Book of Abstracts

Physik der Vulkane 2019

Physics of Volcanoes 2019

P o V

Lehrstuhl für Angewandte Botanik und Vulkanbiologie

UNIVERSITÄT DUISBURG ESSEN

DEUTSCHE VULKANOLOGISCHE GESELLSCHAFT

DGG

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Excursion: V. Reppke

Schedule

Physics and Chemistry of magmatic processes and melts: *Thursday morning*

#	time	author	Title
	09.00	Pfanz	INTRODUCTION
		Landrat Saftig Bgm.Lempertz	WORDS OF WELCOME
	Chair	**Hansteen**	
	9:30 -	Friedrichs	Contrasting magma evolutions at Mt. Erciyes and Mt. Hasan stratovolcanoes, Central Anatolia, Turkey
		Allabar	Spontaneous phase separation of hydrous Vesuvius melt even at low decompression rates
		Colombier	Soluble salt concentrations on volcanic ash aggregates from a variety of eruption types and deposits
		Schmitt	Investigation of bromine chemistry in volcanic plumes in smog chamber experiments
		Soldati	Rheological variability of the 2018 Kilauea eruption
6	-11:00	Woith	Fluid migration, fast and slow
			COFFEE BREAK
	Chair	**Walter**	
	11.30 -	Witt	How does lava fountaining and vent morphology influence each other? A case study 2014-2015 Holuhraun fissure eruption
		Zorn	The extrusion of spines during lava dome growth using analogue experiments
		Dahm	Long period volcano-seismic crises offshore Mayotte, Comoros Islands: indications of submarine caldera collapse?
		Dagoy	Surface loading changes as top-down controls on magma reservoir formation
		Plank	Space-based monitoring of the 2015 eruption of Villarrica Volcano, Chile
12	- 13:00	Rummel	Insights into the compositional evolution of crustal magmatic systems from coupled petrological-geodynamical models
			LUNCH BREAK

Volcano hazard and risk mitigation: *Thursday afternoon*

#	time	author	Title
	Chair	**Bobrowski**	
	14:00	D'Alessandro	Gas hazard: an often neglected volcanic hazard
		Einarsson	On the success rate of public warnings based on short-term seismic precursors to Icelandic eruptions
		Neuberg	The role of shear-stress in volcanic systems: a paradigm shift
		Rebscher	Necessity for and Challenges of Long-term Predictions of Volcanic Activity
		Schmid	The effect of vent asymmetry on volcanic jet dynamics
		Berberich	Degassing rhythms and fluctuations of geogenic gases in a red-ant nest, in soil and three mineral springs – Neuwied Basin (East Eifel Volcanic field, Germany)
19	-15.45	Sievers	Volcanic clouds: how aviation deals with them
			COFFEE BREAK and POSTER
	Chair	**Lühr**	
	16.15	Dinger	Analytical approach on the link between the Earth tidal potential and volcanic degassing
		Stern	Role of temperature and water content in the generation of volcanic lightning
		Van Camp	Repeated gravity measurements across the Rhenish massif
		Strecker	Interpreting volcanoes and volcanism: Explosive potential
		Mania	Dome growth during the 2016-2017 eruption sequence at Bezymianny volcano, Kamchatka, measured by high-resolution TerraSAR-X and photogrammetric data
25	17.45	Büchner	The Stolpen volcano in the Lausitz Field – volcanological, petrographic, and geochemical investigations at the type locality of basalt
			POSTER
	19.30		DINNER

Monitoring: *Friday morning*

#	time	author	Title
	Chair	**Platt**	
	8:30 -	De Siena	Imaging source and dynamics of Campi Flegrei unrest in the last 40 years
		Gottschämmer	New insights from long-term seismic, infrasound and thermal measurements at Santiaguito volcano, Guatemala
		Drach	Fluid flow source model for harmonic tremor at Santiaguito volcano, Guatemala
		Rohnacher	Characteristics of central explosions at Santiaguito volcano
		Müller	High resolution mapping of the hot pots and geysers in El Tatio, Chile, reveals Structural and lithological controls on geothermal activity in El Tatio
		Vossen	Electrical monitoring of volcanic plumes: a multi-parametric analysis
		Walter	Imaging the 2013 explosive crater excavation and new dome formation at Volcán de Colima with TerraSAR-X, time-lapse cameras and modelling
33	-10:30	Sesterhenn	Energy-optimized and GPS-synchronized data acquisition system network for volcanic (infra)sound monitoring
			COFFEE BREAK
	Chair	**D`Alessandro**	
	11:00	Thomalla	Dynamics of carbon dioxide exhalations in Eifel and Vogtland mofettes
		Pfanz	Mofette vegetation as a geogenic indicator. The relation between plants and geogenic CO_2 at the banks of the Laacher See/Vulkaneifel
		Ortenzi	Volcanic outgassing and early atmosphere build-up
		Niedermann	Noble gas, carbon and nitrogen isotopes in free gases of the Eifel volcanic area as tracers for a deep plume involvement
		Bräuer	Mantle-derived gases in the European Cenozoic Rift system: A comparison of gas signatures in the Eifel area with those in the French Massif Central and NW Bohemia
		Klügel	Magma plumbing at the Quaternary Emmelberg volcano (West Eifel volcanic field)
		Rout	Laacher See Phonolite, Cumulates and Syenites: Different eruption products that constrain the pre-eruptive history
41	- 13:00	Hornby	An experimental basis for estimating particle properties following volcanic ash emissions
			LUNCH BREAK

Eifel (invited talks and discussion): *Friday afternoon*

#	time	author	title
	Chair	**Dahm**	
	14:00 -	Schmincke	Evolution of the Laacher See eruption (LSE), its environmental impact and ongoing research
		Ritter	Seismological Constraints on Magmatism below the Eifel
		Wörner	Geochemical constraints on physical models of the Laacher See Magma system
45	15:20	Hensch	Seismological constraints on the magmatic plumbing system beneath Laacher See Volcano: Deep low-frequency earthquakes
	15:20-16:30	Dahm	Discussion on the present state of knowledge on a potential eruption of the Laacher See volcano
	16:30 – 17:00	Pfanz	Discussion, next PoV-2020 meeting. Excursion; final fair well.
			END OF POV 2019

I
Oral Presentations

Contains all abstracts in alphabetical order according to the name of the first author:

Table of Contents (oral presentations)

Spontaneous phase separation of hydrous Vesuvius melt even at low decompression rates

Anja Allabar
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The phase separation of H_2O fluids from supersaturated hydrous silicate melts determines the starting point of explosive volcanic eruptions. The number of fluid vesicles per unit volume of silicate melt (VND) is a basic property that controls the efficiency of fluid-melt separation and as a result the acceleration of magma ascent. Continuous decompression experiments were performed at superliquidus temperatures to simulate the phase separation of single phase hydrous silicate melts during ascent with AD79 Vesuvius white pumice composition. This pumice buried Herculaneum and Pompeii and is representative of other catastrophic phonolitic and trachytic explosive eruptions like the violent 39 ka Campi Flegrei and the 1815 AD Tambora eruption.

Experiments were conducted in an internally heated pressure vessel equipped with a high-pressure valve that facilitates continuous decompression. During equilibration at 200 MPa and 1523 K for 96 h, 5.3 wt% H_2O were dissolved in the melts, which corresponds to an H_2O saturation pressure of 195 MPa. After hydration the hydrous melts were isothermally decompressed at 1323 or 1373 K with rates of 0.024-1.7 MPa·s-1. At final pressures (Pfinal) between 110 and 70 MPa, the samples were isobarically quenched with ~150 K·s-1. The VND of the vitreous samples were determined with optical microscopy and quantitative backscattered electron image analysis using computational 2D to 3D transformation.

Homogeneously dispersed vesicles are observed in the samples decompressed to a Pfinal $\leq$ 100 MPa, corresponding to a ΔP of 95 MPa is necessary to induce homogeneous phase separation. High logVND's of ~5.2 (in mm-2) are observed, irrespective of decompression rate within the investigated range. A nucleation theory based decompression rate meter, which is commonly used to estimate magma ascent velocity from VND of volcanic ejecta, cannot be adapted to explain the experimentally observed decompression rate independent VND. Alternatively, decompression induced H_2O-silicate melt phase separation may be described by the theory of spinodal decomposition at the limit of thermodynamic stability.

A decompression rate independent VND has profound consequences for the degassing dynamics of natural polyphase hydrous magma. Even at low decompression rates, the formation of vesicles with such high VND inevitably causes efficient melt degassing within seconds due to short H_2O diffusion distances on a 10 µm scale from the melt into fluid vesicles, causing rapid density decrease accompanied by sudden increase of magma buoyancy required for explosive volcanism.

Degassing rhythms and fluctuations of geogenic gases in a red wood-ant nest, in soil and three mineral springs – Neuwied Basin (East Eifel Volcanic Field, Germany)

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Geochemical tracers of crustal fluids provide a useful tool for the identification of buried fault structures. We acquired geochemical data during 7-months of continual sampling to identify causal processes underlying correlations between degassing patterns of three gases (CO2, He, Rn) in a nest of red wood ants (Formica polyctena; "RWA") and in the soil at the Goloring site and in three nearby mineral waters (Nette, Kärlich and Kobern) in the Neuwied Basin, a part of the East Eifel Volcanic Field (EEVF). We used a combination of geochemical, geophysical, and statistical methods to identify potential causal processes underlying the correlations of degassing patterns, earth tides, and tectonic processes. We explored whether temporal relations and degassing rhythms in soil, nest gas and mineral waters could be indicators of hidden faults through which the gases migrate to the surface from depth. In nest gas, the coupled system of CO2-He and He concentrations exceeding atmospheric standards by factors of 2-3suggest that RWA nests may be biological indicators of hidden degassing faults and fractures at small scales. Temporal analyses of the CO2-He couple indicate that Nette and Kärlich are directly linked via a continuous tectonic fault in an ENE-WSW trending direction. There is also evidence that Kärlich and Kobern (NNE-SSW fault system) and Nette and Kobern (NW-SE fault system) are tectonically linked. These fault linkages were previously unknown but could be related to the increasing number of earthquakes occurring in this area since 2010. We did not find any evidence that weather processes (e.g., barometric pressure), earth tides, or small local earthquakes actively modulate degassing. Because volcanic activity in the EEVF is dormant, more detailed information on the EEVF's tectonic, magmatic, and degassing systems and its active tectonic fault zones are needed. Such data may provide additional insights into earthquake processes that are related to magmatic processes in the lower crust.

