream gaming, and does this effect player's understanding of real-world activity?**

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Volcanoes are a very common staple in mainstream video games. Particularly within the action/adventure genres, entire missions (e.g. *Monster Hunter: Generation Ultimate*) or even full storylines (e.g. *Spyro: The Reignited Trilogy*) can require players to transverse an active volcano. With modern advancements in video game capabilities and graphics, many of these volcanic regions contain a lot of detail.

Most video games nowadays have gameplay times in excess of 50 hours. *The Legend of Zelda: Breath of the Wild* for example brags a minimum of 60 hours to complete. Therefore, players can spend a substantial amount of time immersed within the detailed graphics, and unknowingly learn about volcanic traits while playing.

If these details are factually accurate to what we observe in real world volcanic systems, then video games can prove to be a powerful learning tool. However, inaccurate representations could instil a false understanding in thousands of players worldwide.

Inaccuracies may be introduced into a game for a variety of reasons: cost/developing time too high, lack of research conducted by the developers, or that it provides a higher entertainment value/risk factor than realistic expectations.

We are therefore very interested in accessing the accuracies of volcanology portrayed in mainstream video games and determining whether they are having an educational impact on the general public playing such games. Or, whether these volcanic details are overlooked by players as they focus solely on the entertainment factor provided.

## **Radiation, risk perception and raw material exploration: science communication and social license.**

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Within our modern world, high-tech communications and low carbon energy and transport are growing the need for raw materials. Alkaline rocks and carbonatites are key sources for such raw materials. However, most alkaline rock and carbonatite-related ore deposits contain hundreds of parts per million thorium and smaller amounts of uranium. Therefore, radiation can be a key hazard at exploration and mine sites.

Our study of publically available data on radiation levels at exploration projects and mines, compared with records of protests associated with these sites, shows that:

- Radiation levels in ore deposits, waste materials and by-products from mines vary considerably between different sites.
- Protests about exploration projects and mines are associated with a wide range of concerns, sometimes, but not always, including radiation.
- In some cases high levels of radiation-related concern are found at sites with lower radiation levels.
- Insufficient trust and community engagement are repeatedly associated with protests associated with exploration and mine sites.

Perception of radiation risk is important and needs to be addressed at all exploration projects in alkaline rocks and carbonatites. Background levels of radiation and concentrations of uranium and thorium in ore should be published as early as possible in exploration, even if these levels are low. No information is likely to lead to assumption of a problem.

More broadly, best practices for good community – company relations and communication echo the best practice lessons learned in volcanic and other risk management scenarios and reflect the wider issues about science engagement and communication. Trust development, community engagement and transparency are essential in all cases and are key to effective relationships between communities and specialists working together in many circumstances.

### *Acknowledgement:*

This project has received funding from the European Union's Horizon 2020 research and innovation programme (grant agreement no. 689909).

## **Animals as agents of geohazard knowledge, perception and communication: Human-Animal-Geos assemblages in the risk zones of Popocatépetl volcano, Mexico**

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There is a comprehensive body of anecdotal literature and media that highlights the importance of animals and human-animal relationships for hazard and disaster planning, perceptions, responses, and recovery worldwide. Despite this, the majority of national and international policy outputs for Disaster Risk Reduction do not incorporate animals, and human-animal interactions relevant to disaster have been little-researched globally.

This study focuses on populations living at risk from the active Popocatépetl volcano in Mexico, a complex geohazard and disaster context encompassing over 20 million people, where animal ownership is also highly prevalent. The at-risk communities are heterogenous, and perspectives on animals and human-animal interactions vary significantly. Within the closest rural communities, economic and working animal species remain central to human livelihoods and identity, as well as to historical evacuation refusals, whereas nearby urban populations have transformed dramatically towards a culture of pet ownership in the past decade.

Despite some limited inclusion of animals within official evacuation plans for Popocatépetl, the influences of human-animal interactions upon perceptions and responses to hazards, and their implications for planning and resilience in this complex setting, are poorly understood.

We are presenting the results of a thematic analysis of qualitative, semi-structured interviews undertaken between March-June 2018, across rural and urban regions at risk from Popocatépetl. An assemblage theory framework, which includes animals as active agents within hazard assemblages, is utilised to conduct an exploratory assessment of Human-Animal-Geos interactions. We discuss to what extent human-animal bonds, shared human-animal volcanic health impact knowledges, and mythologies about the animal-geos relationship can be prominent influencers and drivers of human volcanic hazard perception and response in this region.

## Session 7 – Research in Progress

### Velocity profiles in sedimenting pyroclastic density currents

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Pyroclastic density currents pose a threat to life at active volcanoes around the world, and mitigation of their impacts requires a better understanding of their complex flow behaviours. Understanding the internal dynamics of these flows, and how their propagation behaviours link to sedimentary processes is a critical link in tying process observation to interpretation of existing deposits, and hence the development of improved risk models.

Experiments using sustained gas fluidisation of <90 micron diameter granular materials doped with tracking particles allow some of the first insights into velocity profiles through sedimenting currents. We observe pulsatory behaviour, developed spontaneously from steady supply, and are able to explore the evolution of the flow boundary zone between static and shearing deposit, and over-riding current as the flow evolves, and as the sediment bed grows and steepens.

These experiments raise questions about the nature of the flow boundary zone in PDCs, and provide a new angle of investigation in understanding bedform development and growth.

### Reconstructing volcanic processes spanning the December 2018 lateral collapse at Anak Krakatau, Indonesia

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The lateral collapse of Anak Krakatau volcano, Indonesia, on 22<sup>nd</sup> December 2018, generated a tsunami that caused extensive damage on coastlines around the Sunda Straits, and resulted in 437 fatalities. The event highlights the devastating potential of lateral-collapse generated tsunamis, which locally can attain very high elevations. The precursors to such

events are poorly understood, and as a result, monitoring and identifying any signals of incipient collapse is challenging.

