Physics of Volcanoes 2016

2nd Workshop held in Mainz, Germany
March 02 - 04, 2016

Program and Abstracts

University of Mainz • Heidelberg University • MPI for Chemistry Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MAX-PLANCK-INSTITUT FÜR CHEMIE

Contents

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March 2nd, 2016	March 3rd, 2016	March 4th, 2016
13:00 Registration	***Seismic methods***	***Volcano remote sensing (II)***
14:00 Opening	09:15 Keynote - J. Neuberg: Volcano seismology in a wider volcanological	09:15 *P. Hedelt* : Monitoring volcanic SO_2 emissions using GOME-2/Metop-A & -B
Physics of magmatic processes (I)	09:45 *J. Battaglia* : Seismicity and SO_2 associated with the eruptive activity of Tungurahua volcano (Ecuador)	09:35 *K. Bigge* : Influence of radiative transfer on ground-based DOAS SO_2 flux measurements
14:20 ***Keynote -*** *L. Caricchi:* Physical processes controlling the frequency and magnitude of volcanic eruptions	10:05 *T. Dahm* : The collapse mechanics at the Bardabunga calder during the 2014/2015 volcanic eruption	09:55 *A.S. Dinger* : Accurate Prototype remote sensing of correlated carbon dioxide and sulfur dioxide emissions at
14:50 *M. Cassidy:* Volatile dilution during magma injections and implications for volcano explosivity	10:25 *V. Schlindwein* : Teleseismic earthquake swarms and local seismicity during volcanic episodes at ultraslow spreading mid-ocean ridges	10:15 *A. Heck* : Application of bistatic TanDEM-X Interferometry at Shiveluch volcano, Kamchatka
15:10 *J. Schierjott, (presented by E. Rivalta):* A numerical and analogue study of dike ascent in asymmetric continental rift zones	*10:45 Coffee break*	*10:35 Coffee break*
15:30 *S.B. Müller (LMU):* Experimental aggregation of volcanic ash: the role of liquid bonding	11:15 B.-G. Lühr: The KISS project - Seismological Network monitors Central Kamchatka's volcanoes	11:05 *U. Platt* : Quantitative Imaging of Volcanic Plumes – Recent Developments and Future Trends
15:50 Coffee break	***Volatiles in melts and volcanic plumes***	11:25 *T. Walter* : EPOS and the volcanology contributions from Germany
16:20 *J.J. Peña Fernández* : Linking bubble size with the governing parameters of a volcanic jet	11:35 **Keynote** - *T. Hansteen:* Magmatic Degassing: Continuous and Episodic	11:45 *N. Bagdassarov* : Electrical Structure beneath Oldoinyo Lengai Volcano
16:40 *J. von der Lieth* : Modelling conduit processes using realistic magma rheology: Strombolian volcanism	12:05 *D. Neaves* - Diffusive over-hydration of melt inclusions	12:05 *L. Fieber* : Designing a muon detector for volcanoes
17:00 *M. Hort* : Strombolian eruption dynamics: insight from small scale experiments and Stromboli, Yasur and Mt. Erebus	12:25 *N. Bobrowski* : The birth of a new lava lake -Nyamulagira volcano, DR Congo	12:25 *S. Plank* : Monitoring of active volcanoes by means of multi-sensor remote sensing – a case study of the 2014/15 Holuhraun fissure eruption
17:20 *W. Song* : Role of heating rate on the melting dynamic of volcanic ash relevant to aviation hazards	*12:45 Lunch break*	*12:45 Farewell*
17:40 Poster session	13:45 *F. Dinger* : Variations of the BrO/SO_2 molar ratios during the 2015 Cotopaxi eruption	
18:40 Icebreaker	14:05 *J.Gliss* : SO_2-flux measurements at Guallatiri volcano, Altiplano, northern Chile using two UV SO_2 cameras	
	14:25 *L. Simon* : Characterization of multi-rotor unmanned aerial vehicles (UAV) for gas measurements at volcanoes: a case study at Mount Etna, Sicily	
	Physics of magmatic processes (II)	
	14:45 *L. Probst* : Cross correlation of chemical profiles in minerals: insights into the architecture of magmatic reservoirs	
	15:05 *E. Gerwing* : Transport of Volcanic Emissions Using an Adaptive Semi-lagrangian Advection Model	
	15:25 Coffee break	
	Volcano remote sensing (I)	
	15:55 **Keynote -** *S. Carn:* Exploiting the full spectrum of remote sensing for volcanic hazard mitigation	
	16:25 *V. Keicher* : Determining volcanic SO_2 plume heights in satellite observations using meteorological wind fields	
	16:45 *K. Zaksek:* Simulation of satellite observations of volcanic hotspots	
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	19:00 Departure to conference dinner *20:00 Conference dinner at the "Eisgrub"*	

Session Conveners

Physics of magmatic processes:
Jon Castro
Ulli Küppers

Seismic methods:
Thorsten Dahm
Joachim Wassermann

Volatiles in melts and volcanic plumes:
Nicole Bobrowski
Kai-Uwe Hess

Volcano remote sensing:
Ulrich Platt
Thomas Wagner

Poster Presentations

Author	Titel
	Physics of magmatic processes
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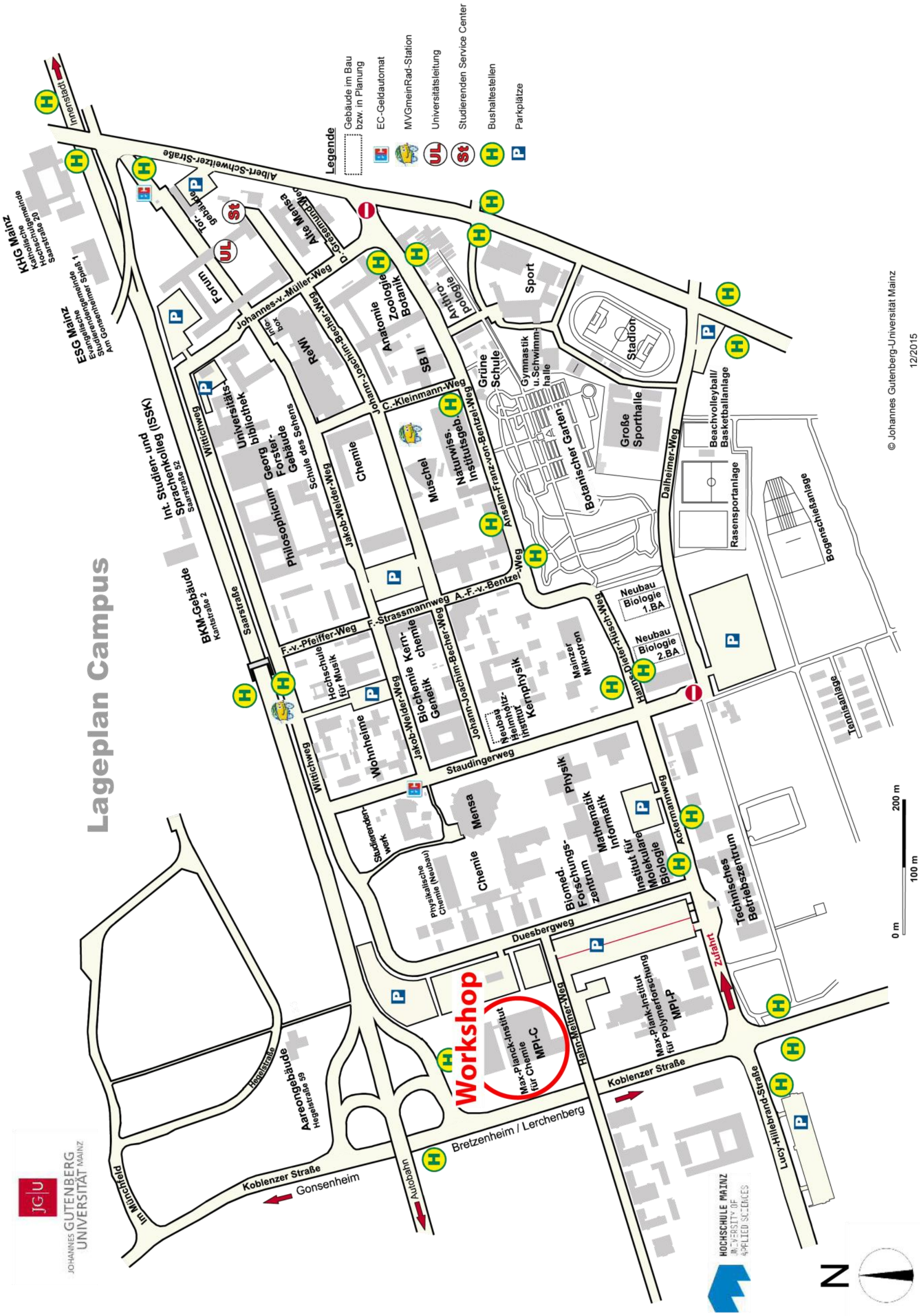
Colombier, Mathieu	The evolution of pore connectivity in magma: Insights on eruptive processes
Forte, Pablo	From shrinking to fragmentation: new findings from 1 atm - high temperature experiments with rhyolitic glasses.
Gaete, Ayleen	The 2013 and 2015 eruptions of Lascar volcano, Chile
Gottschaemer, Ellen	Loss to residential buildings of a re-eruption of the Laacher See Volcano
Hache, Ingo	A closer look at the strombolian eruptions pulses using different CFD modeling cases of ascending gas slugs
Klein, Johannes	The influence of crystal size distributions (CSD) on the rheology of magma: new insights from analogue experiments
Küppers, Ulli	Environmentally-mediated ash aggregate formation: example from Tungurahua volcano, Ecuador
Laeger, Kathrin	Internal structure and chemical characterization of accretionary lapilli from Stromboli Island (Aeolian Archipelago, Italy)
Maccaferri, Francesco	How the differential load induced by normal fault scarps controls the distribution of monogenic volcanism
Paredes, Joali	Evaluation of eruptive energy of pyroclastic fall deposits by using fractal theory
Rummel, Lisa	Coupling geodynamic with thermodynamic modelling for reconstructions of magmatic systems
Sheldrake, Tom	Understanding the role of magma reservoir processes on the frequency and magnitude of volcanic eruptions
Steinke, Bastian	Graben-structures complexities at Mt. Laki, Iceland, investigated by camera drones and modeling
Weber, Gregor	Rhyolite magmas in the Icelandic crust: Insights from experimental petrology
	Seisimic methods
Schmid, Florian	From mantle to crust: Tomographic image of a mid-ocean ridge volcano
	Volatiles in melts and volcanic plumes
Hoshyaripour, Gholam Ali	From the lithosphere to the atmosphere: modeling the physical chemistry of volcanic eruption plumes
Julia Rüdiger	Halogen speciation in volcanic plumes - Development of compact denuder sampling techniques with in-situ derivatization followed by gas chromatography-mass spectrometry and their application at Mt. Etna,
Spang, Arne	A quantitative analysis of bubble coalescence in basaltic magmas
Warnach, Simon	Variations of the BrO/SO2 ratios from Tungurahua volcano, Ecuador
	Volcano remote sensing
Bredemeyer, Stefan	Radar path delay effects in the volcanic gas plume of Láscar volcano, Northern Chile
Müller, Daniel	Geomorphology at the 2014 Holuhraun eruptive fissure
Penning de Vries, Marleos	Satellite observations and EMAC model calculations of sulfate aerosols from Kilauea: a study on aerosol formation, processing, and loss
Scharff, Lea	First observation of pyroclastic flow dynamics with a Doppler radar
Hidalgo, Silvana	Cotopaxi volcano's unrest and eruptive activity in 2015
Schultz, Amelie	Statistical analysis of the repose intervals at Volcán de Colima

Campus Map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Bus Lines on Campus