Keywords: geogenic gases; East Eifel Volcanic field (EEVF); earthquakes; Earth tides; mineral waters; soil gas; Formica polyctena; red wood ant; nest gas

Mantle-derived gases in the European Cenozoic Rift system: A comparison of gas signatures in the Eifel area with those in the French Massif Central and NW Bohemia

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Mantle-derived gases in the European Cenozoic Rift system: A comparison of gas signatures in the Eifel area with those in the French Massif Central and NW Bohemia.
In general, the main component of mantle derived fluids escaping at the surface is CO2. In order to determine the origin of such gases, isotope analyses are necessary. Helium isotope ratios are the best tool to evaluate gas sources and to distinguish between upper mantle and crustal origin of volatiles, because the two reservoirs are substantially different in their helium isotope composition.
Studies of lithospheric mantle xenoliths have shown that the 3He/4He ratio in the subcontinental lithospheric mantle is somewhat lower than in MORB. For instance, Gautheron et al. (2005) reported helium isotope ratios ranging between 5.9 and 6.7 Ra (Ra = 1.39×10–6 is the 3He/4He ratio in air) in xenoliths from the European subcontinental lithospheric mantle.
High contributions of mantle-derived helium were identified in free gases from areas in the French Massif Central (MC; e.g. Matthews et al., 1987; Bräuer et al. 2017), the Eifel (e.g. Griesshaber et al, 1992; Bräuer et al., 2013) and NW Bohemia (e.g. Weinlich et al. 1999; Bräuer et al., 2008, 2009, 2018). In proximity of all identified degassing sites with subcontinental helium signature, Quaternary volcanoes are present and often seismicity occurs. The last volcanic activity occurred 11 ka ago in the East Eifel, 6 ka ago in the Massif Central and 0.3 Ma ago in the Cheb Basin (NW Bohemia), while the strength of seismicity decreases in the order NW Bohemia> MC> Eifel.
Based on detailed investigations of the regional distribution patterns of gas and isotopic compositions by means of time-series studies, the geodynamic situation of the studied degassing areas in the European Cenozoic Rift System is evaluated.

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The Stolpen Volcano in the Lausitz Volcanic Field (East Germany) – volcanological, petrographic and geochemical investigations at the type locality of basalt

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The Stolpen Castle Hill, which was designated in Germany as a "national geotope" in 2006 represents the type locality for the rock name basalt. Agricola used und published this term the first time in connec-tion with Stolpen in the year 1546 in his publication "De natura fossilium". The presentation looks more closely at the origin of the term basalt, which stretches back to Antique time, especially to Gaius Plinius Secundus (Pliny the Elder, AD 23–79). Agricola (1546) does not call Pliny, but the content clearly follows Pliny (ca. 77: Naturalis historia. – Issue XXXVI, Chapter 58). Violently discussed was considered the term basalt since the first use in the early modern peri-od by Agricola (1546).
Various source analyses in antique writings and the find of a new hand written copy from Pliny (ca. 77) in the year 1851 makes it probable, that Pliny had not use the term basaltes, but instead the term basanites [1]. It is probably an emendation! Beside this scribal error by the handmade copies of the original manuscript, also the rock type described by Pliny is not clear. Probably it was not basalt in today's sense, because Pliny does not mention the typical columns, in contrast to Agricola, he described only the strong hardness and the grey colour like iron. Therefore, various other rock types are also considered in the literature, e.g. lydite or greywacke. Also the regional localization of the "basalt" from Pliny in Egypt and/or Ethiopia is not helpful for the determination of the described rock by Pliny, because she is to general and the text translation is ambiguous (it could also mean Egyptian instead of Egypt). Also not the mentioned sculptures and buildings, which Pliny connected with his "basalt" description, can help, because these objects exist not today or probably only as copy (for the last three topics see among others [2]). For the reasons mentioned above, it is difficult today to determine the linguistic origin and the rock type, which Pliny has originally meant. Presumably, that can barely satisfactorily clarified today. Nethertheless, Acrigola had descripted a basaltic rock with the use of the term basalt at first time from the Castle Hill Stolpen in Saxony (East Germany).
Since Agricola (1546) many different investiga-tions took place at the basaltic Stolpen Castle Hill. But physical-volcanological reconstructions are rare; they are only essentially made by [3] and by [4]. These authors interpret the former volcanic edifice from Stolpen as volcanic plug or (intrusive) lava dome. A geological mapping since 1994 of almost 100 temporary outcrops and recent field observations could give a new and different view [5]. After them, two phases of the volcano formation and a third phase with a morphological overprint of the volcanic edifice can be distinguished. The first phase creates an over 1000 m deep maar-diatreme structure as result of a phreatomagmatic eruption. The maar crater was located in the Cadomian granodiorite with about 450 m x 300 m in size at the former earth surface, the elongated shape is the result of the granite tectonics with main joint direction in NE-SW. After them arose a small scoria cone at the north-western margin of the maar crater and initiates the second phase. The final lava of the phreatomagmatic scoria cone filled the whole maar crater; the scoria wall was almost completely destroyed und float up in the basanitic lava lake. An in situ remnant of a scoria ash tuff between the granodioritic frame and the basaltic lava body and several single scoria inclusions in the basaltic lava of the Castle Hill

indicate this scoria cone phase. Both volcanic phases are closely linked in terms of genetic and time, so that the Stolpen Volcano can be described as a monogenetic or monocyclic volcano.

The age is after one K-Ar-isotopic determination 25.3 ± 0,5 Ma [6], but K-K isotopic age determinations in the Lausitz Volcanic Field [7] suggests an older age of about 30 Ma. Much later, the uplift processes of the Lausitz Block, especially during the Pleistocene, began 1.3 million years ago to denudate the granodioritic rock frame and the lava body was morphologically exposed and dominate the landscape as isolated hill today. The minimum denudation amount can be esti-mated at 100 m to 150 m. Thereafter, the erosion and uplift rate can be calculated of 3.3 mm up 5 mm/ka since the volcanic time before 30 Ma, which confirms the previous data for the Lausitz Block [8].

In addition mineralogical (QAPF) and geochemical (TAS) research into the petrography of the Stolpen lava rock was undertaken [9]. The results reveal that, in the context of present rock nomenclature, the rock at Stolpen Castle Hill is not basalt and is rather best described as basanite with tendencies towards nephelinite, a typical rock type in the Lusatian Volcanic Field. Therefore and based on the further demonstrated inhomogeneities in the Stolpen lava rock, the Stolpen Castle Hill is not in a scientific sense a suitable type locality for basalt or basanite. However, outcropping volcanic rocks as well as its scientific historical importance undoubtedly give Stolpen relevance as a type locality for volcanic rocks.

The example of Stolpen poses the question of to what extent historical type localities can be combined with present day rock nomenclature. And furthermore, the question arises whether the definition of type localities for natural rocks makes sense, because these often show transitions and convergences; homogeneous rock bodies occur rarely or not at all in nature.

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Long period volcano-seismic crises offshore Mayotte, Comoros Islands: indications of submarine caldera collapse?

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The unusual, long-lasting and heterogeneous seismic sequence offshore Mayotte, Comoros Islands, Western Indian Ocean, started in May 2018. The first activity was recognized by the occurrence of deep crustal seismic swarms with a peak magnitude of Mw 5.9 on May 15, 2019 and slow decay in the following months with almost no Mw4.5+ between mid July and mid September. Since early June a new type of peculiar very long period (VLP) activity developed, characterized by a long duration up to 10-20 min, dominant periods of ~16 s. The VLP signals are energetic and can be observed up to >2000 km distance. In the months after June the VLP activity continued steadily and experienced a substantial increase in the number of events in September 2018, accompanied by new sequence of shallow high-frequency, volcano-tectonic activity closer to Mayotte Island. In the last days of December 2018, the VLP activity experienced a new increase. The seismic sequence is accompanied by continuous surface subsidence up to ~8 cm and Eastward horizontal movement up to ~10 cm recorded at GNSS stations on Mayotte Island.

We present first results from the analysis of seismological and surface deformation data, and develop a conceptual model on caldera collapse process triggered by magma inflow from depth and a shallow reservoir depletion from upper crustal diking. The VLP activity is likely generated by the resonance of a reservoir, which slow depletion can explain the large surface subsidence.

Soluble salt concentrations on volcanic ash aggregates from a variety of eruption types and deposits

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Ash aggregation is a well-known phenomenon to happen in particle-laden environments such as volcanic eruption plumes of pyroclastic density currents. A key factor to the stabilization and hence survival of the fragile aggregates is cementation by soluble salts. Although successfully tested in laboratory scale experiments, it is yet unknown which quantitative scales of ash concentrations are required in natural systems to provide aggregates enough stability to survive atmospheric transport and final deposition.

In this study, we collected and analyzed aggregates generated in a broad spectrum of eruptive settings: a dry, salt-poor subaerial plume at El Salvador, PDCs interacting with freshwater at Tungurahua volcano (Ecuador), PDCs entering the ocean at Montserrat and high humidity, salt-rich Surtseyan plumes in Tonga. We used aqueous leaching to characterize surface salt loading of ash and measured the concentrations in Al, Ca, Fe, K, Mg, Mn, Si, Na, Cl and SO4. We additionally performed chemical mapping and morphological observations on these agglomerates using a Hitachi SU 5000 Scanning electron microscope (SEM) at LMU. The concentrations of Cl, Na, SO4, Ca, Mg and K evolve in a similar pattern between the aggregates from different settings. The highest and lowest concentrations are in aggregates from Tonga and El Salvador, respectively. The molar concentrations between the cation-anion pairs Na-Cl and Ca-SO4 show 1:1 trends implying that NaCl and CaSO4 are the most ubiquitous soluble salts in the aggregates examined here. This was confirmed by chemical mapping at the SEM.

We generalize our results in a conceptual model linking the amount of external water and external salt source to the salt concentrations found for the different eruptive settings. This study is the first one to explore aggregates from a range of eruptive settings, from dry eruptive plumes where aggregates where sampled in their pristine state immediately after deposition, to a Surtseyan eruption with the abundant involvement of seawater. The presented dataset of salt concentrations can serve as a tool for ash dispersal modelling.

