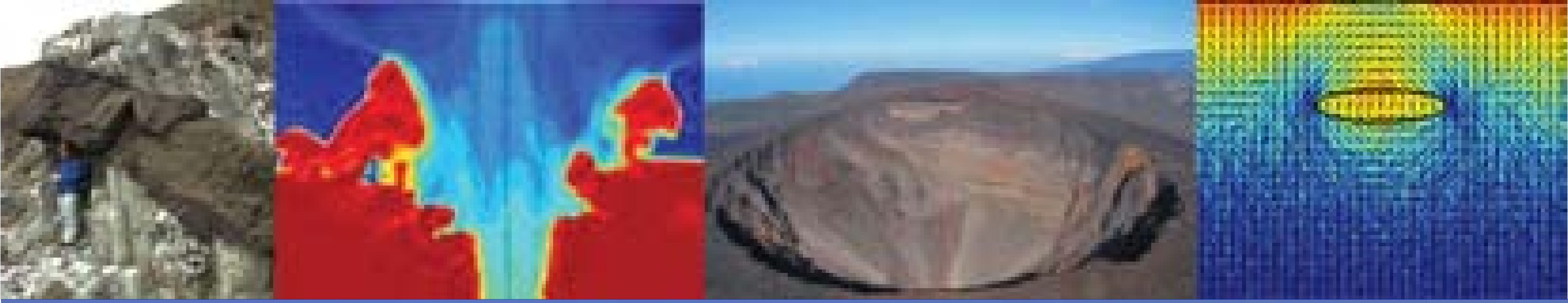

International workshop on:

Mechanics of magma emplacement and volcanotectonics

4-6 February 2013

Physics of Geological Processes, University of Oslo

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Workshop motivations

Abstract

The physics that govern magma emplacement in the Earth's crust have been studied through a wide range of methods and approaches, which have so far been poorly linked and coordinated. We propose a workshop to (1) coordinate the European expertise and disseminate the state-of-the-art for methods dedicated to studying volcano-tectonic and magma emplacement processes, (2) establish a scientific strategy for future advances in the discipline, and (3) establish a robust and systematic procedure to integrate results from distinct approaches, i.e. fieldwork, geophysical monitoring, experimental and numerical modelling.

Scientific summary

Magma emplacement in the Earth's crust and associated volcano-tectonic processes are fundamental to the evolution of volcanic systems and the way magma is supplied to eruptive vents and conduits. A common feature of these two phenomena is that they are controlled by the state of stress within the magmatic system and host rock, and the resulting mechanical behaviour of the surrounding rocks.

Historically, the mechanics of magma emplacement and volcano-tectonic processes has been addressed through field observations on outcrops and/or geophysical monitoring. The main limitation of field studies is that we are observing static volcanic systems frozen in time. These comprise the superimposed products of numerous governing processes, the distinct mechanics of each being hence very challenging to isolate. Geophysical monitoring on the other hand provides dynamic and *in situ* measurements, such as seismological and geodetic data, but is not always optimised by field constraints. As an active system is not directly accessible, interpretation of such geophysical data hence becomes extremely challenging and solutions are typically non-unique.

Modelling offers an alternative means of gaining insights into the problems of magma emplacement and volcano-tectonics by enabling the controlled simulation of numerous processes and the evaluation of their individual impacts. Several teams in Europe have independently developed or adopted a variety of experimental approaches/techniques and a number of numerical methodologies. Because magma emplacement and volcano-tectonics involve complex 4-dimensional (space and time) elasto-plastic-viscous rheological behaviour of rocks, however, many processes are hard or impossible to address by conventional methods.

Analogue models have long played an important role in advancing our understanding of these processes, as (1) they are relatively simple and fast to implement, and (2) they allow for monitoring of the simulated processes through time. Analogue modelling studies include sandbox models (e.g., Merle and van Wyk de Vries, 2000; Troll et al., 2002; Burchardt and Walter, 2009; Mathieu and van Wyk de Vries, 2011), sand-silicone models (e.g., Acocella et al., 2000; 2001; 2004; Delcamp et al., 2008; Montanari et al., 2010), gelatine models (Takada, 1990; 1994; Walter and Troll, 2003; Rivalta et al., 2005; Menand et al., 2010), and silica flour/vegetable oil and powder/Golden Syrup models (Galland et al., 2006; Mathieu et al., 2008; Kervyn et al., 2009; Galland, 2012). The main limitation of most analogue models is the uncertainty of over how their results scale quantitatively to the geological systems.

Numerical approaches promise to address this issue, and they have become more important during the last two decades as computing power has advanced. Approaches used include analytical solutions (e.g. Rivalta, 2010; Bunger and Cruden, 2011), as well as models based on the Boundary Element Method (e.g. Walter and Amelung, 2006), Finite Element Method (e.g. Van Wky de Vries and Matela, 1999), or Distinct Element Method (e.g. Holohan et al., 2011). Most models, however, account only for elastic properties of rocks, whereas visco-elasto-plastic processes are fundamental. In addition, the spatial resolution of the models must be extremely high, given that large-scale systems are often controlled by small-scale processes (e.g., dyke tip propagation, fault mechanics, etc.); therefore, model spatial resolution must be extremely high, but this is computationally expensive. Finally, the physics of the studied systems (e.g., dyke propagation criterion) are not yet fully understood, and are therefore extremely complex to model.

One major reason that these individual approaches have failed to provide a comprehensive understanding of the mechanics of magma emplacement and volcano-tectonic processes is that they have mostly been considered in isolation, have lacked coordination and have not been optimised by cross-fertilisation of concepts and outcomes. Thus, despite this substantial body of research, many aspects of magma emplacement and volcano-tectonics remain far from well understood. These include:

- *The mechanics of dyke emplacement.*
- *The mechanics of sill emplacement.*
- *Magmatic stoping.*
- *The mechanical effect of faults on magma transport.*
- *Ground deformation in volcanoes.*
- *Onset of caldera and volcano flank collapse.*
- *Incremental magma supply.*
- *Scaling and integration with geological/geophysical data.*

To address these challenging processes, field observations, geophysical monitoring, experimental and numerical modelling approaches all need to fertilise each other. We hence propose to organize a workshop to gather the leading international experts to address the potential ways forward in respect to mechanics of volcano-tectonics and magma emplacement processes. The aims of the workshop will be to:

1. Catalogue the current European state-of-the-art expertise and methods dedicated to study volcano-tectonic and magma emplacement processes to promote and facilitate networking among research groups active in the field.
2. Discuss the complementary aspects of the classic geoscientific methods and new approaches to overcome the limitations of individual methods and create synergy effects.
3. Establish a scientific strategy for future advances, by coordinating scientific tasks between the different laboratories/expertises, thus facilitating long-term joint efforts and coordinated progress.
4. Establish a robust and systematic procedure for integrating results from distinct approaches, such as fieldwork, geophysics, experimental and numerical modelling to

support coordinated problem-based work in the future and foster long-term cross-disciplinary networks and research teams.

The objective of this proposed workshop is to become the starting point of a series of meetings to coordinate and follow the progress of the research of the involved teams.

Olivier, Steffi, and Valentin

Workshop schedule
Magma emplacement and volcanotectonics
4-6 February 2013

Monday 4th February: Volcanotectonics

1030-1045	*Olivier Galland (PGP, University of Oslo)* Welcome
1045-1100	*Bjørn Jamtveit (PGP, University of Oslo)* PGP: the host institution

Chair: Olivier Galland

1100-1300	*Benedikt G. Ófeigsson (Icelandic Meteorological Office, Reykjavik)* Volcanic activity in Iceland: Divergent plate boundary influenced by a hot spot
1130-1200	*Jun Okada (University of Azores)* Unveiling the mechanisms of regional tectonics and volcanic deformations by GPS data
1200-1300	Lunch

Chair: Olivier Galland

1300-1330	*Valerio Acocella (University Roma Tre)* 15 years of analogue volcanoes at Roma Tre. What have we done, where are we now, where do we go?
1330-1400	*Matthieu Kervyn (Vrije Universiteit Brussel)* Advanced techniques to image the dynamics of 3D structures of gravity-driven volcano deformation in analogue models
1400-1430	Coffee break

Chair: Steffi Burchardt

1430-1500	*Valentin Troll (University of Uppsala)* Unravelling the deep plumbing system of caldera volcanoes using petrology
1500-1530	*Eoghan Holohan (University College Dublin-GFZ Potsdam)* Advances in volcano-tectonic modeling from the Distinct Element Method
1530-1600	Coffee break

Chair: Steffi Burchardt

1600-1630	*Olivier Galland (PGP, University of Oslo)* Ground deformation associated with shallow magma intrusions
1630-1700	*Benjamin van Wyk de Vries (University of Clermont-Ferrand)* The Macro-Micro problem and the use of scaling with the real life analogues
1700-1730	Concluding remarks and discussions
1800-	Workshop dinner downtown Oslo

Tuesday 5th February: Magma emplacement processes

Chair: Valentin Troll

0930-1000	*Lukas Baumgartner (University of Lausanne)* Intrusion mechanism and life time of the Torres del paine igneous system
1000-1030	*Sverre Planke (Volcanic Basin Petroleum Research)* Paleogene igneous deposits and processes on the conjugate Mid-Norway – Northeast Greenland margins
1030-1100	Coffee break

Chair: Valentin Troll

1100-1130	*Steffi Burchardt (University of Uppsala)* Modelling the emplacement of cone sheets and dykes in volcanic systems
1130-1200	*Mansour Abdelmalak (University of Oslo)* 2D experiments of shallow intrusion propagation in brittle materials
1200-1300	Lunch

Chair: Valerio Acocella

1300-1330	*Thierry Menand (University of Clermont-Ferrand)* Plutons versus magma chambers
1330-1400	*Eleonora Rivalta (GFZ Potsdam)* Laboratory and theoretical modeling of dyke emplacement in layered media
1400-1430	Coffee break
1430-1600	*Olivier Galland, Karen Mair, Håvard Bertelsen (PGP, UiO)* Lab. visits
1600-1730	Concluding remarks and discussions. Discussions about the future evolutions of the group (LASI, IAVCEI, EPOS).
1800-	Dinner downtown Oslo

Wednesday 6th February: Brainstorming activities

0900-1000	**Theme 1** Field observations provide constrains on structures and/or geochemical patterns. How can we simulate such structures/patterns in experimental and numerical models? Which geophysical signals do such structures/patterns correspond to?
1000-1030	Coffee break
1030-1130	**Theme 2** Petrology and thermo-barometry provide quantitative information on the dynamics and thermodynamics of magmas. How can such information be sensibly combined with structural field and geophysical observations? How can it be used for constraining initial and boundary conditions of laboratory and numerical models?
1130-1230	Lunch
1230-1330	**Theme 3** Geophysical monitoring produces quantitative data of geophysical signals (seismological; ground deformation), but the processes generating these signals are poorly constrained. How could we reproduce these signals in experimental and numerical models to understand their origin? What type of field data is required to fully understand these geophysical signals?
1330-1400	Coffee break
1400-1500	**Theme 4** Experiments and numerical models provide quantitative understanding by defining empirical laws based on dimensionless parameters and/or quantitative morphological patterns that have often not been addressed through fieldwork or geophysical monitoring. What is the best way to systematically constrain these parameters and study such morphological patterns in the field and through geophysical monitoring?
1500-1530	Concluding remarks

List of abstracts

15 years of analogue volcanoes at Roma Tre. What have we done, where are we now, where do we go?