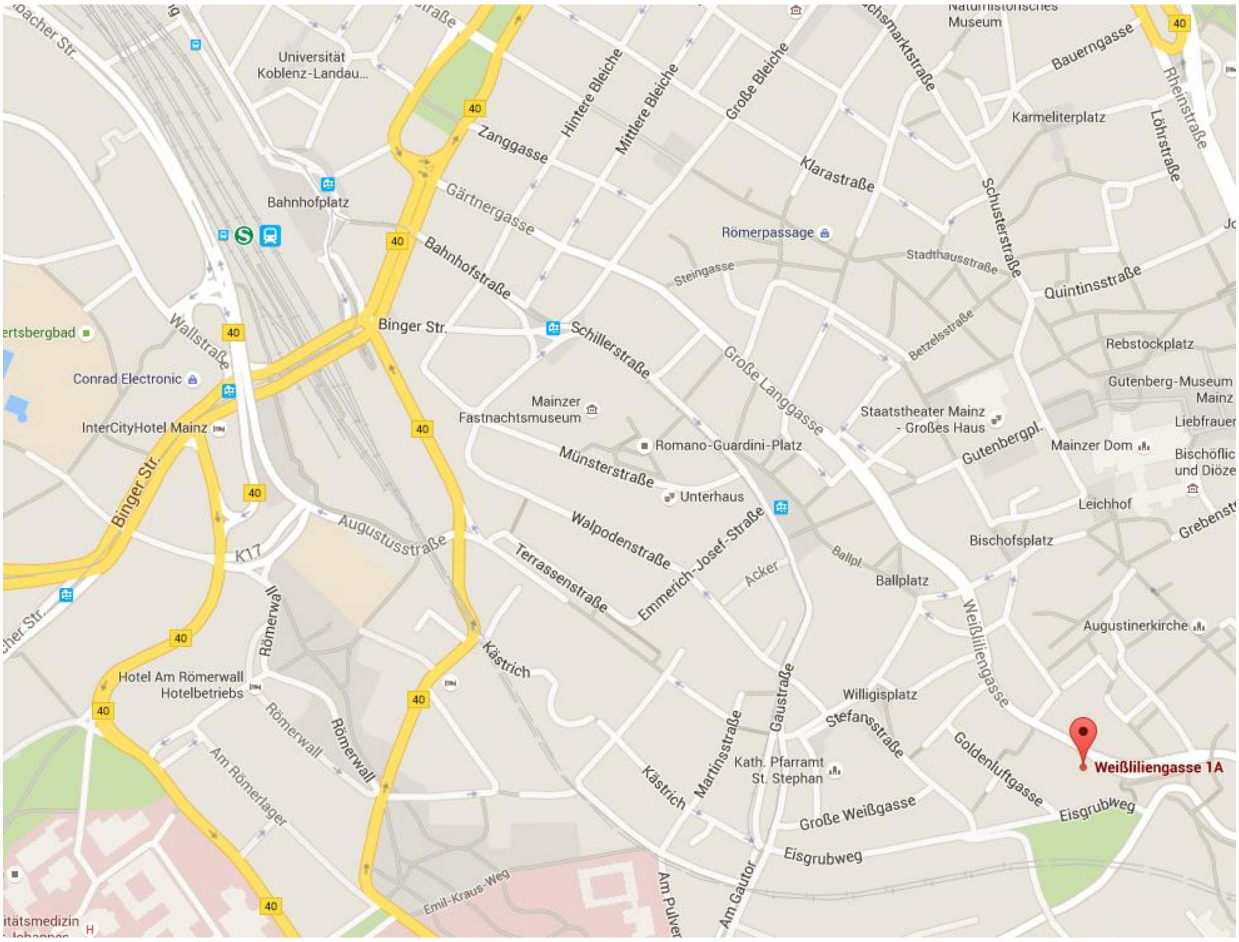
Conference Dinner

on March 3rd, 20:00, at the *Brauerei Eisgrub*, Weißliliengasse 1a, Mainz

Directions from the Central Station:

Bus 64 direction to *Mainz-Laubenheim*
Bus 65 direction to *Mainz-Weisenau*
Bus 92 direction to *Mainz-Laubenheim*

Get off at the stop "*Pfaffengasse*" walk down the street (Weißliliengasse) for ~ 100 m.



Abstracts

Electrical Structure beneath Oldoinyo Lengai Volcano

Nikolai Bagdassarov

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The stratovolcano Oldoinyo Lengai is constructed by nephelinitic, phonolithic and carbonatite lavas. Rock samples of nephelinitic, melilitic, basanitic compositions and carbonatitic samples from the volcano Oldoinyo Lengai area were collected by H. Mattsson & R. Nandekar. The carbonatite lava sample was taken from the 2006 eruption site. The electrical conductivity of these rock samples have been measured at pressure 0.5 GPa and in the temperature range 200-800°C. These rocks are representative of the Oldoinyo Lenghai magma chamber and Gregory rift zone. The electrical conductivity of melilitic, nephelenitic and parental magma composition rocks has been measured at 1.6 GPa and T=300-850°C by the use of electrical impedance measurements in piston-cylinder high pressure apparatus. The activation energy of electrical conductivity of carbonatite lava sample is 0.66 eV, the activation energy of nephelenite-melilite rocks decreases from 0.68 to 0.3 eV with the increase of oxide ratio (Na_2O+K_2O+CaO)/(SiO_2+Al_2O_3). The models of electrical conductivity of carbonatite magma and nephelenitic-melilitic rocks as a function of temperature and composition have been incorporated in 2D model 80 x 60 km of electrical structure beneath the Lake Natron – Engaruka region. The finite element model consisted of the solution of temperature field which satisfies the heat flux on the surface and the variable thickness of the lithosphere beneath Gregory Rift in Northern Tanzania. The temperature field has been used to model the electrical conductivity of rocks including carbonatitic and silisic/carbonatitic magma chambers beneath Oldoinyo Lengai volcano and basaltic magma chamber beneath Gelai volcano. The model of electrical structure beneath the Lake Natron – Engaruka area has been used to calculate TM and TE magnetotelluric response by using COMSOL program. The calculated apparent resistivity and phase delay for different observation points on the surface can be compared with the field MT measurements.

Seismicity and SO_2 associated with the eruptive activity of Tungurahua volcano (Ecuador)

J. Battaglia (1), S. Hidalgo (2), A. Steele (3,2), S. Arellano (4), M. Ruiz (2)

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(4) Chalmers University of Technology, Gothenburg, Sweden.

Tungurahua is an andesitic stratovolcano located in Central Ecuador. It has been erupting since 1999 with repeated phases of enhanced activity during which explosions, ash emissions and occasional pyroclastic flows have occurred. The volcano is monitored by the IG in Quito whose monitoring networks include 5 broadband and 6 short period seismic stations, 5 acoustic sensors and 4 DOAS permanent NOVAC-1 type instruments for measuring SO_2.

The seismicity related to eruptive/degassing processes is dominant with explosion quakes and longer duration tremors. To quantify both phenomena, we proceeded in two ways. First, we established the acoustic and seismic energies of individual explosions and calculated cumulative daily values. Secondly, to quantify the intensity of background tremor we calculated sliding median amplitudes. NOVAC DOAS instruments provide valid SO_2 measurements only under good weather and daylight conditions, leading to intermittent and sometimes sparse time series. To determine the daily observed SO_2 masses we use a routine which consists in summing all the highest validated SO_2 measurements among all stations during the 11 h of daily working-time.

The comparison of these datasets shows that the correlation between seismic/acoustic and SO_2 degassing is not straightforward. On the time scale of months, a good qualitative correlation is found in the sense that seismo-acoustic activity and SO_2 degassing occur mostly during the eruptive phases. However, when focusing at the time scale of days to weeks, the comparison of the different time series displays variable correlations. Often, temporal variations in SO_2 emissions are poorly reproduced by seismic parameters. In contrary, rough qualitative correlations are sometimes observed between SO_2 emissions and explosive activity, tremor and sometimes with both. Our results suggest that the relation between seismic activity and SO_2 degassing is strongly controlled by the vent conditions.

Influence of radiative transfer on ground-based DOAS SO_2 emission rate measurements

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(1) Institut für Umweltphysik, Universität Heidelberg
(2) Institut für Geowissenschaften, JGU Mainz

The Differential Optical Absorption Spectroscopy (DOAS) technique is often used for measurements of volcanic gas emissions using scattered sunlight. SO_2, a very abundant gas in volcanic plumes but with low atmospheric background concentration, can easily be detected and emission rates calculated. However, results have unknown uncertainties, due to radiative transfer effects which can strongly influence the light path and thus the absorption signal.

We have used the Monte Carlo atmospheric radiative transfer model McArtim to investigate main influential parameters in several simple case studies. For a cylindrically-shaped plume with a set SO_2 emission of 643 t/day, corresponding DOAS measurement emission rates have been modeled for different sun positions, plume-detector distances and aerosol loads. All studies showed SO_2 absorption features in off-plume detector elevation angles. Including those angles in the emission rate calculation partly compensates or sometimes even overcompensates for light dilution effects.

Accordingly, while underestimation of SO_2 emission rates can happen, most results show an overestimation, with results between 85 and 155% of the true value. Additionally, varying the sun position leads to a variation of up to 35% in the emission rate results. Background aerosol variations lead to about 10% differences in the determination of the emission rate at close distances and 20% at farther distances. Plume aerosol variations caused about 20% variation in emission rates.

In total, the determined variations were lower than feared. However, the result emphasizes that only correcting for one effect (light dilution or multiple scattering) might increase emission rate errors.

The birth of a new lava lake - Nyamulagira volcano, DR Congo

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Nyamulagira, in the Virunga volcanic province, is one of the most active volcanoes in Africa. It is a shield volcano of about 3000 m height, with a 2000 m wide caldera and it is located about 25 km north-northwest of Lake Kivu in the Western Branch of the East African Rift System within a distance of only 15 km to Nyiragongo, which is well known for its persistent lava lake. Nyamulagira is characterized by frequent eruptions, occurring from both the summit crater and the flanks (31 flank eruptions over the last 110 years) and contained a lava lake in its caldera from 1912-1938. Due to its low viscosity lava, wide lava fields cover over 1100 km^2 and lava flows often reach > 20 km length.

During the last decades gas emissions at Nyamulagira have been only reported during eruptions, this changed in 2012. Since then Nyamulagira shows a persistence gas plume above its crater and in the end of 2014, beginning of 2015 a lava lake was born, which is still growing, by the time of writing.

Very little is known about gas composition of Nyamulagira's plume. We report gas composition measurements of Nyamulagira's plume during the birth (November 2014) and after a year of the persistence of the lava lake (October 2015). Nyamulagira is known to be a significant SO_2 emitter but shows low CO_2/SO_2 ratios. In contrast to Nyiragongo the H_2O contribution to the volatile budget of Nyamulagira is high (> 92 % of total gas emissions in 2014). We further determined molar plume gas ratios of Cl/S, F/S and Br/S and present as well tephra composition erupted during 2014. Gas composition changes (2014-2015) will be discussed in the light of the visually observed evolution of the lava lake and an interpretation on the volcanic system is attempted.

Radar path delay effects in the volcanic gas plume of Láscar volcano, Northern Chile

Stefan Bredemeyer (1), Franz-Georg Ulmer (2), Thor H.Hansteen (1), Nicole Richter (3), Elske De Zeeuw van Dalfsen (3), Thomas Walter (3)

(1) GEOMAR Helmholtz Centre for Ocean Research, Kiel
(2) Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen
(3) GFZ Potsdam

The accuracy of satellite radar ground deformation measurements (InSAR) is largely affected by changes in atmospheric refractivity, in particular by changes which can be attributed to the distribution of water vapor in the observed atmospheric column. Gas emissions from continuously degassing volcanoes contain abundant water vapor and thus produce variations in the atmospheric water vapor content above and downwind of the volcano. These variations may in turn cause differential phase errors due to excess radar path delay effects within the volcanic gas plume. Mitigation of such phase signatures demands estimation of the precipitable water vapor (PWV) content in the plume at the time of SAR acquisitions. In this work water vapor estimates were retrieved from ground-based scanning Mini-DOAS (Differential Optical Absorption Spectroscopy; UV spectrometer) and multi-GAS (multi-component Gas Analyzer System; IR spectrometer and electrochemical gas sensors) sensors. Sulfur dioxide emission measurements, obtained from a permanent ground-based scanning Mini-

DOAS, were scaled by H_2O/SO_2 molar mixing ratio, derived from gas concentration measurements of a multi-GAS instrument. These estimates were used in combination with TerraSAR-X observations, in order to investigate the atmospheric delay generated by volcanic gas emissions.

Physical processes controlling the frequency and magnitude of volcanic eruptions

Luca Caricchi

Department of Earth Sciences, University of Geneva, Rue de Maraîchers 13, 1205 Geneva, Switzerland

Volcanic eruptions occur with a frequency that is inversely proportional to their magnitude. Large eruptions producing up to few hundredth cubic kilometres of magma occur every few tens of thousands years on our planet, while events such as the 1980 eruption of Mt. S. Helens have a global recurrence rate of about one event every ten years. However, this is a relationship observed globally, but the recurrence rate of volcanic eruptions is somehow related to physical processes and parameters that vary locally such as magma productivity, physical properties of the crust, and tectonic environment. Therefore, using the global rate of volcanic eruptions to forecast the recurrence rate of these events at regional scale (i.e. Japan or Europe) is potentially incorrect. To improve our capability of anticipating the recurrence rate of volcanic eruptions at different spatial scales, it is essential to establish the link between the geological record and the physical processes responsible for volcanic activity.