Surface Loading Changes as Top-Down Controls on Magma Reservoir Formation

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Loading due to the growth of volcanic edifices generates stresses in the crust comparable to the order of magnitude of tectonic stresses. Crustal stresses control the pathways and velocity of magma-filled dikes and thus may affect the geometry and location of magma storage zones. We mainly investigate how the loading stress provided by a growing volcanic edifice sets a top-down control on the shape of a magma reservoir. Data on the shape and depth of magma storage of deforming volcanoes from available databases (i.e. COMET, Smithsonian) reveal that calderas in general are associated to sills or top-flatted reservoirs, while stratovolcanoes are related to vertically developed reservoirs such as ellipsoids. We explain this observation with 2D numerical simulation of ascent pathways of magma in the crust considering dike-dike interaction. Topographic load plays the main role in our models. Taking into account stresses induced by the previous intrusions introduces complexity to the system thereby facilitating accumulations of dikes resulting in the formation of magma storage zones. Our results are consistent with the observation and suggest that the shape of the volcanic edifice may control, beside being controlled by, that of magma reservoirs.

Do we understand the volcanic hazard in the Eifel volcanic fields? Introduction to the plenary discussion on the "PoV expert report"

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What is the volcanic hazard in the Eifel? Has it changed with new observations and new findings? What are knowledge gaps to be filled, and what experiments should be conducted?
The plenary discussion will be based on a draft report on these and other questions, aiming to develop a common scientific statement from the PoV (DGG) and AG Seismology (FKPE) groups. Aim of such a common statement is to inform politicians and the public on our state of knowledge, and to initiate a research program for filling knowledge gaps.

Gas hazard: an often neglected volcanic hazard

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Volcanic areas release huge amounts of gases, which apart from having important influences on the global climate could have strong impact on human health. Gases have both acute and chronic effects. Carbon Dioxide and Sulfur gases are the main gases responsible for acute mortality due to their asphyxiating and/or toxic properties. On the contrary Mercury and Radon have important chronic effects respectively for its toxicity and radioactivity.
The problem has long been neglected until the "Lake Nyos" catastrophe in 1986, in which about 1700 people were killed by a volcanic CO2 emission, attracted the worldwide attention of mass media.
Some example of hazardous gaseous volcanic emission in the Mediterranean area will be discussed.

Imaging source and dynamics of Campi Flegrei unrest in the last 40 years

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Volcanic calderas are the visible manifestations of some of the most powerful eruptions on our planet, widely cited as a likely trigger of human and economic loss at the global scale. Campi Flegrei, the most dangerous caldera in continental Europe, is unique, presenting long-term historical data complementing modern monitoring and case-studies of failed eruptions with consequent evacuations. Here, we present a full seismic velocity and attenuation 3D model of the sources triggering two of these volcanic unrests (1983-84 and 2011-2013). For 1983-84 we employ seismic attenuation imaging to highlight the principal magmatic source of uplift (1.8 m) located offshore the city of Pozzuoli at a depth of ~4 km, the supercritical fluid reservoir above it, and the caprock that blocked the vertical rise of fluids and magma to surface. 4D localisation and directivity analyses provide a day-by-day description of the unrest dynamics. While deformation and geochemical signals underline the 2011-13 volcanic unrest, the seismic signature is absent, hindering standard earthquake tomography. We thus used ambient-noise interferometry to image the feeder of the unrest, fractured on April 1st 1984 under the Pozzuoli city centre. From this area, fluids propagate through pathways to volcanic vents at Pisciarelli, opened at the end of the unrest. The results of these works are a primary structural constraint in the monitoring procedures of the INGV - Vesuvius Observatory, the institution monitoring the volcano.

Analytical approach on the link between the Earth tidal potential and volcanic degassing

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The tidal forces periodically deform the Earth’s surface and interior. The predominant periodicities of this deformation are semi-diurnal or diurnal, depending on the latitude. The magnitudes of these variations are modified within the spring-neap tide cycle with a periodicity of about 14.8 days. Evidence for tidal impacts on volcanism has been reported since the 1960s from different proxies such as the coinciding timing of Earth tidal extrema and volcanic eruptions or seismic events, and correlations between tidal patterns and volcanic deformation or degassing patterns.
We aim to understand the about biweekly periodic pattern observed in the gas emissions of several volcanoes in the recent decade. The tidal stresses may influence the volcanic degassing on several ways such as a widening of tectonic structures, a periodic decompression of the host rock, a self-sealing of hydrothermal fractures, and a mechanical excitation of the uppermost magmatic gas phase. Additionally, the tide-induced local gravity variations may cause a periodical vertical magma displacement. While debated for long, no quantitative model of a causal link from the tidal potential to variations in the volcanic degassing has yet been proposed.
We model the response of a simplified magmatic system on the gravity variations by an analytical approach and discuss the resulting consequences. We derive for simplified model versions of the Villarrica and Cotopaxi volcanoes vertical magma displacements with an amplitude of only 0.1-1 m, depending on geometry and physical state of the magmatic system. Vertical magma displacements of such a small amplitude have presumably no significant direct effect on the volatile solubility. But we show that the inhomogeneous magma flow profile across the radial conduit caused by the vertical magma displacement may result in a significant increase of the bubble coalescence rate by up to several ten percent in a depth of several kilometres. The bubble coalescence rate is often a major driver of the volcanic volatile degassing rate. We argue that - if the degassing is governed by the bubble coalescence rate - the derived tidal variation may propagate to a manifestation of varying volcanic degassing behaviour.

Fluid flow source model for harmonic tremor at Santiaguito volcano, Guatemala

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A seismic and infrasound network at Santiaguito volcano, Guatemala, was deployed in January 2018 and is operating since. Seismic sensors are Trillium compact 120 s and Lennartz 1 s seismometers and infrasound sensors are iTem prs 100. In January 2019, 7 km from the active vent, a thermal camera was installed. Spectral analysis of the recorded seismic data clearly reveals the appearance of harmonic tremor signals which persist for several minutes. Fundamental frequencies of those harmonic signals range between 0.4 Hz and 0.6 Hz and contain up to 20 overtones. During the appearance of a harmonic tremor signal, frequency gliding can often be observed. Harmonic tremor signals have been recorded at Santiaguito during the complete observation period and could even be found in the infrasound signal in some cases. This, and a comparison of seismic, infrasound and thermal imagery observations indicate a near surface source linked to the exhaust of gas.
Harmonic tremor has been observed at several volcanoes worldwide but is still poorly understood. Understanding the source mechanism may potentially give evidence to structures inside the volcano. There is a number of source models in literature, either suggesting resonating bodies or resonance due to fluid flow as source mechanism. At Santiaguito, we find models using oscillation phenomena due to fluid flow more capable of describing the nature of harmonic tremor. The basic idea is similar to sound generation in musical wind instruments and human vocal chords. We adapt the source model of Julian (1994) who suggests nonlinear excitation by fluid flow of basaltic magma as a source mechanism for Kilauea. We extend his model to water as exciting fluid by including turbulent flow conditions. We solve the resulting equations of motion numerically and find that water at near surface pressure conditions is capable of producing persisting oscillations. We evaluate dimensions and pressures necessary for producing frequencies and frequency gliding in agreement with the observations.

On the success rate of public warnings based on short-term seismic precursors to Icelandic eruptions

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The interaction of the Iceland hotspot with the mid-Atlantic plate boundary leads to volcanism of unusually wide variety. In the 1100 years history of cohabitation with the Icelandic volcanoes several cases have been noted and documented of seismicity immediately preceding eruptions of volcanoes such as Hekla and Katla. As early as the eighteenth century monitoring of seismicity was considered to be a promising tool for eruption warnings. Networks of seismographs of high sensitivity have been in use in the vicinity of active volcanoes in Iceland since 1973. During this time 21 confirmed eruptions have occurred and several magmatic events, where magma has intruded into the crust without finding a way to the surface. All these events have been accompanied by characteristic seismic activity. Long-term precursory activity is characterised by low-level, persistent seismicity, clustered around an inflating magma body. Whether or not a magma accumulation is accompanied by seismicity depends on the tectonic setting, interplate or intraplate, the depth of magma accumulation, the previous history and the state of stress. All eruptions during the time of observation had a detectable short-term seismic precursor marking the time of dike propagation towards the surface. The precursor times varied between 15 minutes and 13 days. In half of the cases the precursor time was less than 2 hours. Three eruptions stand out for their long precursory time, Heimaey 1973 with 30 hours, Gjálp 1996 with 34 hours, and Bárðarbunga 2014 with 13 days. In the case of Heimaey the long time is most likely the consequence of the great depth of the magma source, 15-25 km. The Gjálp eruption had a prelude that was unusual in many respects. The long precursory time may have resulted from a complicated triggering scenario involving more than one magma chamber. The Bárðarbunga eruption at Holuhraun issued from the distal end of a dike that took 13 days to propagate laterally for 48 km before it opened to the surface. Hekla stands out for its short precursor times, ranging between 23 and 79 minutes. Out of all 21 detected precursors 14 were noticed soon enough to lead to a public warning of the coming eruption. In 4 additional cases the precursory signal was noticed before the eruption was seen. In only 3 cases was the eruption seen or detected before the seismic precursor was verified.

Contrasting magma evolutions at Mt. Erciyes and Mt. Hasan stratovolcanoes, Central Anatolia, Turkey

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Mt. Erciyes (3917 m a.s.l.) and Mt. Hasan (3253 m a.s.l.), the two highest stratovolcanoes of Central Anatolia, Turkey, exhibit magmatic activity since at least 300 ka. Due to their close vicinity of only 120 km, their magmatic evolutions in a post-collisional intraplate setting can be compared and contrasted. Here, we present U Th disequilibrium and U Pb (crystallization) and (U Th)/He (eruption) ages and trace elements of zircon rims and interiors and magnetite-ilmenite thermometry for a comprehensive set of 38 samples from both volcanoes. Samples comprise lava and pyroclastic deposits of intermediate to evolved compositions (63 – 76 wt. % SiO2).

Zircon rims from both volcanoes show continuous crystallization age spectra. Zircon interior age spectra for Mt. Hasan are also continuous, whereas those for Mt. Erciyes show distinct crystallization peaks at ca. 10, 90 and 280 ka. These pulses coincide with intense eruptive phases separated by quiescent episodes for Mt. Erciyes, whereas eruptive recurrence at Mt. Hasan is at briefer intervals of ca. 5 – 15 ka over the last 60 ka. Eruption temperatures average 810 °C for Mt. Erciyes' early Holocene rhyodacitic domes Karagüllü, Dikkartın and Perikartın, their related pyroclastics, and the dacitic Yılanlıdağ dome. For Mt. Hasan, eruption temperatures are around 850 °C for most dacitic lavas and block-and-ash-flows, but in some cases up to 1040 °C. Thus, eruption temperatures are usually 50 – 120 °C hotter than mean Ti-in-zircon crystallization temperatures of 730 and 750 °C, respectively, emphasizing the significant reheating of erupted magma batches.