The collapse of Anak Krakatau occurred during an intense eruptive phase that began in June 2018. Although this activity was comparable in style to previous eruptions, there is evidence that the eruption rate was relatively elevated. Coastal extension to the SW is likely to have enhanced edifice instability, with historical observations suggesting past destabilisation in this direction and the potential development of internal structural heterogeneities aligned with the failure orientation. Here, we present results of ongoing research that seeks to understand the coupling of magmatic processes and lateral collapse, to determine if changes in eruptive behaviour initiated the collapse, and understand how the magma system responded to the unloading.

Recent fieldwork collected ash samples spanning the collapse, as well as other observations of the event's impacts. Stratigraphic and textural observations of these samples and older eruptive products are being used to identify changes in eruption style and magma ascent rates. Initial results suggest no change in bulk chemistry, with collapse potentially initiating a decompression driven explosion, followed by intense phreatomagmatic eruptions. Satellite observations of island morphology, remote SO<sub>2</sub> measurements and plume modelling are being used alongside sample analyses and field data to reconstruct the sequence of events involved in the collapse, allowing us to identify evidence for any shift in magmatic behaviour that may have formed a detectable precursor to the event, and the impact of collapse on subsequent magmatic processes.

## **The influence of crystal-rich magma on Strombolian activity: insights from Yasur Volcano**

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Basaltic volcanoes contribute a large fraction of the volcanic volatile outgassing flux to the atmosphere. Many of the most-prolific CO<sub>2</sub> and SO<sub>2</sub> volcanic emitters are basaltic open-vent volcanoes, where strombolian activity and passive degassing direct from magma to atmosphere dominate the degassing regime. Previous efforts to understand these styles of degassing have focussed on two-phase (liquid-gas) flows, in which the stability of a foam in a magma chamber and subsequent gas slug rise plays a key role on the form of gas venting at the surface. However, it has become clear that at many volcanoes exhibiting strombolian activity (including Stromboli, Yasur and Erebus) the magma is highly crystalline (30-50 vol. %). The presence of crystals leads to important differences in the rheology of the melt-crystal mixture, and in turn this may influence bubble dynamics and the style of degassing. Here, we

report a series of analogue 3-phase experiments as well as FTIR spectroscopic acquired in 2018 at Yasur Volcano, Vanuatu to motivate a new degassing model for such volcanoes.

## **Geological evolution of the Alu-Dalafilla volcanic complex, Afar**

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The Danakil depression marks the change from subaerial continental rifting in the Afar region of Ethiopia to seafloor spreading further north in the Red Sea [1]. Extension and volcanism in this incipient spreading centre is localised to the ~70-km-long, 20-km-wide active Erta Ale volcanic segment, with multiple volcanic centres consisting of a combination of fissures, shield volcanoes and stratovolcanoes [2]. This study aims to understand the nature of their interaction, evolution and causes of compositional variation (within and between these complexes) during the transition from continental to oceanic crust.

Here we present results of mapping, using remote sensing, and geochemical analysis of Alu, Dalafilla and Borale in the northern half of the segment. Multispectral images were used to create a high-resolution map and establish a relative chronology of lava flows from the Alu-Dalafilla complex. The results show that the majority of flows are sourced from a combination of craters and fissures, representing in total 15 phases of volcanism within four major eruptive stages. The first stage is large-scale fissure volcanism (containing some submarine basaltic phases). Stage two involves basaltic fissures opening clockwise around the Alu dome. The third stage is dominated by trachy-andesite to rhyolitic (SiO<sub>2</sub> of 59-70%) point source volcanism and the fourth by a resumption of small-scale basaltic/trachybasalt (SiO<sub>2</sub> of 49-55%) fissures. This work reveals a possible cyclic nature of both eruption style and composition of the complex. This increased knowledge of the behaviour of the complex can support future hazard and risk assessments.

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## **Deep geothermal energy from the Cornubian Batholith: preliminary lithological and heat flow insights from the United Downs Deep Geothermal Power Project.**

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The United Downs Deep Geothermal Project (UDDGP) is situated near Redruth in Cornwall and is the first deep geothermal power project to commence in the UK. Two deviated geothermal wells, UD-1 (5057 m TVD) and UD-2 (2214 m TVD), were completed in 2019 and intersect the NNW-SSE-trending Porthtowan Fault Zone (PTFZ) within the Early Permian Cornubian Batholith.

The Cornubian Batholith is composite and can be divided into five granite types that were formed by variable source melting and fractionation [1]. These processes were the primary

control on the heterogeneous distribution of U, Th and K that underpins heat production. Previous high resolution airborne gamma-ray data has demonstrated the spatial variation of near-surface granite heat production [2], and the CSM Hot Dry Rock Project (1977-1991) provided U, Th and K distributions to depths of 2600 m in the Carnmenellis Granite [3]. However, uncertainties in: (i) U, Th and K content in the deeper batholith, (ii) thermal conductivity are still challenges to modelling the high heat flow.

Preliminary evaluation of UD-1 downhole spectral gamma data (900-5057 m) indicates the presence of three major internal batholith contacts on the basis of contrasting U and Th characteristics. QEMSCAN mineralogical analysis of cuttings (720 – 5057 m) demonstrates the overwhelming dominance of two mica (G1) and muscovite (G2) granites and little expression of biotite (G3) granites. There is a substantial increase in Th below 3000 m that indicates the deeper parts of the batholith are likely to contribute substantially to overall heat production. Mineralogical, mineral chemical, whole-rock geochemical and coupled thermal conductivity analysis is ongoing to improve understanding of the construction of this part of the Cornubian Batholith and its implications for the regional thermal resource and sub-surface temperature evaluation.