Thermo-mechanical and statistical modelling results suggest that the flux of magma through the Earth crust play a pivotal role in regulating the tempo of volcanism. Because most of the magma produced at depth is not erupted at the surface, quantifying magma fluxes has been challenging. I will present a method we recently developed to estimate magma productivity from the analysis of zircon age populations retrieved from intrusive rocks and erupted products. This approach allows us not only to estimate magma flux but also, when applied to eruptive products, to determine the extrusive/intrusive ratios. Finally, I will show that the comparison of the geological record of the recurrence rate of volcanic eruptions with thermo-mechanical and statistical modelling provides insights on the main physical processes controlling the recurrence rate of volcanic eruptions at regional and global scale.

Exploiting the full spectrum of remote sensing for volcanic hazard mitigation

Simon A. Carn

Department of Geological and Mining Engineering and Sciences, MichiganTechnological University, Houghton, MI, USA

Remote sensing from various platforms has become an essential tool for global volcanosurveillance, providing unique information on volcanic gas emissions, heat flux and deformation. I will review some notable recent results from satellite remote sensing of volcanic gas emissions, including the development of global databases of volcanic sulfur dioxide (SO2) emissions that can be used to accurately characterize the impact of volcanoes on atmospheric chemistry and climate. Satellite observations of volcanic emissions often occur post-eruption and the identification of pre-eruptive degassing remains challenging. Measurements of volcanic carbon dioxide (CO2) emissions derived from magma reservoirs at depth (coupled with measurements of seismicity, deformation and heat flux) could potentially contribute to eruption forecasting, but it remains unclear whether volcanic CO2 can be robustly detected from space. Despite significant advances in separate fields of volcano remote sensing (e.g., thermal anomaly detection, gas measurements, InSAR), to date there have been relatively few efforts to combine these observations in holistic analyses of volcanic unrest. Such efforts are challenging because satellite data acquisitions from existing assets are rarely optimized for volcano monitoring, and the temporal relationships between the various detectable manifestations of pre-eruptive volcanic unrest (e.g., surface deformation, SO2 emissions, increased heat flux) remain poorly understood. Several recent, large eruptions occurred with little advance warning, presenting an outstanding challenge to volcanologists. Linked analyses of emerging global databases of volcano deformation, volcanic gas emissions, and radiant heat flux should be prioritized in order to characterize the detectable signals of pre-eruptive volcanic unrest and their temporal evolution. The volcano remote sensing community would benefit from a satellite mission specifically dedicated to volcano monitoring, but justification for such a mission is hindered by the relatively infrequent occurrence of major volcanic eruptions.

Volatile dilution during magma injections and implications for volcano explosivity

Mike Cassidy* (1), Jon Castro (1), Christoph Helo (1), Valentin Troll (2), Duncan Muir (2) Frances Deegan (2)

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Magma accumulations underneath volcanoes grow through the emplacement of episodic pulses of magma. For an eruption to occur, this input of magma has to be high enough to keep the magma in a hot and eruptible state. These magma injections can substantially alter the magma's physical state, by changing the temperature, pressure and volatile content. We examine plagioclase phenocrysts from pumices formed in the 2014 explosive Plinian eruption of Kelud (Indonesia), which preserve the progressive capture of small melt inclusions during different stages of crystal growth inside a crystallising and growing magma reservoir. The high-spatial resolution provided by Raman spectrometry is used to measure the dissolved water contents within small melt inclusions (often <300 μm^2) and thus provides a rare glimpse into volatile behaviour throughout a single crystal. Water contents in the melt inclusions are variable (~0.45 - 2.27 wt %) throughout the growth of the magma reservoir, they do not correlate with melt inclusion size nor distance from the rim of the crystals, suggesting water loss via diffusion is minimal. Instead, water contents vary with anorthite content of the host plagioclase, but in a counter-intuitive manner, with high anorthite zones associated with low water contents and vice versa. We posit that injections of hot magma with similar composition, increase the temperature leading to dilution and minor amounts of degassing of the magma reservoir without triggering an eruption. Therefore when an eruption does occur, it may not be directly linked with magma injections cycles observed through traditional monitoring techniques.

Investigating pyroclast ejection dynamics using shock-tube experiments: temperature, grain size and vent geometry effects.

Valeria Cigala[1], Ulrich Kueppers[1] and Donald B Dingwell[1]

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Explosive volcanic eruptions eject large quantities of gas and particles into the atmosphere. The portion directly above the vent commonly shows characteristics of underexpanded jets. Understanding the factors that influence the initial pyroclast ejection dynamics is necessary in order to better assess the resulting near- and far-field hazards. Field observations are often insufficient for the characterization of volcanic explosions due to lack of safe access to such environments. Fortunately, their dynamics can be simulated in the laboratory where experiments are performed under controlled conditions.

We ejected loose natural particles from a shock-tube while controlling temperature (25˚ and 500˚C), overpressure (15MPa), starting grain size distribution (1-2 mm, 0.5-1 mm and 0.125-0.250 mm), sample-to-vent distance and vent geometry. For each explosion we quantified the velocity of individual particles, the jet spreading angle and the production of fines. Further, we varied the setup to allow for different sample-to-gas ratios and deployed four different vent geometries: 1) cylindrical, 2) funnel with a flaring of 30˚, 3) funnel with a flaring of 15˚ and 4) nozzle.

The results showed maximum particle velocities up to 296 m/s, gas spreading angles varying from 21˚ to 37˚ and particle spreading angles from 3˚ to 40˚. Moreover we observed dynamically evolving ejection characteristics and variations in the production of fines during the course of individual experiments. Our experiments mechanistically mimic the process of pyroclast ejection. Thus the capability for constraining the effects of input parameters (fragmentation conditions) and conduit/vent geometry on ballistic pyroclastic plumes has been clearly established. These data obtained in the presence of well-documented conduit and vent conditions, should greatly enhance our ability to numerically model explosive ejecta in nature.

The evolution of pore connectivity in magma: Insights on eruptive processes

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The evolution of pore space in magma and its connectivity are subject to continuous changes throughout magma ascent and eruption. Two main processes contribute: 1) vesiculation (bubble nucleation, growth, coalescence) and 2) densification (bubble collapse, crystallization, compaction, sintering). The evolution of connectivity with respect to porosity during these processes is investigated based on own (Helium pycnometry) and published data, comprising more than 2500 rock samples and incorporating the effects of crystallinity as well as glass and bulk chemistry. Further it is supplemented by textural 2D and 3D images and permeability data. We evaluate the trends of the natural samples from our database in the light of experiments on vesiculation (Okumura et al. 2008) and densification (Okumura et al. 2013; Vasseur et al. 2013).

In contrast with permeability, connectivity is not sensitive to pore aperture and tortuosity but only depends on the degree of pore nucleation, coalescence and collapse. In general, we can show that pore connectivity increases with porosity. This study allowed us to estimate high percolation threshold for plinian datasets (above 40 % porosity), intermediate for vulcanian (20-30 % porosity) and low for dome rocks (0-5 % porosity). We propose that this metric of connectivity permits diagnostic differentiation of eruptive style and processes recorded in eruption products.

The collapse mechanics at the Bardarbunga caldera during the 2014/2015 volcanic eruption

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During the 2014-2015 fissure eruption of Bárðarbunga volcano in Iceland the central caldera experienced continuous subsidence of more than 65 meter. The subsidence was accompanied by a notable seismic sequence of 77 M> 5 earthquakes, for which full moment tensors and relative centroid locations were estimated. Strain release by earthquake rupture cluster mostly beneath the northern and southern caldera rims. We interpreted the earthquake radiation as frictional controlled rupture at segments of the caldera ring fault and additional sub-vertical CLVD sources below, possibly related to the response of the magma reservoir feeding the Bardabunga fissure eruption.

We discuss the magma reservoir depletion and develop an outflow models to understand the caldera subsidence. The strain buildup at the caldera ring faults is compared to the co-seismic stress release and the earthquake occurrence. A Brownian passage model is compared to a rate and state model to explain the observed inter-event times of earthquakes. We discuss simple physical relations between seismic and magmatic parameters.

Accurate Prototype remote sensing of correlated carbon dioxide and sulfur dioxide emissions at Mt.Etna

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Volcanic carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions have a direct as well as indirect impact on climate and air quality. Moreover these two gases, and in particular their ratio, are tracers for dynamic processes inside volcanoes and hence volcanic activity. Continuous in-situ measurements of CO_2 and SO_2 have been conducted for a decade, demonstrating already the great potential of such data. However, in-situ measurements are linked with great effort and risk due to the difficult environment. Remote sensing of volcanic emissions allows for monitoring volcanic activity from a safe distance to the volcano. Further it enables sampling of cross sections of the entire plume thus, suffering less from representativeness errors than the in-situ technique. Remote sensing of SO_2 is already well developed, whereas the measurement of CO_2 is challenged by the high ambient background concentration and therefore requires high accuracy in order to measure little concentration enhancements in the volcanic plume. To overcome this challenge, we employed combined direct sunlight spectroscopy for SO_2 (UV-DOAS) and CO_2 (FTIR). The beam of a common sun tracker was coupled into both instruments. The whole setup was installed on a mobile platform, which allowed for sampling plume cross sections in a stop-and-go pattern. Measurements were conducted during a three-week campaign at Mt.Etna, Sicily. We measured significant CO_2 and SO_2 column density enhancements, even though the CO_2 enhancement was only slightly above the detection limit. Our measured CO_2 and SO_2 column densities showed a strong correlation and their emission ratios were in the range of 5 - 15. This result in combination with SO_2 fluxes from a parallel employed SO_2 camera allows for estimating the CO_2 flux of Mt.Etna.

Variations of the BrO/SO2 molar ratios during the 2015 Co-topaxi eruption

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Cotopaxi volcano is located 50 km south of Quito, the capital of Ecuador. After almost 140 years of relative quiescence, increasing activity is observed in seismicity and gas emissions since May 2015. Since 2009 Cotopaxi volcano is part of the Network for Observation of Volcanic and Atmospheric Change (NOVAC) which regularly monitors the SO2 emissions of more than 30 volcanoes using scanning UVspectrometers. The interpretation of SO2 emissions can be improved by additionally recording halogen/sulphur emission ratios. Recently, it has been shown that spectra from NOVAC instruments can also be used to retrieve the BrO/SO2 molar ratio by applying Di_erential Optical Absorption Spectroscopy (DOAS). We apply DOAS to analyse the plume composition of Cotopaxi volcano and will present time series of the BrO/SO2 molar ratios as monitored by the ground-based NOVAC instruments since March 2015. Prior to the phreatic explosions in August 2015 the BrO signal was below the detection limit. Soon after the explosions the BrO/SO2 molar ratio was low as $1*10^{-5}$, but during September-December 2015 this ratio varies between 3 – $11*10^{-5}$.

Designing a muon detector for volcanoes

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High energy muons can penetrate several kilometer of rock. Measurements of the absorption of cosmic ray muons can be used to determine the density pro le of the material traversed by these particles. Applying this method to a volcanic edifice can open a window to its inner structure and even the magma level. This method improves the resolution by one order of magnitude compared to traditional measurement methods like seismologic and electromagnetic ones.

E.g. Tanaka et al. [2009] carried out such investigations using scintillator detectors with an exposure time of the order of a month. The results obtained are very promising and could indicate that muon detection techniques will play a key role in volcano structure analysis and understanding volcano eruption dynamics.

Our aim is to build a muon detector, using a detector material such that the exposure time can be reduced by enlarging the detection area without unduly increasing the costs. The detector should be functional in the given environment of volcanoes, meaning low power consumption, relatively small and easy to transport. To achieve this goal, we look into alternatives to the standard detection devices. Theoretical considerations andpractical tests will be presented.

Tanaka, H. K. M., et al. (2009), Detecting a mass change inside a volcano by cosmic-ray muon radiography (muography): First results from measurements at Asama volcano, Japan, Geophys. Res. Lett., 36, L17302, doi:10.1029/2009GL039448

From shrinking to fragmentation: new findings from 1 atm - high temperature experiments with rhyolitic glasses.

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Rhyolitic systems are responsible for the most explosive volcanic activity in our planet. Due to the extensive environmental and social consequences that these events could cause, effort was invested to understand how these complex systems work. Since the pioneer study of Murase and McBirney (1973), a number of experimental studies were carried out using natural rhyolitic glasses with the goal of understanding the physical and chemical processes related to gas exsolution and vesiculation in rhyolitic systems (e.g. Bagdassarov and Dingwell (1993), Bagdassarov et al. (1996), Stevenson et al. (1997) and Ryan et al. (2015)). Notwithstanding the importance of these existing studies, our knowledge about these systems is still incomplete to fully explain their dynamics, and in particular, how explosive fragmentation occurs.