Long-term magma fluxes are estimated at 0.5 – 5 km^3/ka based on zircon crystallization age spectra for both Mt. Erciyes and Mt. Hasan. Episodes of intensified zircon growth and eruptive activity at Mt. Erciyes may be related to transient recharge at higher rates. Protracted zircon rim crystallization indicates continuous presence of small fractions of melt in both systems. This is explained by minor but frequent magma recharge, supported by frequent eruptions in case of Mt. Hasan. The overall longevity of zircon crystallization suggests that magmatic activity persists to the present day at both volcanoes. Melt presence and Holocene eruptive activity (previously unrecognized for Mt. Erciyes) emphasize the hazard potential for the population in the surroundings of Mt. Hasan and Mt. Erciyes including the metropolis of Kayseri with 1.4 million inhabitants in close proximity to Mt. Erciyes, calling for further investigations of both volcanoes.

New insights from long-term seismic, infrasound and thermal measurements at Santiaguito volcano, Guatemala

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Santiaguito volcano (Guatemala) which formed in 1922, consists of four volcanic domes aligned within the collapse scar of Santa Maria volcano. Present activity is concentrated at Caliente, the easternmost of the four domes and characterized by small to moderate gas and ash emissions from the central vent and at the eastern flank. We observed substantial dome growth at Caliente between January 2018 and January 2019. On January 16, 2019, we witnessed an explosion followed by a rockslide at the southern part of the dome leaving a reddish surface visible from INSIVUMEH observatory New OVSAN, 7 km south of Caliente. This event was accompanied by ash fall at New OVSAN.
In order to gain a better understanding of dome growth, its collapse, and eruption dynamics, we operate a permanent seismic and infrasound network at Santiaguito. Today, it consists of five permanent stations continuously recording at 75 Hz and 100 Hz, respectively. The seismic data is received in real-time via modem from four of the seismic stations. Seismic sensors deployed are Trillium compact 120 s seismometers as well as Lennartz 1 s seismometers and infrasound sensors are iTem prs100. In January 2019, we deployed an additional temporary network consisting of twelve Lennartz LE3D 1Hz seismometers and six infrasound sensors. We also installed a permanent infrared camera which records images every second and transmits in real-time.
A comparison of seismic and infrasound data with thermal images allows us to distinguish between explosions from the central part of the vent and those from the eastern flank which can also be discriminated by their frequency content. Central vent explosions contain mainly frequencies between 2 – 4 Hz while activity at the eastern flank radiates frequencies around 6 – 10 Hz. The comparison between seismic and thermal data also reveals that the actual emission of ash and gas persists much longer than the seismic explosion signal which marks only the opening of the vent. Harmonic tremor signals with up to 20 even and odd overtones can occasionally be observed after explosions and coincide with the emission of hot material. The fundamental frequencies of harmonic tremor range between 0.4 and 0.6 Hz and show clear evidence of frequency gliding. Both, harmonic tremor episodes with increasing and decreasing fundamental frequency can be found. Furthermore volcano-tectonic earthquakes have been registered at depths between 1 – 2 kilometers less than two kilometers south-west of the active vent.

Seismological constraints on the magmatic plumbing system beneath Laacher See Volcano: Deep low-frequency earthquakes

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Seismic signals observed beneath volcanic systems have a broad range of frequencies and are associated with different processes at depth. While high-frequency volcano-tectonic earthquakes reflect brittle failure mostly in the shallow crust, the occurrence of deep low-frequency (DLF) earthquakes is commonly attributed to unsteady mass transport in the magmatic plumbing system and used to infer feeding channels from and into magma reservoirs. The key question is how magmas migrate from depth to the shallow crust and whether magma reservoirs are currently being recharged.

For the first time since the improvement of the local seismic networks in the East Eifel region, we detect and locate recurrent DLF earthquakes in the lower crust and upper mantle beneath the Laacher See Volcano (LSV), using a joint data set of permanent sensors and a temporary deployment. So far, eight DLF earthquake sequences were observed in four distinct clusters between 10 km and 40 km depth. These clusters of weak events (ML < 2) align along an approximately 80° south-east dipping line south of the LSV.

Activity occurs in short-lived pulses, with several DLF earthquakes within only a few minutes. Moment tensor solutions of these events have large shear components and predominantly show normal faulting mechanisms. Low corner frequencies suggest a very low apparent stress drop during rupture. The favored mechanical model to explain these characteristics involves shear cracks occurring in the vicinity of conduits, batches or reservoirs of magma or magmatic fluids. The low frequencies of P- and S- wave codas are suggestively generated by slow rupture velocities in the viscoelastic upper mantle and lower crust, possibly enhanced by resonance effects. The short duration of the earthquake pulses might be explained by fast strain accumulation, only lasting for the time while the fluid is moving. Near-vertical P-axes indicate a stress field in the depth interval of DLF events which supports vertical fluid migration.

The observed DLF earthquake activity in the East Eifel region is the first seismological evidence for an active magmatic system beneath the LSV, possibly connected with an upper mantle melt zone. A comparison to DLF earthquake occurrences beneath other volcanoes is considered for scenario prognoses.

An experimental basis for estimating particle properties following volcanic ash emissions

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In recent years, mitigating the impact of volcanic ash emissions has risen up political and research agendas. Despite intense research efforts, challenges remain as to the detection and forecasting of emissions, and subsequent interactions in the earth system. Monitoring instruments and ash dispersal models usually require the input of volcanic ash properties in order to operate effectively, however forensic methods are poorly suited to volcanic eruptions where near-real-time data is required, and default values are commonly used. Here, we take an experimental approach to demonstrate that the surface composition and the initial size and shape distribution of volcanic ash particles depends upon i) the initial rock texture, chemistry and mineralogy and ii) the fragmentation processes that produced the particles.
We compare natural pyroclasts with particles produced in fragmentation experiments using fresh rock samples at Volcán de Colima and Mt Etna. Experiments were conducted under varying conditions in shock tube, tumbling and fault friction apparatuses to simulate natural eruption processes. Using QEMSCAN, an SEM-based automated mineralogy technique, we produce micron-scale maps showing the size, shape and phase distribution of hundreds of thousands of ash particles in over 40 samples. We measure particle size-, shape- and phase distribution in each sample and demonstrate that particle size distribution and shape show characteristic variation between different experimental methods and eruptive activity. Some phases, particularly groundmass glass (or tachylite), feldspars, Fe(Ti) oxides and pyroxenes are found to vary significantly at particles boundaries compared to the bulk. The pattern of enrichment and depletion of phases is shown to relate to the fragmentation mechanism and the rock texture at the macro- and micro-scale, and correlations between experimental and natural samples indicate a robust signal.
Volcanic ash presents hazards to aviation, health and the environment and better constraints on ash particle properties immediately following activity may improve estimations of the intensity and spatial extent of ash-related hazards.

Magma plumbing at the Quaternary Emmelberg volcano (West Eifel volcanic field)

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The Emmelberg quarry near Üdersdorf (West Eifel volcanic field) reveals excellent exposures of the crater and proximal wall facies of a deeply dissected scoria cone. It is made up by a pyroclastic sequence of alternating phreatomagmatic and magmatic units, capped by welded bombs and agglutinates. Two main eruptive centers can be recognized, with agglutinate beds at former crater walls indicating a syn-eruptive northward migration of the main vent as the volcano grew upward. The erupted lavas are olivine nephelinites (9.2-11.1 wt% MgO, 124-175 ppm Ni, 359-455 ppm Cr) with olivine (7-10 %) and clinopyroxene (3-5 %) phenocrysts; reversely zoned olivines and green-core clinopyroxenes are common. There are no systematic compositional changes across the eruptive sequence; geochemical variations appear random and largely reflect mildly varying amounts of phenocrysts.

We have carried out thermobarometric investigations of lavas and cumulate xenoliths to infer conditions of magma storage and transport. Thermobarometry based on clinopyroxene-melt equilibrium was applied to the compositions of phenocryst rims and groundmass of the rocks. Calculated pressures for 29 phenocrysts range from 630 to 830 MPa (mean 720 MPa), and temperatures from 1155 to 1195 °C (average 1180 °C), which we interpret as pre-eruptive conditions of magma storage. The data overlap remarkably well with pressure estimates of 600-700 MPa for CO2-rich fluid inclusions in crustal xenoliths from Kempenich (East Eifel volcanic field), that were interpreted to reflect an intrusive horizon in the lower crust near the Conrad discontinuity (Sachs and Hansteen, 2000). In contrast, microthermometry of CO2-dominated fluid inclusions in cumulate xenoliths from Emmelberg yields significantly lower pressures of 100 to 410 MPa (mean 280 MPa), within the upper crust.

Our data suggest that final storage and crystal fractionation of the Emmelberg magma took place in a reservoir at ca. 26 ± 3 km depth, probably at a level near the lower to upper crust boundary that is marked by lithological and/or rheological changes. Reverse zonations at olivine phenocrysts indicate a magma mixing event that occurred a few days to weeks prior to eruption. During the eruption the ascending magma must have stalled within a putative intrusion horizon at ca. 15 ± 5 km depth, or picked up cumulate fragments from such a horizon. The proposed scenario of multi-stage magma ascent is consistent with a generalized model for the evolution of olivine nephelinites from the West Eifel (Duda and Schmincke, 1985). We note that both magma stalling horizons inferred in this study coincide with depths of abrupt change in P-wave velocity (Sachs and Hansteen, 2000). Our barometric data also overlap with pressure estimates between 150 and 720 MPa for the Meerfelder Maar, Gemündener Maar and Baarley volcanic centers of the West Eifel (Shaw, 2004), but use a more precise barometer that reduces the data variance.