Acocella V.[1]

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This presentation provides an overview of the analogue models simulating volcanoes performed at Roma Tre in the last 15 years, with the aims to: 1) show the local state of the art on modelling; 2) highlight main unsolved experimental problems and future trends.

The main facilities of the Roma Tre lab include different apparati to simulate volcano deformation, a 3D laser scanner to monitor surface deformation (resolution of 10^2 mm), a rheometer with Peltier temperature control and high resolution videocameras for PIV analysis (up to 30 frames per sec).

The main studies on magmatism include caldera formation, resurgence, dike emplacement, sector collapse, pluton emplacement. There is an evident progression in the performed studies, from the earlier descriptive and basically-monitored experiments, to the later experiments monitored with more sophisticated equipment (laser scanner, high res videocameras) and analysis/tools (DEM, PIV, Matlab). This results in a significant improvement in the geometric and kinematic monitoring of the deformation, allowing a much more precise and quantitative analysis.

Two are the major outcome of this improvement. On the one side, it is becoming possible to use high resolution laser scanning to detect any surface deformation induced by the magma analogue and compare this with geodetic data (if extrapolated on a slightly longer time frame, though). These models, if further improved, may provide support to the inversion techniques of the numerical models, to better establish the relationships between the observed deformation and the inferred sources. On the other side, the PIV provides a robust kinematic analysis; this allows investigating even well-known models (as those on calderas, presented by various labs in the last decade) with a new perspective, opening new fields for future analysis and a closer comparison with geophysical data (as seismicity).

This technical improvement allows to make detailed comparisons to specific well-known volcanoes, also on the mean to short term (decades to years), rather than continuing to evaluate general behaviours of many volcanic systems on the longer term (hundreds to thousands of years). Under these premises, analogue models can be used to reproduce and understand specific conditions.

The main challenges we are currently facing include the need to: search for new materials, especially for magma (possibly with a temperature dependent behaviour); deepen the use of analogue models as tools to invert the deformation, evaluating the responsible source, also to better test the reliability of the numerical models; the development of a network where all the major experimental limitations in the apparati, materials and monitoring system are made clear, shared and jointly faced. In this frame, one often misleading aspect of the analogue models should be better emphasized: models are not made to reproduce reality, but to understand it.

Intrusion mechanism and life time of the Torres del Paine igneous system

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The Torres del Paine intrusive system reflects a shallow igneous system, located between the extensional back-arc and the compressional volcanic arc environment. Due to its topography and excellent outcrops it offers a 3-D view into the fossil magma chamber and its country rocks (Fig. 1).

Fig.1 The roof and the base of the laccolith are excellently exposed in several places in the Torres del Paine, Patagonia, Chile. The verftical cliffs allow us to map the individual granite laccoliths, which are stacked in this picture, with the oldest granite on top. Cuerno Norte and Cuerno Principal.

To take advantage of this aspect, we developed a multi-prong approach: detailed mapping of the intrusions was used to establish the (laccolith) geometry of the larger intrusions, their volumes and contacts; high-precision chemical erosion single zircon analysis from well characterized magma batches were dated to analytical precisions of ±10-20Ka to establish magma accumulation rates; field and AMS studies were conducted to establish the internal structure of pulses, identify the source area for the laccolith; major, minor, trace and rare earth element geochemistry of the intrusive rocks were used to obtain information of co-magmatic magma suite, identify contamination (or lack thereof), obtain information on the source region, its composition, and its link to the Andean subduction zone. Finally, we investigated in detail the metamorphism and structure of the host rocks to establish the mechanism of space accommodation for the intrusion. It turned out that the thermal history of the contact aureole places additional constraints on the number of the pulses building up each batch of magma.

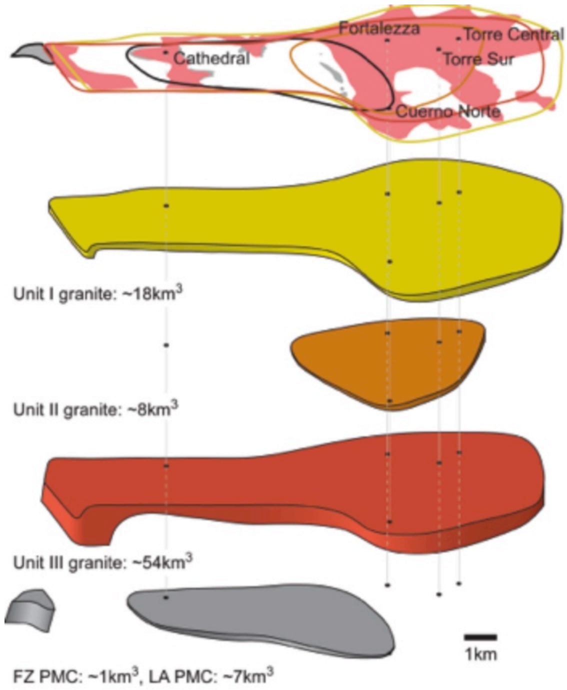

Fig. 2 Volume estimates for the Paine granites and mafic rocks. Unite I is the oldest, unite III the youngest. FZ Paine mafic complex (PMC) has the same age as unite I. The Paine mafic laccolith is younger than granite unite III. Leuthold et al. 2012

The majority of the Torres del Paine laccoliths (Fig. 2) were fed from the western side of the intrusions. At 12.6Ma a mafic pulse, as well as the oldest granite laccolith intruded at a depth of about 3 km (75MPa). Subsequent granit batches intruded underplated the previous, with the last major granite pulse at 12.50Ma. The mafic laccolith complex underplating the granite. It build up by overplating previous mafic pulses within 50Ka, from 12.50Ma to 12.45Ma. Space for magmas was accommodated by ballooning of the roof. Older granites laccoliths ballooned, and younger granite pulses sent a myriad of dykes into the overlaying older granites.

Detailed thermal models using different multi-puls formations of magmas reveal that the metamorphic zoning is best obtained by rapid succession of pulses building up one batch (Fig. 3).

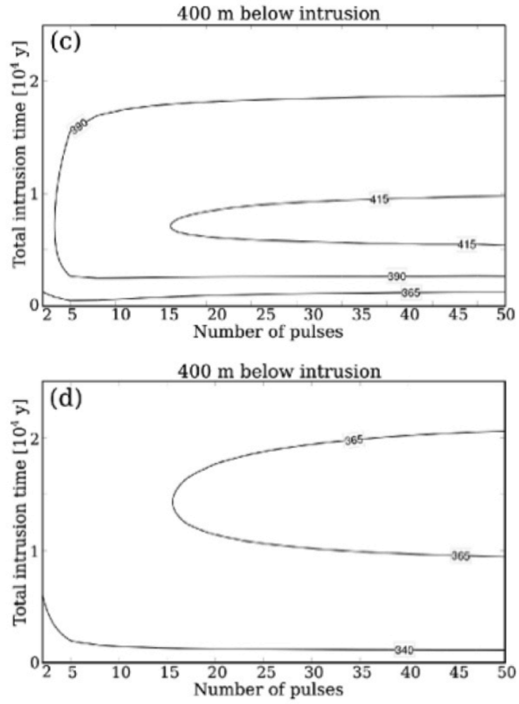

Figure 3: results of thermal models for a 800m thick laccolith (batch). The y-axis gives the overall build-up time, while the x-axis gives the number of pulses that formed the batch. Models use heat of fusion and metamorphic reaction enthalpies. The model on the right uses variable temperature thermal diffusivities (Nabelek et al. 2010). The cordierite-in metamorphic reactions requires at 400 meters even higher temperatures, so that we favour rapid intrusion of multiple pulses to form a macro-pulse, here called a batch. Bodner and Baumgartner, ms

Despite a concerted effort it turned out to be very difficult to uniquely determine the source of the magmas. Nevertheless, several intermediate magma chambers are needed to explain the composition and modal abundances of the magma, as is outlined in Fig. 4

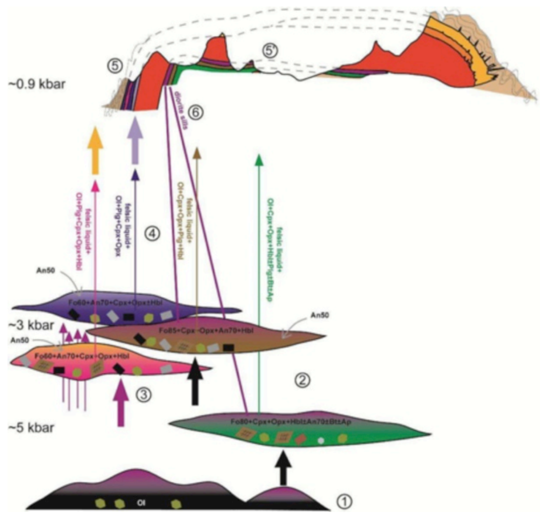

Figure 4: Preliminary schematic model for the evolution of magmas using petrography and semi-quantitative thermo-barometers. Leuthold et al., ms

References

Leuthold, J., Müntener, O., Baumgartner, L.P., Putlitz, B., Ovtcharova, M., Schaltegger, U., 2012. Time resolved construction of a bimodal laccolith (Torres del Paine, Patagonia). Earth and Planetary Science Letters, 325-326: 85-92.

Nabelek, P.I., Whittington, A.G., Hofmeister, A.M., 2010. Strain heating as a mechanism for partial melting and ultrahigh temperature metamorphism in convergent orogens: implications of temperature-dependent thermal diffusivity and rheology. Journal of Geophysical Research. 115, B12417.

Modelling the emplacement of cone sheets and dykes in volcanic systems

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Volcanic systems generally host two main types of magmatic sheet intrusions: moderately-dipping cone sheets and subvertical dykes. Together, they represent the main transport channels of magma through the crust to feed other intrusions at depth and volcanic eruptions at the surface. However, so far their emplacement has been explained through distinct conceptual models, even though their coexistence points to a common source.