In this study, 80 experiments were performed in the laboratories of the Johannes Gutenberg University with the aim of investigating an unexplored field of H_2O - temperature conditions. Experiments were carried out at 0.1 MPa, temperatures between 740°- 1030°C and H_2O contents ranging from 0.62 to 1.3 wt.%. The materials used for the experiments were cylindrical obsidian cores obtained from bombs of 2008 Chaitén volcano (Chile) eruption. Taking advantage of new technologies, an experimental design that allowed us to observe and monitor the evolution of the experiments was used. It includes a Nabertherm® LT24/12 furnace with a sapphire window and the use of a high speed camera and an IR thermometer laser.

Three types of behaviors were identified that appear to be linked to different H_2O - T experimental combinations: a) expansion + equilibrium, b) expansion + shrinking and c) expansion + fragmentation. This presentation will present a detailed description of the phenomenological traits of each of these behavioral categories.

The 2013 and 2015 eruptions of Lascar volcano, Chile

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Lascar (23°22' S, 67° 44' W, 5592 m) is the most active volcano in the north of Chile. It is located close to the touristic city San Pedro de Atacama (68 km) and every day groups of tourist climb to the volcanoes' summit.

On February 2013 Lascar increased the seismic activity and this behavior was kept for the next seven months. During this period a weak eruption was reported by OVDAS (Volcanic Observatory of South Andes) on 3 April 2013 where our monitoring cameras showed an ash and gas plume ejecting into the atmosphere. This episode was kept for less than one hour and its maximum height estimated was 320 m above the crater. No seismic signal was recorded during this particular eruption, showing the risk of spontaneous explosions threatening mountaineers at Lascar. A very similar eruption occurred again in 2015, once more without clear precursory activity and with very limited amount or even absence of juvenile material erupted.

Analyzing the brightness changes of the gas and eruption plume in fixed installed time lapse camera data, we are able to identify periods of constant degassing and the occurrence of spontaneous explosions. The four days preceding the explosions show no significant fluctuations in pixel brightness, underlining that the explosions were spontaneous, possibly phreatic in origin. A systematic behavior is observed in a longer time period that cover 2 months of camera images, where in general the month before to eruption, pixel brightness recorded in the plume is generally higher than in the month after the explosion. We compare these result to seismic data in order to understand which type of events are related to each period of degassing cycle and determine if precursory activity can be identified more clearly.

Transport of Volcanic Emissions Using an Adaptive Semi-lagrangian Advection

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In the aftermath of the eruption of Eyjafjallajökull in 2010 a considerable effort went into improving and testing models for the dispersion of volcanic emission in the atmosphere. Those model calculations were mainly carried out on uniformly spaced grids using either an Eulerian or Lagrangian formulation for the transport of volcanic emissions. For a recent review on volcanic emissions see Folch (2012, doi:10.1016/j.jvolgeores. 2012.05.020).

One of the main problems of these uniform Eulerian models is that in case one does not use an extremely high grid resolution, small filaments of the volcanic cloud cannot be properly resolved. In order to improve resolution while keeping computational cost low, we extended an adaptive semi-Lagrangian transport model (Behrens, 1996, http://dx.doi.org/10.1175/1520-0493(1996)124<2386:AASLAS>2.0.CO;2; Behrens, et al., 2005, doi:10.1016/j.ocemod.2004.06.003) for volcanic emissions including particle sedimentation. For the setup and for model evaluation we used the Mt. Pinatubo eruption 1991, which was one of the largest eruptions in the last century. The advection of particles is driven by an external wind field. We carried out simulations in 2D as well as 3D to study the advection of the Pinatubo cloud. Different models for particle settling have been compared in order to choose the one most applicable to our problem. We found the best results for the transport of the cloud when we included multiple grain sizes into the simulation. We were able to reproduce the general advection of the ash cloud at high local resolution while at the same time computational cost were very small. Difference between the simulation results and reality are mainly due to the uncertainty in input parameters and the pass of Typhoon Yunda, which is not properly resolved in the wind field.

SO_2-flux measurements at Guallatiri volcano, Altiplano, northern Chile using two UV SO_2 cameras

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Sulphur dioxide (SO2) fluxes were measured at Guallatiri volcano using two UV SO2 cameras. Guallatiri (18° 25′ 00′′ S, 69° 5′ 30′′ W, 6.071 m a.s.l.) is situated in the Altiplano in northern Chile, close to the Bolivian border. The measurements were performed during a short-term field trip on two days in November 2014 (21.11.-22.11.2014). The volcano showed a quiescent degassing behaviour from the summit crater and from a fumarolic field situated on the southern flank. The plume was slightly condensed during all measurement times. Both UV cameras were equipped with two interference filters (SO2 on-band / off-band). An internal spectrometer plus optics was used to retrieve time series of SO2 slant-column-densities (SCDs) for the camera calibration (using a DOAS algorithm).

Additionally, a temperature stabilised high performance DOAS instrument was collecting spectra during the camera measurements, sampling with higher frequency compared to the spectrometers embedded in the cameras. The corresponding data are used both for additional camera calibration and to investigate abundances of reactive bromine (BrO) in the plume. The spectral calibration of the individual spectrometers was compared mutually and was furthermore compared with a classical gas-cell calibration.

We will present SO2-flux estimates for Guallatiri during these two days and an inter-comparison of the results retrieved with the two cameras. A preliminary evaluation of the spectral data showed considerably low SO2-SCDs up to 3.5 E+17 cm-2. First SO2-flux estimates were low showing values below 1 kg/s (< 86.4 t/d). We furthermore attempt to estimate SO2-fluxes of the central crater and the fumarolic field separately for suited time windows.

Loss to residential buildings of a re-eruption of the Laacher See Volcano

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We estimate damage and loss to the residential building stock by tephra fallout for a re-eruption of the Laacher See Volcano in Germany with similar volcanological features as compared to the 10.900 BC eruption (VEI = 6) but current population and wind conditions.

This eruption was the largest eruption north of the Alps since the Late Quaternary. It generated several fallout fans with proximal deposits of several meters of height. The main cities that would be affected today are Cologne, Bonn, Koblenz and Frankfurt with a total population of 2,2 mio.

people. We derive possible wind fields from an analysis of 44 years of radiosonde observations provided by the Deutsche Wetterdienst (DWD). As they vary significantly with season the loss numbers and patterns reflect this dependency. We use the HAZMAP software to calculate the spatial distribution of tephra. HAZMAP simulates the tephra distribution using a 2D advection-diffusion-sedimentation model. The tephra pressure serves as hazard parameter that leads to roof and building damage. As the physical parameter for snowload damage is also pressure we utilize the available knowledge on snowload damage to buildings and derive vulnerability curves that are representative within a geocell of 1 x 1 km. Available information on the replacement values in each geocell allows estimating the loss. We find – depended on wind conditions - a range of 18 to 27 billion 2015-Euros.

A closer look at the strombolian eruptions pulses using different CFD modeling cases of ascending gas slugs

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Strombolian eruptions are characterized by short duration eruptions, triggered by ascending and finally bursting gas bubbles, also called gas slugs, at the magma surface. Recent observations suggests that a single eruption consists of several separate pulses. These pulses occur in close and regular intervals on the order of seconds.

In order to better understand the processes at work during ascend and slug burst we carried out systematic CFD-calculations using the commercial package FLOW3D. The first step was to build a simple model to simulate an ascending gas slug in a vertical conduit filled with magma consisting of constant density and viscosity. We carefully tested various grid sizes and time steps as well as different solvers to verify the numerical results and we compared them with an analytical solution of James et al. (2008, doi: 10.1144/SP307.9). Following this exercise we examined various simulations cases of an ascending gas slug in order to obtain individual pulses. For example, a narrowing of the conduit which favors the slug distribution, multiple ascending bubbles that interact with one another during the ascent, a viscous plug at the magma surface and an inclined conduit were explored. Selected different results will be presented on the paper.

Magmatic Degassing: Continuous and Episodic

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Any magma reaching fluid oversaturation is prone to degassing. Following the first bubble nucleation and growth (vesiculation) at depth, the early magmatic fluid phase typically occurs as a multitude of fluid droplets dispersed throughout the magma body, thus inducing changes in density, rheology and chemistry of the magma. Depending on magma composition, dissolved volatile contents and pressure, chemical species compatible in the magmatic fluid rapidly partition into the droplets, and therefore get depleted in the coexisting magma. Fluid geochemistry data can thus be used to identify magmatic processes at depth. Deep crustal degassing is typically addressed by the analysis of melt and fluid inclusions in minerals, and shallower events can be traced through the chemistry of volcanic gases and fluids sampled or measured at or close to the Earth´s surface.

The solubility of the major volatile species H_2O and CO_2 are strongly pressure dependent, and the degassing efficiency of trace compounds like SO_2 and halogen species are related to fluid chemistry and redox state. Thus magmatic volatiles change their composition through fractionation in the course of degassing.

Magmatic degassing occurs on several time scales, and can be classified as semi-continuous (also called quiescent), pre-eruptive and eruptive degassing, which all show different characteristic behavior. Last but not least, degassing plays a major role as eruption trigger.

Application of bistatic TanDEM-X Interferometry at Shiveluch volcano, Kamchatka

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Shiveluch volcano is one of the largest and most active volcanoes on Kamchatka Peninsula. Since the last Plinian eruption in 1964, the activity of Shiveluch is characterized by periods of dome growth and explosive eruptions. The recent active phase began in 1999 and continues until today. Due to present circumstances at active volcanoes, such as smoke development, danger of explosions or lava flows, as well as poor weather conditions and inaccessible area, it is difficult to observe the interaction between dome growth, dome destruction, and explosive eruptions in regular intervals. Consequently, a reconstruction of the eruption processes is hardly possible, though important for a better understanding of the eruption mechanism as well as for hazard forecast and risk assessment.

A new approach is given by the bistatic radar data acquired by the TanDEM-X satellite mission. This mission is composed of two nearly identical satellites, TerraSAR-X and TanDEM-X, flying in a close helix formation. On one hand, the radar signals penetrate clouds and partially vegetation and snow considering the average wavelength of about 3.1 cm. On the other hand, in comparison with conventional InSAR methods, the bistatic radar mode has the advantage that there are no difficulties due to temporal decorrelation. By interferometric evaluation of the simultaneously recorded SAR images it is possible to calculate high-resolution digital elevation models (DEMs) of Shiveluch volcano and its surroundings. Furthermore, the short recurrence intervals of 11 days allows to generate time series of DEMs, with which finally volumetric changes of the dome and lava flows can be determined.

Here, this method is used at Shiveluch volcano with data from June 2011 to September 2014. Although Shiveluch has a fissured topography with steep slopes, the changes caused by volcanic activity can successfully be derived and quantified.

Monitoring volcanic SO_2 emissions using GOME-2/Metop-A & -B

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SO_2 emissions are a good indicator for volcanic activity, since besides weak anthropogenic emissions there are no other known sources for atmospheric SO_2. Furthermore it can be a proxy for the much harder to detect volcanic ash, which can be hazardous not only for the local population but also for aviation.

Under the leadership of IMF, DLR-EOC provides operational trace gas measurements, including total SO_2 columns, in near-real-time (i.e., within 2 hours of recording) in the framework of EUMETSAT's Satellite Application Facility on Ozone and Atmospheric Chemistry Monitoring (O3M-SAF). After the launch of the Sentinel-5 Precursor mission, DLR-EOC will also provide near-real-time total SO_2 columns based on data from the TROPOMI instrument.

We will present here latest results of recent volcanic eruptions detected by GOME-2 aboard MetOp-A & -B as well as latest updates and developments of our operational GOME-2 SO_2 retrieval.

Cotopaxi volcano's unrest and eruptive activity in 2015

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Cotopaxi volcano (5,897 m) is located 50 km south of Quito. The most dangerous hazards of this volcano are the devastating lahars that can be generated by the melting of its ice cap during pyroclastic flow-forming eruptions.

After 73 years of quiescence, the first sign of unrest was a progressive increase in the amplitude of transient seismic events in April 2015. Since May 20 an increase in SO2 emissions was detected followed by the appearance of seismic tremor on June 4. Both SO2 emissions of up to 5 kt/day and seismic tremor were observed until August 14 when a swarm of volcano-tectonic earthquakes preceded the first phreatic explosions. These explosions produced ash and gas columns reaching up to 9 km above the crater. The ash fall produced by the opening phase covered over 500 km2 with a submillimetric deposit corresponding to a mass of 1.65*108 kg (VEI 1). During this period of explosions, SO2 emission rates up to 24 kt/day were observed. The ash was dominantly hydrothermally altered and oxidized lithic fragments, hydrothermal minerals (alunite, gypsum), free crystals of plagioclase and pyroxenes, and little juvenile material.

