



UNIVERSITY OF  
LIVERPOOL



# IAVCEI Commission on Volcanic & Igneous Plumbing Systems (VIPS)

18<sup>th</sup> - 20<sup>th</sup> June 2024

**Abstract Book**

1<sup>st</sup> International Conference

Hosted by the MAGMA Lab, University of Liverpool























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# Conference Programme

## Wednesday 19<sup>th</sup> June







09:00	ARRIVAL COFFEE & REGISTRATION	
09:30	INTRODUCTION & HOUSEKEEPING	
	SESSION 1 - chaired by Katy Chamberlain	
09:50	 <b>Janine Kavanagh (Keynote)</b>	<b>Modelling magma movement in dykes and sills: Insights from minerals, magnetism and mixing experiments</b>
10:10	 Lorenzo Mantiloni	The Role of Gravity in the State of Stress of Dynamic Magma Mush Reservoirs:
10:25	 Chiara Montagna	Modeling sub-surface volcanic processes with MagmaFOAM
10:40	 Diego Morata	Melt inclusion study from the Quaternary Pudahuel Ignimbrite in the Andean Southern Volcanic Zone
10:55	 Orlando Quintela	Magma batch emplacement in the Slaufudalur pluton, SE Iceland
11:10	COFFEE BREAK	
	SESSION 2 - chaired by Stefano Urbani	
11:30	 <b>Geoff Kilgour (Keynote)</b>	<b>Mantle to surface monitoring of an andesite magmatic-hydrothermal system</b>
11:50	 John Browning	Unravelling volcano-tectonic interactions at the Nevados de Chillan volcanic complex, Southern Andean Volcanic Zone, Chile
12:05	 Kate Williams	Re-conceptualising our understanding of magnetic and crystal fabrics in the Whin Sill
12:20	 Mike Burton	Exceptional eruptive CO <sub>2</sub> emissions from intra-plate alkaline magmatism in the Canary volcanic archipelago
12:35	 Tobias Mattsson	Tracing Laccolith Growth with Palaeomagnetism
12:50	LUNCH	
	SESSION 3 - chaired by Jade Hrintchuk & Dawid Rybak	
13:50	 <b>Prokop Závada (Keynote)</b>	<b>The interplay of deformation and current volcanic activity on the Reykjanes peninsula, Iceland - some insights from analogue modelling</b>
14:10	 Manfredo Capriolo	The mush-dominated plumbing system of Large Igneous Provinces unveiled by glomerocrysts and melt inclusions
14:25	 Caitlin Chalk	Shedding (laser) light on three-dimensional fluid flow in dykes
14:40	 Melina Höhn	Petrographic and geochemical investigation of the magma plumbing system underneath the Rabaul Caldera, Papua New Guinea.
14:55	COFFEE BREAK	
15:15	POSTER SESSION	
17:00	END OF DAY 2	
19:00	CONFERENCE MEAL AT CHAMBER 36	

-  Modelling plumbing systems processes
-  Magma transport & tectonics
-  Magma plumbing systems & georesources
-  Volcanic-plutonic connection
-  Monitoring volcanic plumbing systems
-  Other VIPS-related topic

# Conference Programme

## Thursday 20<sup>th</sup> June







09:00	ARRIVAL COFFEE & REGISTRATION	
	SESSION 4 - chaired by Caitlin Chalk	
09:30	<b>Antonio Costa (Keynote)</b>	<b>Advancements in volcanic conduit modelling: A decade of development, applications, and future perspectives</b>
09:50	Gloria Arancibia	The Nevados de Chillán Volcanic Complex as a structurally controlled multiple magmatic system.
10:05	Barbara Bonechi	Direct observation of magma degassing and crystallisation via HP-HT X-ray transparent Internally Heated Pressure Vessel (IHPV)
10:20	ROUND TABLE 1 - chaired by Janine Kavanagh	
11:00	COFFEE BREAK	
	SESSION 5 - chaired by Tegan Havard & Kate Williams	
11:20	<b>Adelina Geyer (Keynote)</b>	<b>Understanding the internal dynamics of magma reservoirs: A pending challenge</b>
11:40	Oleg Melnik	Numerical simulation of the formation of rhyolitic melt at Krafla volcano, Iceland
11:55	Halldór Geirsson	Interconnected neighbouring volcanic systems and tectonic drivers of magmatic activity: crustal deformation during the Reykjanes Peninsula unrest 2020-2024, Iceland
12:15	Ed Llewellyn	Localization in basaltic fissure eruptions
12:30	LUNCH	
	SESSION 6 - chaired by Katy Chamberlain	
13:30	Oliver Higgins	Plagioclase-phyric basalts record variable crystal accumulation on millennial timescales beneath Wolf Volcano, Galápagos
13:45	Sonja Greiner	The influence of variable host rock cohesion and magma viscosity on intrusion-fault interaction: Insights from laboratory models
14:00	Stefano Urbani	Complex magma flow dynamics recorded in fossil dykes: insights from the Reyðarfjörður dyke swarm, eastern Iceland
14:15	<b>Steffi Burchardt (Keynote)</b>	Deformation related to magma transport in the Earth's crust - not just in the host rock
14:35	ROUND TABLE 2 - chaired by Janine Kavanagh	
14:50	COFFEE BREAK	
15:10	ROUND TABLE 3 - chaired by Janine Kavanagh	
15:40	IAVCEI VIPS COMMISSION	
16:00	END OF DAY 3 - CONFERENCE END	

-  Modelling plumbing systems processes
-  Magma transport & tectonics
-  Magma plumbing systems & georesources
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-  Other VIPS-related topic

# Poster Session













## Wednesday 19<sup>th</sup> June







No.		Presenter	Title
1	Yellow	Maggie Williams	GeoHub Liverpool: Supporting teachers and students in Geology for over 30 years
2	Teal	Brooke Benz	Gabbros at Askja: The Bringers of Chaos
3	Green	Rahul Subbaraman	Icelandic Nodules – Windows into Actively Evolving Mush
4	Green	Tegan Havard	Modelling dyke remobilisation using gelatine analogue
5	Dark Blue	Matías Poblete	Dynamics and conditioning factors of Holocene explosive and effusive eruptions at Lonquimay volcanic complex, Southern Andes of Chile.
6	Green	Claire Harnett	Modelling host rock deformation and surface displacement during magma intrusion
7	Light Green	Brendon Rolfe-Betts	Magma evolution and lateral collapse in shield-stage volcanism of Fogo, Cape Verdes
8	Dark Purple	Hilary Downes	Messages from the magma mush: glass-bearing plutonic xenoliths from Fogo, Cape Verde
9	Green	Stanley Yip	Exploring the effects of magma and crustal heterogeneity on volcano deformation
10	Green	Stanley Yip	Magma accommodation and ground movement analysis: testing the reliability of analytical volcano deformation models
11	Green	Sara Crozier	Using Triple-Fe to distinguish mush vs melt storage systems.
12	Green	Matías Clunes	Influence of crustal structures in dyke propagation: observations from analogue modelling
13	Dark Purple	Kurimi Iwahashi	Variations in the temperature and composition of high-crystallinity magma reservoirs on the scale of hundreds of years to tens of thousands of years
14	Dark Blue	Chiara Petrone	The February-March 2021 lava fountains events of Mt. Etna South-East crater (SEC): insights from clinopyroxene.

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# Poster Session

## Wednesday 19<sup>th</sup> June

No.		Presenter	Title
15		Xavier de Bolós	Geophysical insights into magma plumbing system and subsurface hydrothermal activity of Lāna'i volcano (Hawaiian Islands)
16		Ceri Allgood	Complex dyke architecture suggests flow localisation during magma propagation
17		Alexandra Morand	Analogue experiment of magma reservoir fracturing under different magma buoyancy.
18		Réka Lukács	Peraluminous to metaluminous magma transition within a magmatic plumbing system: evidence from zircon, garnet and amphibole crystal chemistry
19		Jasmine Dibben	Using a 3D seismic velocity anomaly to delineate a deforming magma reservoir at Soufrière Hills Volcano
20		Dawid Rybak	Synchronous intrusion of a dyke pair: experimental simulation
21		David Neave	Interpreting clinopyroxene records of magma redox with thermodynamic models
22		Oleg Melnik	Magma Chamber Formation by Dike Accretion and Crustal Melting: 2D Thermo-Compositional Model.
23		Jade Hrintchuk	Investigating magma flow dynamics using plagioclase alignment in the Little Mount basaltic dyke, Victoria, Australia
24		Alex Walton-Keeffe	Tracing the source conditions of Central Andean ignimbrites through Machine Learning thermobarometry and thermodynamic modelling
25		Harangi Szabolcs	Rapid reactivation of long-standing crystal mush by mafic magma recharge: the 135 ka Ciomadul Mic eruption, eastern-central Europe
26		Catherine Annen	The IAVCEI Commission on VIPS

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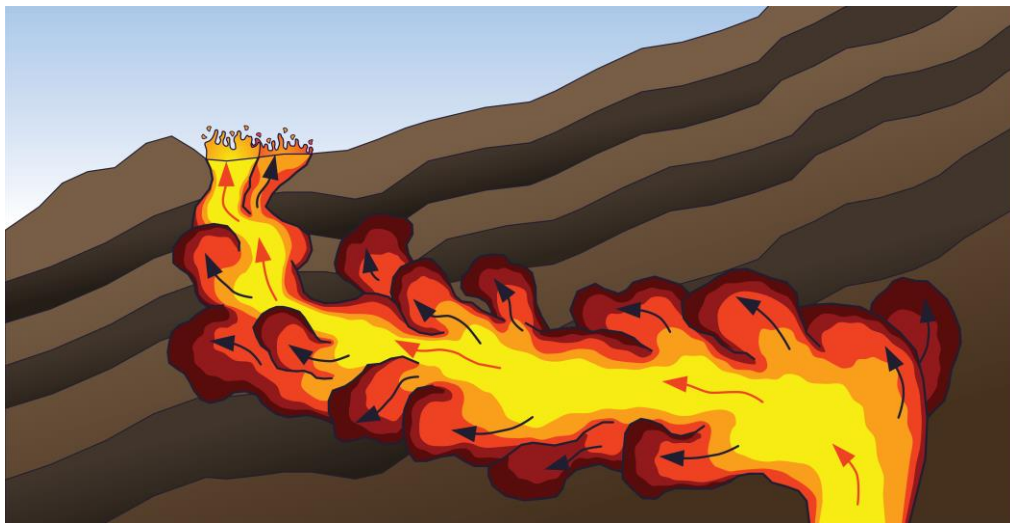
# Abstracts

## Complex dyke architecture suggests flow localisation during magma propagation.

Ceri Allgood<sup>1</sup>, Edward W. Llewellyn<sup>1</sup>, Ariane A. Loisel<sup>1</sup>, & Richard J. Brown<sup>1</sup>.

<sup>1</sup> Department of Earth Sciences, Durham University, UK

The three-dimensional geometry of dykes is complex and evolves through time. Dyke architecture describes the dynamic plumbing system that is constructed by interactions between magma and host rock. Magma both creates and responds to the complexity of its transport network, which determines the location, behaviour and longevity of fissure eruptions should magma reach the surface. Dykes are commonly found to be segmented along their length, but their true, three-dimensional architecture often remains unknown, with interpretations hindered by limited exposure. Here we present a rare example of a dyke with segmentation on both horizontal and vertical exposures, providing an insight into its complex, three-dimensional architecture and flow pathways. The dyke consists of branching, overlapping, plate-like lobes, reminiscent of pahoehoe flow field, and its internal textures indicate flow localisation within segments. We propose that such a structure is likely to have arisen due to preferential flow pathways developing within a dyke advancing on multiple fronts, producing a network of linked segments and dead-end branches. Our findings suggest that dyke emplacement not only involves interactions with the host rock, but thermal feedback within the narrow dyke tip. Such complex behaviour has implications for the way we view dykes in the field and for our understanding of dyke propagation, and provides context for the interpretation of seismicity associated with subsurface magma transport.



Schematic representation of complex dyke architecture. The dyke propagates on multiple fronts and develops preferential flow pathways, similar to a pahoehoe flow field. When the dyke is eventually exposed by erosion, these pathways present themselves at the surface as segments.

# Abstracts

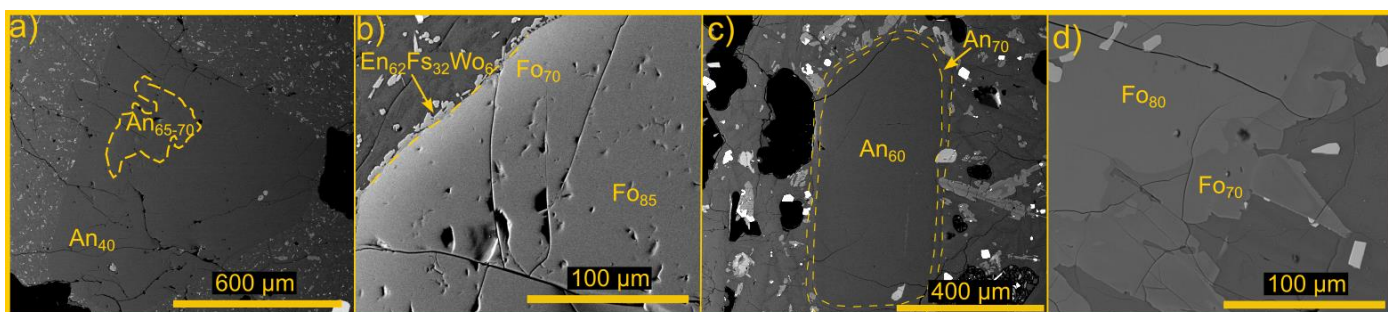
## The Nevados de Chillán Volcanic Complex as a structurally controlled multiple magmatic system.