Through a series of scaled laboratory experiments, we analysed the emplacement of cone sheets and dykes to improve our understanding of the conditions, under which either of the two intrusion types form. We used silica flour to model the brittle crust and vegetable oil to model low-viscosity magma (Fig. 1a). In each of 46 experiments, we injected the vegetable oil through an inlet into the silica flour at a constant injection flow rate. The oil would fracture the silica flour and produce a sheet intrusion that would feed an extrusion when the intrusion had pierced the surface. From experiment to experiment, we varied the diameter of the inlet (d), the depth of the inlets below the silica flour surface (h), and the injection flow rate (Q). After the experiment was finished, the vegetable oil would cool and solidify so that the intrusion that formed during the experiment could be excavated and examined in detail.

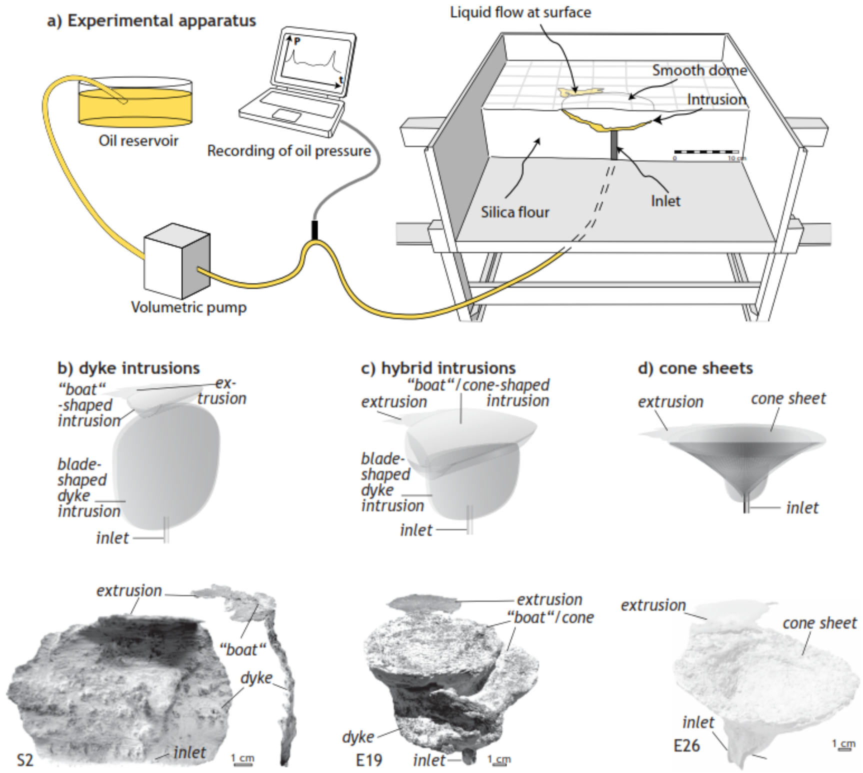

Figure 1. a**)** Sketch of the experimental setup of our experiments. **b)-d)** Sketches and photographs of experimentally-produced intrusions.

The sheet intrusions produced during our experiments resembled either dykes or cone sheets. Dykes were sub-vertical with an elliptical shape and branched into a “boat”-shaped intrusion close to the surface (Fig. 1b), while cone sheets were characterized by an inverted-cone geometry with rims that flattened towards the surface (Fig. 1c), giving them a cocktail-glass shape at depth and a trumpet-shape closer to the surface. The intrusions in a few of the experiments had a dyke-like lower part feeding a conical sheet intrusion higher up (Fig. 1d). We thus termed them “hybrids”.

A robust dimensional analysis of our experimental results revealed that there are two dimensionless parameters that describe the formation of dykes and cone sheets. The first parameter Π_1 is geometric and describes the ratio between inlet depth and diameter ($\Pi_1 = h/d$), while the second parameter Π_2 is dynamic and defined by the relationship between the viscous stresses induced by magma flow and the strength of the host rock as $\Pi_2 = v\eta/Cd$ (with η magma viscosity, v magma velocity, C cohesion of the crust). A plot of the individual values of each experiment in a diagram Π_1 vs. Π_2 reveals that there are two basic regimes, characterising either cone-sheet or dyke formation. The hybrid intrusions in turn tend to fall on the transition line between both regimes. This transition line may be described by an empirical power law.

Our experimental results therefore indicate that the formation of cone sheets and dykes can be described by a unified emplacement model. According to this model, cone sheets preferentially form at large Π_2, which is consistent with high injection rates from a shallow source chamber. In turn, dykes form preferentially at high Π_1, i.e. they are fed from relatively deep magma sources.

For a better interpretation of our macroscopic results, we need to better understand the small-scale mechanisms that govern the nucleation of cone sheets and dykes. Achieving this aim requires integrating our experimental results with (1) structural observations of cone sheets swarms and their relationships with their magmatic sources, (2) field data to constrain the rates of influxes in magmatic sources, which might be derived from geochronology and geophysics, (3) in situ quantitative monitoring in experiments of the strain/stress field at the initiation of dykes and cone sheets, and (4) results from numerical modelling.

Ground deformation associated with shallow magma intrusions

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Active volcanoes experience ground deformation as a response to the dynamics of underground magmatic systems. The analysis of ground deformation patterns provide important constraints on the dynamics and shape of the underlying volcanic plumbing systems. In addition, ground deformation upon shallow intrusions, such as sills, exerts a positive mechanical feedback on magma transport, leading to *e.g.*, the formation of saucer-shaped sills (Fig. 1a; Polteau et al., 2008; Galland et al., 2009).

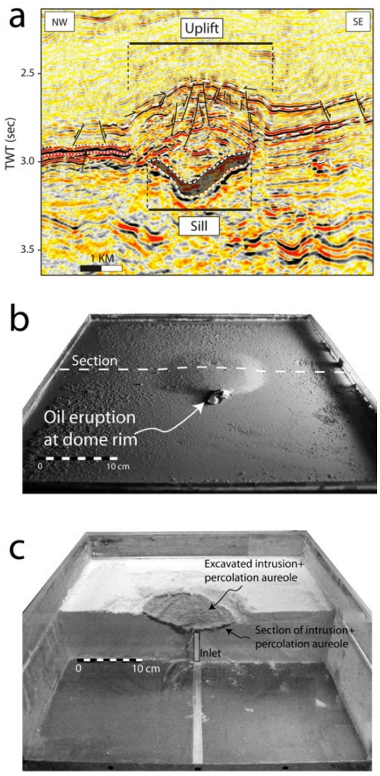

Fig. 1 – a. Seismic profile illustrating the relationships between a saucer-shaped sill and the structure in its overburden, Rockall Basin, offshore Scotland (Hansen and Cartwright, 2006). b. Representative oblique view photograph of the model surface during an experiment. The surface exhibited a smooth relief, at the rim of which the oil erupted. c. Representative oblique view photograph of the model after the end of the experiment. The oil solidified and the intrusion was excavated, such that its top surface can be observed.

This contribution presents three experiments of ground deformation patterns due to the emplacement of low viscosity magma in the brittle upper crust (Fig. 1b,c; Galland, 2012). The models simulated three different intrusion shapes: a cone sheet, a dyke connected to a cone sheet, and a saucer-shaped sill. The main conclusions are:

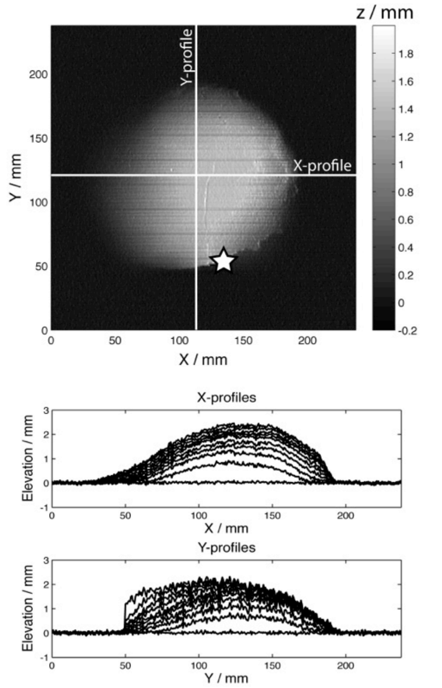

Fig. 2 – Top. Plot of the topographic data monitored during an experiment. The white star locates the eruption site. The white lines locate the corresponding topographic X- and Y-profiles. Bottom. Plots of the topographic profiles located on the maps. Each curve represents a transient stage of the model surface. The time step of monitoring between each profile was constant during each experiment (4s). Notice the vertical scale dilation.

1. The presented experimental setup allows for the first time a quantitative measurement of (1) the ground deformation associated with the emplacement of low viscosity magma through time (Figs. 2 and 3), and (2) the 3D shape of the underlying intrusion.
2. By comparing the ground deformation patterns with the shapes of the intrusions, I show how the complex shapes of the uplifted zones reflected the complex shapes of the underlying intrusions (Fig. 4). In more detail, steeper edges of the uplifted zones were located above the shallower parts of the intrusions.

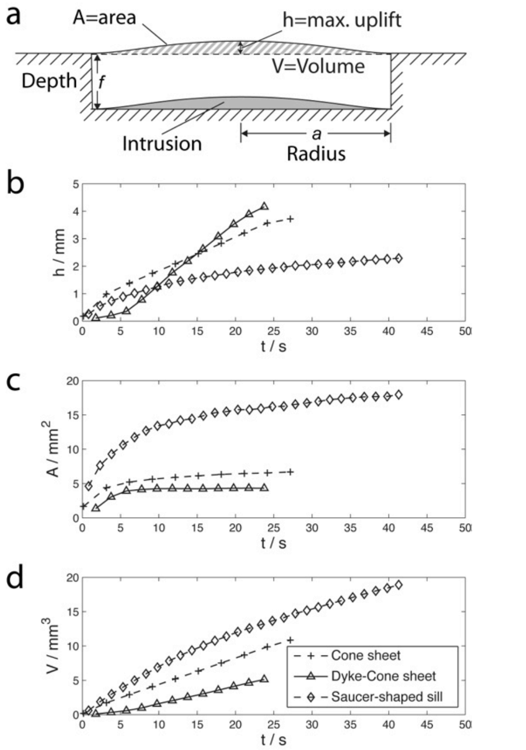

Fig. 3 – a. Sketch describing the maximum uplift *h* (mm), area *A* (mm^2), and uplifted volume *V* (mm^3). b,c,d. Plots of *h, A,* and *V* as a function of time *t* (s). Crosses represent experiment with cone sheet, triangles represent experiment with dyke-to-cone sheet, and diamonds represent experiment with saucer-shaped sill.

3. In each experiment, the time evolution of the ground deformation patterns correlates with the evolution of the underlying intrusions (Fig. 3).

4. The morphology of the uplifted areas, defined by the aspect ratios h^2/A and h^3/V, can be directly interpreted as the signature of the emplacement mechanism of the intrusions.

5. The initial development of an asymmetry in the ground deformation pattern is a precursor of the location of the eruption (Fig. 2).