Unrest continued after August 14, with three episodes of ash emission. However, the intensity of ash fallout, average seismic amplitude, and SO2 emissions during each successive episode progressively decreased, while juvenile component increased. Total ash fallout mass since August 14 yield 1.19*109 kg. During these episodes BrO and HCl were detected in the plume, and airborne Multi-GAS measurements showed that the plume had a CO2/SO2 ratio of 1 to 2.5 and that SO2 was >99% of total sulfur (SO2 + H2S), indicating a shallow magmatic origin for the gas. Temperatures up to 200°C were measured in the column. Since late November 2015, surface activity and the other monitored parameters have shown a marked decrease.

Strombolian eruption dynamics: insight from small scale experiments and Stromboli, Yasur and Mt. Erebus

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Most of the commonly used models to simulate volcanic eruptions assume a steady state or a stationary mass flux for the input of mixtures of ash and gases into the atmosphere. Here we review Doppler radar retrieved tephra velocities from 2 small scale experiments as well as 3 different volcanoes (Mt. Erebus, Yasur volcano, Stromboli volcano) spanning a wide range of compositions and typical eruptive activity. In the Waakiki experiments (in collaboration with the LMU Munich, U. Küppers) and in Würzburg (in collaboration with B. Zimanowski) the release of volcanic ash was achieved either by fragmenting material in a shock tube (Waakiki) or by accelerating ash through the release of highly pressured gas (Würzburg). Both experiments show very similar behavior in terms of the eruption velocity. Furthermore the so called h-value (Alatorre-Ibargüengoitia et al., 2010, doi:10.1016/j.epsl.2009.12.051; 2011, doi:10.1016/j.epsl.2010.11.045) seems to represent the size (length) of the pressurized volume.

Mt. Erebus – being the simplest volcanic system we looked at – provided a direct view onto the magma surface and reveals mainly 2 types of eruptions: (I) a straight acceleration of the magma surface, and (II) two acceleration phases (Gerst et al., 2013, doi:10.1002/jgrb.50234). At Yasur and Stromboli volcano eruptions occur in pulses and vary between ash rich and ash free explosions. Pulse frequencies are dependent on the eruptive regime. The intriguing observation is that in case of a direct view onto the magma surface we do not observe pulses, while when the source of the eruption surface is not visible, and gas and tephra are transported an unknown length through a conduit, the eruptive regime is quite often pulsed. Different models to explain this behavior as well as the importance of the h-value will be discussed.

From the lithosphere to the atmosphere: modeling the physical chemistry of volcanic eruption plumes

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Volcanic eruptions connect the Earth's interior, i.e. lithosphere, to its exterior components, i.e. atmosphere, biosphere and hydrosphere. Physical and chemical characteristics of the volcanic ejecta can therefore be used not only to decipher the source conditions and subsurface processes but also to demonstrate the potential impacts of the erupted material upon the environment and climate system. The chemical processing within the eruption plume and cloud significantly affects these properties. For instance, iron and sulfur oxidation state in the volcanic ash and gas do not necessarily mirror the source conditions; they rather replicate the history of high- and low-temperature gas-ash-aerosols interactions in volcanic plume and cloud, especially when the samples are taken at far distances from the volcano. Therefore, to comprehend the remarkable connection between the source conditions and the climatic impacts of major volcanic eruptions, it is necessary to quantitatively constrain the role of in-plume and in-cloud processing.

Here, we present a numerical model that simulates the gas-ash-aerosols interactions in volcanic plumes and clouds. It deploys a chemical mechanism that considers gaseous and aqueous chemistry as well as the gas-aerosol partitioning. The model structure and the preliminary results are presented. The potential application of the model in volcanology, geochemistry and atmospheric sciences are shown.

Determining volcanic SO2 plume heights in satellite observations using meteorological wind fields

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Satellite observations nowadays provide the global monitoring of volcanic plumes via observations of sulphur dioxide (SO2) that is injected into the Earth's atmosphere. In turn, SO2 may lead to the formation of sulphate aerosols that can influence climate via direct and indirect radiative effects. The evolution of volcanic emission plumes depends strongly on altitude. Also the retrieval of SO2 from satellite observations requires an accurate plume height estimate in order to constrain total amounts for such events.

For example, passive satellite measurements in the UV/vis spectral range offer the opportunity to observe the location and horizontal dimension of a plume, but information about the corresponding height is sparse.

Here, we present first results of volcanic plume heights determined from HYbrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) simulations in combination with SO_2 data as observed by the second generation Global Ozone Monitoring Instrument (GOME-2). The main plume information that can be retrieved by the satellite is the horizontal plume location and observation time. We use this information as initial input parameters for the calculation of back-trajectories, which allows us to estimate both the plume's profile at the time of the satellite measurements and at the volcano. In addition, information about the eruption time can be derived. We apply the algorithm to selected case studies and investigate the sensitivity of the derived results to different choices of the algorithm details (e.g. use of forward and/or backward trajectories).

The influence of crystal size distributions (CSD) on the rheology of magma: new insights from analogue experiments

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Knowing the flow properties, or *rheology*, of magma is of great importance for volcanological research. It is vital for understanding eruptive and depositional features, modelling magma flow rates and distances, interpreting pre-eruptive volcanic unrest and earthquakes, and ultimately predicting volcanic hazards related to magma motion. Despite its key role in governing volcanic processes, magma rheology is extremely difficult to constrain in time and space within a natural volcanic system. The challenge stems from the fact that rheology is dependent upon so many variables like temperature, pressure, composition, deformation rate, suspended particles or bubbles, which also change with time. Therefore, both analogue and experimental studies of permissible yet simplified scenarios are needed to isolate different rheological influences. Despite significant progress in understanding the rheological properties of silicate melts and two-phase mixtures (e.g., melt+crystals), as well as the impact of the volume fraction and shape of crystals on magma rheology, the effect of the **crystal size distribution (CSD)** is still poorly constrained. A highly disperse CSD (i.e., a great variety of different crystal sizes) leads to a much more efficient packing of crystals in a flowing magma. In a sheared particle suspension it is, however, precisely the packing arrangement and the resulting particle interactions that predominantly controls the rheological behavior. Accounting for, or neglecting, the size distribution of crystals can therefore make a considerable difference in magma flow models. We present the results of systematic rheometric experiments using multimodal analogue particle suspensions of well-defined size fractions as magma analogue material. Starting with simple bimodal distributions (i.e. particles of two distinct sizes), the complexity of the samples' PSD will be successively increased towards multimodal distributions (multiple size fractions), and Gaussian distributions with varying variance ('broadness') and skewness ('tailed distributions').

Environmentally-mediated ash aggregate formation: example from Tungurahua volcano, Ecuador

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Volcanic ash is generated during explosive eruptions through an array of different processes; it can be produced in large quantities and can, in some circumstances, have the potential for far-reaching impacts beyond the flanks of the volcano. Aggregation of ash particles can significantly impact the dispersal within the atmosphere, and its subsequent deposition into terrestrial or aquatic environments. However, our understanding of the complex interplay of the boundary conditions which permit aggregation to occur remain incomplete.

Tungurahua volcano, Ecuador, has been intermittently active since 1999. In August 2006, a series of pyroclastic density currents (PDC) were generated during a series of dry, Vulcanian explosions and travelled down the western and northern flanks of the volcano. In some locations, the related PDC deposits temporarily dammed the Chambo river, and the residual heat within those deposits produced vigorous steam plumes. During several field campaigns (2009-2015), we mapped, sampled, and analysed the related deposits. At the base of the Rea ravine, a large delta fan of PDC deposits had dammed the river over a length of several hundred metres. In several outcrops adjacent to the river and in small erosional gullies we found a peculiar stratigraphic layer (up to ten centimetres thick) at the top of the PDC deposits. As this layer is capped by a thin fall unit of coarse ash that we also find elsewhere at the top of the August 2006 deposits, the primary nature is without doubt. In this unit, we observed abundant ash aggregates up to eight millimetres in diameter within a poorly sorted, ash-depleted lapilli tuff, primarily comprised of rounded pumiceous and scoriaceous clasts of similar size.

Leaching experiments have shown that these aggregates contain several hundred ppm of soluble sulphate and chloride salts. Recent laboratory experiments (Mueller et al. 2015) have suggested that in order for accretionary lapilli to be preserved within ash deposits likely requires a combination of sufficient humidity and a pre-existing soluble salt load on aggregating ash particles. We suggest that steam pluming from the dammed Chambo river, coupled with soluble salts emplaced by gas-ash interactions between ejection and deposition, provided a unique opportunity for the formation of accretionary lapilli with sufficient mechanical strength to survive deposition, accounting for their presence in a deposit otherwise absent of such aggregates. This possibility provides an important reminder of the role played by external environmental triggers in shaping the properties volcanic ash deposits.

Internal structure and chemical characterization of accretionary lapilli from Stromboli Island (Aeolian Archipelago, Italy)

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Stromboli is considered as one of the most eruptive volcanoes in Italy. Regarding the last 6 ka the Secche di Lazzaro (SDL) activity is known as the most powerful activity. Its pyroclastic material is the result of a phreatomagmatic explosive eruption that formed by the last major volcanotectonic collapse during the final stage of Neostromboli activity. The collapse has lead to the present Sciara del Fuoco scar, wherein the present day activity is confined. We studied the accretionary lapilli of the SDL that are exposed in the south-west slope of the Stromboli Island. Here, we present 3D X-ray micro-tomography images (X-mCT) to discriminate the particle and grain-size distribution and their spatial distribution within the accretionary lapilli. Further, we performed chemical analysis via electron microprobe and laser ablation inductively coupled plasma mass spectrometry of phenocrysts and glasses. On the one hand, compared to present-day mineral chemistry, plagioclase, clinoproxene and olivine compositions are similar, $An_{\leq 89}$, Mg# = 0.59-0.89 and Fo_{64-69}, respectively. Moreover, Fe-Ti-Oxides of the titanohematite series were identified. On the other hand, the glassy groundmass exhibits a much higher silica content than glass compositions of the last 100 years. The present eruptions are mainly basaltic-andesitic, whereas in this study the chemical composition ranges from latite to trachyte (55.6-64.8 wt.% SiO_2). They belong to the potassic series, moreover, the samples have the highest K_2O values (4.4-9.5 wt.% K_2O) ever measured on Strombolian rocks. Finally, accretionary lapilli of the SDL activity are a very convenient deposit to study ash particles of past phreatomagmatic eruptions are preserved from erosion and weathering over a long time. 3D micro-tomography helps us to understand the spatial distribution of the components. Glasses compositions are well conserved and work as a fingerprint of the pre-eruptive processes of the last most violent eruption of Stromboli Island.

The KISS Project Seismological Network monitors Central Kamchatka's volcanoes

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In a joint initiative of GFZ with Russian (IPGG, IVS, KGBS) and a French partner (IPGP) a temporary seismological network has been installed around the Klyuchevskoy volcanic group in Central Kamchatka. The Klyuchevskoy volcanic group is an ensemble of 13 stratovolcanoes with very different compositions and eruption styles in a ~70km diameter area which produced at least 30 VEI≥2 episodes during the last 15 years. Last activity of the highest volcano Klyuchevskoy (4754 m) was in spring 2015. The group is located right on the triple junction between Asian, Pacifc and North American plates where the Hawaiian-Emperor seamount chain separates the Aleutian and the Kuril-Kamchatka trenches. The complex setting presumably leads to processes like increased melting at slab edges and/or accelerated mantle flow which affect the volcanism and might be responsible for the unparalleled concentration of volcanic activity in the Klyuchevskoy group.

Due to the difficult field conditions and special permitting regulations seismological investigations have been rare in Kamchatka. In this consortium we build strongly on the experience of the Kamchatkan partners for permitting and logistics. Installation was about 50% by helicopter. Funding comes via a grant from the Russian Science Foundation to the IVS/KBGS/IPGG, the GFZ, and the IPGP. 60 of the stations were provided by the GFZ instrument pool GIPP. Including the permanent stations operated by KGBS and temporary stations provided by the partners, the network consist of 98 stations and will record earthquake events over one year in an area of approximately 100 by 100km.

With the data collected in summer next year the seismic activity and the subsurface structure of the Klyuchevskoy complex will be investigated. Of major interest are interconnections between the magmatic systems of the closely spaces volcanoes in the group that — taken together — extend over an area of super-volcano size.