Camila Pineda<sup>1</sup>, Gloria Arancibia<sup>1</sup>, Diego Morata<sup>2</sup>, Santiago Maza<sup>2</sup>

<sup>1</sup> Department of Structural and Geotechnical Engineering, Pontificia Universidad Católica de Chile, Chile

<sup>2</sup> Department of Geology and Andean Geothermal Center of Excellence (CEGA), FCFM, Universidad de Chile, Chile

Nevados de Chillán Volcanic Complex (NChVC) is among the most active volcanos in the Chilean Andes, formed by NW-aligned centers divided in Cerro Blanco (CB, basaltic-andesitic) and Las Termas (LT, dacitic) subcomplexes, and two satellite cones (SW and NE of the main alignment). Evidence indicates strong structural control for magmatic activity by a NW-SE structure, however NE-SW dikes suggests magmatic injections during inter-seismic periods. Previous work proposes a reservoir plumbing system, nevertheless its interaction with the structural setting and how it affects volcanism is still to be understood. Shangri-La aa lavas (10-20m thickness) extends ~8km from their source, located between both subcomplexes, in alignment with the satellite cones. They are dacitic with basaltic-andesitic magmatic-enclaves (millimetric-centimetric with sub-rounded boundaries). Preliminary results show that lavas have plagioclase (rims  $An_{35-40}$ , cores  $An_{80-55}$ ) with core sieve textures, olivine ( $Fo_{80-87}$ ) with  $Fo_{70-75}$  rims and partial pyroxene corona texture, orthopyroxene ( $En_{58-60}Fs_{36-40}Wo_{0-4}$ ) and clinopyroxene ( $En_{38-43}Fs_{12-20}Wo_{37-45}$ ). Meanwhile, enclaves have plagioclase (rims  $An_{80-70}$ , cores  $An_{60-65}$ ), some of which have core and/or mantle disequilibrium textures, olivine ( $Fo_{80}$ ), with  $Fo_{70-75}$  rims and some resorptions, orthopyroxene ( $En_{60-80}Fs_{20-36}Wo_{0-4}$ ), and clinopyroxene (rims  $En_{47-50}Fs_{10-12}Wo_{38-40}$  cores  $En_{30-40}Fs_{17-30}Wo_{40-50}$ ). We suggest Shangri-La represent a mixing between the subcomplexes through NE-SW structures.  $An_{80-70}$  cores in plagioclase lavas would come from a CB-like magma represented by the enclaves. When it reaches a LT-like magma, plagioclases re-equilibrate to the  $An_{35-40}$  rims found in the lavas. This is also supported by olivine coronas indicating a disequilibrium with lava dacitic composition. This work is funded by ANID Regular Fondecyt#1220729 and Postdoctoral Fondecyt#3240166 grants.



a) Lava plagioclase with core sieve ( $An_{65-70}$ ) and  $An_{40}$  rim, b) Lava olivine ( $Fo_{85}$  core,  $Fo_{70}$  rim) with orthopyroxene corona, c) enclave plagioclase with  $An_{60}$  core  $An_{70}$  rim, d) enclave olivine ( $Fo_{80}$  core,  $Fo_{70}$  rim).

# Abstracts

## **Gabbros at Askja: The Bringers of Chaos**

Brooke Benz<sup>1</sup>, Alison Graettinger<sup>2</sup>

<sup>1</sup> Earth and Environmental Sciences, University of Missouri-Kansas City, United States of America

<sup>2</sup> Earth and Environmental Sciences, University of Missouri-Kansas City, United States of America

Over 70,000 years of volcanic activity at Askja Volcano, Iceland, has produced high silica and mafic volcanic deposits that provide a glimpse of the magma plumbing history at Askja. Monitoring at Askja has shown deflation since 1983, which is the result of magma moving to a deeper chamber (de Zeeuw-van Dalftan et al., 2013), however uplift of 60 cm since September 2021 has been detected and suggests inflow of new magma (Icelandic Met Office, 2023). Here, we present descriptions of gabbro xenoliths at Askja and their implications of magmatic processes and storage. Because most of the units at Askja are aphyric, the best insight into magmatic processes are using gabbro xenoliths in Unit 6 of the glacial units. Gabbro xenoliths are categorized into four groups using plagioclase shape, presence of olivine, and relative plagioclase to clinopyroxene abundance. Plagioclase phenocrysts are present in all samples and are up to 2 cm in length, range from elongate to subhedral, contain melt inclusions, and show complex zoning patterns with An #s ranging from 0.71-0.89 (Santilli, 2020). Clinopyroxene phenocrysts are present in all samples up to 12 mm in length, are subhedral to anhedral, and contain melt inclusions. Olivine phenocrysts are present in most of the gabbro xenoliths and are up to 8.5 mm, are subhedral to anhedral, and contain melt inclusions. Crystal analyses are essential in understanding formation of gabbros at Askja, can provide direct insight to the magma processes and storage, and is vital to understanding the current magmatic status of Askja.

# Abstracts

## Geophysical insights into magma plumbing system and subsurface hydrothermal activity of Lānaʻi volcano (Hawaiian Islands)

Xavier Bolós<sup>1</sup>, Nicole Lautze<sup>2</sup>, Mario Boijseauneau<sup>3,4</sup>, Mattox Telwar<sup>2</sup>, Adelina Geyer<sup>1</sup>

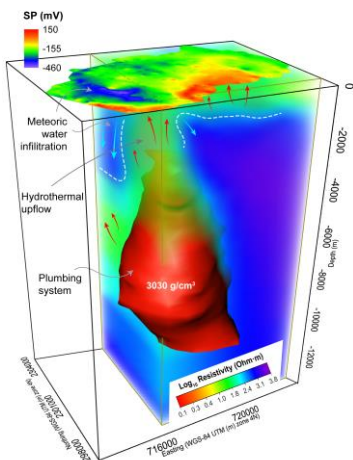
<sup>1</sup>Geosciences Barcelona (GEO3BCN), CSIC, Barcelona, Catalonia, Spain.

<sup>2</sup>Hawaiʻi Groundwater & Geothermal Resource Center, Institute of Geophysics and Planetology, University of Hawaiʻi, Honolulu, Hawaii, United States of America.

<sup>3</sup>Posgrado en Ciencias de la Tierra, UNAM, Morelia, Michoacán, México.

<sup>4</sup>Mineral & GeoData Analytics, Morelia, Michoacán, México.

The Hawaiian Islands, renowned for their volcanic activity and intricate hydrogeological systems, face energy challenges due to their dependence on imported fossil fuels. Therefore, the exploration of geothermal sources is imperative for sustainable development, particularly considering the islands' isolation. Simultaneously, understanding freshwater reservoirs is crucial for effective water resource management. This multidisciplinary study on Lānaʻi Island integrates geophysical, groundwater, and mineralogical data, providing insights into the concealed deep hydrothermal activity and its magma plumbing system. Correlations observed in newly acquired self-potential (SP) data, alongside earlier gravity and magnetotellurics (MT) data, reveal the presence of a hydrothermal upflow, possibly originating from deep magma reservoirs beneath the Pālāwai caldera. This concealed hydrothermal system emerges as a potential geothermal resource at depths exceeding 2 km, necessitating further deep drilling research for verification. Additionally, XRD analysis indicates varying degrees of hydrothermal alteration, suggesting elevated temperatures during fluid-rock interactions. Surface alteration alignment with existing upflow zones implies persistent active hydrothermal system presence within caldera faults, contributing to warm brackish water occurrence in the Pālāwai basin. Our study introduces a high-density body (~3030 g/cm<sup>3</sup>) with a vertical fusiform shape, correlating with heightened conductivities detected via MT and SP methods, interpreted as the caldera's plumbing system. This finding suggests that post-caldera magma intrusions—without eruptions— from smaller reservoirs during younger periods may explain ongoing hydrothermal system activity. Grasping the convergence between the plumbing system and hydrothermal activity is of paramount importance for promoting sustainability across the Hawaiian archipelago and other volcanic islands worldwide.



3D model showing the SP surveys overlaying deep MT and gravity datasets. A density of 3030 g/cm<sup>3</sup> is fixed for the gravity visualization model, inferred as the plumbing system of the Pālāwai caldera. Blue arrows show the inferred meteoric water infiltration zones, and red arrows indicate the inferred hydrothermal upflow zones.

# Abstracts

## **Direct observation of magma degassing and crystallisation via HP-HT X-ray transparent Internally Heated Pressure Vessel (IHPV)**

Barbara Bonechi<sup>1</sup>, Margherita Polacci<sup>1</sup>, Fabio Arzilli<sup>2</sup>, Giuseppe La Spina<sup>3</sup>, Jean-louis Hazemann<sup>4</sup>, Richard A. Brooker<sup>5</sup>, Elisa Biagioli<sup>1</sup>, Robert Atwood<sup>6</sup>, Sebastian Marussi<sup>7</sup>, Peter D. Lee<sup>7,8</sup>, Roy A. Wogelius<sup>1</sup>, Jonathan Fellowes<sup>1</sup>, & Mike Burton<sup>1</sup>

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<sup>2</sup> School of Science and Technology, Geology Division, Camerino, Italy

<sup>3</sup> Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Catania, Italy

<sup>4</sup> Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France

<sup>5</sup> School of Earth Sciences, University of Bristol, Bristol, United Kingdom

<sup>6</sup> Diamond Light Source, Harwell Science and Innovation Campus, United Kingdom

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<sup>8</sup> Research Complex at Harwell, Rutherford Appleton Laboratory, Harwell, Oxfordshire, United Kingdom

Transitions in eruptive style strongly depend on magma-gas decoupling during ascent. Stronger gas-melt coupling favours highly explosive eruptions, whereas weaker coupling promotes lava fountaining and lava flows. The mechanism fostering the transition from closed- to open-system degassing is still poorly understood due to a lack of bubble dynamics direct observations under natural magma ascent conditions. We combined X-ray radiography with our novel high-pressure/high-temperature IHPV to observe and quantify bubble growth and coalescence from 100 MPa to the surface, in real-time. For low-viscosity basaltic magmas, bubbles coalesce and recover a spherical shape within 3 s, implying that, for lava fountaining activity, gas and melt remain coupled during the ascent up to the last hundred metres of the conduit. For higher viscosity magmas, instead, the recovery time becomes longer, promoting connected bubble pathways leading to some degree of decoupling that we observed as bubbles expand until they connect to an open pathway and then contract as gas escapes.

Together with degassing, also crystallisation plays a key role in determining eruptive style transitions by affecting magma rheological properties and its ability to move, rise in the crust and erupt. Thus, we combined X-ray microtomography with our IHPV to simulate magma storage at  $P \leq 100$  MPa and  $T \leq 1200^\circ\text{C}$  in presence of volatiles. We captured, visualised and quantified in 4D crystallisation and vesiculation kinetics in a tephritic magma, fundamental to improve our understanding of magma behaviour and mitigating the volcanic risk associated with mafic systems like the one that fed the 2021 Tajogaite eruption (Canary Islands).

# Abstracts

## Unravelling volcano-tectonic interactions at the Nevados de Chillan volcanic complex, Southern Andean Volcanic Zone, Chile

John Browning<sup>1</sup>, Jose Cembrano<sup>1</sup>, Gloria Arancibia<sup>1</sup>, Javier Espinosa<sup>1</sup>, Valentina Mura<sup>1</sup>, Flavia Rojas<sup>1</sup>, Max Moorkamp<sup>2</sup>, David Healy<sup>3</sup>, Julian Mecklenburgh<sup>4</sup>, Nico Bignaroni<sup>4</sup>, Natalie Farrell<sup>4</sup>, Ashley Griffith<sup>5</sup>, Philip Meredith<sup>6</sup> & Thomas Mitchell<sup>6</sup>

<sup>1</sup> Faculty of Engineering, Pontificia Universidad Catolica de Chile, Chile

<sup>2</sup> Department of Earth and Environmental Sciences, University of Munich, Germany

<sup>3</sup> School of Earth and Environment, University of Leeds, UK

<sup>4</sup> Department of Earth and Environmental Sciences, University of Manchester, UK

<sup>5</sup> School of Earth Sciences, Ohio State University, USA

<sup>6</sup> Department of Earth Sciences, University College London, UK

Nevados de Chillan, located in the Southern Andean Volcanic Zone, has been active for around 650 ka and over that time has likely experienced several seismic cycles imposing potentially transient tectonic regimes. In this study, we attempt to unravel the evolution of the volcanoes' magma plumbing system and tectonic interactions. We combined data from volcano scale dyke, fracture and fault systems, in order to perform stress and strain reconstructions, with laboratory characterization of the physical properties of representative samples from the basement underlying the active complex. These data are further complemented with preliminary crustal resistivity models from a dedicated magnetotellurics campaign. Results indicate predominant NE-SW and E-W trends of dykes and faults which is curious considering the alignment of volcanic centres is roughly NW-SE. There are apparent deviations from the general structural trends near the intersections of long-lived fault zones at the southern-most extent of the volcanic complex. To determine the potential influence of different rock properties on the volcano stress field we measured P and S wave velocities and porosity at ambient pressure, and P wave velocity at elevated confining pressure up to 140 MPa (simulating around 5.5 km of crustal depth), allowing us to model crack closure and compliance variation with depth. Results indicate that Young's moduli varies from between around 10 GPa in volcanoclastic units up to around 80 GPa in granodiorites. Stiffness differences compare well with measured porosities, ranging from around 13% in the most compliant rocks, down to around 1 % in the stiffest rocks.



Image, facing NE over the Shangrila lavas, towards the Nevados de Chillan volcanic complex

# Abstracts

## Deformation related to magma transport in the Earth's crust - not just in the host rock

Steffi Burchardt<sup>1,2</sup>, Taylor Witcher<sup>2</sup>, Tobias Mattsson<sup>1,3</sup>, Emma Rhodes<sup>1,2</sup>, Orlando Quintela<sup>1</sup>, Sonja Greiner<sup>1,4</sup> & Tobias Schmiedel<sup>5</sup>

<sup>1</sup> Department of Earth sciences, Uppsala University, Uppsala, Sweden <sup>2</sup> Center of Natural Hazards and Disaster Science, Sweden <sup>3</sup> University of St Andrews, United Kingdom <sup>4</sup> Nordvulk, University of Iceland, Iceland

<sup>5</sup> Technical University of Delft, The Netherlands

Monitoring of active volcanic areas typically highlights both pre-eruptive ground movements and seismicity. These signals testify to deformation related to the movement of magma through the Earth's crust. Studies of extinct and eroded volcanic plumbing systems have traditionally focussed on brittle and ductile deformation of the host rocks to magmatic intrusions, including e.g. fractures, faults, foliation, and folds. These studies mostly assumed that magma is behaving as a Newtonian fluid during transport, which implies that magma is a passenger without any strain memory. Here we report on deformation features within silicic intrusions and show that these features formed during magma transport and emplacement. Deformation of silicic magma occurs due to its complex material properties as a non-Newtonian fluid with a strain-dependent rheology controlled by the magma composition, suspension fractions (crystals and bubbles), volatile content, and ambient conditions. The deformation features range from viscous to brittle and have a major effect on magma outgassing. Moreover, the non-Newtonian rheology of magma implies that strain is localising, leading to the development of shear zones within intrusions. This in turn causes significant changes in the style of subsequent magma emplacement, including how the host rock deforms.