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## **Halogen heterogeneity in the Icelandic mantle source**

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The Icelandic mantle displays a great degree of chemical and lithological heterogeneity with primordial domains, domains depleted by melt extraction, and a component of recycled crustal material. The spatial distribution of this recycled component is poorly constrained, but is proposed to contribute 4-10% of the Icelandic mantle [1].

Fluid-mobile halogens (F, Cl, Br, I) are concentrated in subducting slabs, making them powerful tracers of recycled material in the mantle. Breakdown of hydrous minerals releases halogens into the subduction zone and domains supplying back-arc volcanism. Recent studies have suggest nominally anhydrous minerals in the dehydrated slab residue may store small quantities of halogens [2] which may be transported to the deep mantle. Others have suggested that the transition zone acts as a 'halogen filter' preventing this material from reaching the deep mantle [3].

To determine the halogen content of Iceland's different mantle domains we have selected olivine- and plagioclase-hosted melt inclusions from glassy sub-glacial pillow lavas from three field areas. Miðfell, in Iceland's Western Volcanic Zone, has noble gas isotopic ratios indicating that it was fed by melts derived from a relatively undegassed, near-primordial mantle

component [4]. In contrast Snæfellsjökull, far from the plume centre, erupts incompatible element-enriched melts possibly sampling recycled material. Oræfajökull erupts trace-element enriched melts in another flank far from the plume. Melt inclusion analyses from these three localities constrain both short-wavelength heterogeneity, as well as long-wavelength 'plume-' and 'non-plume-like' sources in the Icelandic mantle.

We present major and trace element, F and Cl compositions of melt inclusions from the three sites. Snæfellsjökull (582-1170 ppm F, 487-802 ppm Cl) has much higher F and Cl concentrations than Miðfell (4-135 ppm F, 3-236 ppm Cl). Miðfell and Snæfellsjökull both show heterogeneity within individual samples: Miðfell contains on average  $73 \pm 31$  ( $1\sigma$ ) ppm F and  $46 \pm 52$  ppm Cl, and Snæfellsjökull contains  $857 \pm 223$  ppm F and  $616 \pm 123$  ppm Cl. The flank zones have a small amount of variation in F/Nd ( $23.1 \pm 5.4$ ) and near-constant Cl/K ( $0.08 \pm 0.01$ ) ratios across a range of La/Yb ratios (7-33), suggesting that halogens from recycled material may be recycled efficiently into variably trace element enriched mantle domains supplying the flank zones.

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## **Session 7 – Posters**

### **Investigation on potential sources of Rare Earth Elements (REEs) in Loch Borralan, Northwest Highlands, Scotland: Insight from Geological, Mineralogical and Geochemical Characterisation, and their geochemical behaviour during the mining process**

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Rare earth elements (REE) are defined as the 15 elements of the lanthanide series plus Sc and Y. The use of REE is vital in many applications in our modern society. The production and entire value chain for these elements are controlled by China which is a global concern. Most of the EU countries and the USA consider the RE market an issue of national security. This study further investigates carbonatite and alkaline igneous complex of Loch Borralan as a source for REEs. The Loch Borralan complex is located on the southern side of the Assynt district, in the NW Scottish Highlands. Loch Borralan intrusion considered being the only silica-undersaturated alkaline complex that exhibits some of the most 'exotic' and diverse rock types of all the Caledonian alkaline intrusions in the British Isles. Geochemical analysis of targeted

rocks indicates a diverse group of REE-bearing minerals, including allanite-Ce, loparite, törnebohmitite-Ce, RE-carbonates, apatite and titanite. The most significant REE concentration was found in törnebohmitite-Ce up to 60 wt%. This RE grade comparable to other commonly mined RE-minerals, such as bastnäsite and monazite (76 and 71 wt% respectively). The mineral analysis also shows high concentrations of thorium and to lesser extent uranium, in minerals such as thorianite and in some of the RE-minerals. A high concentration of uranium and thorium might be an economic benefit, but the radioactive hazard produced from these elements might prove to be an environmental challenge. The current work extends to target areas with high RE enrichment in Loch Borralan and other Caledonian alkaline intrusions to evaluate their economic future and environmental security. The Loch Urigil carbonatite was analyzed for its RE content and although no significant discoveries were made. Quantitative mineral analyses found loparite and RE carbonates in strontium-rich calcite, in a calcite-serpentine sample from Ledmore Marble quarry. This has been interpreted as a carbonatite, thus extending the possible range of the Loch Urigil carbonatite and its RE hosting possibilities by at least 3km.

## **ETV-ICP-OES method development: A highly efficient technique for the detection of volcanic aerosols in peat**

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The Northern European distal Icelandic tephra record has significant spatio-temporal gaps [1]. Volcanic eruptions are known to produce varying amounts of aerosols, which can include suites of heavy metals such as Hg, Cd, Pb and Zn [2]. Electrothermal Vaporisation-Inductively Coupled Plasma-Optical Emission Spectrometry (ETV-ICP-OES) offers a new and efficient, multi-element technique for detecting volcanic aerosols in ombrotrophic peat, assuming the peat surface records primary volcanic deposition [3]. Traditional methods for aerosol detection involve solution Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), following ashing and acid digestion; however this process is time consuming and may preclude analysis of volatile elements. ETV-ICP-OES has been shown to be a fast and effective method of sample introduction for solid samples, where good accuracy and sensitivity are still achieved even at sample masses <2mg [4] [5] [6]. Here, we discuss the development of analytical procedures for detecting and quantifying volatile heavy metals in peat. We demonstrate the capabilities of this approach using coal and fly ash certified reference materials and well characterised peat samples. Investigated parameters include; sample mass, the effect of gas flow on analyte intensity, and the use of an Ar emission line as an internal standard. Typical detection limits are 0.1ppm for 1mg of sample.