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Dome growth during the 2016-2017 eruption sequence at Bezymianny volcano, Kamchatka, measured by high-resolution TerraSAR-X and photogrammetric data

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Lava domes grow through the interaction of extrusions and intrusions of magma initiating from a central volcanic vent. Rates of effusion control recurrent growth cycles that often concur with perilous explosive eruptions and devastating pyroclastic flows. Thus, close monitoring of dome building processes is crucial, but often limited to low data resolution, hazardous access and poor weather conditions. Satellite Synthetic Aperture Radar (SAR) in turn enables sustained and accurate detection and quantification of dome growth related ground motion. Here, we investigated the 2016—2017 eruptive sequence of the dome building Bezymianny volcano, Kamchatka, with high-resolution TerraSAR-X acquisitions and complement the analysis with webcam imagery as well as seismic data, which revealed clear deformation associated with intrusions and extrusions. We examined different dome growth regimes in consecutive SAR amplitude scenes, and quantified corresponding ground deformation with pixel offset measurements to determine rates of extrusion and intrusion. Results show seven to nine months of precursory plug extrusion chiefly without perceptible seismicity. Subsequent three months of lava dome evolution were characterised by interactions of endogenous and exogenous growth. Our data suggest that growth mechanisms were significantly governed by magma supply rate and upper conduit solidification, and that the transition between growth regimes initiated at shallow depths above the base of the dome. The integrated approach contributes significantly to a better understanding of heralds of volcanic activity and complex growth interactions at dome building volcanoes.

High resolution mapping of the hot pots and geysers in El Tatio, Chile, reveals Structural and lithological controls on geothermal activity in El Tatio

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Hot pots and geysers are the surface expression of uprising volcanic fluids, with locations that are thought to be permeability controlled, and with activities that are affected by the tectonic and hydrometeorological surrounding. Details on the spatial appearance and structural control, however, as well as on the variability of their locations are rarely investigated. At El Tatio (Chile), one of the largest geyser fields of the world, we use close-range aerial photogrammetric remote sensing techniques to investigate the El Tatio geothermal area. From over 10,000 images taken by optical and thermal cameras mounted on drones and balloons, we compute spatial data at centimeter-scale resolution. We were able to identify, classify and characterize 1863 objects related to geothermal activity, identified in digital elevation models, aerial images, and thermal anomalies, providing an unprecedented catalogue of hot pots and geysers. Those objects were analyzed regarding their thermal and morphological signature, spatial distribution, aggregation and clustering. Raster analysis additionally allow us to investigate erupted sinter volumes and identify active from inactive vents. Geothermal activity of El Tatio occurs in distinct regions resembling an L-shape, and can be classified in the upper, middle and lower geyser basin and some smaller groups. Our more focused study on the upper geyser basin reveals a SW-NE trend along which the majority of El Tatio's geysers are grouped. We observed a high degree of organisation and well defined compositions of geothermal species with locally high densities, that tend to consolidate in clusters on a smaller scale and group to well confined active regions on a larger scale. Further we observed activity along lineaments and intersecting lineaments, resembling the azimuth of a local normal fault, but also oblique ones. We found multiple spatially distinct temperature regimes with high temperatures occurring along a very narrow segmented belt. The arrangement of geothermal objects, combined with the occurrence and orientation of active and extinct lineaments, distinct characteristics of active regions and the local geological setting may provide important information to a better understanding of the mechanisms controlling the appearance and evolution of geothermal areas.

The role of shear-stress in volcanic systems: a paradigm shift

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Seismic swarms and tilt measurement on active silicic volcanoes have been successfully used to assess their eruption potential. Swarms of low-frequency seismic events have been associated with brittle failure or stick-slip motion of magma during ascent and have been used to estimate qualitatively the magma ascent. Tilt signals are extremely sensitive indicators for volcano deformation and their interpretation includes shear stress as a generating source as well as inflation or deflation of a shallow magma reservoir. Here we use data sets from different tiltmeters deployed on Tungurahua volcano, Ecuador, and contrast the two source models for different locations and time intervals. We analyse a simultaneously recorded seismic data set and address the question of shear stress partitioning resulting in both the generation of tilt and low-frequency seismicity in critical phases prior to Vulcanion explosions.

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Noble gas, carbon and nitrogen isotopes in free gases of the Eifel volcanic area as tracers for a deep plume involvement

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The Quaternary volcanic area of the Eifel, Germany, is presently characterized by the degassing of magmatic volatiles at numerous locations (Bräuer et al., 2013). Both in the East Eifel around the Laacher See and in the South Eifel at the location Heckenmünster, CO_2 concentrations >99% and $^3He/^4He$ ratios >4 Ra (Ra = atmospheric $^3He/^4He$ ratio of 1.4□10^{-6}) clearly indicate the predominance of a mantle-derived component; carbon and nitrogen isotopic compositions are consistent with that inference. Nevertheless, even after correcting for shallow-level modification of the isotopic compositions occurring at some locations, distinct differences between the East and South Eifel signatures remain. In the East Eifel, □^{13}C values (indicating the permil difference of the $^{13}C/^{12}C$ ratio with respect to Pee Dee Belemnite [PDB]) are -4.6±0.6‰, indistinguishable from the range reported for mid ocean ridge basalts (MORB). Similarly, $^3He/^4He$ ratios up to 5.6 Ra are close to values typical for the subcontinental lithospheric mantle (SCLM). On the other hand, □^{15}N values (denoting the permil difference of $^{15}N/^{14}N$ from air composition) are clearly higher than those of MORB, while Ne and Ar isotopic compositions are dominated by atmospheric components and do therefore not provide information about mantle sources. This is in sharp contrast to the South Eifel sites Victoriaquelle and Schwefelquelle in Heckenmünster, with □^{15}N within the MORB range (~ -2‰) and distinctly elevated $^{20}Ne/^{22}Ne$, $^{21}Ne/^{22}Ne$ and $^{40}Ar/^{36}Ar$ ratios indicating substantial contributions from a mantle reservoir. □^{13}C values around -2.1‰ are higher than in MORB, but essentially the same as reported for the mofette Bublák (Czech Republic), which is thought to represent unmodified gas compositions from a magmatic reservoir beneath the Cheb Basin (e.g. Bräuer et al., 2018). Interestingly, $^3He/^4He$ ratios at Heckenmünster are not quite as high as in the East Eifel or at Bublák, only ~4.3 Ra.

The differences between the isotopic signatures of East and South Eifel gases have been interpreted to indicate their supply from distinct magmatic reservoirs having different melt compositions and/or melt fractions (Bräuer et al., 2013). However, no evidence for the involvement of a deep mantle plume was found in these data. Such evidence was reported earlier based on neon isotopes in a few mantle xenoliths from Dreiser Weiher (West Eifel; Buikin et al., 2005) and more recently in a xenon isotope study of the Victoriaquelle gas (South Eifel; Caracausi et al., 2016). Noble gases, in particular He and Ne, are known to be excellent tracers not only for mantle sources in general but also for distinguishing different types of mantle sources, such as the convecting upper (MORB) mantle, the SCLM, or deep mantle plumes. Nevertheless, rather frequently He and Ne, and sometimes the heavier noble gases, do not give the same answers, which may be related to element fractionation caused by differences in physical properties such as diffusivity, solid-melt and melt-vapor partitioning etc. (e.g. Stroncik and Niedermann, 2016). The equivocal geochemical evidence for a deep mantle plume involvement in the Eifel volcanism has to be assessed in that context.

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Volcanic outgassing and early atmosphere build-up

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The early phase of the Earth´s evolution was characterized by the presence of a magma ocean or several magma ponds. The heat generated during the late accretion of the Earth and soon after the Moon forming impact was likely high enough to produce the thermodynamics conditions for a total or partially molten mantle. The focus of the present research is to analyse the magma ocean volcanic outgassing in the C-O-H system and the related development of the Earth´s atmosphere. The gas chemical speciation and the atmosphere evolution are investigated through numerical model simulations. By using the "Equilibrium and mass balance method", the volatile chemical outgassing is analysed for a range of pressures, temperatures, and oxidation states which are representative for the magma ocean scenario. The results collected through this method show the variation in the volatile composition due to the redox conditions of the melt during the outgassing process. For reduced states (QIF and IW buffers) the dominant outgassed phases are CO and H2. On the other hand, in oxidizing states (NiNiO and QFM buffers) the principal volatile species are H2O and CO2. The results show the strong connection between the interior of the planet and the development of the early atmosphere. The gas speciation model is coupled with a 2D mantle convection model, with which we will investigate the volatile pathways from the mantle to the atmosphere. Our coupled interior-speciation model will analyse the build-up of early Earth's atmosphere for different redox evolution scenarios starting after the magma ocean solidification phase until the end of the late Archaean.

Mofette vegetation as a geogenic indicator. The relation between plants and geogenic CO_2 at the banks of the Laacher See/Vulkaneifel

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A geogenic CO_2 emitting site (mofette U1) at the banks of the Laacher See/Eifel Mountains was selected to study the relationship between heavy geogenic soil degassing and vegetation. A rectangle of 54 x 7 m was identified within a forested area and laid out with a 1m grid. Soil as well as vegetation analysis was performed each meter. Soil parameters like degassing patterns of carbon dioxide and oxygen showed an inhomogeneous degassing pattern which centered at the inner part of the research area. CO_2 concentrations ranged from zero to 100%. CO_2 concentrations increased with soil depth (0 to 60cm). Soil CO_2 fluxes nicely correlated with soil CO_2 concentrations. Soil permeability as measured with a penetrologger correlated quite well with the soil skeleton and with CO_2 gas emission. Oxygen concentration linearly decreased with increasing CO_2. Soil pH and conductivity followed the pattern of CO_2 emission. From 69 species found within the area, only one proved to be mofettophilic (*Carex acutiformis*) and exclusively grew on strong CO_2 emitting sites, whereas all other species within the area avoided CO_2 emission (mofettophobic species) and grew on control plots or only slightly degassing soil. Strictly high soil CO_2 avoiding species were *Symphoricarpos albus*, *Stellaria holostea*, *Ranunculus ficaria*, *Corydalis solida*, and *Poa nemoralis*. Total number of growing species was highest in low CO_2 soils (max. 17 species per m2) and lowest at high CO_2 emitting sites (one species per m2). Plant coverage followed the same pattern. Total plant coverage reached values of up to 84% under control or slightly degassing soils and 5-6% at CO_2 venting sites.