How the differential load induced by normal fault scarps controls the distribution of monogenic volcanism

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Understanding shallow magma transfer and the related vent distribution is crucial for volcanic hazard. In the present study we investigate the link between the stress induced by topographic scarps and the distribution of monogenic volcanoes at divergent plate boundaries. With a numerical models of dyke propagation we show that vertical dykes beneath a fault scarp tend to deflect towards the footwall side of the scarp. This effect increases with the scarp height, is stronger for dykes propagating underneath the hanging wall side, and decreases with the distance from the scarp. A comparison to the East African Rift System, Afar and Iceland shows that: 1) the inner rift structure, which shapes the topography, controls shallow dyke propagation; 2) differential loading due to mass redistribution affects magma propagation over a broad scale range (100–105 m). Our results find application to any volcanic field with tectonics- or erosion-induced topographic variations.

Geomorphology at the 2014 Holuhraun eruptive fissure

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Accompanied by an intense seismic swarm in August 2014 a dike laterally formed, starting under Icelands Vatnajökull glacier, propagating over a distance of more than 45 km within only two weeks, leading to the largest eruption by volume since the 1783-84 Laki eruption. Along its propagation path, the dike caused intense surface displacements up to meters. Based on Seismicity, GPS and InSAR the propagation has already been analysed and described as segmented lateral dike growth (Sigmundsson et al., 2015 in Nature). We now focus on few smaller regions of the dike. We consider the Terrasar-X tandem digital elevation map and find localized zones where structural fissures form and curve. At these localized regions we performed a field work in summer 2015, applying the close range remote sensing techniques Structure from Motion (SfM) and Terrestrial Laser Scanning (TLS). Over 4 TLS scan were collected, along with over 5,000 aerial images. The aim is to analyse the structural expression of the fissure eruption at the surface and try to understand conditions that influenced the magma propagation path. We will study the connection of the surface structures to the underlying dike intrusion. Preliminary results show that an unprecedentedly high resolution digital elevation map could be constructed. Point clouds from SfM and TLS are merged and compared, and local structural lineaments analysed.

Experimental aggregation of volcanic ash: the role of liquid bonding

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Explosive volcanic eruptions may release vast quantities of ash. Because of its size, it has the greatest dispersal potential and can be distributed globally. Ash may pose severe risks for 1) air traffic, 2) human and animal health, 3) agriculture and 4) infrastructure. Such ash particles can however cluster and form ash aggregates that range in size from millimeters to centimeters. During their growth, weight and aerodynamic properties change. This leads to significantly changed transport and settling behavior. The physico-chemical processes involved in aggregation are quantitatively poorly constrained.
We have performed laboratory ash aggregation experiments using the *ProCell Lab System*® of Glatt Ingenieurtechnik GmbH. Solid particles are set into motion in a fluidized bed over a range of well-controlled boundary conditions (e.g., air flow rate, gas temperature, humidity, liquid composition). In this manner we simulate the variable gas-particle flow conditions expected in eruption plumes and pyroclastic density currents.
We have used 1) soda-lime glass beads as an analogue material and 2) natural volcanic ash from Laacher See Volcano (Germany). In order to influence form, size, stability and the production rate of aggregates, a range of experimental conditions (e.g., particle concentration, degree of turbulence, temperature and moisture in the process chamber and the composition of the liquid phase) have been employed. We have successfully reproduced several features of natural ash aggregates, including round, internally structured ash pellets up to 3 mm in diameter. These experimental results help to constrain the boundary conditions required for the generation of spherical, internally-structured ash aggregates that survive deposition and are preserved in the volcanological record. These results should also serve as input parameters for models of ash transport and ash mass distribution.

Diffusive over-hydration of melt inclusions

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Melt inclusions trapped in primitive crystals during early phases of magmatic evolution are appealing targets for determining the pre-eruptive volatile content of magmas. However, interpreting the volatile content of melt inclusions can be complicated by a range of pre-entrapment and post-entrapment processes. Using three suites of naturally quenched melt inclusions from Eastern Volcanic Zone of Iceland (Laki, Skuggafjöll and the 10 ka Grímsvötn tephra series) we demonstrate that primitive olivine- and plagioclase-hosted melt inclusions can experience significant diffusive gain of H^+ shortly before eruption as a result of magma mixing, a process we refer to as diffusive over-hydration. Furthermore, melt inclusions that experienced insulated surface transport prior to quenching in lava selvages underwent significant diffusive loss of H^+. Melt inclusion H_2O contents must therefore be considered within a framework of diffusive exchange and are not closed systems with respect to H^+ and thus H_2O. Nevertheless, subglacially quenched matrix glasses and rapidly quenched melt inclusions can record the final pre-eruptive H_2O content of magmas, even if information about their original H_2O contents has been overprinted. Moreover, by modelling the diffusive gain and loss of H^+ through host crystals it is possible to place constrains on magma mixing and lava transport timescales.

Volcano seismology in a wider volcanological context

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Seismic and infrasonic monitoring of active and dormant volcanoes is the key element of any monitoring program undertaken by volcano observatories or research institutions. Major advances in volcano seismology have been made in recent years allowing us to identify several categories of volcanic seismic events, and interpret them in terms of different magmatic or tectonic processes encountered on a volcano. Attempts based on multi-disciplinary methodologies turned out to be particularly successful. This talk is dedicated to latest developments in volcano seismological monitoring techniques, interpretation and modelling methodology in a wider volcanological context.

Evaluation of eruptive energy of pyroclastic fall deposits by using fractal theory

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Particles size distributions (PSD) of pyroclastic fall deposits carried fundamental information regarding the mechanisms generating explosive eruptions. The principles of fractal theory were applied in several studies and it has been demonstrated that fractal dimension on PSD could be used as a proxy for estimating volcanic explosivity. The methodology proposed here is based on two different techniques for determining the grain-size distribution of samples: the first, manually, by dry sieving (particles larger than 297µm), and the second, automatically, via a CamSizer-P4®, that measure the distribution of projected area and obtain a cumulative distribution based on volume fraction for particles up to 30mm. The size distributions data has been analyzed using the fractal theory, hence D_f, the fractal dimension of fragmentation, has been calculated for each sample. Matching the results from manual and automated techniques will give us a value for the “fragmentation energy” of explosive eruptive events. In order to test our protocol we applied it to the Cretaio eruption, Ischia island, Italy. PSD analyses were performed on ten samples corresponding to ten different pulses during the eruption. Samples were divided in juvenile fraction, (JV) and lithic fraction, (LC). Each fraction was analyzed separately. The results for the investigated size range (300µm to 3mm) showed that the fragmentation process is well characterized by a fractal law, exhibiting a multi-fractal behavior that can be explained by different and sequential processes of fragmentation. The results demonstrate that fractal statistics is a possible tool for addressing volcanic risk based on the analyses of PSD directly on natural samples. In the future, the ultimate goal is to standardize and validate this protocol on several deposits from different volcanoes.

Keywords: volcanic fragmentation; fractal dimension of fragmentation, multifractal behavior, sequential fragmentation.

Linking bubble size with the governing parameters of a volcanic jet

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A volcanic jet is generated when a gaseous bubble reaches the magma surface. We study the discharge of fluid from the pressurised bubble into the atmosphere. The governing parameters of the compressible starting jet are the nozzle pressure ratio, the Reynolds number and the non-dimensional mass supply. We focus here on the relationship between the nozzle pressure ratio and the Reynolds number with the non-dimensional mass supply in order to characterise the bubble size that originated the volcanic eruptions under study. We simulated a compressible starting jet and identified its governing parameters by solving numerically the compressible Navier-Stokes equations. We estimated the governing parameters of the volcanic jet from acoustic measurements and by linking the governing parameters with visual records from the eruption. We computed the bubble size from the governing parameters with the help of the continuity equation and identified the relationship between the governing parameters of a starting volcanic jet with the bubble size, which is basically the volume of the bubble. If the characteristic length of the bubble is much smaller than that of the nozzle, it has typically a spherical form, but if the characteristic length is much larger than that of the nozzle, the bubble has typically a cylindrical form. The shape of the bubble affects the eruption, leading to a longer or shorter duration. Our results provide a way to estimate the governing parameters of the starting volcanic jets, leading also to a prediction of the bubble size that generated the eruption. This study will improve the real-time monitoring of volcanoes by evaluating the bubble size as the critical variable and will help the characterisation of volcanoes since we describe the circumstances that led to a determinate eruption.

Satellite observations and EMAC model calculations of sulfate aerosols from Kilauea: a study on aerosol formation, processing, and loss

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The currently most active volcano on Earth is Mount Kilauea on Hawaii, as it has been in a state of continuous eruption since 1983. The opening of a new vent in March 2008 caused half a year of strongly increased SO2 emissions, which in turn led to the formation of a sulfate plume with an extent of at least two thousand kilometers. The plume could be clearly identified from satellite measurements from March to November, 2008. The steady trade winds in the region and the lack of interfering sources previously allowed us to determine the life time of SO2 from Kilauea using only satellite-based measurements (no a priori or model information). The current investigation focuses on sulfate aerosols: their formation, processing and subsequent loss. Using space-based aerosol measurements by MODIS, we study the evolution of aerosol optical depth, which first increases as a function of distance from the volcano due to aerosol formation from SO2 oxidation, and subsequently decreases as aerosols are deposited to the surface. The outcome is compared to results from calculations using the EMAC (ECHAM/MESSy Atmospheric Chemistry) model to test the state of understanding of the sulfate aerosol life cycle. For this comparison, a particular focus is on the role of clouds and wet removal processes.

Monitoring of active volcanoes by means of multi-sensor remote sensing – a case study of the 2014/15 Holuhraun fissure eruption

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The Holuhraun fissure eruption in 2014/15 is one of the largest volcanic events in modern Icelandic history. The fissure eruption is a dike intrusion that originated from the Bardarbunga Volcano.

In this contribution a combined analysis of multi-sensor remote sensing data monitoring this large volcanic eruption is presented. SO_2 and BrO total columns are retrieved from the ultraviolet spectrometer GOME-2 onboard the polar satellites MetOp-A and -B. The sensor measures Earthshine reflectances from nadir-view scans on a daily basis. The atmospheric trace gas retrieval is operationally performed in near-real time (i.e. within 2 hours after measurement) based on the differential optical absorption spectroscopy (DOAS) method in the UV wavelength range. BrO and especially SO_2 emissions showed a strong increase when the fissure first erupted in late August 2014.
The comparison with Earth Observation satellite imagery of higher spatial resolution showed a strong correlation between the area covered by lava and the amount of SO_2 emission. A time series of synthetic aperture radar (SAR) imagery acquired by Sentinel-1 and TerraSAR-X as well as a dataset of Landsat-8 daytime acquisitions was used to monitor the temporal evolution of the lava extent. In addition, very high spatial resolution optical imagery of WorldView-2 and -3 were used for very detailed investigations of the spatio-temporal evolution of the lava extent.
Monitoring the hot spot development, datasets of the MODIS fire product have been used and nighttime acquisitions of Landsat-8 as well as imagery of the first satellite of DLR's FireBIRD mission (TET-1 – Technology Experiment Carrier) were exploited to measure the temperature of the lava over time. The mid-wave infrared channel of TET is ideal for the detection of high temperature events. By additionally interpreting the long-wave infrared channel of TET, it is possible to estimate the kinetic temperature and area of high temperature events simultaneously

Quantitative Imaging of Volcanic Plumes – Recent Developments and Future Trends

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Recently developed remote sensing techniques allow two-dimensional and three-dimensional imaging of trace gas distributions in volcanic plumes in real time. In contrast to older, one-dimensional remote sensing techniques that are only capable of measuring total column densities, these new imaging methods give a new level of insight into details of transport- and mixing processes as well as chemical transformation within plumes.
We give an overview of gas imaging techniques already being

applied at volcanoes (SO_2 cameras, imaging DOAS, Fabry-Pérot Imaging, FT-IR imaging), present techniques where first field experiments were conducted (LED-LIDAR, tomographic mapping), and describe some techniques where only theoretical studies with application to volcanology exist (e.g. Gas Correlation Spectroscopy, bi-static LIDAR). We present the basic physics of the above techniques and derive capabilities and limitations.

Finally, we discuss current needs and future trends in imaging technology for volcanic applications.

Cross correlation of chemical profiles in minerals: insights into the architecture of magmatic reservoirs

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Analysis of chemical zoning in minerals offers the opportunity to reconstruct the pre-eruptive conditions and temporal evolution of magmatic reservoirs. The chemical composition of minerals is a function of the thermodynamic conditions of the reservoir from which they grow and therefore minerals record the evolution of residual melt chemistry and intensive parameters within the magmatic system. A quantitative approach is required to determine on a statistically significant base the relative proportions of crystals that recorded similar variations of the thermodynamic environment in which they grew. We present a modified version of a numerical method, which compares the zonation pattern of minerals to identify if they share the totality or part of their growth history, initially developed by Wallace and Bergantz (2004). This modified version allows us to compare minerals also collected in different outcrops.
We use a cross-correlation mathematical tool that permits to quantifying the difference between two signals such as a geochemical or grey-scale profile. We first show the results of tests performed on synthetic profiles, and then we will present results of a study performed on cathode-luminescence images of zircons collected on a large ignimbrite (Kilgore Tuff, Heise Volcanic Field, USA).
This analysis shows that this large eruption (2000 km^3; DRE) was fed by distinct pockets of eruptible magma (represented by distinct families of zircon grey-scale zoning profiles) and also that the relative amount of zircons of the different families are present in different relative abundance in outcrops located around the caldera rim.