6. In the absence of flank destabilization, asymmetrical ground deformation patterns may result from the emplacement of a complex sill, a cone sheet or inclined sheet (Fig. 4); these complex shapes may have to be considered in the analyses of ground deformation in active volcanoes.

7. The models deformed mainly elastically, though plastic deformation can locally occur at the tips of the sheet intrusions and at the surface. Such features are similar to those observed on volcanoes, suggesting that the models properly simulate the mechanical behaviour of natural volcanoes.

The experimental technique presented here appears to be a powerful tool for (1) understanding the ground deformation patterns due to the emplacement of a shallow intrusion of complex shape, and (2) interpreting the ground deformation patterns monitored on active volcanoes.

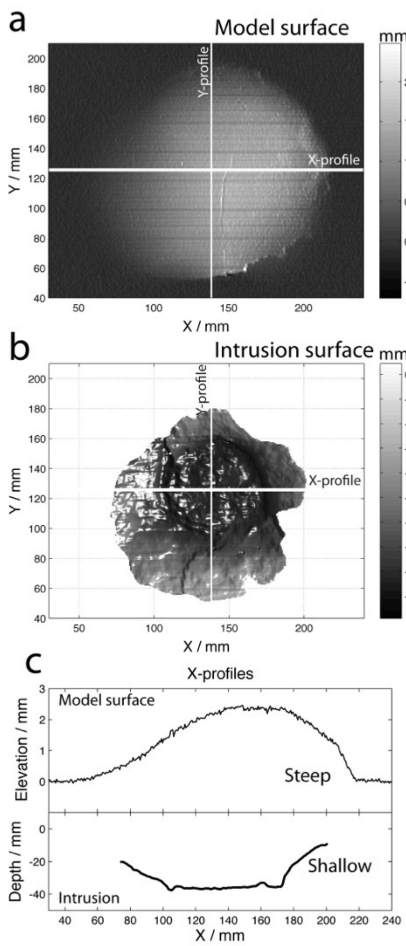

Fig. 4 – Topographic map of model surface before the eruption of the oil. b. Topographic map of the top surface of the excavated intrusion. Plots of topographic profiles of the model surface (top) and the underlying intrusion (down) parallel to the Y-axis (Y-profile).

Acknowledgements

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Advances in volcano-tectonic modeling from the Distinct Element Method

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Introduction

Volcano-tectonic processes commonly produce high strain deformation of rock masses that involves large discontinuous (i.e. fault- or fracture-controlled) displacements. Analogue models can readily reproduce such deformation, but often with large uncertainties surrounding their exact scaling to the natural systems. Numerical models promise to resolve such uncertainty, but highly discontinuous volcano-tectonic phenomena are intrinsically difficult to simulate in the continuum-based approaches most commonly used to date.

Distinct Element Method (DEM) models

The DEM bridges past analogue and numerical approaches, by simulating the finite displacements and rotations of discrete particles. In the 2D DEM code PFC2D[1], the particles are rigid discs (***Fig. 1***). These interact with others and with rigid boundary walls through a contact law based on linear force-displacement and Coulomb friction. Inter-particle bonds, transmitting both forces and moment, break if their tensile or shear strength is exceeded.

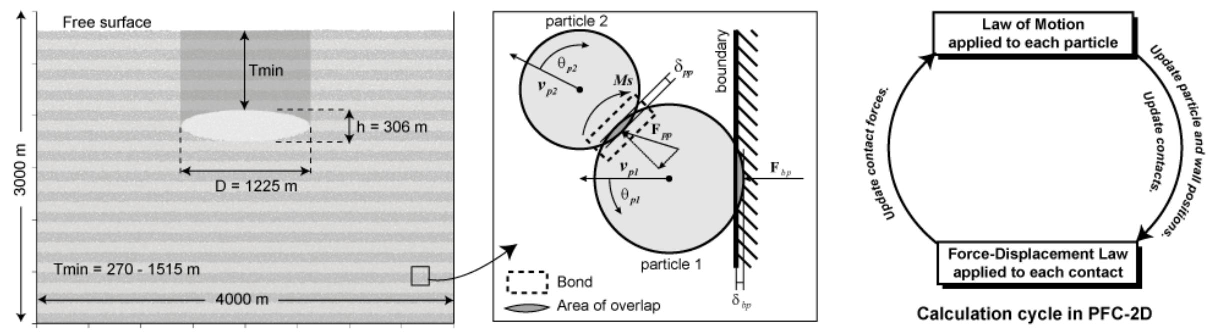

Figure 1: Overview of DEM as implemented in PFC-2D. ***Left:*** Pre-depletion view of a collapse caldera model. Boundary wall conditions are free-slip. ***Centre:*** Close up of particle-bond-wall relations. ***Right:*** Schematic of PFC calculation cycle.

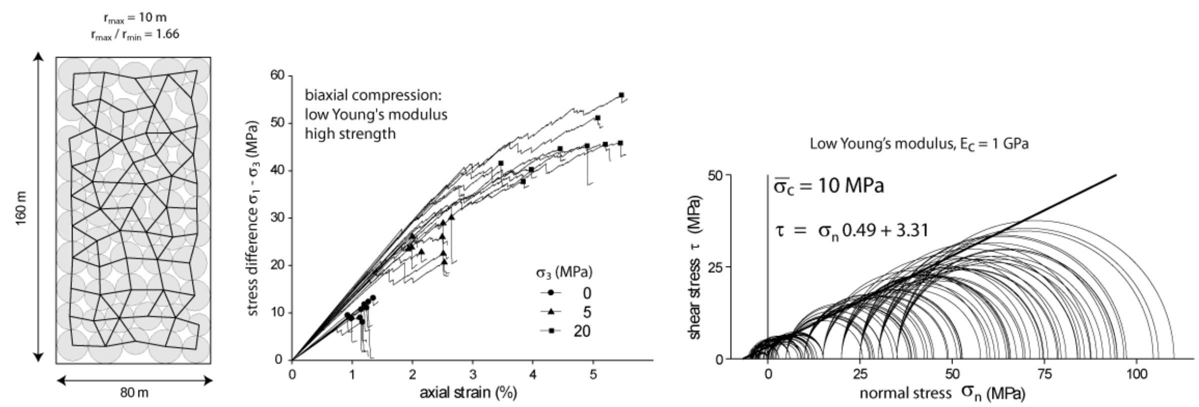

Figure 2: Bulk property calibration in DEM models. ***Left:*** Sample of model subject to biaxial compression and tension tests. ***Centre:*** Stress-strain plot for biaxial compression at various confining pressures, each with 10 realisations. Symbols on curves denote peak strengths. Post-peak curves are removed for clarity. ***Right:*** Compression test results fitted to a Mohr-Coulomb failure envelope.

From properties defined at the bond-particle scale, emergent bulk material properties (elasticity, strength, friction) are calibrated by means of simulated rock deformation tests (***Fig. 2***). By varying particle and bond properties, a range of bulk material properties and deformation behaviours characteristic of natural rock masses is obtained.

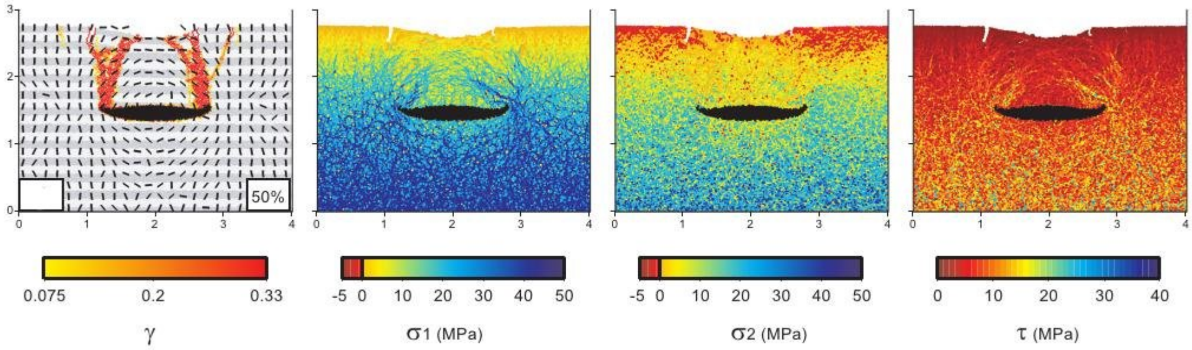

Figure 3: DEM model of pit crater or caldera collapse at 50% depletion. Plots show, from left to right, trajectories of maximum principal stress and values of maximum finite shear strain (**γ**), as well as magnitudes of maximum principal stress (**σ_1**), minimum principal stress (**σ_3**), and maximum shear stress (**τ**). Magma reservoir particles are here coloured black.

The DEM produces the main structural features seen in both analogue models and nature. These include reverse faults that are steeply outward-inclined from the crater centre, as well as more peripheral near-surface tensile fractures and inward-dipping normal faults. Moreover, the DEM reveals how stresses in the reservoir and its roof relate to these structures formation and how those stresses change throughout the course of progressive deformation.

Other Applications in Volcano-tectonics, Limitations and Future Directions

Recent applications of the DEM in volcano-tectonics include simulations of volcano-spreading, volcano flank collapse, and sill intrusion. That all applications published thus far have been 2D studies reflects one of the main limitations of the DEM: its computational intensity. This necessitates a trade-off between model size, particle resolution, and computing time, which particularly impacts simulations at length scales typical for many volcano-tectonic processes. Advances in computing power are nonetheless reducing DEM computing times, such that high-resolution 3D-DEM modelling is now an increasingly viable approach for volcano-tectonic studies.

These developments open the door for the closest yet integration of volcano-tectonic models with geodetic and seismic observations. The close comparison of such data to DEM results represents an important future step in the application of DEM to this discipline.

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Advanced techniques to image the dynamics of 3D structures of gravity-driven volcano deformation in analogue models

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Introduction

Gravity-controlled deformation strongly influences the structure and eruptive behavior of volcanoes. Using scaled analogue models, it is possible to characterize a range of structural architectures produced by volcano sagging, volcano spreading or caldera collapse. While sand box analogue models have been used over two decades to study these processes, the characterization of the deformation dynamics and the 3D structure pattern has been limited by the imaging techniques. Here we present results from different sets of analog experiments of gravity-driven deformation using Particle Image Velocity (PIV), high resolution radiography and computerized X-ray microtomography (µCT) to image and quantify the evolution of the deformation in 2D and 3D.

Methods

Our scaled analogue set-ups are similar to 'sandbox models' used in most fundamental analogue modelling studies. A low cohesion sand-and-plaster mix, golden syrup and silicone are used as volcanic rock, magma and ductile rock analogues, respectively. High density garnet sand was used as a marker in some experiments. The first set of experiments investigates the interactions between volcano lateral spreading along a basal décollement and the vertical sagging of the volcano when its weight causes down-flexure of its underlying basement. A second set of experiments investigates the structures formed by directional spreading using a 2D spreading experimental setup. A third set of experiments reproduces the classical caldera collapse experimental setup using fluid withdrawal from the setup base.