Space-based monitoring of the 2015 eruption of Villarrica Volcano, Chile

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Many volcanoes in the world are located in remote areas, which are in most cases not accessible during volcanic eruptions. Satellite-based Earth Observation (EO) provides a non-restrictive global monitoring of all sub-aerial volcanoes. As a case study, we will present the analysis of the 3 March 2015 eruption of Villarrica Volcano, Chile.
This eruption was investigated based on a time series analysis of thermal data acquired by the small experimental German Aerospace Center (DLR) satellite Technology Experiment Carrier-1 (TET-1). We will present a newly developed workflow for an atmospheric correction of the thermal satellite imagery and an analysis of the detected thermal hotspots at sub-pixel level, including their temperature, area coverage, and radiant power. The detected thermal anomalies were compared with observations derived from Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) data. Nine days before the eruption thermal hotspots were detected. After the decrease of the radiant power following the 3 March 2015 eruption, a stronger increase of the radiant power was observed on 25 April 2015. Moreover, the eruption-related ash coverage of the glacier at Villarrica Volcano was investigated by TET-1 imagery.
Furthermore, the volcanic activity of this ice-capped volcano was studied by a combined high resolution optical and synthetic aperture radar (SAR) rapid mapping approach, which is based on a combined time series analysis of Sentinel-1 and Landsat-8 data.

Necessity for and Challenges of Long-term Predictions of Volcanic Activity

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Countries that have been using nuclear energy for power production are looking for underground storage sites for high lever radioactive waste. Due to the lasting radiation, this waste shall be isolated from ecosystems for at least one million years. In order to guarantee such a safe long-term storage, geodynamical rather stable storage regions are required. Hence, hazards of seismicity, active faulting, deep erosion, or volcanism have to be avoided, by selecting appropriate storage sites. The German Repository Site Selection Act, short StandAG lists exclusion criteria including Quaternary volcanism and expectation of volcanic activity in the future (StandAG §22).

Within central Europe, basic magmas erupted in single monogenetic volcanoes and several volcanic fields during the Cenozoic era. In some of these fields, higher differentiated magmas evolved within the Earth's crust, resulting in larger eruptions affecting wider areas.

Probabilities and risks for this kind of volcanic activity are difficult to quantify based only on the past eruption histories. Therefore, new methods have to be developed in order to provide a way to assess spatially differentiated levels of hazards for future volcanic activities. The German geological survey, BGR initiated a research project in order to develop a methodology for such a long-term activity assessment. It shall consider information from multiple geological, petrological, geochemical, and geodynamic indicators for past volcanism, present status of the Earth's crust and mantle, and numerical models of future developments of mantle convection, melting and lithospheric dynamics that could facilitate generation and ascent of magmatic melts and fluids.

Current models of Cenozoic geodynamics and magmatism shall be evaluated by inter-disciplinary panels of experts in order to define the state of science and, if possible, agree upon a scenario for the next one million years. Semi-quantative ways are being sought in order to weight the significance of individual indicators and for the synopsis of the different indicators. Uncertainties and the limitations of data coverage need to be addresses in this procedure and in the application of this methodology to map areas that should be excluded in the site selection process.

As the selection of a high-level radioactive waste repository is a politically sensitive topic, a transparent, science based methodology that can be applied to the entire area of the Federal Republic of Germany is essential for unbiased advice to politics and to ensure public trust. Experts are welcome to contribute to this challenge and apply scientific knowledge to provide necessary answers to solve one of the serious problems of our society.

Seismological Constraints on Magmatism below the Eifel

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The Quaternary volcanism in the Eifel volcanic fields, Germany, started about 700,000 years ago. Since then about 350 eruptions occurred in the West and East Eifel volcanic fields (WEVF, EEVF), ranging from small-scale scoria cones and maars of different sizes, to large-scale paroxysmal eruptions. The deep structure underneath the Eifel, especially the upper mantle, was studied during the Eifel Plume Project. The main findings are deep-reaching seismic low-velocity anomalies which are interpreted as regions of increased temperature and partial melt content. This interpretation infers that there is about 4,000 km^3 of melt in the upper mantle. A recent seismological study by a group of scientists on the local seismicity indicates a probable ongoing intrusion of magmatic fluids which is fed by the mantle melts.

Characteristics of central explosions at Santiaguito volcano

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Since 2018, Santiaguito volcano in Guatemala is permanently monitored by 4 seismic and 3 infrasound stations. In order to gain more information about the observed explosions and tremors, we installed a temporary seismic antenna consisting of 9 Lennartz Le3D 1 Hz seismometer and 5 infrasound sensors for 11 days in January 2019. The stations were deployed at a distance of 2 km to the active vent (Caliente). Additionally, we installed 1 new infrasound sensor and 3 additional temporary seismometer, as well as 1 new permanent broadband seismometer. Together with the permanent network, our temporary array covered a distance range from Caliente between 0.5 and 4 km which allows us to investigate the amplitude decay of the explosion signals. Furthermore, we use the data of a thermal camera to compare the seismic and infrasound data to the actual activity at the crater.
This study focuses on the explosions accompanied by ash and gas rise at the central vent, for which a slowness of 0.3-0.6 s/km can be estimated with fk-analysis using our temporary antenna. The calculated backazimuth is smaller than expected which might be explained by a zone with reduced seismic velocity under the previous active domes La Mitad, El Monje and El Brujo. The data of the stations nearest to the vent show for multiple central explosions a signal preceding the main explosion impulse. The length of this precursor varies between
2-10 s and no activity is observed during this time with the thermal camera at the crater.

Laacher See Phonolite, Cumulates and Syenites: Different eruption products that constrain the pre-eruptive history

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Time-scales extracted from chemically zoned minerals provide insights into crystal residence time, magma storage and compositional evolution of magmas and allow better understanding of pre-eruptive history of large and potentially dangerous magma chambers. We studied chemical diffusion across zoning and exsolution patterns of alkali feldspars in phonolite, carbonatite-bearing cognate syenites and cumulates: different products from the 6.3 km3 (D.R.E) phonolitic Laacher See Tephra (LST) deposit in western Germany (12.9 ka).

Diffusion chronometry was applied to zoned alkali feldspars from each of the eruption products separately. A diffusion modelling of K-Na interdiffusion in sanidines from syenites of known pre-eruptive age gives 630-670 oC as the range of effective storage temperature. These values along with a conduction model constrain the radial growth speed of the syenite carapace at ~8 cm/year. Diffusion across the exsolution boundaries constrain the maximum time between the destabilisation of the system prior to eruption to be only 40-50 days. A similar diffusion modelling was applied to Ba-diffusion across zonations in sanidine phenocrysts from phonolite samples. The phenocrysts in the felsic samples (the top of the magma chamber), being very similar to those of the syenites and not being in equilibrium with the surrounding matrix, are interpreted to be xenocrysts that were entrained from the syenites into the phonolite during the unrest before the eruption. The phenocrysts in the mafic phonolites (the base of the magma chamber) have Ba-rich outermost rims of 2-10 μm and diffusion modelling on the corresponding boundary gives a time scale of 4-7 years, which is interpreted to be the maximum duration between the most recent recharge event by basanite magma and eruption. However similar time-scale is not obtained from the phonolite of intermediate composition (middle of the magma chamber) suggesting that the effects of the basanite intrusion were limited only to the base of the magma chamber. Diffusion time-scales obtained from the inner zones of the sanidine phenocrysts from both mafic and intermediate phonolites suggests another similar recharge event 1500-3000 years before the last basanite recharge. The cumulates, however lack zoned crystals. Although crystals with resorbed boundaries or very thin overgrowths (a few microns) with very sharp compositional changes imply the activation of cumulates only months before eruption. Based on the diffusion time-scales and storage temperatures obtained from the zonation and exsolution in feldspars from different products of the same magma system, we present a genetic model for the process and timing of storage and activation of the system prior to the eruption of Laacher See.

Insights into the compositional evolution of crustal magmatic systems from coupled petrological-geodynamical models

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The evolution of crustal magmatic systems is incompletely understood, as most studies are limited either by their temporal or spatial resolution. Exposed plutonic rocks represent the final stage of a long term evolution punctuated by several magmatic events with different chemistry and generated under different mechanical conditions. Albeit the final state can be easily described, the nature of each magmatic pulse is hampered. This study presents a new method to investigate the compositional evolution of plutonic systems while considering thermal and mechanical processes. A thermo-mechanical code (MVEP2) extended by a semi-analytical dike/sill formation algorithm, is combined with a thermodynamic modeling approach (Perple_X) to investigate the feedback between petrology and mechanics. Melt is extracted to form dikes while depleting the source region. The evolving rock compositions are tracked on markers using a different phase diagram for each petrological composition. The rock compositional evolution is thus tracked with a high precision by means of a database with more than 50'000 phase diagrams. This database is able to describe how density, melt fraction, chemical compositions of melt and solid fractions and mineralogical assemblages change over crustal to uppermost mantle P-T conditions for a large range of rock compositions. Each bulk rock composition is composed of the 10 major oxides (SiO2-TiO2-Al2O3-Cr2O3-MgO-FeO-CaO-Na2O-K2O-H2O) including an oxygen buffer.
The combined modeling approach is applied to study the chemical evolution of the crust during arc magmatism and related melt extraction and magma mixing processes. Basaltic sills are periodically injected into the crust to model heat influx for the mantle. Accumulated sills are turning into long-lived mush chambers by using a lower rock cohesion or due to high intrusion depths. The resulting melts can be highly evolved and are extracted to form dikes in the overlying crust. Associated partial melting of crustal host rocks is promoted by the water amount, and occurs around dense distributed dikes and sills. High silica rocks (e.g. granites) are generated by melting of the host rocks, melt segregation within dikes, and from high-degree crystallized basalts. For the genesis of arc continental crust are these highly in silica enriched rocks only of minor relevance, as mafic to intermediate rocks dominate.

The effect of vent asymmetry on volcanic jet dynamics

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Explosive volcanic eruptions pose threat to health and infrastructure due to their highly energetic and dynamic nature. Gas overpressure derived from magmatic volatile exsolution is the driving force for magma fragmentation. The production of pyroclasts occurs primarily within the conduit, whereas the direct observation of eruptive processes is limited to processes above the vent. Thus, an enhanced quantitative understanding of volcanic eruptions must rely on laboratory experiments as well as analogue and numerical models.

Scaled rapid decompression experiments, employing four circular symmetrical vents, were conducted to investigate the influence of geometric features (conduit length, fragmentation depth and vent geometry) and physical parameters (particle load, particle size and temperature) on the dynamics of gas-particle jets. Previous experimental results reveal a paramount influence of tube length, particle load and vent geometry (Cigala et al., 2017). Natural volcanic vents are 1) less regular in geometry and 2) change on very short time-scales, as has been observed for example by repeated drone surveys.