# Abstracts

## **Exceptional eruptive CO<sub>2</sub> emissions from intra-plate alkaline magmatism in the Canary volcanic archipelago**

**Mike Burton<sup>1,2</sup>, Alessandro Aiuppa<sup>3</sup>, Patrick Allard<sup>4</sup>, María Asensio-Ramos<sup>5</sup>, Ana Pardo Cofrades<sup>1</sup>, Alessandro La Spina<sup>2</sup>, Emma J. Nicholson<sup>6</sup>, and co-workers**

<sup>1</sup> Department of Earth and Environmental Sciences, University of Manchester, UK

<sup>2</sup> Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Italy

<sup>3</sup> Università degli Studi di Palermo, Dipartimento di Scienze della Terra e del mare, Palermo, Italy

<sup>4</sup> Université Paris Cité, Institut de Physique du Globe de Paris, France

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<sup>6</sup> University College London, Earth Sciences, London, United Kingdom

Alkaline mafic magmas forming intra-plate oceanic islands are believed to be strongly enriched in CO<sub>2</sub> due to low-degree partial melting of enriched mantle sources. However, until now, such CO<sub>2</sub> enhancement has not been verified by measuring CO<sub>2</sub> degassing during a subaerial eruption. Here, we provide evidence of highly CO<sub>2</sub>-rich gas emissions during the 86-day 2021 Tajogaite eruption of Cumbre Vieja volcano on La Palma Island, in the Canary archipelago. Our results reveal sustained high plume CO<sub>2</sub>/SO<sub>2</sub> ratios, which, when combined with SO<sub>2</sub> fluxes, melt inclusion volatile contents and magma production rates at explosive and effusive vents, imply a magmatic CO<sub>2</sub> content of  $4.5 \pm 1.5$  wt%. The amount of CO<sub>2</sub> released during the 2021 eruptive activity was  $28 \pm 14$  Mt CO<sub>2</sub>. Extrapolating to the volume of alkaline mafic magmas forming La Palma alone (estimated as 4000 km<sup>3</sup> erupted over 10 Ma), we infer a maximum CO<sub>2</sub> emission into the ocean and atmosphere of 1016 moles of CO<sub>2</sub>, equivalent to 20% of the eruptive CO<sub>2</sub> emissions from a large igneous province eruption, suggesting that the formation of the Canary volcanic archipelago produced a CO<sub>2</sub> emission of similar magnitude as a large igneous province.

# Abstracts

## The mush-dominated plumbing system of Large Igneous Provinces unveiled by glomerocrysts and melt inclusions

Manfredo CAPRIOLO<sup>1</sup>, Sara CALLEGARO<sup>2</sup>, Frances M. DEEGAN<sup>3</sup>, Renaud MERLE<sup>3</sup>, Heejin JEON<sup>4</sup>, Martin J. WHITEHOUSE<sup>4</sup>, László E. ARADI<sup>5</sup>, Malte STORM<sup>6</sup>, Paul R. RENNE<sup>7</sup>, Don R. BAKER<sup>8</sup>, Jacopo DAL CORSO<sup>9</sup>, Robert J. NEWTON<sup>10</sup>, Csaba SZABÓ<sup>11</sup>, Bruna B. CARVALHO<sup>5</sup>, Nasrddine YOUBI<sup>12</sup>, & Andrea MARZOLI<sup>13</sup>

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The nature of the magma plumbing system of Large Igneous Provinces is still poorly understood. Among these exceptional magmatic events from Earth's past, the Central Atlantic Magmatic Province (CAMP [1], ca. 201 Ma) and the Deccan Traps (DT [2], ca. 66 Ma) emplaced synchronously with end-Triassic and end-Cretaceous mass extinctions, respectively. Glomerocrysts containing abundant primary melt inclusions from both CAMP and DT basaltic lava flows were investigated via a multi-analytical approach, combining optical microscopy, confocal Raman microspectroscopy, Synchrotron Light X-ray microtomography, electron microprobe and secondary ion mass spectrometry. The analysed glomerocrysts, dominated by augitic clinopyroxenes, represent portions of crystal mushes. The analysed melt inclusions, consisting of an intermediate to felsic composition glass and CO<sub>2</sub>-bearing bubbles, represent relics of interstitial melts and fluids entrapped during the evolution of these crystal mushes. The MgO-rich composition of glomerocrysts and whole rocks is in contrast with the SiO<sub>2</sub>-rich composition of melt inclusions, unveiling disequilibrium conditions of entrapment. The oxygen isotope compositions of clinopyroxene in glomerocrysts indicate that they crystallized from mafic melts with normal (i.e., mantle-like) to slightly low δ<sup>18</sup>O values. However, the oxygen isotope compositions of glass in melt inclusions indicate that they entrapped distinct, intermediate to felsic melts with normal (i.e., mantle-like) to extremely high δ<sup>18</sup>O values, pointing to variable degrees of crustal assimilation and partial mixing in an open system. Our geochemical data and microstructural observations suggest a dynamic evolution of multiphase (i.e., solid + liquid + gas phases) crystal mushes within the magma plumbing system of both CAMP and DT.

[1] Marzoli *et al.* (1999), *Science* **284**, 616–618. [2] Sprain *et al.* (2019), *Science* **363**, 866–870.

# Abstracts

## Shedding (laser) light on three-dimensional fluid flow in dykes

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Dyke propagation is a complex solid-fluid (rock-magma) interaction problem, and understanding the governing physical processes is vital for interpreting subsurface signals of magma movement in real time. As dyke propagation is naturally hidden from view, experimental and numerical models are essential. To simplify the complex physical problem, numerical models often either neglect magma flow completely, or assume that it has a simple unidirectional profile. However, the fluid dynamics within propagating fractures has a major impact on the overall fracture behaviour. Propagation is driven by internal fluid pressure (due to fluid injection, buoyancy, or a combination of the two), which is distributed and dissipated by the internal flow. Furthermore, the flow of magma influences the mixing efficiency within the dyke and the style of eruption at the surface. Recent analogue experiments – involving the constant injection of fluid into gelatine – have challenged the assumption of unidirectional flow in dykes. These experiments used an optical technique called Particle Image Velocimetry (PIV) to get two-dimensional fluid velocity profiles inside fractures, showing that Newtonian fluids consistently exhibit a complex recirculatory flow in dykes. However, to advance our understanding of flow in dykes further and enable the development of state-of-the-art numerical models, three-dimensional (3D) insight is essential. Using a laser-based stereoscopic PIV imaging system, we have measured 3D flow in analogue dykes for the first time. Our results show that, despite their thin geometry, 3D flow in dykes is significant. This has strong implications for the behaviour of dykes and how they are modelled.

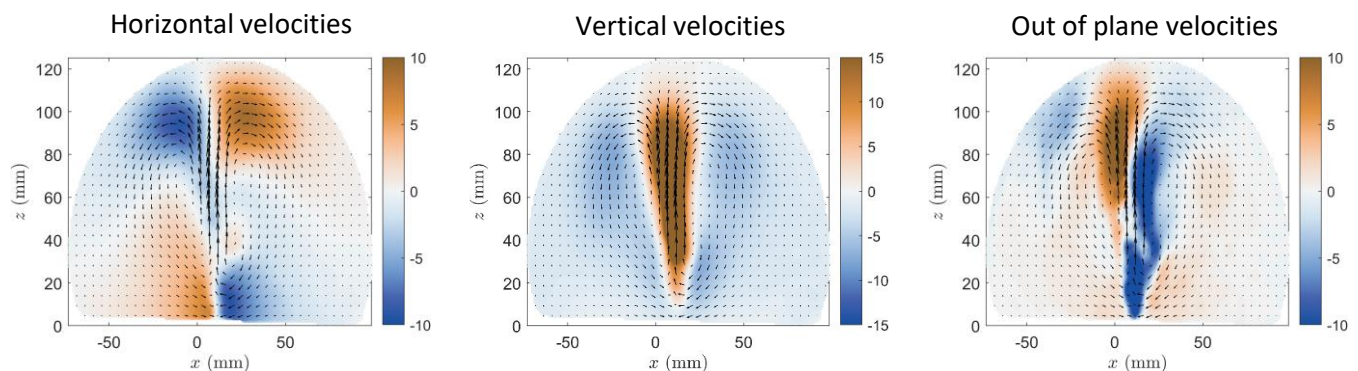


Figure 1: Filled contours of velocity (mm/s) and vectors of flow direction (black arrows) half-way through a flux-driven fracture experiment involving the injection of a glycerol solution into gelatine. Each of the three velocity components – horizontal, vertical, and out-of-plane – are shown in the plane of lateral fracture growth (perpendicular to the strike).

# Abstracts

## **Influence of crustal structures in dyke propagation: observations from analogue modelling.**

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Analogue experiments often simplify crustal structures, representing them as either homogeneous or with horizontal layers. However, in regions affected by orogenesis and volcanic settings, this simplification may misrepresent reality. We conducted experiments injecting water into a layered elastic analogue crust, comprising gelatine layers with different stiffness, separated by a 45° dipping interface. Dyke growth was monitored with HD cameras, while polarised light visualised gelatine stress evolution. Surface elevation changes were measured with an overhead laser, and subsurface strain evolution using particle image velocimetry in gelatine seeded with fluorescent particles.

Results showed that vertical dyke propagation occurred when the lower layer was stiffer and the interface strong, narrowing the dyke upon crossing. Sill formation resulted from dyke deflection along a weak interface, regardless of layer stiffness contrast. With a stiffer upper layer, dyke widening was observed during deflection parallel to the weak interface until interface intrusion, when velocity increased, and width reduction occurred. When the lower layer was stiffer, the dyke first deflected away from the interface and then intruded into the weak interface. Dyke deflection was also observed when the upper layer was stiffer, and the interface was strong. Dyke-induced strain and stress exhibited asymmetrical distribution around the dyke tip, with surface elevation profiles like those found in models for inclined sheets propagating through a homogeneous crust.

These results highlight the importance of considering heterogeneous dipping layers in volcano monitoring, crucial for accurately characterising deformation sources of deformation by ground deformation signal inversion.

# Abstracts

## Advancements in volcanic conduit modelling: A decade of development, applications, and future perspectives.

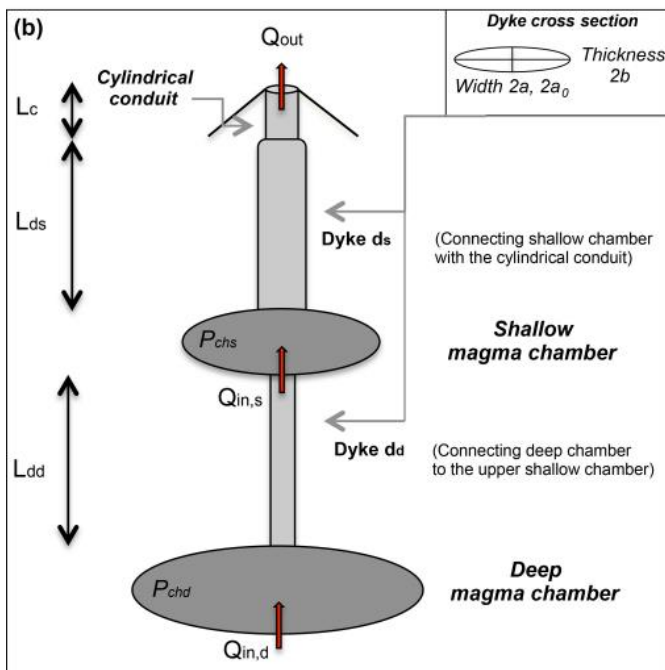
Antonio Costa<sup>1</sup>,

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Over the past decade, significant advancements have been made in the development and application of volcanic conduit models, contributing to a deeper understanding of the dynamics and processes within volcanic systems. This review summarizes the evolution of conduit models, highlighting physical formulation, computational techniques, and insights gained. Initial models predominantly focused on fluid dynamics and magma ascent, while recent advancements have incorporated multi-phase flow, thermo-mechanical interactions with host rocks, and complex rheological behaviors.

Integration of observational data with numerical simulations has facilitated more accurate and predictive models, enhancing our ability to assess volcanic hazards and mitigate associated risks. Applications of these models have extended beyond numerical simulations to practical implications in hazard assessment, eruption forecasting, and volcano monitoring.

Looking forward, the future of volcanic conduit modeling is poised to benefit from advancements in computational capabilities, machine learning algorithms, and geophysical and geochemical observations. These innovations hold promise for refining existing models, incorporating additional complexities, and expanding the scope of predictive capabilities. Furthermore, interdisciplinary collaborations between volcanologists, geophysicists, and computer scientists will be crucial in driving forward the next generation of volcanic conduit models, ultimately leading to improved volcanic hazard assessment.



Schematic view of the conduit feeding system framework for lava dome eruptions

(modified after Melnik and Costa, 2014; doi: 10.1144/M39.3).

# Abstracts

## Using Triple-Fe to distinguish mush vs melt storage systems.

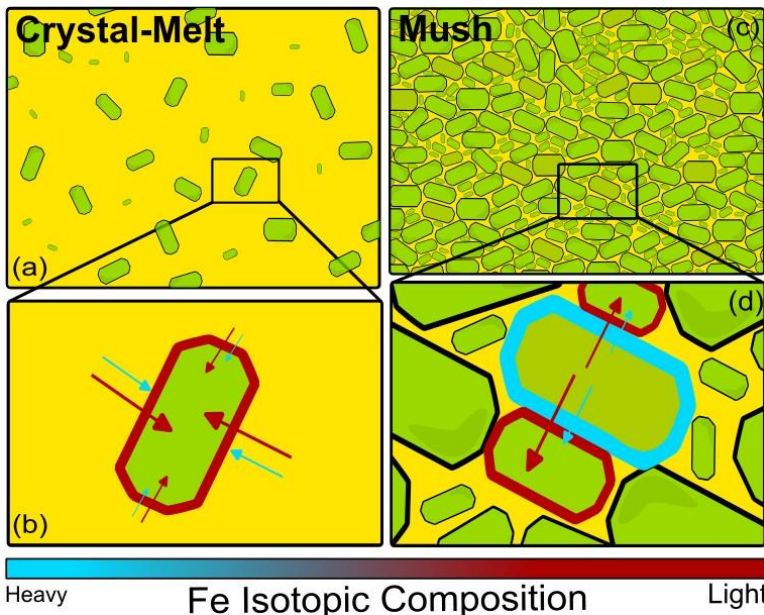
Sara Crozier<sup>1</sup>, Simon Matthews<sup>2</sup>, Oli Shorttle<sup>1</sup>, & Helen Williams<sup>1</sup>

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The upper mantle exhibits chemical and isotopic heterogeneity, with iron isotopes serving as vital indicators for distinguishing mantle source lithologies. However, conventional equilibrium mass-dependent stable iron isotope fractionation models fail to capture the full extent of natural variation, suggesting contribution from disequilibrium processes like kinetic isotope exchange via inter-mineral diffusion or open system transfer. Diffusion induces fractionation as isotopes diffuse at varying rates based on their masses. The assumption of diffusion ubiquity is crucial in employing diffusion profiles for chronometry, although previous methods often focus on major elements or volatiles in melt inclusions. Diffusion-driven processes can lead to isotopic zonation and signature modification.