Horizontal displacements and strains were quantified by Particle Image Velocimetry (PIV) analysis of time-lapse photos. PIV enables the documentation of strain localization with sub-millimeter spatial resolution and detection of displacements at the scale of individual sand grains, highlighting the geometry and dynamics of faults in plan view (3D models) of in cross section (2D models).

X-ray computerized microtomography (µCT) is based on the physical process of X-ray beam attenuation while it passes through a volume of material. The most important attenuation factors are material density, material thickness and the effective number of the elements composing the material. Fault formation in the granular material of sandbox models causes dilation in the granular packing, subsequently attenuating differently from the surrounding material unaffected by fault formation

High resolution radiographies were acquired during caldera collapse model deformation with a time interval of 2 minutes. On a radiograph image, the 3D spatial information is projected on a 2D plane, providing 2.5D documentation of the model deformation evolution during drainage. These radiograph sequences, and differences between successive radiographies, are used to document the structure formation and kinematics of the deformation. Multi-angle µCT scans of the caldera and spreading models, after deformation ended, allows for a full virtual 3D reconstruction of the model. This leads to an unprecedented record on the model topography and enables us to virtually slide the reconstructed model in order to map the 3D fault geometry.

Results and discussion

Figure 1 illustrates the 3D µCT reconstruction of a spreading experiments. Contrast in the X-ray attenuation caused by material dilation highlight the 3D geometry of graben-bounding faults and the heavy fracturation of the volcano mid-flanks. Figure 2 illustrates the capacity of a radiograph sequence to monitor caldera-bounding fault development and decompaction of the collapsing block material. Analysis of these sequences allows the derivation of the temporal evolution of depth-specific collapse velocity.

Moreover models imaged by PIV enable to highlight a continuum between volcano spreading and sagging, depending on the coupling of the volcano with its basement and the flexural rigidity of the basement. Relevant comparisons are made between model results and geophysical or morphological observations from terrestrial or martian volcanoes.

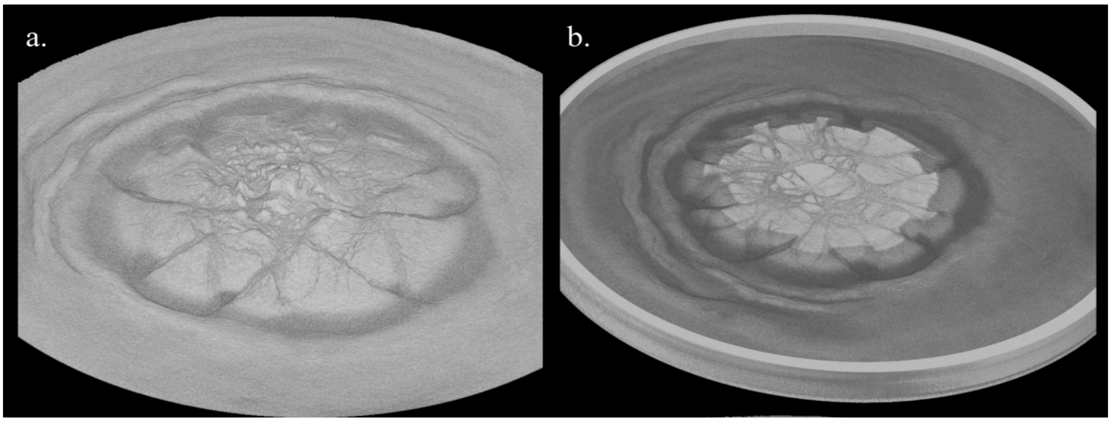

Figure 1. Reconstructed 3D volume of a low cohesion sand cone from X-ray scan after 72 h of gravitational spreading over a 4.5 mm silicone layer. The cone is 7.9 cm in diameter, and 1 cm high. (a) Oblique 3D view of model surface with 100 µm spatial resolution; (b) virtual horizontal cross section at mid-height through the cone, showing radial pattern of graben-bounding faults as low density dark areas (from Kervyn et al. 2010).

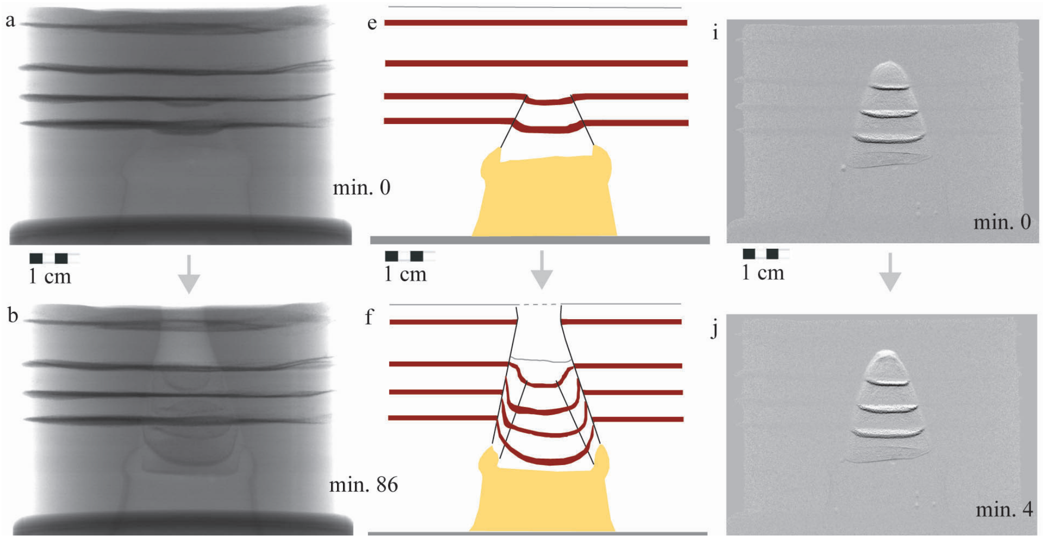

Figure 2: a. Radiograph sequence acquired during GS drainage in caldera collapse model, at H/D equal to ~0.8; b. structures observed in the radiographs (red: garnet sand, yellow: golden syrup); c. Radiograph difference image, highlighting increase (black) or decrease (white) in material density (from Poppe et al. in prep).

The developed method is a step towards the quantitative documentation of volcano-tectonic models that would render data interpretations immediately comparable to monitoring data available from recent deformation at natural volcanoes. The models carry the potential for a better understanding of the kinematics of a variety of volcano-tectonic processes. Further improvement of the model setups and quantitative analysis methods are however still needed, together with a better integration with field observations and numerical models.

Acknowledgments

Research presented in this abstract benefited from collaborations with S. Poppe, A. Delcamp (VUB), V. Cnudde and M. Bonne (UGCT, Ugent), P. Byrnes (Carnegie Inst.), E. Holohan and Th. Walter (GFZ) and B. van Wyk de Vries (Clermont Ferrand).

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Plutons versus magma chambers

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Emplacements styles and rates of magma bodies within the crust have fundamental implications for magma differentiation, country rock metamorphism and assimilation, as well as magma chamber formation. The formation and growth of magma bodies are now recognised as involving the amalgamation of successive, discrete pulses such as sills. Sills would thus represent the building blocks of larger plutons (sensu lato). Thermal considerations for the transport of magma in the crust and the development of magma chambers reveal two different flux scales. A first, critical, instantaneous flux limits magma transport. Below this critical flux magma cooling by heat conduction operates faster than heat advection by magma flow. This critical instantaneous flux is thus the minimum rate at which a dyke could feed a magma body; any lower flux would prevent the dyke from reaching that crustal level. Whether magma storage at this level ultimately evolves as a dead pluton or an active magma chamber depends on another, additional condition. Numerical thermal models show that below a long-term average value of 10^{-3} – 10^{-2} km^3/yr, successive sills emplaced in a crustal region will solidify completely and form a dead pluton. Magma chambers can only develop above this long-term-average threshold. These thermal investigations raise also the question of our ability to read geodetic surface signals, and whether we can differentiate between surface deformation produced by an influx of magma bound to form a frozen pluton from one recharging an active magma chamber.

2D experiments of shallow intrusion propagation in brittle materials

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Seismic and outcrop studies have led to the recognition of shallow-level sandstone and magmatic intrusions in sedimentary basins, showing similar dykes-, cone-, saucer- and cup-shaped geometries. Such geometries imply that emplacement mechanisms (e.g. hydraulic fracturing) are likely to be controlled by common physical parameters in both settings. The emplacement of these intrusions involves multi-scale deformations of host rocks. For instance, uplift of the overburden is envisaged during sill inflation at a large scale whereas, at a smaller scale, local damage are produced around the fracture tip, potentially modifying the intrusion propagation. The present study focuses on the understanding of multi-scale deformations resulting from the emplacement of shallow magmatic intrusions, and more generally during hydraulic fractures growth in elastic-plastic host rocks. To do so, we have developed a 2D scaled experimental approach. The current experimental setup allows a through-time monitoring of (1) the intrusions morphology, (2) the deformation field around the fractures (PIV technique) and, (3) the surface deformation associated with the intrusion.

Method

The experimental apparatuses (Fig.1a) consist of modified Hele-Shaw cells, 0.5 to 1m long and 2.5 cm thick. To reduce silo effects, which may perturb vertical stress, experiment transparent walls are made of low friction glass and models are not thicker than 20 cm. Hydraulic fractures are initiated by injecting a fluid through a central injector within a brittle, host material (diatomite powder or silica powder). To simulate magmatic processes, a viscous fluid (Golden syrup) made of silica powder is injected. Diatomite and silica powders are used in experiments of natural hydraulic fracturing caused by very low viscous fluid (e.g. gas, water). In such experiment, air is used as fracturing fluid. Diatomite powder is thus used as an analogue material of highly permeable rocks where pressure diffusion occurs quickly and silica powder is used to simulate low permeable rocks. Depending on the injected fluid nature and the fracture growth rate, experiments are photographed or filmed with a high speed CEMOS camera (100fps). We use a Particle Imaging Velocimetry (PIV) technique to calculate maps of displacements and strain and to resolve the small-scale deformation field associated with hydraulic fractures (White et al., 2003; Adam et al., 2005). The displacement is computed by cross-correlation from the translation and distortion of the particle pattern in successive images with a given time interval. P.I.V. cross-correlation allows the calculation of displacements with sub-pixel accuracy (< 0.1-0.2 pixel). Thus, displacements down to 30 μm can be monitored.