Coupling geodynamic with thermodynamic modelling for reconstructions of magmatic systems

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Coupling geodynamic with petrological models is fundamental for understanding magmatic systems from the melting source in the mantle to the point of magma crystallization in the upper crust. Most geodynamic codes use very simplified petrological models consisting of a single, fixed, chemistry.

Here, we develop a method to better track the petrological evolution of the source rock and corresponding volcanic and plutonic rocks by combining a geodynamic code with a thermodynamic model for magma generation and evolution (pMELTS), which calculates Density, melt fraction and the composition of the liquid and solid phase in the chemical system: SiO_2-TiO_2-Al_2O_3-Fe_2O_3-Cr_2O_3-FeO-MgO-CaO-Na_2O-K_2O-P_2O_5-H_2O.

The implementation of several melt extraction events take the change in chemistry into account until the solidus is shifted to such high temperatures that the rock cannot be molten anymore under upper mantle conditions. An advantage of this approach is that we can track the change of melt chemistry with time, which can be compared with natural constraints.

In the thermo-mechanical code the informations from pre-computed phase diagrams are carried by each particle using marker-in-cell method. Thus the physical and chemical properties can change locally as a function of previous melt extraction events and P-T conditions. After each melt extraction event, the residual rock composition is compared with the bulk composition of previous computed phase diagrams, so that the used phase diagram is replaced by the phase diagram with the closest bulk chemistry. The melt is extracted directly to the surface as volcanites and within the crust as plutonites.

We have investigated the influence of several input parameters on the magma composition to compare it with real rock samples from Eifel (West-Germany).

Halogen speciation in volcanic plumes - Development of compact denuder sampling techniques with in-situ derivatization followed by gas chromatography-mass spectrometry and their application at Mt. Etna, Mt. Nyiragongo and Mt. Nyamulagira in 2015.

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Volcanoes are a large source for several reactive atmospheric trace gases including sulfur and halogen containing species. The detailed knowledge of volcanic plume chemistry can give insights into subsurface processes and can be considered as a useful geochemical tool for monitoring of volcanic activity, especially halogen to sulfur ratios. The reactive bromine species bromine monoxide (BrO) is of particular interest. BrO is formed in the plume by a multiphase reaction mechanism under depletion of ozone in the plume. The abundance of BrO changes as a function of the reaction time and therefore distance from the vent as well as the spatial position in the plume. The precursor substance for the formation of BrO is HBr with Br_2 as an intermediate product. The reaction of HBr to BrO involves heterogeneous reactions involving aerosol particles. Due to the lack of analytical approaches for the speciation of halogens (HBr, Br_2, Br, BrCl, HOBr) there are still uncertainties about the magnitude of volcanic halogen emissions and in particular their species and therefore also in the understanding of the bromine chemistry in volcanic plumes.

In this study a gas diffusion denuder sampling method using a 1,3,5-trimethoxybenzene (1,3,5-TMB) coating for the derivatization of reactive halogen species was characterized by reaction chamber experiments. The coating proved to be suitable to collect selectively gaseous bromine species with oxidation states of +1 or 0 (such as Br_2, BrCl, BrO(H) and $BrONO_2$), while being ignorant to HBr. The method was applied in 2015 on volcanic gas plumes at Mt. Etna (Italy), Mt. Nyiragongo and Mt. Nyamulagira (DR Congo) giving reactive bromine mixing ratios from 0.3 ppb (Nyiragongo) up to 22 ppb (Etna). Compared with total halogen data the reactive bromine mixing ratios allow the investigation of the conversion of HBr into reactive species due to plume chemistry with progressing plume age

First observation of pyroclastic flow dynamics with a Doppler radar

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Beginning in November 2014, Volcán de Colima (Mexico) showed increased activity encompassing pyroclastic flows. Some of these pyroclastic flows traveled down the south flank, directly toward a Doppler radar, which had been deployed 3km from the vent to monitor the volcano's tephra emissions in March 2014. The Doppler radar measures tephra velocities and provides an estimate of the amount of material inside the probed volume (radar beam). Because the radar beam is roughly parallel to the volcano's topography (it follows the terrain at 100-200m height), and the radar was recording activity in 600m long distance intervals along the radar beam (i.e. along the topography), we can infer the flow velocity and approximate run-out distance of individual pyroclastic flows.

The data shown here are the first ground-based remote sensing data of pyroclastic flow dynamics measured at a real volcano in the field.

The Doppler radar was positioned (at least for most of the flows) far enough that pyroclastic flows did not reach it. Unfortunately, Volcán de Colima's activity increased further so that the Doppler radar finally got destroyed in July 2015.

A numerical and analogue study of dike ascent in asymmetric continental rift zones

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In continental rift zones, tectonic extension generates deep topographic depressions, typically graben or half-graben structures, confined by large border faults. Volcanism may be distributed within, at the border and outside of the depressions, and the mechanisms controlling this distribution are debated. Maccaferri et al. (2014) proposed that the reorientation of the principal stresses linked to crustal thinning and crustal mass redistribution in rift zones modifies the expected trajectory of ascending magma pockets. The goal of this study is to investigate the relation between the characteristic distribution of volcanism at the surface, the dike nucleation area, and the observed geometric asymmetry of the grabens at most rift zones. By using a boundary element model for dike propagation and analogue laboratory experiments we evaluate the ascent path of magmatic dikes in asymmetric continental rifts.

We find that the position of the magma source along the cross section of the rift, its spatial extent and the asymmetry of the graben cross section are the most important factors controlling one-sided volcanic activity at surface. For dikes starting beneath the rift's center, the more asymmetric the rift structure the more likely is asymmetric volcanic activity. However, if the position of the magma ponding region is offset towards the deep side of the graben, the dikes tend to emerge on the rift shoulder adjacent to such deep side. To a minor extent, also the starting depth of the dikes, any topographic loading on the graben flanks due to flank uplift and the background tectonic stress impact the surface distribution of volcanism. Mostly, all the latter mechanisms influence the distance between the graben's edge and dike arrival at surface. Our analogue experiments show similar results supporting that the graben geometry and the dike nucleation region are major controls on the surface distribution of volcanism in rifts.

Teleseismic earthquake swarms and local seismicity during volcanic episodes at ultraslow spreading mid-ocean ridges

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The massive volcanic centres of ultraslow spreading mid-ocean ridges are capable of unusual volcanic eruptions. Mid-ocean ridges spreading slower than 20 mm/y produce little melt and volcanism is discontinuous along-axis. A pronounced along-axis topography of the lithospheric base may guide melts towards the volcanic centres spaced up to 100 km apart where they ascend through a thick and cold lithosphere.

We present two case examples of recent volcanic episodes at locations on Gakkel Ridge and the Southwest Indian Ridge where we installed local seismic networks during and after presumed spreading events.

At 85E on Gakkel Ridge, the strongest known mid-ocean ridge earthquake swarm with more than 200 events including 11 events of M>5 in 1999 marked the onset of an activity period. In 2001, a hydrothermal event plume and widespread volcanic ash on the seafloor were discovered there. Seismometers on ice floes registered the sounds of explosions originating from weak Strombolian-type eruptions. In 2007, the event plume and eruption sounds had disappeared and seismicity was recorded throughout the rift valley at depths up to 15 km.

At the segment-8 volcano on the Southwest Indian Ridge, 18 teleseismic earthquake swarms were detected between 1996 and 2001. A network of 8 ocean bottom seismometers recorded local seismicity from October 2012 until June 2013. The volcano is marked by a circular aseismic area and a low-velocity anomaly identified in seismic tomography, indicating increased temperatures and potentially recent activity.

At both locations, the teleseismic earthquake swarms consist of mostly normal faulting events. There are no signs of hypocentre migration as is typical for mid-ocean ridge swarms. Instead we suggest that complex tectono-magmatic interaction characterises spreading events. The cold thick lithosphere allows stress build-up, that is released in large earthquakes triggered by melt intrusion and melt ascent, in turn, is facilitated by large fault systems.

From mantle to crust: Tomographic image of a mid-ocean ridge volcano

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Volcanoes are an integral part of mid-ocean ridges. At ultraslow spreading ridges, volcanic centres receive more melt than is produced locally and hence are centres of very efficient magmatism. The cause of melt focussing and the structure of the underlying magma plumbing systems at these volcanic centres are still enigmatic. We present microearthquake data and local earthquake tomography results, based on a one-year deployment of ocean bottom seismometers from 2012 to 2013 on a volcanic centre at the ultraslow Southwest Indian Ridge. In the period 1996-2001, several tectono-magmatic earthquake swarms including unusually strong teleseismically recorded events indicated recent magmatic activity at the experiment site. The distribution of recorded microearthquakes reveals a prominent gap in seismicity of approx. 20 km diameter immediately beneath the volcano indicating elevated temperatures. Tomography results show distinct velocity anomalies in the area of the seismicity gap. An eminent circular low *Vs* anomaly was found at 4-6 km depth beneath the volcano, imaging a potential crustal magma chamber. Another anomaly of high *Vp/Vs*-ratios is located at the eastern rim of the seismicity gap, capped by a cluster of microearthquakes and underlain by another low *Vs* anomaly in the upper mantle. We propose anomalies of reduced seismic velocity to result from recent magmatic activity that is further manifested in elevated temperatures beneath the volcano. Clustering microearthquake foci might be associated with steep temperature gradients and thermal fracturing, due to hot upwelling material is confronted with a cold, rigid crust. Our results provide the first direct observation of a melt lens beneath any ultraslow ridge and give unprecedented insights to potential magma pathways from the upper mantle to the crust.

Statistical analysis of the repose intervals at Volcán de Colima

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Volcanic activity is often described as a chaotic and random process with no obvious characteristics. However, statistical analysis and probabilistic methods can be used to find hidden patterns in eruption behaviour and therefore play an important role in volcanic hazard assessment.
Especially the analysis of volcanic repose intervals can be useful to find these patterns.
In our work Doppler radar data was used, which was recorded at Volcán de Colima from May 2014 until the 11th of July in 2015.
Eruption onset times were retrieved for eruptions containing tephra; pure gas emissions cannot be perceived by the radar. In addition, the dynamic of the ash plume and the exit velocity of erupting material can be examined with the acquired data.
In the data set presented here (2014-2015) the number of events remarkably increases from 29 per month (June 2014) up to 23 per day in February 2015.
This leads to the assumption that probably more material is rising from a magma reservoir through the conduit.
Among others we consider the repose intervals between eruptions and try fitting common distributions like Weibull, exponential and log-logistic distributions.
Statistical analysis shows that the repose times from 2014 until 2015 best fit a log-logistic distribution.
This distribution has also been found in other studies on volcanoes and probably indicates the interplay of two competing processes: “for example short duration pressure release within a few seconds through a shallow fracture network against long term (tens of seconds) gas supply from deeper regions.”
With the acquired Doppler radar data and statistical analysis we gain an indirect insight into the mechanism that leads to eruptions.

Understanding the role of magma reservoir processes on the frequency and magnitude of volcanic eruptions

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The frequency of volcanic eruptions is fundamentally related to processes controlling the accumulation of eruptible magma at depth and the pressurisation of the magmatic reservoir. Here we present a combined statistical-empirical approach to link the frequency and magnitude of volcanic eruptions observed in different arcs to important parameters controlling the growth of subvolcanic reservoirs of eruptible magma. Such understanding is important for two reasons; firstly it presents an insight into how and why the frequency of eruptions varies between different groups of volcanoes; and secondly, it provides constraints for models that are used to interpret geochemical and geophysical data. To perform the analysis we further develop an analytical model that uses a Monte Carlo sampling approach to simulate the accumulation and eruption of magmatic reservoirs (Caricchi et al., 2014). By inverting the geological record of volcanic eruptions we can solve the Monte Carlo model to quantify parameters such as magma input and frequency of magma injection. Our results indicate systematic variation in the frequency of eruptions of various magnitudes between exchangeable groups of volcanoes, which can be related to variations of parameters such as average magma fluxes and thickness of the crust.

Caricchi, L., C. Annen, J. Blundy, G. Simpson, and V. Pinel, 2014, Nature Geoscience, v. 7, no. 2, p. 126–130, doi:10.1038/ngeo2041.