Olivines, rock-forming minerals rich in Fe and Mg, offer insights into volcanic plumbing systems, with mush regions often serving as open systems susceptible to disequilibrium through processes like magma recharge, mixing, and reactive porous flow, though distinguishing these environments using isotopic investigations has thus far been difficult. This study focuses on Fe isotopic compositions of olivines, measured via mineral separation, column chromatography, and LA-ICP-MS, to understand how mantle signatures endure or evolve during crustal processes. A novel method visualises diffusion fractionation models in 3-isotope space, assessing the environments conducive to diffusion-driven profiles, that being a crystal mush vs magma setting (See Figure 1). The study underscores that the natural dataset defies explanation solely through equilibrium or disequilibrium processes, stressing the need for further research to comprehensively grasp the observed variation and characterise the parameters governing Fe diffusion.



**Figure 1** – Diagram of diffusion in a melt-dominated chamber vs diffusion in a crystal-dominated mush. In the former, lighter <sup>56</sup>Fe diffuses into the olivine from the melt causing the crystal to become progressively lighter in isotope composition, while having little effect on the isotopic composition of the ‘infinite’ melt reservoir. In the latter, inter-diffusion occurs between crystals of varying iron contents, with iron moving into a crystal causing it to be light, but leaving behind the slower heavier <sup>57</sup>Fe, making that initial crystal heavier.

# Abstracts

## Using a 3D seismic velocity anomaly to delineate a deforming magma reservoir at Soufrière Hills Volcano

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Volcano deformation models aim to contribute to hazard assessment by simulating magmatic system dynamics. Traditional magma reservoir pressure source shape assumptions often fail to replicate irregular, geophysically identified geometries, with uncertainties regarding the influence of reservoir geometry limiting the effectiveness of using deformation models to decipher unrest signals. Here, we determine the feasibility of using a magma reservoir geometry directly derived from a seismic tomography survey in a volcano deformation model for Soufrière Hills Volcano, Montserrat. To evaluate the new method, 3D deformation models were created to simulate displacement using a low seismic velocity anomaly geometry pressure source, contrasted with a traditional ellipsoid reservoir geometry. We also test a “hybrid” model combining a seismically inferred reservoir upper geometry and ellipsoidal base. The results of each model are evaluated against displacement observed on Montserrat from 2010-2022, to identify our best-fitting reservoir geometry and pressure combinations. Results show that different reservoir geometries change the horizontal and vertical displacement fields across the island: the ellipsoid reservoir best reproduces vertical displacement magnitude, while the hybrid reservoirs best simulate horizontal displacement vectors and the region of maximum uplift. Overall, the ellipsoid-shaped reservoir provides our best-fit to the observed data, but we note this result could be biased due to prior years of optimization helping constrain the ellipsoid shape, size, and location. Our results show the potential for further use of geophysically constrained reservoir geometries in deformation modelling, and our methods could be applied to other deforming volcanoes worldwide.

# Abstracts

## Messages from the magma mush: glass-bearing plutonic xenoliths from Fogo, Cape Verde

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Plutonic ultramafic xenoliths are abundant in silica-undersaturated highly alkaline shield-stage lavas of Fogo [1]. They are composed of different proportions of olivine and clinopyroxene, with minor amounts of Cr-spinel, Ti-magnetite, mica and apatite, and are entirely free of orthopyroxene. Many are cross-cut by veins of either clinopyroxene or phlogopite (occasionally both). Although some xenoliths have experienced deformation, others retain cumulate textures, with minor fresh interstitial glass (Figure 1) which varies from basanite to phonolitic in composition. The modal abundances of the xenoliths range from pure dunite (olivine±Cr-spinel) through wehrlite (olivine > clinopyroxene+Cr-spinel/Ti-magnetite), to olivine clinopyroxenite (clinopyroxene+Cr-spinel/Ti-magnetite > olivine) to pure clinopyroxenite (clinopyroxene+Ti-magnetite). This order of crystallisation is identical to that deduced for the magmatic evolution of the host basanitic-foiditic shield-stage magmas from bulk rock XRF analyses of ~100 lavas [1] and their phenocryst assemblages. REE analyses of clinopyroxenes in the xenoliths indicate that they crystallised from magmas similar those of the host lavas. We therefore conclude that the xenoliths were derived from a semi-crystallised magma mush formed from magmas similar to their host lavas in magma reservoirs within the volcanic edifice, and are an important link between plutonic and volcanic processes.

[1] Rolfe-Betts et al., 2024, *JVGR*, 446, p.107996

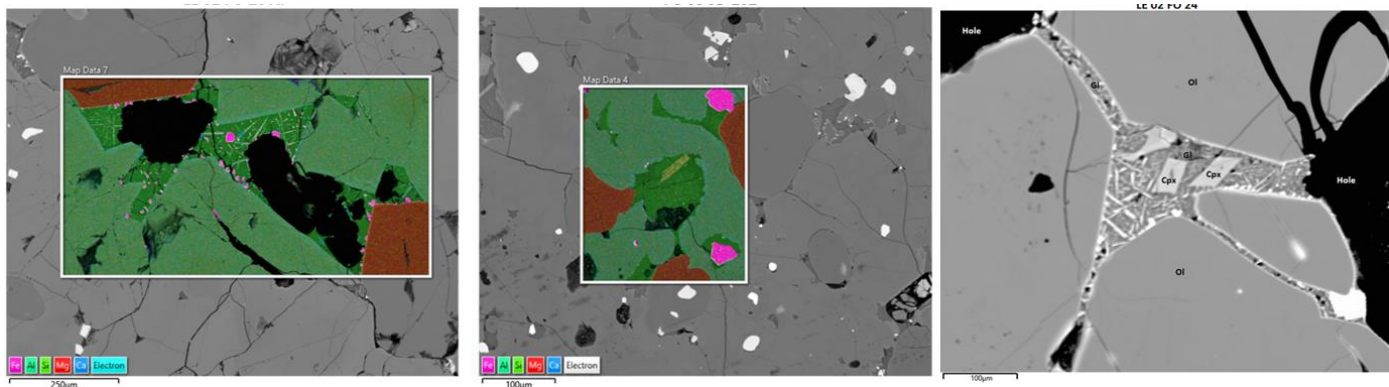


Figure 1. Left and centre: False-coloured X-Ray image of an ultramafic cumulate xenoliths from Fogo showing euhedral olivine (orange) and clinopyroxene (dull green) with interstitial glass (bright green). Black = voids; pink = Ti-magnetite. Scale = 250 µm. Background = Back-Scattered Electron (BSE) image. Right: BSE image of interstitial glass between olivine crystals, with clinopyroxene daughter crystals. Scale = 100 µm.

# Abstracts

## **Interconnected neighbouring volcanic systems and tectonic drivers of magmatic activity: crustal deformation during the Reykjanes Peninsula unrest 2020-2024, Iceland**

Halldór Geirsson<sup>1</sup>, Michelle Parks<sup>2</sup>, Freysteinn Sigmundsson<sup>1</sup>, Vincent Drouin<sup>2</sup>, Benedikt Ófeigsson<sup>2</sup>, Chiara Lanzi<sup>1</sup>, Áslaug Gyða Birgisdóttir<sup>1</sup>, Cécile Ducrocq<sup>1,3</sup>, Andrew Hooper<sup>4</sup>, Páll Einarsson<sup>1</sup>, Kristín Jónsdóttir<sup>1</sup>, Sigrún Hreinsdóttir<sup>1</sup>, Sonja Greiner<sup>1</sup>, Hildur María Friðriksdóttir<sup>2</sup>

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Neighboring volcanic systems sometimes show interconnected behavior, for example by inflating or deflating either in phase or in anti-phase. The Reykjanes Peninsula hosts 6 volcanic systems. All but one have shown signs of magmatic unrest in the past years: Three inflation episodes occurred at Svartsengi in 2020; two inflation episodes at Reykjanes in 2020; inflation at Krýsuvík in summer 2020.

Three eruptions occurred at Fagradalsfjall (2021, 2022, 2023) and four eruptions at Svartsengi in (Dec-2023, Jan-, Feb-, Mar-2024). Each eruption was preceded by a dike intrusion, often accompanied by complex patterns of faulting, fracturing, and creep. Several dike intrusions did not breach the surface. The dike growth spans timescales from hours to weeks. The dikes were emplaced in the brittle crust, were decimeters to meters thick, and released a great amount of plate-tectonic stresses. Re-inflation followed most eruptions or dike intrusions; however, the temporal style of uplift rates varies considerably. Co-eruptive deflation was observed during the 2021 Fagradalsfjall eruption, however, little co-eruptive deformation for other eruptions. Slight inflation was observed during the first days of the March 2024 eruption. The detailed deformation data reveals complex interactions of tectonics and magmatism across several volcanic systems on the RP. During 2020-2024, deformation and seismicity have alternated between the volcanic systems, such that only shows activity at each time, indicating deep pressure coupling between systems. Furthermore, stress changes affect neighboring volcanic systems, including probability of dike propagation and seismicity. Geological history suggests centuries of continued unrest in the area.

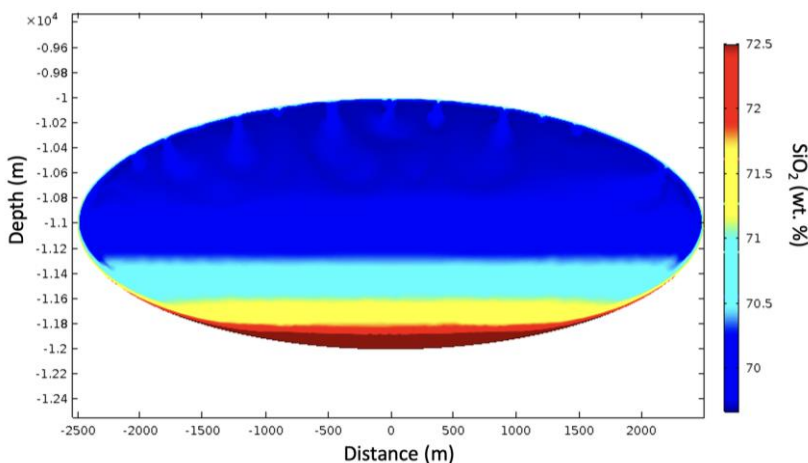
# Abstracts

## Understanding the internal dynamics of magma reservoirs: An pending challenge

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<sup>1</sup> Geosciences Barcelona (GEO3BCN), CSIC, Lluís Solé i Sabarís s/n, 08028 Barcelona

The internal dynamics of magma reservoirs represent a fundamental yet unresolved challenge in volcanology and earth sciences. A full comprehension of the internal dynamics, as well as the controlling parameters, of magma reservoirs is crucial for properly understanding the past and future evolution of volcanic systems, interpreting monitoring signals during unrest periods, and assessing the potential volcanic hazards (type and magnitude) during eruptive events. During the last decades, important efforts have been made to model (numerically and experimentally) the process occurring inside magma bodies, including mixing and mingling due to the arrival of fresh magma or those related to the temperature variations occurring due to cooling, among many others. However, the internal dynamics of magma reservoirs remain poorly understood due to limited direct observations and the inherent complexities of subsurface processes. Through a brief overview of the current state of the art regarding numerical and experimental modelling applied to understand the internal dynamics of magma reservoirs, the objective is to point out the main controversies and knowledge gaps. Of particular interest is to highlight the necessity to compare the experimental and mathematical results with the information given by nature by means of field exposures, microtextures, geophysical and geochemical data, etc. Ultimately, the final goal is to open a discussion aimed at refining the roadmap for future research, which strongly necessitates interdisciplinary collaboration and an innovative research strategy.



Example of the result of finite element modeling reproducing the cooling path of a magma body emplaced at c. 11 km depth (depth of the reservoir center). Thermal differences set in the magma chambers along its horizontal and vertical axes develop instabilities that trigger ascending and descending magma-cells, as well as accumulation of magma at the reservoir bottom. These thermal differences within the magma may be translated into variations in the  $\text{SiO}_2$  content.

# Abstracts

## **The influence of variable host rock cohesion and magma viscosity on intrusion-fault interaction: Insights from laboratory models**

**Sonja H. M. Greiner<sup>1,2,3</sup>, Olivier Galland<sup>4</sup>, Freysteinn Sigmundsson<sup>1</sup>, Steffi Burchardt<sup>2,3</sup>, Halldór Geirsson<sup>1</sup> & Rikke Pedersen<sup>1</sup>**

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Volcanic activity frequently occurs in areas affected by tectonic structures, such as faults. Numerous examples of pre-existing faults serving as magma pathways are known, but many aspects of this process remain poorly understood. Improving our understanding about the influence of faults on magma transport dynamics is important for studying volcanic plumbing systems in the upper crust, as they may affect inferred propagation paths.

We present laboratory experiments, which investigate how pre-existing strike-slip faults affect intrusion emplacement. Dry mixtures of fine-grained silica flour and micro-glass beads of variable cohesions and angles of friction represented brittle, dominantly plastic crust. Simulating low and high-viscosity magmas, we injected two liquids into intact and pre-faulted model crust. Surface deformation was monitored to assess intrusion-fault interaction.