In this study, six vents with bilateral symmetry (cylindrical and diverging inner geometry and slanted top plane at 5°, 15° and 30°) have been used to elucidate the dynamics of a) gas-only and b) gas-particle starting jets upon decompression. Additionally, varying pressure ratio (8, 15 and 25 MPa) and particle size (monomodal particle size distributions with 125-250 µm, 0.5-1 mm and 1-2 mm diameter) were employed. Experiments were recorded with a high-speed camera at 10000 frames per second in order to examine gas and gas-particle jet dynamics and reveal inclination of the jets. Increasing the slant of the top plane and the pressure ratio correlate positively with the degree of jet deviation. Particle size showed a negative correlation with particle spreading angle while particle exit velocity was positively correlated with overpressure.

Inclination in the gas-thrust region of volcanic jets can influence the behaviour of the entire eruption column and therefore may lead to a preferential directivity for ballistics and pyroclastic density currents. Since vent geometry can easily and repeatedly be observed at high precision by drones, even during phases of elevated activity, increased knowledge about eruption dynamics based on vent geometry has the potential to support identifying hazard zones for explosive volcanoes.

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Evolution of the Laacher See eruption (LSE), its environmental impact and ongoing research

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Part I Summary of major aspects of the Laacher See Eruption (LSE)

(selected papers published work between 1970 and 2009)

The phonolithic LSE is characterized by:
(1) a pre-Plinian hydroclastic opening blast; (2) many interruptions of eruptive activity due to repeated major collapse of the vent/conduit; (3) repeated and pronounced changes in eruptive and transport mechanisms; (4) pronounced stratification of the tephra deposits resulting from the unsteady eruption dynamics; (5) many tephra layers extremely rich in lithoclasts (*big bang* events) resulting from clearing the blocked conduit/vent system; (6) major chemical and mineralogical zonation of the magma reservoir resulting in a prominent change in color, crystal content and composition of the juvenile clasts incorporated within a LST section from base to top; (7) pronounced hydroclastic terminal eruptive phase, characterized e.g. by textbook antidunes and chute-and-pool structures; (8) extreme abundance of subvolcanic crystal aggregates (subvolcanics); (8) long duration of late phase (at least many months); (9) sulfur-rich magma composition resulting in massive and widespread syn- and post-eruptive climate impacts.

Part II Major syn-eruptive impact of LSE on the Rhine River (publications 2019)

The Rhine River was impacted by two contrasting types of eruptive activity during the LSE - fallout and pyroclastic flows - resulting in damming at two opposite locations. Dam formation at the *upstream* entrance of the tectonic Lower Neuwied Basin close to the city of Coblence (Coblence lakes) was triggered solely by fallout directly into the Rhine River during active Plinian fall. Each breach of Coblence Dam consisting of loose fallout tephra washed together during breaks between fallout phases caused massive flooding resulting in severe erosion of the previously deposited tephra throughout the entire Lower Neuwied Basin. The floods deposited impressive, large-scale upper flow regime structures such as in-phase wave draping, chute-and-pool structures and antidunes consisting almost entirely of gravel-sized tephra components.
A second giant lake – Lake Brohl - started to accumulate behind a pyroclastic flow-generated dam blocking the narrow Rhine valley at Brohl, c. 30 km downstream of Coblence Dam and c. 7 downstream of the Lower Neuwied Basin about halfway through the eruption at the end of MLST-A. Lake Brohl had a volume of 2.6 km^3 and a surface area 300 km^2 immediately prior to breach of Brohl Dam - its backwater extended up to 140 km upstream as far as the Upper Rhine Graben. The upper 13 m of the lake (ca. 2 km^3) were drained very rapidly triggered by the powerful resumption of eruptive activity after a break of ca. 8-10 days, while the lower water body (0.56 km^3) drained more slowly interrupted by breaks. Drainage of the upper water body resulted in a catastrophic flood wave downstream that can be traced at 20 localities as far as 52 km downstream of Brohl dam. There is evidence that the flood wave even reached the Netherlands, > 400 km downstream.

Part III Ongoing collaborative work on LSE

1. The origin and age of the Younger Dryas stadial (YD) subsequent to late-glacial Alleroed warming

The old idea of Reginald Newell (MIT) of LSE having triggered the YD by climate impact (written comm. to HUS in 1974) was subsequently replaced by a broad international consensus that the Younger Dryas (YD) started about 200 years after the LSE and that the cause of the thousand year long cold spell was potentially a sudden influx of cold St. Lawrence water into the Atlantic. Present speculations include: (1) The exact onset of the YD varies depending on the latitude; (2) The YD was triggered by a major cosmic impact event as indicated by the deposition of 10 million tonnes of impact spherules across four continents; (3) The YD was triggered by the climate impact of LSE, because a Pt (platinum)-peak is thought to correlate with the beginning of the YD. Pt may have been released to the atmosphere by the LSE (or by a cosmic impact in northern Greenland). In collaboration with Brown et al. (GB) we have collected LST tephra across the stratigraphy in October 2018 for Pt analysis.

2. Ultraprecise dating of LSE

At an international workshop (Cambridge, ETH Zürich, GEOMAR) in early January 2019 in the Eifel, the boundary conditions, methods and need for an ultraprecise dating (by year (!)) of LSE were discussed, including 2 field days to collect wood samples of trees grown at the time of LSE. High-resolution ^{14}C dating of individual tree rings is done at ETH facilities (Buentgen et al.).

3. Low frequency earthquakes

Deep low frequency earthquakes, generally interpreted to be generated by fluids (e.g. magma) rising through the mantle/crust were detected in a sector between Ochtendung and Glees, parallel to the Mendig graben, raising the prospect of new magma rising beneath the LS and possibly heralding a new eruption in the - distant – future (Hentsch et al. 2019).

Speculations of a second LS eruption voiced by several workers over the decades were discounted by us based on clear field evidence. Several large (meters across) clastic pipes with fluidized structures and basalt/Devonian blocks meters across found by us in the Glees area and between Rothenberg and Bell are unconformably overlain by LST. The Bell pipes are located above the NW group of DLF earthquake epicenters. Their origin - so far unstudied - and a potential connection to an early developmental stage of the LS magma system will be studied in the near future.

4. Hazard and risk

A reevaluation of the hazard and risk implications of a potential renewed LSE activity is planned.

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CO_2 vs. H_2O: young West Eifel maars revisited

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The origin of Pulvermaar in the southern Westeifel Volcanic Field (WEVF), a prototype maar conventionally attributed to magma-water interaction since the early 1970ies, shows compelling evidence for a strong magmatic component. Some tephra beds are volumetrically dominated by subround igneous nodules. In these, a cumulate-textured plutonic/subvolcanic core of variably vesicular pyroxenite/hornblendite is surrounded by a rim of fine-grained hauyne-rich melilite-nephelinite lava. While Lloyd and Bailey (1975) interpreted the cores as evidence for mantle metasomatism, Duda and Schmincke (1985) re-interpreted the cores as intermediate-pressure plutonics as shown by several criteria, especially undeformed cumulate textures. CO_2-dominated fluid inclusions in cpx of the nodule cores suggest crystallization of the magmatic body at ca 20 km crustal depth (Hansteen pers. comm.). This depth corresponds to that measured on fluid inclusions from crustal xenoliths in the EEVF (Sachs and Hansteen 2000). Metamorphic crustal rock fragments are relatively common in the Pulvermaar deposits and likely represent fragments of the lower crust. Structurally, the nodules resemble magmatic *pellets* or *autoliths*, common in (melilite) nephelinites, including the melilite nephelinites of the EEVF (Herchenberg, Leilenkopf) (Bednarz and Schmincke, 1990), and in kimberlites worldwide. A major role of CO_2 in the formation and upward transport of the nodules is suggestive.
Four young maars of contrasting chemical composition in the southwest WEVF (Ulmener Maar, Pulvermaar, Sprinker Maar (Wartgesberg), Meerfelder Maar) (Mertes and Schmincke 1985) show a suggestive relationship between magma composition and eruptive mechanism. Maar deposits of CO_2-rich melilite nephelinite and derivative magmas contrast with those of basanite magmas. Classical criteria for magma-water interaction (hydroclastic fragmentation mechanisms; Schmincke 1977) are clearly developed in the *basanitic* Wartgesberg/Sprinker maar deposits but are poorly developed to absent in the strongly silica-undersaturated Ulmener, Meerfelder and Pulvermaar volcanic tephra components. Eruptive mechanisms inferred from volcanic particles of Meerfelder Maar tephra that comprise glassy lapilli (lava fountain spray) but are dominated by angular tachylite particles within the volcanogenic tephra fraction, are equivocal. Microvesicular, *non-glassy* and subround essential lapilli in the more evolved Ulmener Maar (UM, the youngest volcano in Germany) tephra deposits contrast with those in typical hydroclastic maar deposits. The ubiquitous carbonate cement suggests a major role of CO_2 in the origin of UM. More detailed work on the deposits of all four maars focussing on the role of fluids (CO_2 *vs* external H_2O) is planned.

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Investigation of bromine chemistry in volcanic plumes in smog chamber experiments

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Volcanic gas emissions are of importance for atmospheric chemistry on local and global scales. The discovery of reactive halogen chemistry in volcanic plumes brought new insights into the significance of volcanic halogen emissions. The investigation of reactive halogen species (RHS, e.g. BrO, OClO, IO, I2) made great progress in recent years, but also revealed uncertainties concerning the formation mechanisms and the impact of environmental parameters (e.g. plume gas and aerosol composition, relative humidity). Understanding the influence of these parameters on the halogen activation (i.e. conversion from hydrogen halides to RHS) in volcanic plumes is essential for an interpretation of field observations e.g., relating them to magmatic processes and investigating the atmospheric impact of volcanic halogen emissions (e.g. ozone destruction, oxidation of mercury or reduced methane life time).
Atmospheric simulation chamber experiments were undertaken at Bayreuth to investigate a simplified volcanic plume (initial conditions: sulfuric acid aerosols with H2O (RH 10-70 %), SO2 (10 ppm) and HBr (5 and 25 ppb) as trace gas components) under controlled conditions in a 4 m3 Teflon chamber. Solar like radiation was provided by a solar simulator. A White multi-reflection cell as well as a multichannel cavity enhanced DOAS (Differential Optical Absorption Spectroscopy) instrument enabled online observation of BrO formation and other trace gases. Additional instruments and sampling techniques were employed such as alkaline trap sampling for total bromine and sulfur measurements and gas diffusion denuders for bulk reactive bromine species measurements. Particle size distributions were determined by SMPS (Scanning Mobility Particle Sizer Spectrometer) and SO2, NOx and O3 were monitored by standard in-situ gas analyzers. The artificial plume was diluted with a constant admix of ozone and zero air to simulate the dilution of volcanic gases by the atmosphere after being emitted from a volcanic vent.
By varying the initial experiment conditions, the influence of following parameters on the extent and rate of BrO formation were investigated: (1) initial HBr/SO2 ratio, (2) relative humidity, (3) O3 admixing, (4) particle abundance and composition. Within the scope of the experiments, BrO formation with peak values between 100 and 900 ppt was observed with BrO/SO2 ratios ranging from 0.3E-4 to 1.8E-4. The choice of the initial plume composition also had a significant impact on the delay of the BrO formation. Surprisingly, although not a strict prerequisite for Br-activation, SO2 seems to have an accelerating effect on the formation of reactive bromine species. Primarily in experiments with high initial HBr, O3 was depleted to a few ppb after the first occurrence of Br activation strongly limiting the formation of BrO within the simulated plume.