Results

In experiments with golden-syrup, various types of intrusion morphologies show several evolutional stages and several fracture modes. Firstly, intrusions result in vertical dykes at depth (Fig1b). Their propagation was controlled by both shear deformation and tensile opening cracks, forming smooth symmetrical dome due to the model surface uplift. In the second stage, two types of behaviour were identified. On Figure 1b, the intrusion gradually rotates, forming an inclined sheet dipping from 45° to 65°. This rotation results in asymmetrical surface uplift and shear failure upon the tip of the dyke. In other experiments, the dyke tip interacts with tensile cracks formed during the first stage. The fracture framework controls the subsequent propagation of the dyke toward the surface. In general, intrusions result in surface uplift, which can be accommodated by reverse faults.

Limitations of the approach and further developments required

Although these experiments allow to access small scale deformation field during the fracture growth, the current approach shows a number of limitations. For instance, the models confined into between two glass plates, the simulated processes are considered to be 2D (plane strain configuration). This may have significant consequences on large-scale surface deformation that cannot be directly compared with natural 3D systems. Moreover, required pressure for fracture initiation is slightly larger than in 3D experiments because of silo effect. Nevertheless, similarities between our results and those obtained in 3D experiments (Mathieu et al., 2008, Galland et al., (2009, 2012) may suggest that the boundary effects played a minor role on the studied processes.

The difficulties encountered with 2D experiments are thought to be resolved with a complementary approach involving 3D apparatus. Combination of 2D and 3D complementary approaches is a key to understand the links between large-scale observations and small-scale processes involved during magmatic processes and more generally hydraulic fracturing. This is the goal of a starting collaborating project between PGP and the University of Maine (Le Mans).

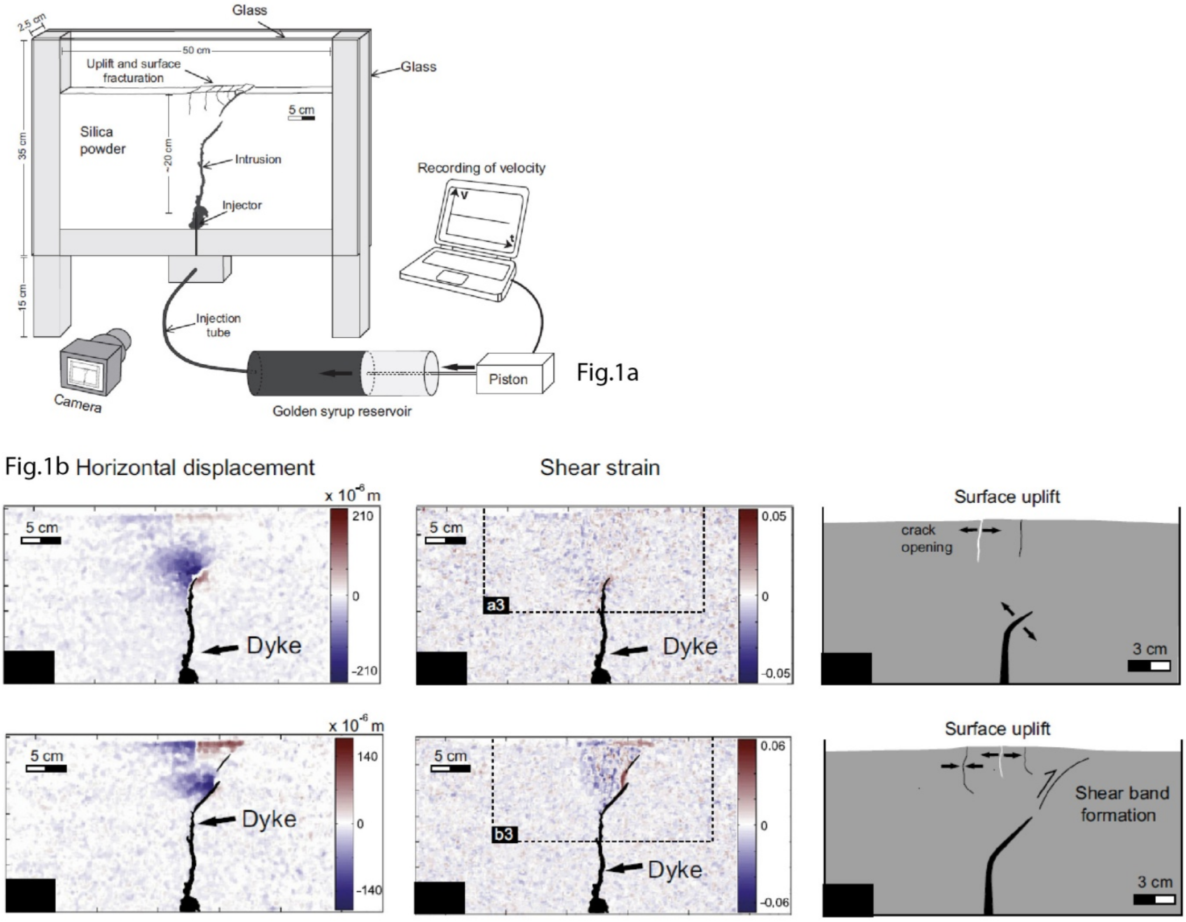

Fig1. a. Drawing of the experimental setup for experiments involving a viscous fluid (golden syrup). The apparatus consists of Hele-Shaw cell (50 cm long, 35 cm high and 2.5 cm thick). Fluid is injected at the base of the model through a linear injector. b. Example of dyke (golden syrup) propagation near the surface. Left: Results of calculation of horizontal displacements and shear strain by PIV. Right: schematic diagram. A rotation of stresses modifies the direction of propagation following a mode 1 (pure tension) opening. Then, a shear band forms and is infiltrated by the golden syrup in the final stage.

Volcanic activity in Iceland: Divergent plate boundary influenced by a hot spot

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Good comprehension of the detailed mechanics of magma emplacement in the Earth's lower and upper crust is essential to fully understand the dynamics of volcanic systems in order to predict there behaviour on divergent time scales. Although simple models can give some insight into volcanic systems experiencing unrest, they do not give any indications of future developments of a volcanic system as it is very dependent on the state of stress in the surrounding rock and the properties of the rock as well as the magma itself. In Iceland, situated on the divergent plate boundary between North American and the Eurasian plates influenced by a hot spot, this is quite apparent. The plume-ridge interaction with its excessive volcanism, has created a natural laboratory of very diverse set of volcanic systems. The volcanism in Iceland ranges from relatively simple basaltic volcanism, rifting with intrusive activity and fissure eruptions, sub-glacial volcanism, variable types of silicic volcanism and different combination of all the above. This is all controlled by a plume-ridge interaction as well as by Iceland's glaciers. Which both influence volcanoes buried beneath them directly as well as through regional effects due to stress changes and variable strain rates caused by mass variations through melting and precipitation. The plate-spreading deformation cycle associated with rifting episodes does also affect the strain rates in areas where there is rifting.

There is extensive geophysical monitoring done in Iceland by the Icelandic Meteorological Office (IMO) in collaboration with the Institute of Earth Sciences, University of Iceland (IES). There are two major geophysical networks operated, seismic and GPS. Also there is a network of hydrological instruments are run in all of the major glacial rivers. An Extensive crustal monitoring using radar satellites through InSAR technique has been done by IES in collaboration with Delft university. There are also smaller scale networks of strain meters (around Hekla). Tilt meters on Grímsfjall and close the edge of Vatnajökull. Recently, there have been efforts to start monitoring gas release around volcanoes and to measure dissolved volcanic gases from glacial rivers. The core of the Geophysical monitoring is the Seismic monitoring.

Three of Iceland's most active volcanoes represent a good example of the diversity of Icelandic volcanism. Hekla, Grímsvötn and Katla have all erupted frequently in historic times. Hekla Volcano, situated east of the South Iceland Seismic Zone has erupted 18 times during the last 1100 years. Until 1947, Hekla erupted 1-2 times every century including large explosive eruptions, but since an eruption in 1970 Hekla has erupted approximately every 10 years, in 1980-1981, 1991 and 2000. Various seismic and geodetic studies have addressed magmatic system associated with Hekla. It is aseismic between eruptions although eruptions are typically preceded with seismicity around 1_2 hours beforehand. Geodetic observations have been used for long term monitoring but a complex geodetic signal has made it difficult to determine the pluming system of Hekla but recent studies suggest a magma accumulation deeper then 16 km. This is supported by seismic studies, which argue against a sizable molten body in the depth range of 4-14 km. The seismisity prior to an eruption however starts at depths around 3 km. Grímsvötn, a subglacial basaltic volcano beneath the Vatnjökull glacier, is historically the most frequently erupting volcano. The most recent eruptions occurred in 1983, 1998, 2004 and 2011. It hosts a caldera complex where a high temperature geothermal area melts ice and sustains a subglacial caldera lake. The volcano has a low seismic velocity anomaly down to ?3 km depth interpreted as a magma chamber, and deeper intrusive complex inferred from a gravity high. Interaction of magma, ice, and meltwater causes fragmentation of magma into tephra, leading to phreatomagmatic explosivity. Many of the eruptions are small. One nunatak, Mt. Grímsfjall, stands out of the ice on the caldera rim where a seismometer, a GPS station and a tiltmeter are located. The measurements reveal glacio-isostatic uplift due to melting of the ice cap as well as uplift and displacement away from the caldera between eruptions, perturbed by periodic pressure changes in the caldera lake due to accumulation of melt water followed by subglacial fluting from the lake and interrupted by sudden co-eruptive displacement towards the caldera. Katla, a subglacial basaltic volcano beneath the Mýrdalsjökull ice-cap. It is a highly active volcano with twenty confirmed eruptions breaking the ice cover in the past 1100 years, the last confirmed in 1918. It hosts a 100km2 caldera with several known geothermal areas melt the ice and can be observed in cauldrons on the ice surface. The melt water does not accumulate in the same amount as in Grímsvötn. Most of the melt water drains from beneath the glacier as it melts although some accumulation of melt water can be observed in the cauldrons. Since 1952 Katla has been the most seismically active volcano in Iceland, though with variable activity. Periods of elevated seismic unrest have occurred, most notably 1955 - 1962, 1966 - 1967, 1976 - 1977, 1999 - 2004 and 2011- with less activity between. Jökulhlaups, mostly associated with geothermal activity, are frequent from below the ice-cap. Most of these are relatively small but regularly, major floods occur. In 1955 and 2011, major floods swept away a bridge on the main road in south Iceland and in 1999 a major flooding occurred from beneath the glacier. These events have been associated with geothermal or magmatic events causing sudden increase in meltwater. Extensive seismic, geodetic and hydrological monitoring is ongoing around the volcano. These observations reveal a very complex interaction between the glacier, the magmatic- and geothermal-system influenced by accumulation and drainage of melt water.