In high-cohesion materials, sheet intrusions formed, with some segments clearly propagating along pre-existing faults. Low-cohesion materials produced subcircular laccoliths that grew by prominent doming of the model crust. Dome growth was accommodated by newly formed structures that were barely affected by pre-existing faults. Models of intermediate cohesions exhibited hybrid behaviour where intrusions both generated new fractures and followed pre-existing fault segments. Intrusions with both tested viscosities showed similar trends, although the hybrid behaviour only occurred with the low-viscosity model magma and magma-fault interactions appear slightly less prominent for high-viscosity magmas.

These analogue models demonstrate that the structural control of pre-existing faults on magma emplacement is variable and highly dependent on the host rock cohesion. In the tested range, magma viscosity plays a secondary role for fault reactivation during magma ascent.

# Abstracts

## Modelling host rock deformation and surface displacement during magma intrusion

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Inflation of viscous magma intrusions in Earth's shallow crust often induces strain and fracturing within heterogeneous host rocks and dome-shaped ground deformation. Most geodetic models nevertheless consider homogeneous, isotropic, and linear-elastic media wherein stress patterns indicate the potential for failure, but without simulating actual fracturing. We present a two-dimensional Discrete Element Method (DEM) application to simulate magma recharge in a pre-existing laccolith intrusion. In DEM models, fractures can propagate during simulations. We simulate (1) the effect of rock toughness and stiffness on intrusion-induced stress, strain, displacement, and spatial distribution of deformation; and (2) the effect of host rock heterogeneity on intrusion-induced displacement, through incorporation of pre-existing fractures into the model. We find that intrusion into a high stiffness rock results in extensive cracking of the host rock, multiple fractures that propagate from the surface down toward the magma body and two broad fracture zones that propagate upward and outward from each intrusion edge. Intrusion into high toughness rock results in limited cracking and one central vertical fracture with two fractures above the intrusion edges. We also find that considering pre-existing fractures in the host rock concentrates deformation in narrower zones, but generates higher surface displacements than homogeneous host rock. Importantly, we find that abrupt increases in surface displacement magnitude occur in response to fracturing, even at constant magma injection rates. Our modelling provides a novel approach to considering host rock mechanical strength and fracturing during viscous magma intrusion and associated dome-shaped ground deformation, with important implications for interpreting geodetic signals at active volcanoes.

# Abstracts

## **Modelling dyke remobilisation using gelatine analogue experiments**

Tegan A. Havard<sup>1</sup>, Janine L. Kavanagh<sup>1</sup>, Stefano Urbani<sup>1</sup>, & Caitlin M. Chalk<sup>1</sup>

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Basaltic magma can be transported from many kilometres depth to surface fissures by dykes. However, magma can often stall in the crust due to a variety of factors and be later remobilised by an injection of new magma which can be similar or differ in composition and physical properties. Here, we use a novel experimental methodology to explore the factors controlling the dynamics of magma remobilisation and magma mixing of dykes in the crust.

We present results from scaled analogue experiments where an array of miscible fluid pairs, representing magmas of differing composition through differing densities, are injected into a solid, elastic crustal analogue to simulate magma mingling and mixing in dyke-like geometries. A higher density fluid is injected first until the vertical dyke tip has reached halfway through the gelatine height, then the injection is paused, the fluid source switched to the lower density fluid and the injection restarted. Photographs were captured in the planes along and across the dyke thickness and processed to quantify dyke tip velocity and qualitatively assess the internal fluid interactions. The experiments were repeated using particle image velocimetry (PIV) to quantify flow velocities within the dyke and the strain in the surrounding gelatine. Our results show the fluid dynamics of mingling and mixing and how this impacts the physical and chemical properties of the mixture, the dyke propagation velocity, and potentially the eruption style and longevity. We relate our results to (1) dykes with pauses in propagation, (2) magma recharge events, (3) the evolution of physical properties of magma, and (4) to the Streitishvarf composite dyke in Iceland, a natural case study for magma remobilisation and mixing.

# Abstracts

## **Plagioclase-phyric basalts record variable crystal accumulation on millennial timescales beneath Wolf Volcano, Galápagos**

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Crystal disaggregation prior to volcanic eruption is an important and widely recognised process in basaltic magmas. Accumulation of crystals may affect the physical properties of ascending magmas, as well as posing clues as to the enigmatic structure of the sub-volcanic plumbing system. At Wolf Volcano in the Galápagos, a series of otherwise homogeneous basaltic magmas have accumulated highly variable quantities of plagioclase (0-35 vol%) over millennial timescales. Here we use these magmas to constrain the physical-chemical structure of the magmatic system through time, using a combination of mass balance modelling, thin-section-scale chemical maps, surface chemical analysis, and published remote sensing data. We find that the over-accumulation of plagioclase requires a process that generates crystal mushes in non-cotectic proportions within the magmatic system, which are separate to the gabbroic mush that buffers all crystal-free magmas and matrix glasses upon ascent. Our findings have broad implications for the structure and evolution of the oceanic crust across numerous tectonic settings.

# Abstracts

## **Petrographic and geochemical investigation of the magma plumbing system underneath the Rabaul Caldera, Papua New Guinea.**

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Rabaul has historically been the most active volcano in Papua New Guinea. Rabaul is capable of large volume, high intensity caldera-forming eruptions and lower intensity but more frequent intra-caldera eruptions. All eruptions pose a significant risk to nearby communities [1]. Rabaul's volcanic rocks are basaltic to rhyolitic in composition and lie on a common liquid line of descent controlled by fractional crystallization [1,2]. Additionally, magma mixing and mingling are common, evidenced by basaltic enclaves [1,2]. Seismic tomography imaging shows the presence of an extensive magma chamber underneath Rabaul at a depth of 3–4 km and an additional deep magma storage extending to 12 km depth [3].

The main goal of this study is to identify the key magma chamber processes influencing mineral chemistry and texture in magmatic products erupted from different intervals in the caldera cycle of Rabaul volcano. Here, we present EPMA mineral analysis and thermobarometry model outputs for products of the 1937, 1994 and 2014 eruptions as well as for the most mafic eruption products known, the Kombiu basalts. Our thermobarometry data complement existing geophysical observations of the structure of Rabaul's magma plumbing system. Furthermore, we present SEM imagery to reveal how mineral textures in samples from different eruptions at Rabaul reflect magma chamber processes such as mafic recharge, magma mixing and crystallisation.

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# Abstracts

## Investigating magma flow dynamics using plagioclase alignment in the Little Mount basaltic dyke, Victoria, Australia

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Plagioclase is a mineral that often forms throughout magma crystallisation and is commonly used to investigate magma flow dynamics in dykes and sills. Microlites of plagioclase are amongst the final crystals to form during magma intrusion at shallow crustal depths and can potentially record the near-surface flow behaviour and deformation processes in the lead-up to eruption.

Here we examine an oriented rock sample from a basaltic dyke of the Budj Bim Volcanic Complex, a fissure-fed eruption in the Newer Volcanics Province in Victoria, Australia. Extensive quarrying of the Little Mount scoria cone has exposed the internal architecture of its feeder dyke. Optical microscopy observations show the dyke is comprised of olivine phenocrysts (20%, <0.5 mm diameter), clinopyroxenes (20%, <0.1 mm diameter) and a plagioclase microlite-rich groundmass with minor iron-titanium oxides (5%, <0.05 mm diameter). Crystallographic analyses of plagioclase microlites using electron backscatter diffraction (EBSD) in a scanning electron microscope (SEM) show the microlites share strong shape and crystallographic preferred orientations (SPO and CPO) with a- and c- axes forming a girdle sub-parallel to the dyke wall, while the pole to the b faces cluster perpendicular to it. Based on these results, we suggest plagioclase preferred orientation formed by magma flow and pure shear processes during magma emplacement in the Little Mount dyke. By understanding the physical and chemical processes governing flow dynamics in fissure eruptions such as the Budj Bim Volcanic Complex, we will be able to inform hazard mitigations of future fissure eruptions worldwide.

# Abstracts

## **Variations in the temperature and composition of high-crystallinity magma reservoirs on the scale of hundreds of years to tens of thousands of years.**

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The highly crystalline mushy magma reservoir exists in many volcanoes, especially arc volcanoes. Many volcanic products show evidence of having passed through these highly crystalline magmas. These highly crystalline magma makes it relatively difficult for volcanoes to erupt, but is thought to be capable of eruption under certain melting conditions. It is therefore important to determine the composition and temperature and their changes in order to assess the volcano's potential for eruption.

We focus on how the high crystallinity, evolved magma reservoir changes its composition and temperature over the timescale of several hundred to tens of thousands of years. To this end, we have studied the magma reservoir from the perspective of crystal clots, the aggregation of crystals and phenocrysts. We have focused mainly on the amphiboles of these crystals. We use the products of Unzen volcano, which is known to have a highly evolved magma reservoir beneath it from about 200 ka to the present. In this presentation, we present the characteristics of temperature and chemical composition changes in the magma reservoir estimated from amphiboles from tens of thousands of years ago to the present. Our previous studies mainly focused on historical volcanic eruptions and looked at magma reservoir evolution on a time scale of several hundred years. We now look at magma reservoir evolution over several hundred to several tens of thousands of years by adding the older products of Unzen volcano.

# Abstracts

## **Modelling magma movement in dykes and sills: Insights from minerals, magnetism and mixing experiments**

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How explosive a volcanic eruption will be and how long it will last is fundamentally controlled by the physical, chemical and thermal processes of magma movement in the subsurface. We have conducted a range of scaled analogue experiments, involving fluids injected into elastic and transparent gelatine solids and laser-based particle image velocimetry (PIV) to explore the dynamics of magma intrusion and mixing in the crust. To inform and test the results of these models, we have conducted field experiments on well-exposed dykes and sills in Iceland, Australia and the UK to study the static record of magma flow at multiple scales and spanning magma compositions from basalt to rhyolite. We have used drone imaging to measure the thickness and breadth of magma fingers, and direct outcrop inspection to map mafic enclave shape and distribution, phenocryst alignment, stretched vesicles and ropey flow textures and collected hand samples and rock cores. Crystal size, shape, and preferred orientation of the phenocrysts and/or microlites have been mapped using electron back-scattered diffraction (EBSD) in the scanning electron microscope (SEM). Magnetic fabrics have been mapped on the same samples using Anisotropy of Magnetic Susceptibility (AMS) and Anisotropy of Anhysteretic Remanent Magnetisation (AARM). This multi-method approach provides the opportunity to compare and reconcile the evidence of magma flow preservation, from magma intrusion to magma mixing and solidification, across orders of magnitude in scale. Instigating a step-change in the physical modelling of magma movement in dykes and sills using a multidisciplinary approach is needed to improve volcanic hazard assessments.

# Abstracts

## **Mantle to surface monitoring of an andesite magmatic-hydrothermal system**

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Magmatic systems that feed andesite volcanic eruptions are often envisaged as trans-crustal complexes that extend over several kilometres from the upper to lower crust. Several case studies have shown that more mafic inputs from deeper in the magmatic system prime and often trigger magma ascent to eruption. The timescales of these triggering events have been determined through diffusion chronometry to occur several weeks to months prior to eruption. Once the eruption episode has begun, it is plausible that continued magma mingling could drive extended eruption durations.

Whakaari (White Island, New Zealand) is an andesite cone volcano located in the northern portion of the Taupo Volcanic Zone. Whakaari is the subaerial portion of a largely submerged edifice. With a high frequency of eruption, it is generally considered to be one of New Zealand's most historically active volcanoes.

Here we utilise petrological data and diffusion chronometry from past magmatic eruptions at Whakaari (White Island, New Zealand) to show that mantle-derived basaltic melts briefly mingled with more evolved andesite-dacite melts. Using rapidly diffusing halogen elements, we show that the timescales of mingling occurred syn-eruptively. This observation highlights that primitive basalts were able to ascend through the ~20 km thick crust, bypassing the entire transcrustal magmatic system; an extreme example of an open magmatic system.

Whakaari's hydrothermal system is less-well constrained, is highly dynamic, exhibiting transient hydrothermal features caused by a dynamic hydrological system. To monitor the fine-scale variations in hydrothermal system activity, we use new high-resolution (0.25-1 m) Synthetic Aperture Radar data to track small-scale changes in and around the vent area. Our results show the highly dynamic nature of the vent area, including the formation of new sub-vents and fine-scale fluctuations in the lake level. In addition, deformation timeseries allow us to track subtle displacements associated with changes in the shallow hydrothermal and magmatic systems, and active landslide.

# Abstracts

## Localization in basaltic fissure eruptions

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Basaltic fissure eruptions typically localize over time into one or more vents. The timing and location of localization determines the evolution of lava, gas, and ash hazards; however, the in-conduit processes that control localization are poorly constrained. Here, we present the results of field studies and laboratory experiments that inform on the nature and timing of localization, and the various physical processes involved. Field investigation of architecture and textures of ancient, eroded dykes in Tenerife (Spain) provides evidence that thermo-rheological localization of dykes occurs at depth, supporting the leading conceptual model for localization. However, observations of active and historic eruptions in Hawaii (USA) indicate that the early stages of localization (hours-to-days), during which a near-continuous lava curtain segments into discrete fountains, are not associated with segmentation of the feeder dyke. Vent structures typically overlie a fissure that is fully connected at depths of only a few metres, implying that thermo-rheological processes do not drive the observed localization. Laboratory experiments provide a potential resolution to this conundrum. Molten wax driven through an analogue dyke forms conduits via thermo-rheological localization over a timescale determined by the balance between heat advected in with the liquid and conducted away through the walls, corresponding to weeks-to-months for a typical basaltic fissure. In other experiments, gas injected into an analogue dyke forms convective cells with localized plumes of ascending liquid. Synthesizing lab and field observations, we propose that early localization is driven by multiphase fluid dynamics; whereas longer-term localization is driven by thermo-rheology and solidification.

# Abstracts

## **Peraluminous to metaluminous magma transition within a magmatic plumbing system: evidence from zircon, garnet and amphibole crystal chemistry**

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Zircon in the garnet-bearing rhyodacites of the Visegrád and Börzsöny volcanoes (northern Hungary) has a unique compositional feature, showing an elevated Al content (Al=5-18 ppm). This is a typical peraluminous character and confirms the primary origin of the almandine. Interestingly, zircon in some of the genetically related garnet-free andesites also has an elevated Al content, indicating an inheritance from peraluminous magmas. Amphibole is often associated with garnet in the dacites and has an overlapping composition with the experimental data. However, they show a strong heavy REE enrichment which is atypical for magmatic amphibole worldwide. This feature, as well as the variation in glass trace elements, can be explained by remelting of garnet at shallow depths and further crystallisation of amphibole and zircon.