Characterization of multi-rotor unmanned aerial vehicles (UAV) for Gas Measurements at Volcanoes: a case study at Mount Etna, Sicily

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In this case study at Mount Etna, Sicily (Italy), in July 2015, we explore the utility of two quad-rotor UAVs (Phantom 2 Vision, V+) and one octo-rotor UAV (S1000+), all three manufactured by DJI. The focus of this campaign was to test the performance of manually controlled multi-rotor UAV platforms in extreme conditions including high wind, high altitude, topographic effects related to over-crater flight, in-crater flight, in-plume flight, low temperatures and payload to perform in-situ volcanic gas measurements.

We used the two “ready-to-fly” Phantom 2 Visions for aerial photo/video documentation. They are rapidly deployed, easily maneuverable, portable and have a long flight time (~20min with 5.2Ah battery) with a stabilized small FHD camera. In contrast to the ease of use of the Phantom copters, the S1000+ is bulkier with a takeoff weight of ~10kg. It was outfitted with a 4K professional camera (Panasonic-GH4) and a sensor package consisting of a self-made multi-gas-sensor for CO_2/SO_2 and a mobile Differential Optical Absorption Spectroscopy system (DOAS). Notably, its power system compromising 16Ah LiPo-batteries (~2,1kg) and high take-off weight left the flight times greatly shortened (<10mins).

Both multi-rotor UAVs demonstrated exceptional flight capabilities in winds ranging from 10-17m/s, highlighting the utility of octo-rotor UAV drones for conducting measurements in both plumes and craters. We found however, that the S1000+ was challenged by many hardware and firmware related troubles, in addition to relative cold temperatures (~9°C) on the summit that greatly shortened battery life. The manual flight (i.e., non-autonomous) mode was used exclusively during this campaign, which furthermore reduced flight longevity because of the pilot's inability to discern the craft's position over the crater. This means that the flight-track for sampling could not well positioned in the plume and the DOAS under-plume traverses where done gently to keep the UAV within the range of vision.

Role of heating rate on the melting dynamic of volcanic ash relevant to aviation hazards

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The recent 2010 eruption of Eyjafjallajökull, Iceland, has reminded all of us of the potential threat and economic loss imposed by the emission of volcanic ash clouds, when across Europe, airlines chose to respect a zero-tolerance policy and all air traffic was grounded. The ingestion of volcanic ash into jet engines is widely recognised as a potentially fatal hazard for aircraft operation. Ash particles ingested in jet engine are subjected to very high temperature (1200-2000 °C) for very short duration. During their course through this extreme environment, particles are heated at very high rate, which may generate a dynamic influence on melting process. To simulate such dynamics and their potential kinetic consequences, we utilize heating microscopy to test the four characteristic geometries corresponding to temperature and time of the Sant Maria and Eyjafjallajökull volcanic ash at normal controlled heating rates (10 °C min^{-1} ≤ 40 °C min^{-1}) and fast heating rates (200 °C min^{-1} ≤ 450 °C min^{-1}), respectively in order to study how the heating rate influences fusion and sticking behaviour and melting kinetics. Our results demonstrate the main characteristic temperatures (that is, deformation temperature (DT), hemispherical temperature (HT), and flow temperature (FT) increase linearly with heating rate from 10 to 40 °C min^{-1} and the corresponding to kinetic time points of these main characteristic temperatures at fast heating rates from 200 to 450 °C min^{-1} also present a remarkable linearity with the function of heating rates. Using this we can estimate the temperature and heating rate window for which different ash may melt and stick in jet engines.

A quantitative analysis of bubble coalescence in basaltic magmas

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The following bachelor thesis studies the coalescence behavior of two air bubbles ranging from a few microliters to 15 milliliters volume during their ascent in a Newtonian fluid. This serves as an analog model for gas bubble coalescence in the conduit of basaltic magmas. The results show a threshold of a few millimeters diameter, below which bubbles do not coalesce with other bubbles. This threshold depends on the volume of the other bubble, the surface tension between the fluid and the gas as well as on the viscosity and density of the fluid. Bubbles larger than the threshold value always coalesce during or after the formation of different bubble complexes to form one big bubble. Depending on the absolute volumes of the bubbles, the coalescence can be delayed by seconds to a few minutes. The results show that after their nucleation, bubbles in basaltic magmas have to grow by diffusion and decompression before they can coalesce with other bubbles.

Graben-structures complexities at Mt. Laki, Iceland, investiged by camera drones and modeling

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Fissure eruptions are often associated with formations of structural lineaments and a tectonic graben. Asymmetrical surface structures formed by the fissure eruption of Laki volcano (Iceland) in 1783/84 are investigated for genesis and development in relation to loading and geometrical effects.
The Laki craters, which form a WSW-ENE oriented row of approximate 140 vents over a distance of 25 km, are accompanied by asymmetrical ruptures close to the fissure. The graben forming ruptures show local complexities that are especially large at Mt. Laki. The dependence of the rupture's form and orientation on dyke-geometry, loading-effects and topography shall be studied here by using camera drones as central working method and stress modeling. Therefore, over 5000 photos, taken in several overflights with two camera drones over the top of Mt. Laki and on the northeastern/southwestern sides, were collected and converted into 3D-models using structure from motion (SFM). Afterwards, offset and orientation of the graben structures have been measured by profiles along and across to the ruptures. The so calculated development of offset and distance to the vents provides a geometric constrain on the orientation and geometry of the underlying dyke. We compared this geometry of surface fractures to simulated fractures. Additionally, stress and strain parameters have been determined and varied by changing in depth and dip of the simulated dyke by using finite element method (FEM).

The results of FEM are then compared to the photo results and provide an overall picture of the formation of the surface structures' local complexities at Mt. Laki and at other sites of the fissure eruption.

Modelling conduit processes using realistic magma rheology: Strombolian volcanism

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The dynamic processes inside the conduit of an active volcano cannot be observed directly. Instead, they have to be inferred from indirect data, e.g. geodetic or seismic recordings, while direct observation is only possible close to the vent using visual or thermal imagery, Doppler radar, infrasound, geochemical analysis etc. In order to interpret these observations with regard to the processes deep within the volcanic conduit, physical models are needed, either analogue or digital ones.

For strombolian activity a popular model assumes that volatiles in degassing basaltic magma coalesce into gas slugs that ascend buoyantly through the conduit. While they rise towards the vent, they get dynamically pressurized until they burst at the surface. Modelling this process requires making assumptions and simplifications on several often badly constrained parameters like the conduit geometry. On the other hand, magma composition, texture, temperature and their pressure/depth-dependence can be modelled quite reliably, so that realistic models of the magma rheology can be constructed.

Magma as a three-phase system of liquid melt, solid crystals and gaseous volatiles exhibits significant non-Newtonian shear-thinning behaviour. Nonetheless, models usually ignore the good data basis and assume a constant Newtonian viscosity.

The results of a non-Newtonian analytical and a CFD model show the importance of a realistic magma rheology: The effective viscosity in the conduit spans about two orders of magnitude, the slug being surrounded by a low-viscosity 'aureole'. The slug is also subject to rapid expansion in the upper conduit leading to a pronounced pre-burst pressure drop. Finally, comparing the two modelling approaches presented here shows the limitations of either of them.

EPOS and the volcanology contributions from Germany

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EPOS is coordinating European research Infrastructures for solid earth science, including e-science, monitoring, and studying dynamic and complex geosystems. EPOS just received funding for the implementation phase. One idea of EPOS is to obtain an efficient and comprehensive multidisciplinary research platform for the Earth sciences in Europe, define transparent use of data, and herewith to obtain a better understanding of the physical processes controlling earthquakes, volcanic eruptions, unrest episodes and tsunamis as well as those driving tectonics and Earth surface dynamics. The working group 2 of EPOS focusses on volcano observations.The main aims of that working group are (i) to optimize the best architecture for the multidisciplinary distributed research infrastructure among the volcano observatories and laboratories, (ii) to guarantee the technical interoperability of the distributed research infrastructures, (iii) to guarantee the adoption of common standards and practices, and (iv) to facilitate the access to data centres and to the use of modelling and processing tools. Therefore, EPOS can be used to foster and coordinate volcano research approaches in Germany, and also allows to speak with one voice to define joints research themes, to talk to decision makers and international partners. Advantage for research in Germany is to improve networks for data, laboratory and method exchange, and to improve student and research interactions amongst different instutions. In this presentation i will provide a brief summary of EPOS, EPOS-Germany and the volcanology organization, and discuss a vision on how interdisciplinary research in German volcanology may gain visibility and productivity.

Variations of the BrO/SO2 ratios from Tungurahua volcano,Ecuador

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The composition of volcanic gas emissions, in particular the ratio of BrO/SO2, can yield information about magmatic processes. The amount and composition of volcanic gas emissions, in particular the molar ratio of BrO/SO2, has shown the potential for interpreting volcanic activity. The potential of long term spectral data collected with UV-scanning spectrometers of the Network for Observation of Volcanic and Atmospheric Change (NOVAC) for determining the BrO/SO2 ratio and its correlation to magmatic processes has been shown at Nevado del Ruiz.

We retrieve the BrO and SO2 column densities at Tungurahua volcano, Ecuador, and present a time series of the BrO/SO2 ratio for several eruptive phases between 2007 and 2014. The variation of the BrO/SO2 ratio during these eruptive phases is compared to seismic data and volcanological phenomenological observations as well as satellite and ground based SO2 measurements. During several eruptive phases we observe an increase in the BrO/SO2 ratio on the transition from high explosive activity to low explosive activity. On such a transition during December 2010 for example we observe an increase of the BrO/SO2 ratio from $5,1*10^{-5}$ and to $8,5*10^{-5}$.

Rhyolite magmas in the Icelandic crust: Insights from experimental petrology

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Petrological experiments have been a successful tool for reconstructing the storage conditions of rhyolitic magmas in arc settings, while studies of this kind are so far lacking for Icelandic volcanoes. However, knowledge about rhyolite magma storage in the Icelandic crust can yield important implications for assessing volcanic hazards, and has recently gained much attention as a promising source for enhanced geothermal energy production.

We carried out experiments on Plinian pumice from the largest eruption of Hekla volcano, and on obsidian from the Krafla caldera in Iceland, in order to clarify where and under which P-T-x state these rhyolitic magmas accumulate.

The Hekla phase equilibria experiments were buffered with cobalt metal, and run under H_2O-saturated conditions. Matching of the experimental and natural phase assemblage, glass chemistry and textures can be used to infer pre-eruptive magma storage conditions. The magma last equilibrated at 130 to 170 MPa, equivalent to a depth of 4.6 - 6.0 km, and at a temperature of about 850°C. These conditions are very different from the currently inferred deep crustal storage zone of more frequently erupted intermediate magmas. Hence, these findings provide valuable implications for the interpretation of monitoring signals at Hekla, as surface deformation and seismicity can be expected to be different from modern day observations, which are related to the deep crustal storage zone.

For Krafla experiments we used the subglacially-emplaced rhyolite dyke Hrafntinnuhryggur as starting material. Its major element bulk composition is nearly identical to the rhyolite magma that flowed into an exploratory geothermal well (IDDP-1) in 2009. Preliminary results show that this material can be used to reproduce the natural phase assemblage of the IDDP-1 magma at 50 MPa and 850°C. Furthermore, augite overgrowth rims on pigeonite, previously speculated to be related to emplacement from depth, can be reproduced under isobaric and isothermal conditions.

Simulation of satellite observations of volcanic hotspots

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Satellite images are an excellent data source for monitoring the heat emission from volcanic hotspots in close to real-time. The evaluation of the hotspot's size and temperature assists the hazard assessment. However, the accurate determination of the hotspot's size and temperature is afflicted with uncertainty as the lava occupies only a small fraction (< 1 %) of a typically resolved target pixel; Landsat has a 30 m and MODIS a 1000 m spatial resolution. Conventionally this is overcome by comparing observations in at least two separate infrared spectral wavebands (Dual-Band method). We investigate the resolution limits, the influence of the hotspot's and background’s temperature on this technique by means of an uniquely designed indoor analog experiment.

The volcanic feature is simulated by an electrical heating alloy of 0.5 mm diameter installed on a plywood panel of high emissivity. Two thermographic cameras record images of the artificial heat source in wavebands comparable to those available from satellite data. In the conducted experiment the pixel fraction of the hotspot was successively reduced by increasing the camera-to-target distance up to 35 m. On the basis of a chosen target pixel, the expected decrease of the hotspot pixel area with distance at a relatively constant wire temperature was confirmed. The deviation of the hotspot's pixel fraction yielded by the Dual-Band method from the theoretically calculated one was found to be within 20 % up until a target distance of 25 m. This means that a reliable estimation of the hotspot size is only possible if the hotspot is larger than about 3 % of the pixel area, a resolution boundary most remotely sensed volcanic hotspots fall below.

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