The advantages of ETV-ICP-OES are significant. The lack of digestion of solid samples allows for quicker and more economical analyses of bulk peat, while also lessening the risk of

contamination and loss of volatile elements during ashing and acid digestion. With successful refinement of this method, there is potential to address the spatio-temporal tephra gaps in Northern European records by investigating the presence of volcanic volatiles instead. Additionally, solid sampling of bulk peat in this manner may allow the detection of altered basaltic horizons; which are strongly underrepresented in the distal Icelandic record [7].

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### **Characterising the grain-size of volcanic ash using dynamic image analysis**

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The grain size of explosive volcanic products provides insight into fragmentation and ash transport processes. Importantly, the grain size of volcanic ash determines the risk to human health and the total grain size distribution of volcanic products is a crucial input parameter for ash dispersion models. This study describes the Camsizer X2, a particle size and shape analyser manufactured by Retsch Technology, based in the School of Earth Sciences at the University of Bristol. The Camsizer X2 uses dynamic image analysis to measure the size and shape of particles from 0.8  $\mu\text{m}$  to 8 mm. The method computes multiple measures of particle size including equivalent sphere diameter (comparable to laser diffraction), maximum Feret diameter (long axis) and minimum chord diameter (comparable to sieving). We measured multiple size parameters on glass spheres and a suite of natural tephra samples and find that the choice of size measurement can change the grain size statistics calculated for volcanic ash, especially for highly irregular particles. This is important as different fields that study tephra often report grain size differently, for example ash dispersion models use equivalent sphere diameter and cryptotephra studies typically report the long axis. The Camsizer X2 provides a fast and flexible method for characterising the particle size and shape of tephra samples with capabilities that enable the user to obtain multiple size and shape features, which is not possible using laser diffraction methods. The Camsizer X2 is suitable for measuring fine ash

(<63 $\mu$ m) enabling characterisation of the material that is significant for studies on human health and distal ash dispersal.

## **Radar reflectivity of volcanic ash**

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Volcanic ash injected into the atmosphere during explosive eruptions causes a hazard to the natural and built environment, human health and aviation. Ash dispersal is currently forecast with numerical models, the accuracy of which is strongly influenced by the quality of the volcanic source term parameters, e.g. particle size and shape distribution, and the evolution of mass loading with time. Ground-based radar has a powerful potential to quantify such characteristics. However, radar estimates are currently limited because the effects of particle size and mass loading are ambiguous at a single frequency, requiring that values for one parameter must be assumed. In order to resolve this ambiguity, we propose a multi-frequency approach for providing key source term parameters, capable of describing particle size distribution and mass loading simultaneously. To parameterise the radar inversion models required to make a step-change in this science, we must first characterise the radar properties of falling ash particles. Therefore, we are developing a new laboratory experimental ash fall chamber, instrumented with a multi-frequency radar. Experiments will measure radar reflections of particles with a known particle size distribution (PSD) at three different wavelengths (10, 35, 94 GHz) simultaneously. PSDs will be controlled at the onset of the experiments and measured independently via optical measurements during particle fall. In addition to PSDs, varying experimental parameters will include (1) particle type (e.g. soda-glass and silica spheres, analogue ash and volcanic ash) and therefore shape, (2) particle concentrations and (3) particle surface moisture. We will present the system design, initial results on particle dispersion and image processing methods for quantifying particle characteristics. Ultimately, the experiments will provide the calibration required for developing and testing a new multi-frequency radar ash retrieval algorithm.

## **The Pulsatory Nature of Bagana Volcano**

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Bagana, is a young (300-400 yo) polygenetic andesitic volcano situated on Bougainville Island, Papua New Guinea, [1] that lends itself to satellite remote sensing, due to its largely inaccessible location.

The subduction zone beneath Bagana is near a global extreme, with a subduction rate of 110 mm/yr, and a slab dip angle of 75° [2]; factors that increase the production of magma. It has high and sustained lava production which is unusual for this type of volcano, and the lava is thick and slow-moving in comparison to other andesitic cones, arriving in pulses that can last a few months [1]. This characterises the first of Bagana's two eruption styles. Using Sentinel-1 to produce Interferometric Synthetic Aperture Radar (InSAR) and Amplitude change detection images, the frequency and length of these lava pulses is being analysed in conjunction with thermal data from the Moderate Resolution Imaging Spectroradiometer (MODIS/MODVOLC/MIROVA).

Bagana is, at times, a large emitter of SO<sub>2</sub> globally, with a near-constant passive degassing totalling several thousand kilotonnes per year, which tends to accompany the first eruption style. Larger SO<sub>2</sub> plumes can accompany the second of Bagana's eruption styles, which can be up to VEI 4 (Volcanic Explosivity Index) with ash and pyroclastic density currents [1]. Using SO<sub>2</sub> data from the Ozone Monitoring Instrument (OMI), cyclicity in the mass loadings and the thermal radiative power from MODIS, are being examined using wavelet analysis and compared to other andesitic volcanoes that display cyclic behaviour (e.g. Santiaguito, Popocatepetl and Soufrière Hills Volcano).

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## **Understanding melt distribution beneath volcanoes: An experimental approach**

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Models of large-scale magmatic systems have evolved from simple chambers to more complex systems containing transient, layered structures of fluid, melt and crystal mush. Imaging these subsurface structures therefore can lead to better understanding of the threats posed and assist monitoring programmes, but current imaging techniques provide only limited resolution of magmatic structures, with strong trade-offs between seismic waves sensitive to melt fraction and distribution. Despite this, the commonly used relationships linking melt distribution and seismic velocities rely on either 2D images of synthetically melted rock aggregates or simplified geometrical approximations and are therefore not wholly representative of the volcanic system models.