The epsilon Hf values of zircon show a variation from -4 to +2, suggesting mixing of mantle and crustal magmas. This is consistent with petrogenetic modelling calculations based on bulk rock isotopic and trace element data, suggesting interaction between mafic magmas derived from enriched lithospheric mantle and metasedimentary lower crust. Remarkably, this volcanism is not related to contemporaneous subduction, but occurred in response to continental rifting. The preservation of high-pressure garnet can be explained by rapid magma ascent enhanced by crustal extension. In contrast, some magmas stalled at shallow crustal levels. They also contain Al-bearing zircon crystals, suggesting a peraluminous nature of the parental magmas, whereas garnet phenocrysts were probably dissolved at low pressure, as reflected in the amphibole and glass compositions.

# Abstracts

## **The Role of Gravity in the State of Stress of Dynamic Magma Mush Reservoirs: Insights into Surface Deformation and Reservoir Failure.**

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Volcanoes can experience phases of unrest which may or may not result in an eruption. Assessing the stability of magma reservoirs is critical to understand what leads to one outcome rather than the other. The modelling of magma reservoirs is experiencing a shift of paradigm from the static models of melt-dominated magma chambers to trans-crustal magmatic systems (TCMS) where magma flows through a permeable matrix. TCMS can be addressed as poroelastic reservoirs. Failure within and/or at the boundary of such reservoirs is likely to be controlled by the strain-rates produced by magma migration and the full state of stress in the host rocks and elastic matrix, meaning that the response of the medium to gravity must be considered. Numerical modelling of TCMS, including the dynamic processes of magma injection or withdrawal, has advanced considerably in recent years. New models, however, include little investigation of reservoir failure and usually neglect the role of gravity. Here we provide some insights on both aspects with preliminary results within the DV3M project. Specifically, we detail general solutions for the steady-state stresses within and outside a mush reservoir in the Earth's crust under the effect of gravity. Then, we employ Finite-Element numerical models to compare spatio-temporal patterns of surface deformation when magma is supplied to a mush reservoir with and without gravity and analyse the evolution of strain-rates and stress patterns produced in mush reservoirs of different geometries undergoing magma recharge, discussing where and when reservoir failure may be promoted.

# Abstracts

## Tracing Laccolith Growth with Palaeomagnetism

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Palaeomagnetic vectors associated with magmatic intrusions are locked in as the magma cools below the blocking temperature of remanence-carrying grains. If the rim of the intrusion is rotated by later intruding magma after the palaeomagnetic vector has been locked in, the rotated vector represents a passive marker of deformation. The silicic 11.7 Ma Sandfell laccolith in Iceland displays evidence of early sill emplacement and subsequent deflection and brecciation of already emplaced magma (Mattsson et al. 2018). Combining a palaeomagnetic baked contact test with incremental fold tests, Twomey et al. (2021) demonstrated that palaeomagnetic back-stripping effectively constrains intrusion-induced forced folding in the host rocks of the Sandfell laccolith. Here, we advance this work by testing the feasibility of using palaeomagnetic data to track laccolith growth by analysing the remanence directions at sample sites along a normal fault scarp through the centre of the Sandfell laccolith.

The Sandfell laccolith palaeomagnetic directions plot on an N-S girdle with inclinations ranging from sub-vertical to shallow dipping, which indicate that some directions have been rotated after being locked in. We interpret that the laccolith inflation resulted in the initial clockwise rotation that shifted to anti-clockwise rotation of the palaeomagnetic vectors as a trap-door fault formed along the northern margin of the pluton. Finally, lateral bulldozing of the host rock and older already emplaced magma by new intruding magma resulted in clockwise rotation of the palaeomagnetic vectors. Our results show the power of palaeomagnetism to decipher the relative timing of deformation events associated with magma emplacement.

### References

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Twomey, V., McCarthy, W., Magee, C., Petronis, M., and Mattsson, T.: Unravelling the dynamics of magma emplacement through palaeomagnetic backstripping of intrusion-induced host rock deformation: Analysis from the Sandfell Laccolith, SE Iceland, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-15561, <https://doi.org/10.5194/egusphere-egu21-15561>, 2021.

# Abstracts

## Numerical simulation of the formation of rhyolitic melt at Krafla volcano, Iceland.

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We model the formation of rhyolitic magma sampled during drilling by the IDDP-1 at Krafla volcano, Iceland. Our thermochemical model simulates heat transfer, solidification/melting and convection in a basaltic magma layer intruded into host felsic rocks, hence reproducing hot rhyolite magma. The thermochemical model is based on the solution of the Navier-Stokes equations for incompressible fluids, with temperature and crystal content dependent viscosities in the Boussinesq approximation, so that it accounts for both compositional and thermal convection and for the release of crystallization latent heat. The two distinct magmas are simulated with a numerical scheme is based on the VOF method implemented in the opensource platform OpenFoam.

We assume immediate injection of a basaltic sill of thickness 100 m and temperature 1150°C into a cold (400°C) felsic crust. Initially, a layer of solidified basalt is formed on both top and bottom compositional interfaces, that prevents convective heat transfer towards the host crust. As the host rock temperature increases, the melting front starts to propagate upwards and convection develops in the molten part of the rhyolite. At the bottom, melting is inefficient due to the accumulation of solidified basalt. After 45 years, approximately 20 m of molten rhyolite has formed at the top of basaltic sill. Vigorous convection keeps the temperature nearly constant in both layers.

A simplified 1D model with effective thermal conductivity was tuned based on the results of the 2D simulations. With only one fitting parameter we manage to reproduce the whole thermal evolution of the system with reliable accuracy and significantly smaller CPU time.

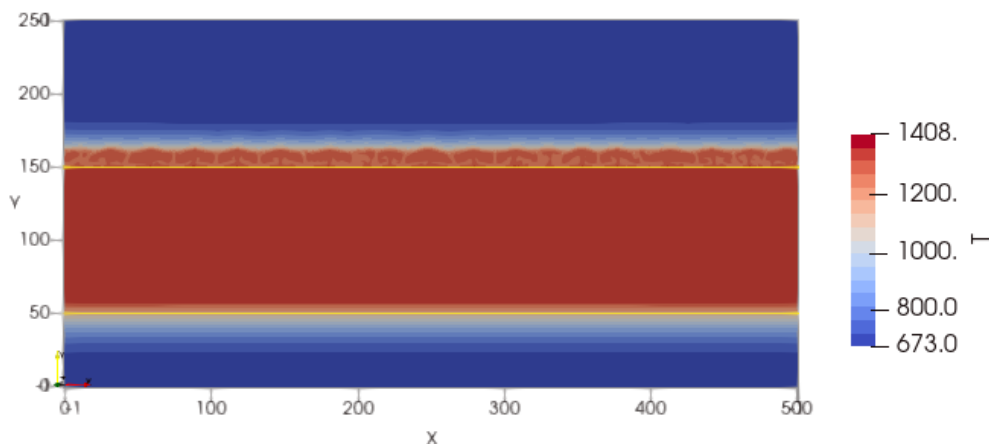


Fig.1. Temperature distribution in double-layered magmatic system

# Abstracts

## **Modeling sub-surface volcanic processes with MagmaFOAM**

Chiara P. Montagna<sup>1</sup>, Federico Brogi<sup>1</sup>, Simone Colucci<sup>1</sup>, & Tomaso Esposti Ongaro<sup>1</sup>

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Subsurface volcanic processes are crucial to determine the evolution of volcanic systems towards unrest and eventually eruption. These processes are hindered from our direct observation: to unravel the mechanisms that cause magmas to ascend, stall, modify their properties and eventually erupt we need to resort to indirect methodologies and observations.

Physical models of magmatic systems are a means to gain insights into otherwise inaccessible volcanic plumbing system dynamics. Given the large range in length and time scales that characterize such systems, from km-sized reservoirs to micrometric bubbles and crystals that nucleate and grow during ascent, a variety of approaches can be used to tackle the multiphase fluid dynamics of magmas.

We have developed and tested a modular computational fluid dynamics framework based on OpenFOAM, that offers solvers suited to tackle problems at different scales, at different flow regimes and including different constitutive equation depending on the specific problem of interest.

Specific applications have been developed to study magma mingling, bubble and slug rise in volcanic conduit, magma-carbonate interaction. The software is freely available with documentation and testing; in the framework of the research infrastructure EU project Geo-INQUIRE, we are able to offer access to our infrastructure in order to learn and use the software, and develop new targeted use cases.

# Abstracts

## **Analogue experiment of magma reservoir fracturing under different magma buoyancy.**

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At active volcanoes, observed surface deformation result from the complex interaction between the magma and the host rock in the magmatic plumbing system. In the case of the recharge of silicic magmatic system, one of the key aspects is the magma buoyancy, which can even be increased by the gas exsolution that occurs at shallow depths. The majority of magma chamber analogue or numerical modelling focused on the effect of the over-pressure, without varying the buoyancy of the injected fluid. Here, we present analogue experiments in which the surface deformation, the shear stress pattern and the chamber pressure have been monitored throughout the injection of liquid at constant volumetric flux. We use the same volumetric flux for all experiments in which the buoyancy of the injected liquid is either positive, negative or null. These experiments isolate the effect of magma buoyancy and provide information on how it affects surface deformations and shear stress patterns during the inflation of a silicic magma chamber. These experiments also investigate if the buoyancy influences where dykes nucleate and propagate away from the chamber. The results will also be used to benchmark the Computational Fluid Dynamics-Discrete Element Methods (CFD-DEM) model which is developed in parallel. CFD-DEM considers the melt as a continuous phase while the rock is discretised in spherical particles which are bonded together.

# Abstracts

## Melt inclusion study from the Quaternary Pudahuel Ignimbrite in the Andean Southern Volcanic Zone

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Large caldera-forming eruptions are extremely hazardous geological events, capable of generating large amounts of pyroclastic material, representing an important risk to nearby populated areas. Understanding how these events could be generated is crucial to the development of risk prevention plans. The volumetric (270 km<sup>3</sup>) Pudahuel Ignimbrite is the result of a Pleistocene caldera-forming eruption and part of an active volcanic complex. Although previous works have determined its pre-eruptive conditions (700–750 °C,  $P_{\text{Total}} > 275$  MPa and at least 6 wt.% H<sub>2</sub>O), processes involved in the generation of this eruption remain unclear. To elucidate possible magmatic process and eruption triggers, we analysed by EMP and SIMS major and volatile elements in plagioclase-hosted melt inclusions (MIs). Major elements present variations only during early magmatic stages, meanwhile H<sub>2</sub>O show an apparent increase with SiO<sub>2</sub> (1-5 wt.%). CO<sub>2</sub> (37-985 ppm) present an apparent decreasing in the last reservoir stage, suggesting that it was most likely reaching H<sub>2</sub>O saturation. Although presence of bubbles in some MIs indicate that volatile concentrations should be considered as a minimum, their behaviour still gives insight to possible eruption triggers. Minimum variations of major elements in plagioclase rim hosted MIs suggest no major disruption by another magma affecting the reservoir before the eruption. However, the high volatile content recorded by MIs point out to the development of an internal over-pressure, which could be enhanced by external factors such as a regional denudation favouring volatile saturation in the magma. We suggest this mechanism as the most probable trigger for this eruption.

# Abstracts

## Modeling sub-surface volcanic processes with MagmaFOAM

Chiara P. Montagna<sup>1</sup>, Federico Brogi<sup>1</sup>, Simone Colucci<sup>1</sup>, & Tomaso Esposti Ongaro<sup>1</sup>

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Physical models of magmatic systems are a means to gain insights into otherwise inaccessible volcanic plumbing system dynamics. Given the large range in length and time scales that characterize such systems, from km-sized reservoirs to micrometric bubbles and crystals that nucleate and grow during ascent, a variety of approaches can be used to tackle the multiphase fluid dynamics of magmas.

We have developed and tested a modular computational fluid dynamics framework based on OpenFOAM, that offers solvers suited to tackle problems at different scales, at different flow regimes and including different constitutive equation depending on the specific problem of interest.

Specific applications have been developed to study magma mingling, bubble and slug rise in volcanic conduit, magma-carbonate interaction. The software is freely available with documentation and testing; in the framework of the research infrastructure EU project Geo-INQUIRE, we are able to offer access to our infrastructure in order to learn and use the software, and develop new targeted use cases.

# Abstracts

## Interpreting clinopyroxene records of magma redox with thermodynamic models

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Multivalent Fe plays a central role in both setting and recording magma redox states, which are commonly expressed in terms of oxygen fugacity deviations from known equilibria such as fayalite-magnetite-quartz (FMQ). Magmas erupted in different tectonic settings are characterised by different redox states, which have implications for understanding how magmatic evolution, ore mineralisation and volcanic degassing vary in space and time. For example, mid-ocean ridge basalts are relatively reduced (FMQ), arc basalts relatively oxidised (FMQ+1) and ocean island basalts are often but far from universally oxidised (<FMQ to ≥FMQ+2). However, current tools for estimating magma redox conditions (e.g., Fe-XANES on glasses, two-oxide oxybarometry) are subject to diverse limitations, making it challenging to draw conclusions about the nature and origins of redox variability between different magmatic systems. Recent work has demonstrated how careful analyses of Fe<sup>2+</sup>- and Fe<sup>3+</sup>-bearing clinopyroxene crystals could offer a new way of investigating variability in Fe valence within and between magmas. Unfortunately, relating the valence state of Fe to magma redox directly is challenging because of the steric effects imposed by the structure of clinopyroxene. In the absence of the experimental data required to separate steric controls over clinopyroxene compositions from those imposed by redox, we have performed calculations using recently refined thermodynamic models to explore how the valence state of Fe in clinopyroxene crystals reflects redox variability in magmas from Iceland and the Azores. Crucially, this work shows how a thermodynamic approach help to circumvent many challenges associated with modelling Fe<sup>3+</sup> behaviour in magmatic systems.

# Abstracts

## **The February-March 2021 lava fountains events of Mt. Etna South-East crater (SEC): insights from clinopyroxene.**

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Mt. Etna is the most active volcano in Europe with four active vents in the summit area. The SEC is the most active crater of the last 20 years and is characterised by sequences of paroxysmal lava fountains with rather variable frequency and duration from a few weeks to months. Between December 2020 and February 2022, the SEC produced over 60 paroxysmal events divided into a first phase (December 2020 – April 2021) and a second phase (May 2021 – February 2022).