The effects of regional stress fields are superimposed on the local processes. Processes such as glacial rebound and plate boundary deformation effect large areas and often produce signals on comparable scales as volcanic processes. In order to isolate such signals from local magmatic ones, a good monitoring of the regional processes is essential. But also, in order to gain better understanding of individual volcanic systems, governed by complex tectonic settings superimposed by regional processes, a move towards joint interpretation and modeling of different geological and geophysical observations has to be taken. In the recent Futurvolc project, one of the aims is to create a platform where the individual approaches will be interpreted in a coordinated way and fed into a model constrained by the all the different data sets. It also focuses on strengthening the existing monitoring infrastructure through connections with the Europiean Plate Opserving System (EPOS).

Unveiling the mechanisms of regional tectonics and volcanic deformations by GPS data

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The Azores archipelago is located across the Mid-Atlantic Ridge, where three mega tectonic plates meet: Africa (Nubia), North America, and Eurasia. The archipelago has many active volcanic systems. The Fogo - Congro area in S. Miguel Island has been recognized as one of the most active seismo-volcanic fields. This area has been repeatedly suffering from intense earthquake swarms, at least in last few decades, such as in 1989, 2003-2006, 2008-2009, and 2011-2012. Since there was no eruption and no geochemical and hydrothermal evidences for a magmatic intrusion reported from monitoring data during the these seismic crisis, basic questions still exist regarding their tectonic and volcanic/magmatic relationship and eruption triggering conditions. To answer these questions and to understand the interactions between regional tectonics and volcanism in the Azores, we focus on (1) Continuous GPS monitoring (2) Reexamination of GPS data series, (3) Deformation modeling and joint analysis with seismic data.

In the scope of tectonic and volcanic monitoring 11 continuous GPS stations are currently operating in the archipelago, Extensional stress regime was evident at Monte Escuro - Congro Area (MECA), between the NE flank of Fogo volcano and the western rim of Furnas Caldera from the timeseries analysis for 2008-2011. It plays about 38% contribution of the total plate spreading (predicted by MORVEL). The rest is maybe taking place in other regions from either tectonic or volcanic contributions in different periods. However, the existence of this extensional regime seems very important for understanding the mechanisms of the repeating seismic swarms and magma ascent (“failed” and possible eruptions).

Figure 1 shows the seismic sequence and the episodic deformation at MECA on late 2008. Localized swarms (in red color) seem to have a volcanic origin placed at the depth of 7-4km and were probably triggered by seismo-tectonic interactions, such as the precursory seismic migrations (from NE flank of Fogo to Furnas) and the abrupt local displacement. More precise analysis of the earthquakes (type, depth, and source mechanism) and the deformation modeling are necessary to confirm this preliminary interpretation. Comparative study can be achieved by the reexamination of the GPS data in the past using the most recent reference frame ITRF2008 and different processing schemes.

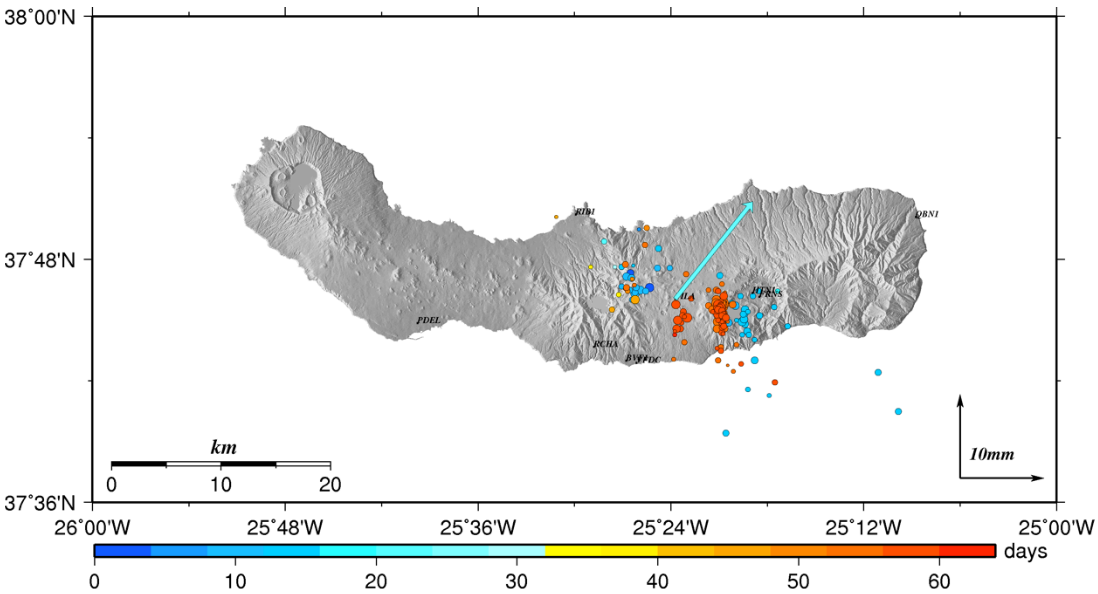

Figure 1. Seismic and deformation sequences on late 2008 (Day counts from October 1st.)

Figure 2 shows c.a. 2cm baseline extension between the north and the south flanks of Fogo during the seismic crisis that started on September 15th, 2011. The timeseries shows the 3 months of pressure accumulation inside the edifice. This volcanic inflation may have resulted from a shallow magmatic intrusion beneath Fogo volcano. The source process (location, magnitude, temporal change) can be addressed by modeling (elastic or numerical models). It is quite interesting to compare the 2011-2012 deformation episode with the deformation 2003-2006 period which was much bigger and the seismic pattern was different. Comparative deformation study by extending the timeseries back to 2003 besides the reexamination of the previous campaign data sets will provide a better understanding about deformation process acting on this area of S. Miguel Island.

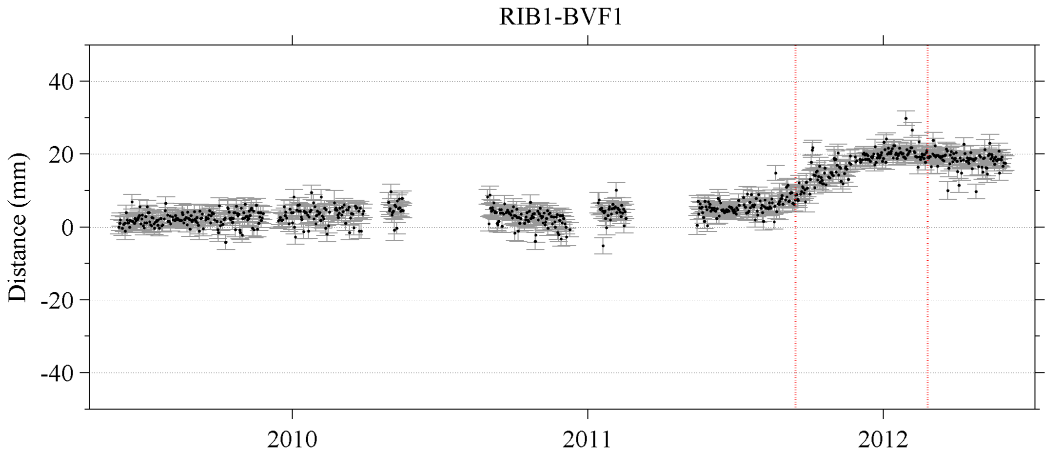

Figure 2. Baseline change between Ribeirinha and Vila Franca do Campo stations
(c.a. 14km distance, Red dot bars indicate September 15th, 2011 and February 25th, 2012)

In this paper, we have shown that continuous GPS data from our network could capture the minor scale deformation episodes that had recently happened in S. Miguel Island. The preliminary analysis has suggested the interactions between the regional tectonics and volcanic deformations. However, without unveiling the source mechanisms it is still very difficult to assess the volcanic and other geological risks. Precise reinvestigation of the longer GPS timeseries by introducing geophysical modeling and joint analysis of the available seismic data would improve our knowledge and enable us to better characterize ongoing volcano-tectonic phenomena in the Azores.

Paleogene igneous deposits and processes on the conjugate Mid Norway – Northeast Greenland margins

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The Paleogene continental breakup between NW Europe and Greenland was associated with massive igneous activity. Large parts of the Norwegian margin are influenced by voluminous igneous complexes that are deeply buried below the seafloor. Their distribution is well defined by geophysical data, and igneous rocks have been sampled by both scientific and petroleum wells during the past three decades. Breakup-related igneous rocks are also abundant both onshore and offshore the conjugate Greenland margin, and offshore on the Jan Mayen micro-continent.

New and reprocessed seismic reflection data allow for detailed seismic volcanostratigraphic interpretation of the breakup complex and sub-basalt sequences. Five main volcanic seismic facies units have been mapped on the new data: Inner Flows, Lava Delta, Landward Flows, Seaward Dipping Reflections (SDRs), and Outer Highs. These units are well-defined and extensive on the mid-Norway margin, and are locally also present on the Jan Mayen micro-continent and the northeast Greenland Margin. Two distinct levels of Inner Flows have been identified in the Møre and southern Vøring basins, the uppermost correlating with the Top Paleocene horizon whereas the lowermost is at a late Paleocene level. The base of the Inner Flows is difficult to identify, and few sub-basalt reflections are present, but the interpretation suggests that the flows are thin (10’s to 100’s of meters). The Inner Flows continue underneath both the Vøring and Møre marginal highs. Here, the base of the volcanic complex is easier to interpret, and well-defined sub-basalt reflections are sometimes present. On the marginal highs, the volcanic complex is typically 1-5 km thick on the central part of the Vøring and Møre margins. However, the complex is substantially thinner, and locally absent, within the Jan Mayen Corridor and on the northern Vøring Margin.

Extensive, multi-layered sheet intrusions and associated hydrothermal vent complexes are present both in the Vøring and Møre basins offshore Norway and in the Thetis and Danmarkshavn basins offshore northeast Greenland. Deep sills are dominantly layer parallel, whereas saucer-shaped sills dominate at shallower levels. In contrast, magma emplaced in very shallow, unconsolidated sediments display flow-like morphologies. Thousands of kilometer-sized hydrothermal vent complexes are associated with the sills. Basin modeling, constrained by well data, suggests that several hundred gigatons of carbon gas were formed in the aureoles around the sills during the intrusive event. The gas migrated out of the aureoles by two mechanisms: (1) The major gas release that occurred immediately after the gas was generated through thousands of hydrothermal vent complexes, and may have caused disruption in the global carbon cycle triggering the Paleocene-Eocene thermal maximum (PETM); and (2) The second mechanism involves slow gas seepage, occasionally to the seafloor, in the Eocene to the Paleogene forming seep carbonates and hydrocarbon accumulations. In addition, significant volumes of aureole gas (dry gas and CO_2-rich gas) are still likely trapped in the source rocks as shale gas. Our results are important for understanding petroleum systems in volcanic basins and the cause of rapid climate changes and mass extinctions in Earth history.