This project aims to develop a new approach to analyse grain-scale structures at different melt fractions through the manufacture of physical models which can be seismically tested. The initial stage is focussed on testing idealised melt inclusions of chosen aspect ratios and comparing them to effective medium models. The solid crystal material is represented by epoxy resin, which is mechanically stable up to 50°C. Materials used to represent the melt fluids include myristyl alcohol, with a melting point of 38°C, and gallium, which melts at 30°C.

Early tests have indicated that these materials have suitable mechanical and acoustic properties for producing physical approximations of melt structures.

Future stages will use a variety of techniques such as 3D printing to develop models of realistic melt structures at varying melt fractions. At completion of the project, a suite of seismic parameters will be determined which will be applied to real-world, active volcanic settings to better describe melt distribution in the crust.

## **The GeoX Suite: Tools for in situ imaging under geological conditions**

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Improving our understanding of the natural world; how it has evolved, how it continues to evolve, and how it responds to human impacts and climate change are the main goals of all earth and environmental researchers. In recent years the development of x-ray imaging techniques has allowed us to see inside our samples without destroying them; meaning we understand the internal structures of rocks, soils, ice, plants, animals and man-made materials better than ever before. However, as cutting-edge imaging systems now permit us to collect 3D images in just fractions of a second, and allow us to put experimental equipment and sample environments inside the imaging equipment, we now have the opportunity to improve our understanding of the processes themselves: by watching them happen.

Developed for the NERC research community, with input from over 20 institutions, the GeoX Suite provides the geological and environmental research communities with a much-needed pool of experimental equipment so that we can exploit the transformative capability of x-ray tomography, and other in situ imaging methods. GeoX provides an internationally unique asset, that delivers new research capability, increase research capacity, and enable innovation across the entire earth sciences remit.

Please come us at our poster to discuss your ideas and see how the temperature, pressure, deformation and flow capabilities of the GeoX Suite could help your research

## **Microstratigraphic analysis of complex ash aggregates**

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Large, complexly layered ash aggregates commonly appear within or in association with pyroclastic density currents (PDCs) and their co-PDC plumes. Evidence contained within the aggregates suggests that they grow at altitude and then descend through the plume and PDC prior to deposition. Textural differences in the layers therefore relate to changing ambient conditions (e.g., relative humidity) during growth. Recent microstratigraphic work on a sample of aggregates from a large volcanic eruption (Tierra Blanca Joven, TBJ) in El

Salvador revealed consistent micro-stratigraphies between aggregates that records a shared growth history. The textural changes from core to rim record initial growth in sub-freezing conditions, followed by growth under saturated conditions. The final growth phase occurred under hot and dry conditions. Here, we compare and contrast the growth history outlined above with that derived from scanning electron microscope imaging of micro-stratigraphic analysis of large and complex ash aggregates from other phases of the TBJ eruption, from the 12 ka Laacher See eruption, Germany, and from the Piano Liguori eruption, Ischia, Italy. We demonstrate the presence of layers with similar textural characteristics in individual aggregates and the consistent organisation and order of those layers within and across aggregate populations. This data will be used to support a general model for the growth of large, complex ash aggregates within PDCs and their plumes during explosive eruptions.

## **Halogens in Icelandic subglacial basalts reveal recycled volatiles in a spatially heterogeneous plume**

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Iceland's 500 km of active neovolcanic zones provides a high-resolution and spatially continuous transect across a mantle plume. High  $^3\text{He}/^4\text{He}$  isotopic signatures in basalts erupted near the putative plume centre indicate that these melts sampled undegassed, near-primordial mantle. Melting models suggest that the Icelandic mantle must also contain at least 5% recycled oceanic lithosphere [1], but the spatial distribution of this recycled component remains enigmatic. The fluid-mobile halogens are promising tracers of recycled material, because they are re-introduced to the mantle through subduction of serpentinized oceanic lithosphere [2]. To investigate the spatial distribution of recycled material in the Icelandic mantle, we have measured heavy halogen concentrations (Cl, Br, I) in a suite of 71 subglacially erupted basalts collected across Iceland's active neovolcanic zones.

Halogen concentrations in Icelandic basalts show an extraordinary two orders of magnitude variation, and are positively correlated with indices of melt evolution such as  $\text{K}_2\text{O}$  content. Primitive basalts with 8-10 wt.% MgO typically contain 5-50 ppm Cl, 10-100 ppb Br and 0.2-3.0 ppb I. High halogen concentrations are associated with enrichment in incompatible trace elements, and with high incompatible trace element ratios such as La/Yb.

We observe systematic compositional differences between Iceland's neovolcanic zones. Basalts from the Eastern Volcanic Zone (EVZ) and Western Volcanic Zone (WVZ) have similar halogen/K and halogen/halogen ratios, while basalts from the Northern Volcanic Zone (NVZ) have notably higher Cl/K, Br/K and Cl/Br than their EVZ and WVZ counterparts. The low halogen/K ratios of the EVZ and WVZ basalts appear to be spatially correlated with high  $^3\text{He}/^4\text{He}$  and low  $^{207}\text{Pb}/^{206}\text{Pb}$  isotopic signatures, suggesting that Iceland's primitive mantle

component is relatively halogen-poor. Elevated halogen/K ratios in NVZ basalts could suggest a higher contribution of recycled volatiles to primary melts beneath North Iceland.