We investigated textural and chemical characteristics of the clinopyroxenes population to constrain frequency of magma recharge episodes and eruption triggering mechanism of the 6 paroxysms from February 16 to March 10, 2021, including the most primitive magma erupted on February 28. Clinopyroxenes show frequent sector zoning superimposed on complex concentric zoning with two main compositional domain: 1) augite (Mg#68-75) which mostly characterise rims; 2) diopside (Mg# 74-80) mainly found in cores and less frequent in mantles and rims. Barometric estimates using the GAIA deep learning-based thermobarometry (Chicchi et al., 2022, EPSL) indicate a shallow reservoir ( $0.4-1.0 \pm 0.3$  kbar) for the augitic domain and a deeper reservoir ( $1.7-2.7 \pm 0.5$  kbar) for the diopsidic domain. Fe-Mg diffusion timescales point to the occurrence of multiple episodes of mafic recharges starting in December 2022 and up to few days prior to eruption in agreement with radiant heat flux and monitoring data.

# Abstracts

## **Dynamics and conditioning factors of Holocene explosive and effusive eruptions at Lonquimay volcanic complex, Southern Andes of Chile.**

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The Lonquimay volcanic complex (LVC) is located in the Southern Volcanic Zone of the Andes (SVZ). It comprises a main stratovolcano and 12 monogenetic cones. The LVC has been active since the Middle Pleistocene and has generated volcanic eruptions exhibiting strombolian to sub-Plinian eruptive styles. We analyzed tephra fall deposits associated with three recent Holocene explosive eruptions: FDLN, FDPK, and FDMA, as well as 7 lava flows. FDPK is the most distinctive deposit, showing banded pumice at the base and a scoriaceous top, while lava flows contain mafic enclaves. Isopach maps show an eastward dispersion pattern, with the summit of the main stratovolcano as the vent. The estimated volumes for FDLN, FDPK, and FDMA are 0.17 km<sup>3</sup>, 0.26 km<sup>3</sup> and 0.22 km<sup>3</sup>, respectively. Textural and geochemical analyses suggest that DCPK and the lavas underwent mixing-mingling processes. Trace element concentrations demonstrate that all volcanic products share the same parental magma, with chemical differences resulting from fractional crystallization. Thermobarometry suggests the presence of two magma reservoirs: one deep mafic reservoir at a depth of 13.7 km and 1130°C, and a shallower one, more evolved at approximately 1.4 km depth and temperatures of 900-1000°C. We propose that mingling and mixing processes could have been eruption-triggering mechanisms irrespective of eruptive style. Subsequent mixing and homogenization led to the generation of intermediate magma compositions. Ongoing studies will further contrast the conditioning factors for explosive and effusive eruptions, as well as correlate the LVC volcanic plumbing system with others in the SVZ.

# Abstracts

## Magma batch emplacement in the Slaufudalur pluton, SE Iceland

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Granitic plutons are formed by the successive emplacement of single magma batches. Understanding the internal structure of igneous intrusions not only improves the knowledge base on magma emplacement mechanisms, the emplacement of single magma batches has also fundamental implications for the transport of hydrothermal fluids, elements and heat during and after the lifetime of the larger-scale magmatic system. We focus on the Slaufudalur pluton in Southeast Iceland to investigate magma batch emplacement and incremental growth of igneous intrusions. We carried out field and GIS mapping, AMS sampling (anisotropy of magnetic susceptibility) and photogrammetry. The pluton as a whole is horizontally layered, except near the margins, where lithologically distinct individual magma batches occur. The transition between horizontally layered interior and non-layered margins is generally defined by zones of intense magma mingling. Magnetic fabrics from individual magma batches show contrasting strain records that imply separate magma flow kinematics. Hydrothermal alteration is focused around faults that occur along the host rock contact and wall-roof transition in the northern part of the study area. We conclude that: **(1)** the magma batches spread from the margins to the horizontally layered interior, **(2)** magma mingling and mixing is more pronounced near the margins, **(3)** wall-roof deformation reflects the interplay between buildup of internal overpressure and magma batch emplacement, and lastly **(4)** wall contacts served as feeders and accommodated vertical pluton growth during cauldron subsidence. The Slaufudalur pluton offers prime examples of features associated with magma batch emplacement and fluid transport in and around cooling intrusions.

# Abstracts

## **Magma evolution and lateral collapse in shield-stage volcanism of Fogo, Cape Verdes**

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Fogo is a shield-stage ocean island volcano, which experienced a major lateral collapse to the east about 70 ka ago. Magma compositions erupted on Fogo are strongly undersaturated and generally lack plagioclase. Fractional crystallisation is the dominant process of magma evolution, with crystallisation of olivine+Cr-spinel followed by olivine+cpx, then cpx+Ti-magnetite, and finally cpx±biotite±apatite±titanite. We have identified, sampled and analysed nearly 100 lava samples from 5 stratigraphically-controlled Formations across the shield-stage volcanic activity in Fogo, both before and after the massive lateral collapse. There is no clear change in magma compositions across the collapse [1]. Before the collapse, strongly clinopyroxene-phyric "ankaramitic" lavas were erupted from mainly N-S trending dykes, aligned perpendicular to the collapse direction. These "ankaramitic" rocks show the same compositional trends as the less porphyritic rocks; hence they are not accumulative. Rather, pre-collapse changes in the stress field may have enabled continuous ascent of magma, without pauses in which suspended crystals could settle out. Early post-collapse lavas include both aphyric and porphyritic tephrites, as well as more mafic rocks such as oceanites. Thus, the magma plumbing system was affected physically, but not chemically, by the massive lateral collapse.

[1] Rolfe-Betts et al., 2024, *JVGR*, 446, p.107996.

# Abstracts

## Synchronous intrusion of a dyke pair: experimental simulation

Dawid T. Rybak<sup>1</sup>, Caitlin M. Chalk<sup>1</sup>, Elliot P. Wood<sup>1</sup>, Geoff Kilgour<sup>2</sup>, & Janine L. Kavanagh<sup>1</sup>

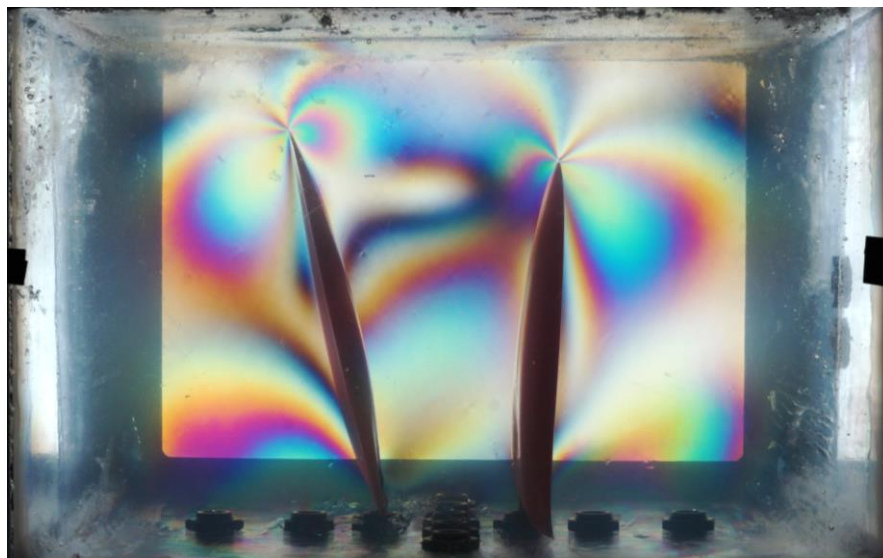
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<sup>2</sup> Wairakei Research Centre, GNS science, New Zealand

Dyke swarms are commonly observed in exposed rock sections of shallow volcanic plumbing systems. A key question is whether their formation is solely a consequence of sequential propagation. If synchronous propagation of multiple dykes under certain conditions is favourable (Bunger, 2013; Jin & Johnson, 2008), can their propagation be detected in nature and observed in outcrops?

We simulate synchronous intrusion and propagation of two dykes by conducting a series of scaled analogue experiments. Two near-parallel dykes are synchronously intruded at varying spacings by injecting water (magma analogue) from a single reservoir into an elastic gelatine solid (crust analogue). Here we employ digital image correlation processing technique to compute evolving incremental strain from tracking the movement of particles seeded in our crustal analogue.

Our results show that the experimental dykes are deflected from each other, to varying extents, depending on the initial spacing between them. The incremental strain develops asymmetrically, generating a leading-trailing dyke behaviour. However, in some experiments the advantage swings and an initially trailing dyke can later become a leading dyke. In all experiments, the trailing dyke experiences a decrease in ascent velocity exactly when the leading dyke accelerates towards eruption. Dyke geometry and variations in ascent velocity can be used as initial, qualitative indicators for possible physical interaction between synchronously propagating dykes.



Polarised light dyke interaction experiment. Dyke neighbours are spaced 7.5 cm apart at the start. The polarisation of light reveals complex stress interactions. The clashing of the respective stress fringes from each of the dykes forces the propagation direction away from the area of maximum compressive stress which results in repulsion of dyke tips from one another. Dyke edge grows in all directions and therefore the deflection is also seen around the whole edge of the dykes creating a bowl shaped growth.

# Abstracts

## Magma Chamber Formation by Dike Accretion and Crustal Melting: 2D Thermo-Compositional Model.

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<sup>2</sup> Department of Earth Sciences, University Oxford, England

We present the results of numerical simulation based on a two-dimensional thermoelastic model of the formation of a magmatic body in the Earth's crust by injection of rhyolite or basalt dikes and sills. Injection of basalt dikes into the granite crust leads to the formation of comparable amounts of rhyolite melt from the remains of dikes and host rocks. Elastic analytical solutions allow us to calculate the displacement of rocks in response to the penetration of magma and its evacuation during volcanic eruptions. The volume of eruptive melt strongly depends on magma influx rates  $Q$ , the width of the injection region  $W$ , and eruptions history.

The obtained mathematical and numerical models allow us to reconstruct unknown parameters of the formation of plumbing systems, for example, preliminary data were obtained for the Campi Flegrei volcano.

The code for the program was written in the Julia language, optimized for calculations on graphics accelerators, which allowed calculations to be performed with extremely high spatial and temporal resolution (Fig.1), allowing individual portions of injected magma to be recorded. The resulting code is at least twice as fast as its CUDA counterpart.

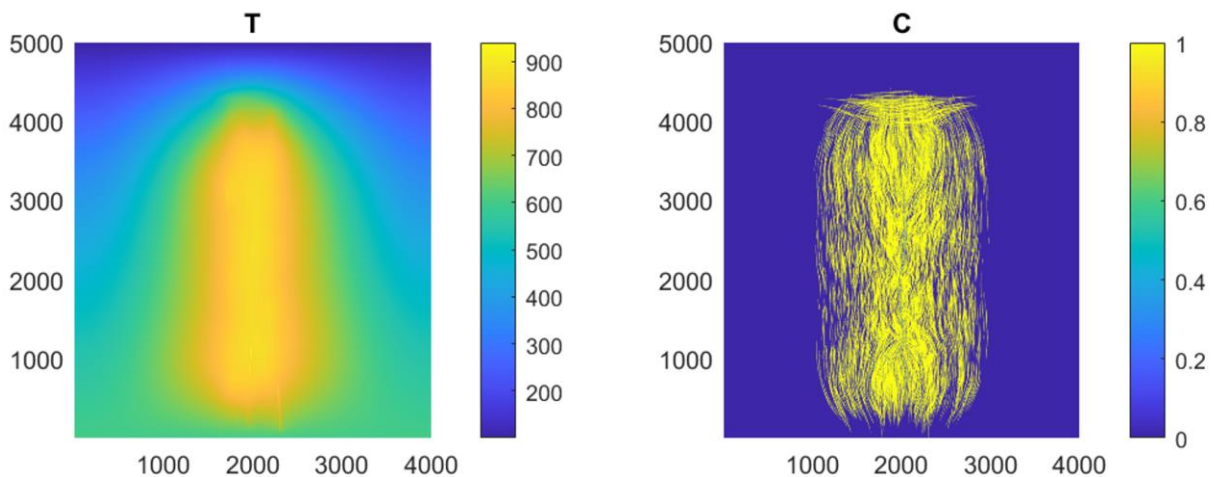


Fig.1. Example of calculation on a grid of  $2 \cdot 10^7$  cells. The size of the area is 20x25 km. On the left is the temperature ( $^{\circ}\text{C}$ ) distribution in the calculated area. On the right, the phase diagram of the separation of rhyolite host rock and injected basalt magma.

# Abstracts

## **Icelandic Nodules – Windows into Actively Evolving Mush Systems.**

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Active volcanoes are fed by vertically extensive magma plumbing systems characterised by solid crystal frameworks known as crystal mushes. Melts percolate and coalesce through these mushes, forming small, ephemeral, eruptible magma bodies. Mushes play a key role in mediating volcanic behaviour and determining the resulting hazards; hence, studying their pre- and syn-eruptive chemistry and textures is crucial for improving magma storage and ascent models. However, this is impeded by challenges such as the disaggregation of mush-derived fragments during magma ascent and post-emplacment modifications in fossil magma reservoirs. Thus, the solution is to study fragments of erupted mushes - gabbro nodules - that preserve mush textures and provide ideal windows into the petrology of an actively evolving mush system. Despite the increasing number of studies on mush-derived crystal clusters, detailed investigations into erupted mush fragments are still relatively sparse. This study addresses this gap by systematically mapping the chemistry and textures of gabbro nodules from Gígöldur in Iceland, combining geochemical analysis using EPMA and LA-ICP-MS with petrographic analysis and 3D textural analysis using XCT. It aims to present the first systematic description of 3D textural and chemical variability within a mush, contributing to our understanding of how the physicochemical properties of mushes evolve and control mush behaviour. Our research particularly focuses on unravelling the intricate feedback mechanisms between melt infiltration, chemical reactions, and mush disaggregation, providing valuable perspectives on these dynamic processes.