Laboratory and theoretical modeling of dyke emplacement in layered media

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Injections of air or liquids in gelatin have been used as an analog of fluid injections in the crust, including magma-filled dikes. This approach allows a direct observation of the dynamics of a phenomenon that in nature is difficult to observe even statically in its entirety, because of the very large spatial scales involved (several km, so that outcrops of frozen dikes have been observed mainly only in cross section, or 2D). A second advantage offered by gelatin experiments is that they can be used to test numerical models. In this presentation, I will offer an overview of our in-house numerical model of dike propagation, and how it can be integrated with laboratory observations to understand the dynamics of the interaction of dikes with external factors, such as the effects of rigidity layering, density layering, the free surface, external tectonic stress fields, the load of a volcanic edifice. Finally, I will present our future plans of numerical and analog research, including interaction with the existing laboratory facilities at GFZ.

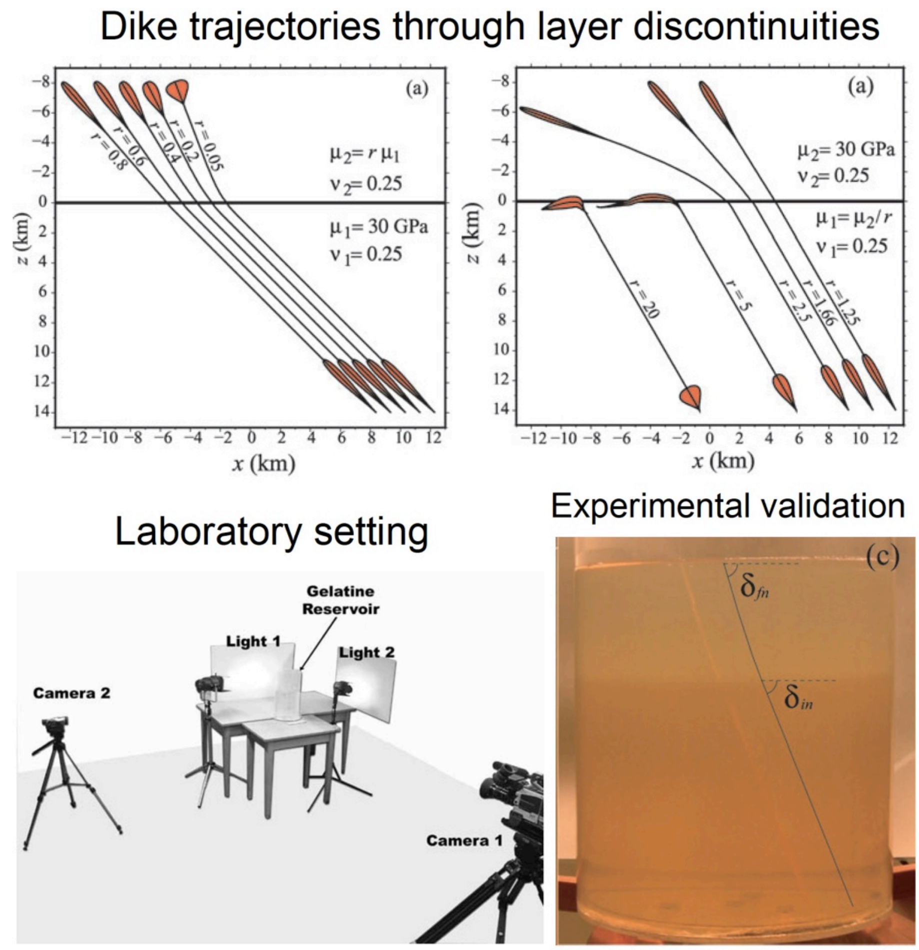

Figure 1. Upper left. Trajectories of propagation of a 45° dipping, fluid-filled fracture, in a layered elastic medium. The figure illustrates the energetically preferred path and initial and final shape of the dyke for different rigidity contrasts. Upper right. Trajectories of propagation of a 60° dipping, fluid-filled fracture, in a layered media. The figures illustrates the energetically preferred path and initial and final shape of the dyke. For different rigidity contrasts. Lower left. Photograph of the experimental apparatus. Lower right. Photograph of a dyke formed in an experiment made of gelatin.

Unravelling the deep plumbing system at caldera volcanoes using petrology

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Silicic caldera systems pose one of the most serious natural hazards to our society, yet their assembly and means to supply larger scale eruptions is poorly characterised at best. Here we employ mineral-melt-equilibrium thermobarometry combined with isotope geochemical methods at the recent Krakatau caldera, the Tejeda caldera on Gran Canaria, and the giant Toba caldera on Sumatra. Krakatau is the smallest of the three systems and shows an apparent repose interval of some 1500 years between caldera-forming events. Its magma reservoir is characterised by three storage levels (at approximately 3 km, 9 km, and >22 km) and crustal involvement was considerable during the1883 rhyolite eruption (≤25%). Current activity at Anak Krakatau shows mainly andesite activity with minor crustal involvement (only ~5-8%). Gran Canaria erupted some 25-30 felsic ignimbrites between 13.9 and 7.9 My from the >20km Tejeda caldera. Repose intervals are on the order of ≤40,000 years and the ignimbrites are widely held to have formed in shallow chambers at some 5-7 km depth. Crustal recycling has seemingly also played a role during late magma evolution of at least some of the ignimbrites with 10-20% crustal material involved. Toba, the most extreme example here, is characterised by a repose period of ~400,000 years and exhibits a presently active magma reservoir at ~10 km depth after the last gigantic eruption some 74,000 years ago. Notably, the percentage of crustal input is very high (≈70%) and there is strong evidence for very late, almost syn-eruptive, crustal additions at Toba, similar to Krakatau and Gran Canaria.

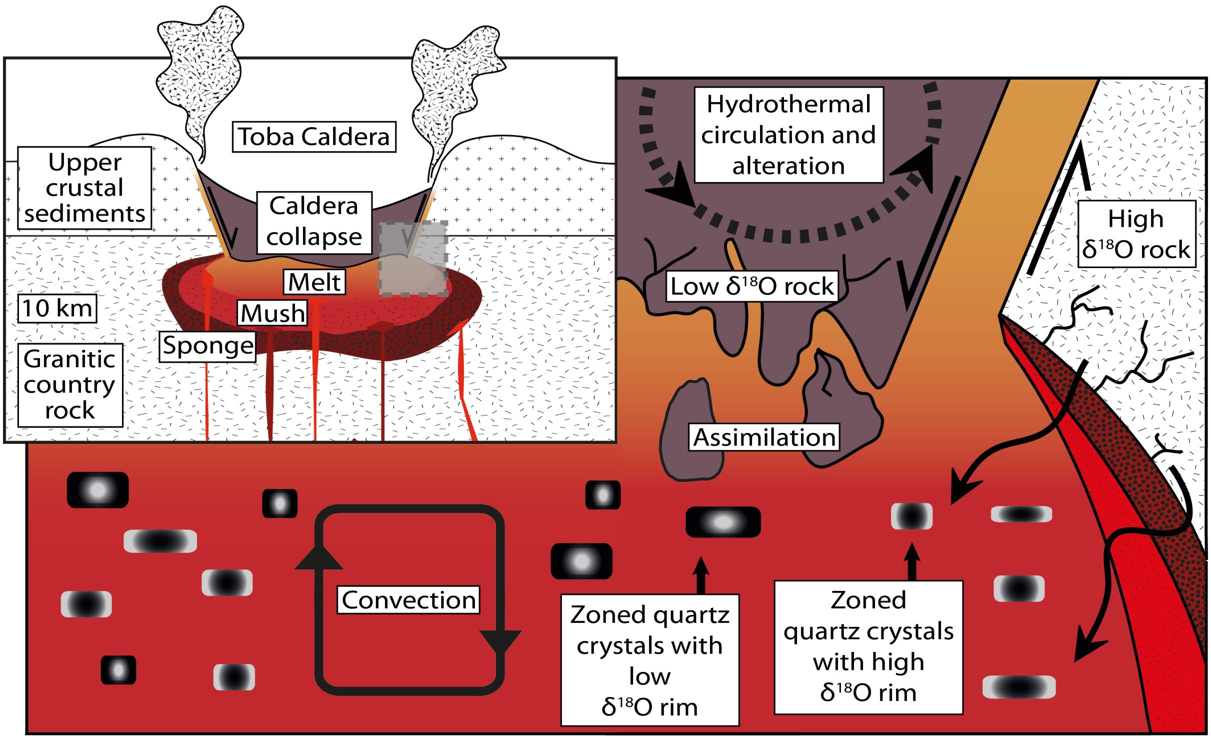

Figure 1. Integrated model for the Toba Caldera Complex. Main diagram displays enlargement of the grey shaded box in inset, showing hydrothermally altered down-dropped caldera roof that undergoes disintegration and assimilation into the Toba magma chamber. Assimilation of lower δ^18 O rocks causes a drop in the $\delta^{18}O$ values of the rims of concurrently crystallizing quartz.

The broad implication from these observations is that late crustal addition may be a critical factor in priming caldera volcanoes for eruption. This phenomenon is likely independent of magma residence time, but rather depends on magma heat capacity, fusibility of crustal rock, and chamber depth. The latter is especially important as it provides the ‘cork in the bottle’ to counteract the progressively increasing magmatic overpressure in caldera systems at time of unrest.

The Macro-Micro problem and the use of scaling with real life analogues

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I suppose that sometimes we get so caught up in models that we don't think about the macro – micro problem, but all too often reviews and outsides have pulled me up on this. So I think its worth a discussion here. So I actually got to know the term from sociology (Everything is obvious: How Common snese fails us, Duncan Watts (2012), psychologist can get to understand quite a lot about how an individual behaves, but that is quite different from judging how a crowd will behave. Modelling flow of traffic on a road, gives you no clue how individual drivers behave. Similarly for us, there are those who happily model large scale features, caldera collapse, landslides, mountain ranges, whole edifice deformation, but don't really get to grips with what is happening at a small scale. Equally there are others who model individual processes, but have some difficulty going to a more general scale. Can the two approaches and scales be at all reconciled, is there really a problem and how can we deal with it? What can we learn from physics

Next, I'd like to look at natural examples. We are able at outcrop, to observe many features that are also reproduced at either the large scale or at a micro scale. Faults and fractures, for example, but also textures. Two examples, 1) micro-scale debris avalanche textures are sees at a 10's of m scale as well, 10 times larger. 2) small-scale dyking seen in Lemptégy quarry, resembles structures on intrusions 10's or 100's of times as large. Can we thus, consolidate our scaling and analogue models with scales natural examples?

Calderas have been a notable subject where this has been done, and we could use that as a basic for discussion, adding in intrusion during caldera collapse and the macro-micro problem to boot.

Notes