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## **Magma storage and mixing during the 2013-2017 activity at Volcán de Colima, Mexico: Estimates of crystallisation conditions from pyroxene thermobarometry**

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Volcán de Colima is an active stratovolcano in western Mexico. Previous work has identified abrupt transitions between effusive and explosive eruption phases and historical evidence also suggest that five Plinian eruptions have occurred the last 500 years. The eruptive activity at Volcán de Colima presents a significant hazard to more than half a million people that live near the volcano.

Here, we present preliminary results from analysis of samples from the 2013 - 2017 phase of activity. Mineralogically the samples are dominated by plagioclase, clinopyroxene and orthopyroxene phenocrysts, glomerocrysts comprising pyroxenes, Fe-Ti oxides, plagioclase and rare resorbed olivine, along with isolated Fe-Ti oxides and amphiboles.

Magma crystallisation and evolution conditions can be constrained by the chemistry and textures of pyroxene phenocryst groups recorded in these samples. Larger opx and cpx phenocrysts and glomerocrysts have mafic cores (Mg# 80-86) and less mafic rims (Mg# ~70-75). Two-pyroxene thermobarometry indicate that that these cores crystallised at ~1040-1070 °C and 5-6 kbar, and rims between 950-980°C and 4-5.5 kbar. Small orthopyroxene phenocrysts and microphenocrysts are mostly homogeneous and in equilibrium with the rims of glomerocrysts with overlapping temperatures and pressures. Reverse zoned crystals have very sharp boundaries between relatively low temperature (~980 °C) and high temperature (~1040 °C), more mafic (Mg# 80-85) rims, representing crystallisation from a hotter, more mafic magma than the cores.

These crystal populations and temperature estimates indicate that mixing between magmas of different compositions have occurred during the current eruptive cycle. A pronounced

change with the formation of a reverse zoned pyroxene crystal population in the 2016 lavas possibly records the injection of new mafic magma triggering the eruption. Future work will include diffusion modelling to constrain the timescales of recharge events, and comparison with monitoring records will explore the relationship between these events and the monitoring record.

## **The sulphur isotope evolution of magmatic-hydrothermal fluids**

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Most magmatic-hydrothermal systems on Earth contain fluids with high concentrations of sulphur. Isotopic investigations of these fluids and the S-bearing minerals they precipitate provide insights into magma chamber processes, the dynamics of hydrothermal systems and mineralization. Although it is well established that S isotopes encode valuable information about the source of a magmatic-hydrothermal fluid, as well as its physical and chemical evolution, it is often challenging to unravel which of these competing processes drives isotopic variability.

Here, we use thermodynamic models to predict S isotope fractionation for geologically realistic hydrothermal fluids and attempt to disentangle the effects of fluid sources, physico-chemical evolution and S mineral disequilibrium. Modelling a range of fluid compositions, we show that S isotope fingerprints are controlled by the ratio of reduced to oxidised S species, and that this is most strongly affected by changing temperature,  $fO_2$  and pH. We then compare our model predictions to natural S isotope data from magmatic arcs, sea floor vents and intracontinental rifts (i.e. alkaline and carbonatite bodies). We find that our equilibrium models accurately reproduce the S isotope evolution of arc fluids, and that most arc fluids require highly acidic conditions and enriched magmatic S sources (0–5 ‰). The S isotopes of seafloor hydrothermal fluids do not fit our model predictions and reflect disequilibrium between the reduced and oxidised S species, and the input of both magmatic and seawater S. Models of alkaline fluids also match natural S isotope data but require near-neutral pH and more oxidised (sulphate-dominated) fluid compositions compared to arcs.

Our study demonstrates that S isotope forward models are powerful tools for identifying S sources, flagging disequilibrium processes and validating hypotheses of magmatic fluid evolution. They can be readily applied at both active and extinct magmatic systems to understand volcanism and ore-forming processes.

## **The explosiveness of the dacitic Ciomadul lava dome complex**

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The Ciomadul is the youngest volcano in the Carpathian-Pannonian Region located at the SE end of the Călimani-Gurghiu-Harghita volcanic chain in the Eastern Carpathians. The last activity occurred ~30 kyrs ago, but Ciomadul has a 1-million-year long history. The volcano consists of lava domes with two explosion craters. Ciomadul is a small volume (~8km<sup>3</sup>) system characterized by a very low average output rate. The volcano were grown in a post collisional tectonic regime. The eruptions were fed by homogeneous high-K crystal-rich (30-40%) dacitic magma. The eruptions were dominantly effusive, explosive activity is known only from the last eruptive period between 60-30 kyrs ago. This period were characterized by several type of eruptions including effusive activity with block and ash flow, or Vulcanian and (sub)Plinian eruptions.

The vesicularity, vesicle and microlite texture and groundmass glass H<sub>2</sub>O content of juvenile fragments from pyroclastic fall and flow deposits and lava dome rocks were studied to understand the effect of conduit processes (degassing/crystallization) on the eruption style of Ciomadul.

Vesicularity was calculated from density data of 100 clasts/sample. The vesicularity distributions of the samples show clear correlation with eruption style/intensity. Plinian phases show high mean vesicularity values (60-80%) and narrowest distribution. Plinian column destabilization is related to decrease of mean vesicularity and the presence of denser clasts. The products of Vulcanian explosions have typical strongly variable vesicularity and low mean values. Lavas have variable vesicle texture with dense parts. Microlite texture is inversely correlating with the vesicularity. The microlites are dominantly plagioclase but amphibole, mica and apatite also occur in the dense clasts. Raman spectroscopy indicate homogeneous and low matrix glass content.

Our observations indicate that the eruption style was largely controlled by the ratio of open vs closed system degassing. The presence of microlites e.g. amphibole should also affect the melt volatile content.