# Abstracts

## Rapid reactivation of long-standing crystal mush by mafic magma recharge: the 135 ka Ciomadul Mic eruption, eastern-central Europe

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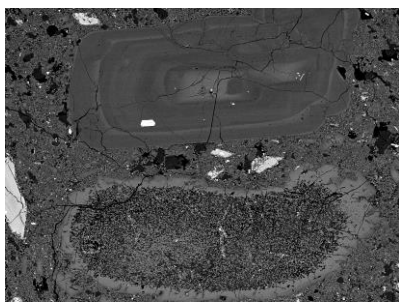
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Ciomadul is a long dormant volcano, where active eruption phases are separated often by several 10's ka quiescence. It is underlain by a long-standing felsic crystal mush with variable melt fraction as common in many potentially active and dormant volcanoes worldwide. Better understanding how such physically un-eruptible highly crystalline magma body can be reactivated is crucial to improve eruption forecasting and volcano monitoring. High-resolution analysis of crystal cargo provides insight into the magma storage along with the eruption triggering and its timescale.

The 135 ka Ciomadul Mic dacite has the most complex crystal cargo among all the eruption products. Amphibole shows a bimodal composition with variable breakdown rims. Plagioclase has a rather homogeneous composition, although it shows wide range of textures from strong resorption to clear crystals. A common feature is the sharp reverse outer thin zone observable in most of the macrocrysts. Titanite, apatite and zircon are the usual accessory minerals. Notably, quartz and K-feldspar as well as high-Mg olivine and clinopyroxene occur together in the dacite. Felsic and mafic crystal clots are frequently observed. This crystal cargo along with the compositional variation clearly suggests intrusion of a primitive mafic magma body into the relatively cold, 700-740 °C crystal mush. A more than 200 °C heating up is detected resulting in partial resorption of the low-temperature mineral assemblage followed by overgrowth by a thin rim from the hybrid magma. The rim thickness as well as diffusion modelling for plagioclase using Mg and Sr imply reactivation timescale within weeks.



Plagioclase macrocrysts with strongly distinct textures in the Ciomadul Mic. Note the thin reverse outer zones having higher An, Fe, Mg and Sr content than the crystal interiors.

# Abstracts

## Complex magma flow dynamics recorded in fossil dykes: insights from the Reyðarfjörður dyke swarm, eastern Iceland

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Dykes represent the main mechanism for magma movement through the Earth's crust and to the surface to feed eruptions. Therefore, understanding the variation of the magma flow dynamics within a dyke is essential for volcanic hazard assessment.

From this perspective, key information can be obtained by studying fossil dykes in extinct and eroded volcanic systems where dykes show a variety of shapes, segmentation, and propagation paths and where rock microstructures and magnetic fabrics may be linked to the primary magma flow. We used a multi-method approach involving drone photogrammetry, rock magnetic analysis and petrography on a fossil dyke, exposed partially in 3D for approx. 900 m along its breadth, from the Reyðarfjörður dyke swarm (eastern Iceland) to combine evidence of magma flow across a wide range of scales to reconstruct the dynamics of emplacement. We collected 364 oriented rock cores for magnetic (anisotropy of magnetic susceptibility, AMS and anisotropy of anhysteretic remanent magnetization, AARM) and petrographic analyses to reveal the nature of microscopic magma flow indicators. The rock cores were sampled with unprecedented density and coverage both across the thickness and, for the first time, along the breadth of the dyke segments, recording each core position relative to different cooling surfaces (i.e. from the dyke margin to its interior) and locating core precisely along the dyke exposure using a 3D virtual model reconstruction obtained from drone images.

Our results show that along the breadth of different segments and cooling surfaces of the dyke, the magnetic fabrics are variable but can be classified into subgroups of data, whereas they are more consistent from across sample sets of the dyke thickness. These results show that sampling along the breadth of the dyke reveals complex flow dynamics, spanning sub-horizontal to subvertical flow, that would otherwise be unrecognised with a standard across thickness sampling procedure. We interpret results from the dyke breadth as due to initial complex magma flow dynamics recorded along the dyke breadth and across adjacent connected segments which has not been recorded by magnetic fabrics across the dyke thickness suggesting a more stable sub horizontal flow.



Captured view from the 3D virtual outcrop model of two sampled overlapping dyke segments showing the exposure along the segments breadth.

# Abstracts

## **Tracing the source conditions of Central Andean ignimbrites through Machine Learning thermobarometry and thermodynamic modelling**

Alex Walton-Keeffe, Gregor Weber, Robert Myhill

School of Earth Sciences, University of Bristol, United Kingdom

Silicic caldera-forming eruptions are the most powerful expression of volcanic activity on Earth and pose profound global catastrophic risk. However, the conditions and processes leading to such events remain not well understood. This information is crucial for identifying early warning signs that could aid in anticipating the evolution toward large magnitude eruptions. In this study, we investigate the pre-eruptive storage conditions and evolution of two major Pliocene ignimbrites: the 2500 km<sup>3</sup> Atana dacite and 200 km<sup>3</sup> Toconao rhyolite, sourced from the La Pacana caldera system within the Altiplano-Puna Volcanic Complex in the Central Andes. The La Pacana caldera is situated at the southern edge of the Altiplano-Puna Magma Body, a 200 km wide mid-crustal geophysical anomaly representing the largest known crystal mush body. The relationship of the ignimbrite-forming eruptions and this giant anomaly remains not well understood. To better constrain this relationship, we will present new textural data and mineral chemistry on phenocrysts and crystal-rich enclaves. These data will be used to determine the pressures, temperatures, and chemical history of the pre-eruptive magma using novel machine learning thermobarometers applied to amphibole, pyroxene, and biotite crystals, as well as thermodynamic modelling of multiple saturation conditions. This will allow us to compare the source conditions of the rhyolite and dacite ignimbrites with the present-day geophysical anomaly. Our study aims to better link geophysical imaging and petrological data to enhance volcanic hazard assessment.

# Abstracts

## Re-conceptualising our understanding of magnetic and crystal fabrics in the Whin Sill

Kate Williams<sup>1</sup>, Stefano Urbani<sup>1</sup>, Elisabetta Mariani, Andy Biggin<sup>1</sup>, John Wheeler<sup>1</sup>, & Janine Kavanagh<sup>1</sup>

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The mechanisms of magma emplacement within mafic sills provide key information on magma transport within the crust, and whether that movement may result in hazardous volcanic activity. 3D geophysical studies suggest that sill complexes transport magma hundreds of kilometres, with spatially and temporally variable magma flow that is poorly constrained. The integration of multiple scales of observation is underutilised to address this issue and dissect the complex syn- and post-emplacement processes of mafic sills.

In this study we use multiscale observations (including field structures, scanning electron microscope petrofabric analysis, and magnetic fabric analysis) from the Whin Sill, a mafic sill located in northern England to explore how these diverse datasets can be reconciled. Field observations of magma fingers, ropy structures, elongated vesicles made at numerous locations across the extent of the Whin Sill all give strong indicators of magma flow direction. However, these are juxtaposed with the lack of shape or crystallographic preferred orientations we have identified through new high-resolution petrofabric analysis of plagioclase feldspar. Backscatter electron images identify multiple populations of titanomagnetite grains, with magnetic fabrics revealed by anisotropy of magnetic susceptibility (AMS) and anisotropy of anhysteretic remanent magnetisation (AARM) reflecting late-stage upward melt migration, which is a process which has not been identified at the Whin Sill previously. The inconsistencies of the field structures, the magnetic and microscopic observations highlight the temporal and spatial complexity that can be revealed from intrusions only by integrating techniques and treating them with caution if being used to infer magma flow.

# Abstracts

## Exploring the effects of magma and crustal heterogeneity on volcano deformation

Stanley Yip<sup>1,2</sup>, Juliet Biggs<sup>2</sup>, & Marie Edmonds<sup>3</sup>, Craig Magee<sup>1</sup>

<sup>1</sup> School of Earth and Environment, University of Leeds, United Kingdom

<sup>2</sup> School of Earth Sciences, University of Bristol, United Kingdom

<sup>3</sup> Department of Earth Sciences, University of Cambridge, United Kingdom

Integrating multi-parameter datasets from volcanic eruptions has improved our understanding of the dynamics of volcanoes. However, many models assume homogeneity for both magma and its surrounding crust. To understand magma heterogeneity, we use petrological data and thermodynamics to model for the change in magmatic gas content, deformation and SO<sub>2</sub> emissions in a two-layered reservoir. We then normalise the time-series of ground deformation by erupted volume and compare our results to timeseries of SO<sub>2</sub> flux. Increasing normalised displacement may indicate decreasing magma compressibility and decreasing gas volume, i.e. a change from relatively gas-rich to relatively gas-poor magma. Conversely, decreasing normalised displacement may be the result of a change from relatively gas-poor to relatively gas-rich magma. We find that the 2004 eruption of Mount St Helens showed decreasing normalised displacement, consistent with the removal of a degassed 'plug'. In contrast, the 2011 eruption of Cordón Caulle showed increasing normalised displacement, consistent with a compressible gas-rich cap. These case study examples are end members, for which additional factors such as magma recharge would complicate the interpretation. The framework presented here provides qualitative insights into changes in gas volume fraction during eruptions. We note that crustal properties such as lateral variations and layering is also key in modulating volcano deformation. Our ongoing research explores crustal heterogeneity using multi-layered gelatine-based analogue models, and we will develop Finite Element models using COMSOL Multiphysics® to constrain realistic parameters of volcanic systems.

# Abstracts

## **Magma Accommodation and Ground Movement Analysis: testing the reliability of analytical volcano deformation models**

Craig Magee, [Stanley Yip](#)

School of Earth and Environment, University of Leeds, United Kingdom

Space for magma intrusion is often created by uplifting and bending of overlying rock, producing a forced fold. This intrusion-induced forced folding can deform the free surface, driving ground movement at active volcanoes. Monitoring such ground movement plays a key role in volcanic eruption forecasting. Yet building accurate ground movement models to reliably estimate intrusion properties requires knowledge of a volcano's subsurface composition and structure; information which is often limited or unavailable. Many ground movement models therefore tend to use analytical or numerical approaches that embed simple intrusion geometries within a homogeneous, isotropic, and linearly elastic medium. To assess the reliability and validity of such ground movement models, it is beneficial to identify scenarios where known and modelled intrusion properties can be confidently compared.

Seismic reflection data image Earth's subsurface in 3D at metre- to decametre-scale resolutions and capture the detailed geometry of ancient intrusions and overlying forced folds. Such data uniquely allow us to measure and model syn-emplacement ground movement driven by forced folding, whilst independently determining the geometry, size, and depth of underlying intrusions. Here, we examine an Early Cretaceous laccolith and forced fold pair imaged in 3D seismic reflection data from the Exmouth Plateau, offshore NW Australia. We consider how burial-related compaction has affected the fold amplitude and reconstruct the original fold geometry. By applying standard analytical methods to estimate intrusion properties from size (displacement) of the original fold geometry, we compare model outputs to the true location, geometry, and size of the seismically imaged intrusion.

# Abstracts

## The interplay of deformation and current volcanic activity on the Reykjanes peninsula, Iceland - some insights from analogue modelling

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<sup>1</sup> Institute of Geophysics of the Czech Academy of Sciences, Prague, Czech Republic

The Reykjanes Peninsula (RP) in southwestern Iceland represents a zone of oblique rifting where the divergent boundary of the Mid-Atlantic ridge is offset to the eastern Iceland along a left-lateral transform fault. A series of earthquake swarms at RP during 2021-2023 indicated development of fracture networks along ENE direction of the plate boundary and two new fissure arrays trending NE and divided by a gap in seismicity. In the last 3 years, the activity culminated in two volcanic eruptions at different locations, bringing magmas from Moho depth at ~15 km. To address the recent tectonic activity at RP, we conducted a series of analogue experiments with photoelastic gelatine and low viscosity silicone as magma, centred at a strike-slip plate boundary. The experiments produced hybrid tensional-shear fractures at the tips of the analog magma chamber, with arrangements similar to the elongated seismic swarms and surface en-echelon fissures on RP. We explored the influence of shape and orientation of the magmatic chamber on the evolution and pattern of progressively developed fractures in strike-slip and oblique rift settings. During the experiment, we captured the stress fringe patterns in the fractured gelatine together with the 3D surface deformation (stereoscopic digital image correlation from LaVision).

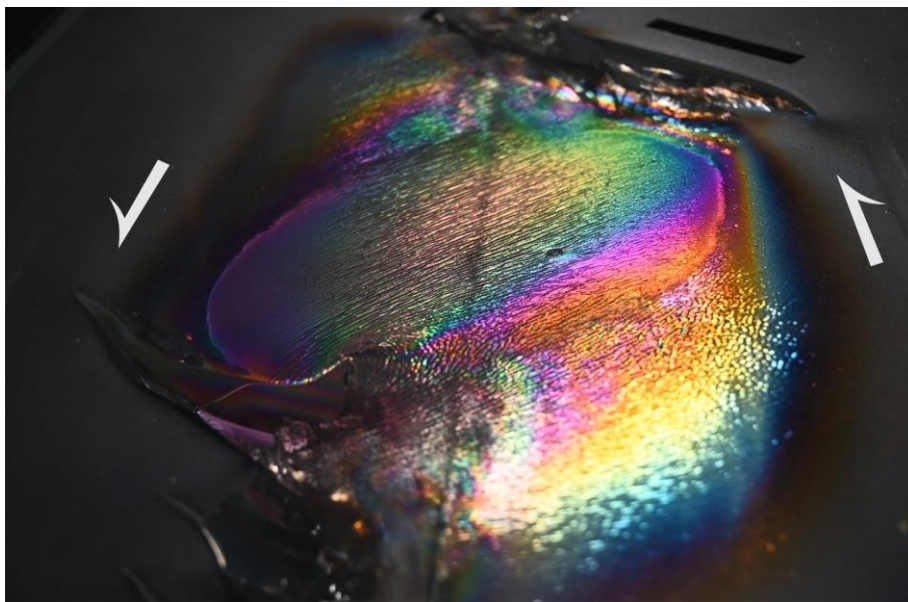


Figure: A thin-sheet jelly experiment, where conjugate tensional fractures developed at the edges of originally pancake-shaped analog magma chamber (silicone) during strike-slip motion along the basal plates. Note the surface wrinkles in the center of the model that indicate the direction of local compression (parallel to the trend of the tensional cracks). Scalebar is 10cm long. The setting of the conjugate cracks is similar to the en-echelon fissures feeding lava of the 2021 and 2023 eruption events, respectively, on Reykjanes peninsula (Iceland).

# Notes

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