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## **Propagation and mobility of lahars and debris avalanches: evidence in sedimentology**

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Debris avalanches and lahars are among the most destructive and hazardous landslides in volcanic environments. Debris avalanches exhibit extremely high mobility compared to what is predicted by simple frictional models; and greater than equivalent phenomena in non-volcanic environments. Lahars are capable of much longer runouts due to the different propagation mechanisms. Models of their propagation and emplacement need to express this mobility; while being consistent with deposit sedimentology and geomorphology. Sedimentological characteristics of deposits are important for assessing the differences between phenomena and their propagation and emplacement mechanisms. Since energy dissipation in granular flows largely depends on inter-particle friction, grain size distribution (GSD) characteristics are likely to influence mobility. Physical and numerical modelling by different authors support this theory; suggesting that the presence of a significant amount of fine particles within a coarser mix, generating bimodality, can reduce energy dissipation and enhance mobility.

The present study compares the sedimentology of debris avalanches and lahars. Findings suggest that lahars and debris avalanches diverge in their sedimentology and GSD evolution during propagation, even when sourced from the same material. This is mainly a result of the high water content of lahars, in contrast to debris avalanches, enabling different processes. Debris avalanches can be considered as dense granular masses where the effect of inertial collisions of solid fragments are far more important than fluid effects. Thus, GSD characteristics such as the percentage of fine particles remains a candidate factor for their high mobility. In order to investigate this further, examination of the mechanisms of mobility will focus on bi- and poly-disperse granular flow laboratory experiments, and on developing a novel method of quantifying bimodality in debris avalanche deposits in the field.

## **Understanding the origins of lithium-enriched geothermal fluids and its implications for Li exploration in Cornwall**

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Elevated lithium concentrations were first reported in Cornish geothermal fluids in 1864 (at 60mg/l) [1], and subsequently noted in tin and copper mines (typically ~200 mg/l) [2] that were worked until the 1990's, when poor metal prices brought an end to metalliferous mining in the South West. Today, Cornish brines are of significant interest due to an increasing demand for Li in low-carbon technologies and advances in techniques for Li extraction from brines.

Cornish Lithium's exploration efforts take a multitude of approaches to constrain the relationship between circulating fluids and the underlying regional batholith. Mineralogy and chemical analyses highlight five types of granites (G1-G5) in Cornwall [3]. In certain granite types, Lithium is hosted by Lithium bearing micas [3]. Collation of chemical fluid data across the region link certain hydrothermally derived fluids to specific granite types, Li enrichment is particularly noted with respect to the G5 granites. Structural mapping in combination with digitised archived mine data and private collections are used to model the deep-seated NW-SE and ENE-WSW trending, permeable fault structures in 3D. These structures were exploited by fluxing Permian-aged magmatic-hydrothermal fluids that led to mineralisation of W, Cu and

Sn. It is supposed that geothermal waters still circulate at depth, heated by the radiogenic granites.

Planned research boreholes will intersect a permeable structure at depth allowing sampling of uncontaminated, circulating fluids to assess the Li concentrations. Further research into temperature dependent, fluid-rock interactions (e.g. Li leaching, mica breakdown) and porosity and permeability modelling of flow pathways are vital to understanding the origins and distribution of Li-enriched fluids at depth. Combining these approaches is informing Cornish Lithium's exploration programme into the viability of Lithium extraction.

[1] Miller W. A. (1864) *Chemical News*, Vol X, No. 254, p 181.

[2] Smedley P. L. et al. (1989) BGS Research Report SD/89/2.

[3] Simons B. (2016) *Lithos*, Vol 260, p 76-94

## **Fracture propagation through vesicular melts and tuffisite preservation: An example from the 2011-12 Cordón Caulle eruption**

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Tuffisite veins (resulting from volcanic hydrofracturing) are highly permeable, transient pathways that facilitate gas escape from the upper conduit of silicic volcanoes. To play a significant role in the outgassing of magmatic systems tuffisites must be capable of interacting with and extracting gas from vesicular magmas at depth. Previous studies have assessed tuffisite veins hosted by dense material within country rock, domes and shallow conduits, but little attention has been given to the fracturing and preservation of tuffisites in vesicular melts.

We present a textural characterisation of a tuffisite vein and its vesiculated host melt, from the 2011-12 eruption at Cordón Caulle in Chile, which record multi-stage fragmentation and healing. Textures document how fractures exploit weak porous networks to further their propagation. The heterogeneous nature of the porous network, and the resulting local variations in strength, promote branching and undulating fracture propagation, rather than localized planar fractures. This results in host material being incorporated into the vein as both larger angular clasts and fine matrix ash. Repeated fracturing and sintering of vein material is concurrent with gas escape resulting in the collapse and compaction of the host on a centimetre scale. Aided by the presence of a permeable porous network, these spatial scales far exceed the limited volumes of diffusive outgassing reported for dense melts. This highlights how the presence of a local porous network adjacent to the fracture promotes efficient outgassing.

We show that the interaction between permeable porous and permeable fracture networks can be preserved in erupted samples. This study strongly supports the notion that tuffisites source their gases from depth through permeable vesicular melts and are capable of degassing much larger volumes of magma than thought previously, allowing them to contribute significantly to pressure release and/or modulation prior to and during explosions during eruptions.

### **Experimental analysis of particle-covered ice**

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Many glaciers in volcanic regions are coated with volcanic particles and have particles buried within them. The presence of particles on an ice surface can modify the thermodynamic behaviour of the system due to changes in solar radiation absorption rates. This can impact heat transfer and ice ablation rates. It is important to understand the physical mechanisms of these systems to aid ice ablation modelling in an environment of climate change punctuated with volcanic eruptions.

We present laboratory experiments that investigate the physical coupling between water-ice and analogue contaminant particles that interact strongly with visible light. Experiments illuminate a transparent block of ice under temperature-controlled conditions with a light-emitting diode radiation source. Particles are placed on the ice surface in the center of the beam. Time-lapse imagery and visual observations capture the response of the particle and ice to the radiation source and allow melt rates to be calculated and features to be described. The behaviours of single (synthetic and natural) particles with a variety of properties (albedo, thermal conductivity, density and size) are investigated.

Results have identified three single-particle modes, in which a particle responds to radiation by (1) sinking into the ice by melting, (2) rising through the ice and re-emerging on the ice surface, and (3) creating a surface meltwater pond. These modes vary depending on particle properties; for example, the ice-melt rate caused by a low albedo particle is higher than that caused by a high albedo particle. Sinking particles can create ice-lidded channels within the ice which, when drainage is possible, can remain open even when they have no contact with the particle. The sphere of influence is larger for low density and low thermally conductive particles relative to high density and high thermally conductive particles. Future experiments will investigate the behaviour of particle layers.

### **The dynamics of buoyant ash plumes coupled to lava fountains**

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Volcanic plumes generated by the explosive basaltic activity at Mount Etna, Italy, are characterised by an ash-laden plume that surrounds a hotter, rising core that is typically referred to as a lava fountain. Visual observations of these eruptions show that the lava fountain is incandescent, composed of coarse material and is not fully coupled with the surrounding ash plume. However, defining the extent of the lava fountain region is challenging, with thermal camera images showing a hot core extending far above the incandescent region in visible light images. Furthermore, despite a high number of observations of these eruptions, little is known about how the presence of a hot inner core affects the dynamics of the surrounding rising ash plume.

We investigate the dynamics of ash plumes that are associated with lava fountains by using a new 1D integral coaxial buoyant plume model. This model allows for interaction between an inner circular buoyant plume (representing the fountain) and an outer, annular-shaped buoyant plume through the processes of entrainment and particle fallout. It also permits different initial source conditions for the inner and outer plumes such as initial velocity, temperature, grain size distribution and gas content. We have explored the effect of having two co-flowing plumes on the plume dynamics as well as the effect of disequilibrium between the initial conditions of the inner and outer plumes. Additionally, we provide initial results comparing the model simulations with observations of the plume generated by Mount Etna's 29<sup>th</sup> August 2011 paroxysmal eruption, where the buoyant plume reached heights of >9km and the lava fountain, as estimated by thermal camera, a maximum height of ~1 km [1].

[1] Calvari S et al. (2018) *Front. Earth Sci.* 6:107

## **What can Olympus Mons tell us about the Martian lithosphere?**

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Olympus Mons on Mars provides an interesting paradigm for modelling because it is the largest known volcano in our solar system. Its summit lies 21.9km above the surrounding Tharsis plains, and its edifice has dimensions of approximately 840 x 640 km [1]. The Martian lithosphere has downflexed under the immense load of Olympus Mons. The geodetic signature of this deformation, which includes a ~600km-wide flexural moat [2], is observed

within topographic and gravimetric data. However, values that define properties of the Martian lithosphere are currently ill-constrained. Here we model the topographic and gravimetric response of the Martian lithosphere to volcanic loading from Olympus Mons. Through comparison of modelled and satellite-observed deformation and residual gravity, we aim to constrain properties of the Martian lithosphere.

We extend previous studies by considering the effects of a wide range of model parameters on the geodetic response of the lithosphere to volcanic loading. Exploiting the flexibility of the finite element method, we vary lithospheric properties including density, elasticity and stiffness, alter the coefficient of friction along the basal decollement, and consider the effects of subsurface features such as magma reservoirs or buoyant plumes that are inferred to exist within Olympus Mons (e.g. [3]). We anticipate that our results will provide improved constraints on Mars' lithospheric properties and contribute to interpretation of the eagerly-awaited seismic data from NASA's InSight mission.

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- [1] Plescia J (2004) J. Geophys. Res. 109:E03003
- [2] Isherwood RJ et al. (2013) EPSL 363:88-93
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## **HiTech AlkCarb - New Geomodels for rare earths and other economic deposits in carbonatites and alkaline rocks**

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The HiTech AlkCarb project is developing new geomodels and sustainable exploration methods for alkaline igneous rocks and carbonatites. It has four main objectives.

- Develop new geomodels to explore for 'hi-tech' raw materials (such as the rare earth elements, scandium, niobium, tantalum, zirconium, hafnium and fluorspar) associated with alkaline rocks and carbonatites.
- Improve and develop interpretation of geophysical and downhole data to understand alkaline rock and carbonatite systems down to depths of approximately one kilometre.
- Build exploration expertise in hi-tech raw materials, and ensure knowledge exchange between Europe and Africa.
- Assess environmental and socio-economic impacts of mining for these raw materials, developing best practice.

The outputs are deliverables to the European Union, most of which are being made available publically and also published as peer reviewed papers. Outputs are listed on the project website [www.carbonatites.eu](http://www.carbonatites.eu) and include:

1. A database of alkaline rock and carbonatites. This website provides an interactive, digitised version of the Alkaline Rocks and Carbonatites of the World volumes, by

Alan Woolley. Information can be accessed by using a map feature, search or occurrence information.

2. Publications investigating key geological questions that help define geomodels and exploration indicators. These include a review of the fenite metasomatic aureoles around carbonatites, sulphur isotope evidence for crustal recycling in alkaline rocks, a model for Italian carbonatites and pyrochlore as a monitor for magmatic and hydrothermal processes.
3. A mineral systems approach to exploration models, using a risk assessment approach used previously in the oil industry.
4. A new geomodel for the Kaiserstuhl natural laboratory, Germany, combining geophysics and geology.
5. Two new conceptual models for alkaline complexes and carbonatites, in 3D PDFs including information on process mineralogy, environment and social factors

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