Energy-optimized and GPS-synchronized data acquisition system network for volcanic (infra)sound monitoring

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The use of acoustic signals in the audible range for volcanic monitoring is a relatively new approach with very promising results as reported in the last years. This approach allows the monitoring in remote areas mainly due to the simplicity of the system, its low cost and its low weight. Until now, the interpretation of the signals has been insufficient, but the last advances in jet noise make the identification of the main parameters for volcanic conditions possible and therefore make the volcanic monitoring based on acoustic measurements feasible. We developed a new data acquisition system that has been optimized for extremely low power consumption (around 3.2 W) based on a Raspberry Pi with a custom lightweight operating system, a GPS module, two microphones (for high and low frequencies), a temperature sensor and an external power bank. The pressure signals are recorded in both, the audible range and the infrasonic range with two different sensors, having an overlapping frequency range and delivering a seamless spectrum from 0.1 Hz to 10kHz, that can be extended up to 100 kHz. Moreover, the temperature in every station is measured to have information about the speed of sound of the environment. The synchronisation of the signals from different stations is based on the Pulse Per Second - signal from the GPS module, which restricts the maximum delay between signals to 5 µs. The system can run up to 32 hours with a conventional 20000mAh power bank. A network of 9 stations was deployed at Stromboli from 08th to 13th September 2018. The data recorded can be treated as a single array or the data from single stations can be evaluated independently. This flexibility is crucial to merge the volcanic monitoring with the volcanic research, in which an efficient alternative monitors continuously the behaviour of a specific volcano while researchers get continuously high-quality data to improve their understanding of the physics of volcanoes and the modelling related to their research.

Volcanic clouds: how aviation deals with them

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´´Ash clouds´´: these words bring to mind near catastrophic encounters of aircraft with such clouds, but also the blue sky over Europe in 2010, which was clear of volcanic ash and aircraft, too, as the regulatory framework was not fully developed. In the presentation, a theoretical eruption of Mt. Etna will be used to introduce aviation ash cloud depictions and associated procedures, moving on to a more realistic example of last years´ ash-exercise in the ICAO Region Europe / North Atlantic.
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Rheological variability of the 2018 Kilauea eruption

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The rheology of lava exerts a first-order control on flow dynamics. Major influences on lava rheology are exerted by thermal, compositional, and textural state. Deciphering their relative contributions in the highly dynamic regime of active lava flows is a major challenge.
During the four month-long 2018 Kilauea eruption, a wide range of effusion temperatures, bulk compositions, and textures was documented for the 18 ephemerally-active eruptive fissures. Using a representative sample suite spanning the compositional range (basalt to andesite) and variety of the erupted lavas, we have initiated a systematic experimental investigation the effects of composition, crystallinity and temperature on lava rheology. High temperature viscosities are being determined using concentric cylinder viscometry. Preliminary results from a distal `a`a flow sample of the Fissure 18 episode indicate a range of melt viscosity from 2 Pa s at 1500 ºC to 40 Pa s at 1200 ºC. Liquid+crystal rheology measurements are currently being conducted at appropriate magmatic temperatures
(1020 ºC – 1140 ºC).
This rheological study will be innovative in its comprehensive treatment of the variability of rheology from this event series. Our goal is to set a new standard for future rheological investigations of multi-episode effusive eruptions. It is anticipated that quantification of the inter-episode variability of lava rheology will enhance our ability to evaluate the sensitivity of observed flow speeds and emplacement dynamics to viscosity variations, greatly improving models of the latter for the future.

Experiments investigating the role of temperature and water content on the generation of volcanic lightning

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Volcanic lightning is the result of ash electrification within volcanic plumes. It is increasingly being detected at erupting volcanoes (Bogoslof, 2017; Ambae, 2018; Fuego, 2018 among the most recent) emphasising its great value for the detection of volcanic plumes and analysis of plume dynamics. However, lack of knowledge on the quantitative relationships between the jet conditions and the electrical activity within the plume hinders efficient analysis of the data. To fill this gap, an increasing number of experimental studies has been recently carried out to constrain these relations (e.g. Cimarelli et al., 2014; Méndez Harper et al., 2018).

In this study, we investigate the influence of water content and temperature on electrification. Decompression experiments were carried out using loose volcanic ash samples (grain size 90 to 300 micrometers). Samples with similar mass (13 g) were pressurised to identical initial pressures (9 MPa). With all parameters kept constant, only temperature (between 25 and 320 °C) and water content (between 0 and 27.0 wt.%) were varied systematically. The samples were ejected into a 3 m high, fully electrically insulated collector tank. The tank itself served as Faraday cage to detect both the built-up and neutralised charge within the jet at a rate of 1/µs. A high speed camera (30000 frames/s) was used to record the experiments.

Temperature has a major influence on the charge and discharge generation processes. At room temperature, we observe no charging of the argon gas, which is used as carrier gas during our experiments. At 120 °C we observe significant gas charging, as well as much higher charge rates (most charge built up before the first discharge) and earlier discharging. The gas charging effect gets smaller towards higher temperatures, so that it gets almost negligible at 320 °C. Open questions persist on how material parameters and jet dynamics might influence the charging at those elevated temperatures.

We observe that an increased amount of water hinders effective charging of the material. Already few weight percent are sufficient to reduce the amount of charge and discharge by orders of magnitude. This is caused by a reduced number of particle-particle collisions, as the jet expands much quicker in presence of water vapour. Additionally, the highly increased conductivity of wet ash compared with dry ash decreases the charge density on the ash particles.

Water can therefore have a two-fold effect on plume electrification. On the one hand, water within the plume (like in our experiments) reduces the amount of charge. On the other hand, water present during fragmentation (like in phreatomagmatic eruptions) would increase the fragmentation rate and thus the amount of fines, which has a positive influence on the electrification.

Future experimental work will cover further parameters, e.g. ash chemistry, crystal content or the presence of ice to develop a model predicting discharge generation for known conditions.

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Interpreting Vulcanoes and Vulcanism : 'explosive' potential ... ?!

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Vulcanoes do have their ‘inherent‘ fascination – as do dinosaurs – nevertheless, relating this (worldwide) phenomenon in different ‘proximities‘/neighborhoods/concerns/ “Betroffenheiten“ to a (still) broader public – and to transformative learning/“ESD“* towards the goal of ‘future-ability‘ (Zukunftsfähigkeit) and the “AGENDA2030“-“SDGs“** : some additional inspirations and instrumentative tools from the “Art of Interpretation“*** might be considerable or helpful … (and result in some ‘added value‘)

*ESD = Education for Sustainable Development (UNESCO and VENRO, among others); **SDG = Sustainable Development Goals (of the UN); ***original author: Freeman TILDEN, 1962

Dynamics of carbon dioxide exhalations in mofettes

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Mofettes are cold geogene carbon dioxide [CO_2] exhalation sites, where CO_2 degasses from the pedosphere into the atmosphere. Mofettes can be found on recent or post volcanic sites, or seismic disturbances. Through cracks and fissures, the carbon dioxide moves towards the earth's surface. Degassing follows a concentration gradient. Annual and periodic CO_2 concentration measurements in the Vulkaneifel (Germany) and Northwest Bohemia (Czech Republic) show that the local outgassing centers are stable, but concentrations can vary. Ten year studies indicate annual and seasonal changes in the carbon dioxide concentrations in the soil. The evaluation of seasonal datasets illustrate that CO_2 concentrations are low during summer and autumn, and high in winter and spring. Results also indicate a correlation between the carbon dioxide exhalations and different weather conditions. In addition, parallels with seismic and non-seismic activities can be found out. A seismic correlation seems to occur in the mofette area of the Cheb Basin (NW-Bohemia). Current measurements after swarm earth quakes in summer 2018 lead to the conclusion that seismic activities may be responsible for the variation of local carbon dioxide degassing.

Repeated gravity measurements across the Rhenish Massif

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In continental plate interiors, ground surface movements are at the limit of the noise level and close to or below the accuracy of current geodetic techniques. Absolute gravity measurements are valuable to quantify slow vertical movements, as this instrument is drift free and, unlike GNSS, independent of the terrestrial reference frame. Since 1996, repeated absolute gravity (AG) measurements have been performed in Oostende (Belgian coastline) and at eight stations along a southwest-northeast profile across the Belgian Ardennes and the Roer Valley Graben (Germany), in order to estimate the tectonic deformation in the area. Since 2011 we have measured absolute gravity at Schalkenmehren and Burg Eltz, in order to monitor possible volcanic activity in the Eifel region. During this conference, we will discuss the installation of a third station around the Laacher See.

Electrical monitoring of volcanic plumes: a multi-parametric analysis

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Volcanic lightning is a common phenomenon in ash plumes, resulting from fragmentation and collision of ash particles in explosive eruptions. Famous recent examples around the world include the eruptions of Eyjafjallajökull (2010), Colima (2015), Fuego (2018), Anak Krakatau (2018) and Sakurajima (almost daily). Large magnitude electrical discharges can be detected up to several hundred kilometres away from the volcano. This allows for the near real-time monitoring of explosive volcanic eruptions at a safe and remote distance. However, the sensitivity of different electrical sensors determines the size and number of the recorded electrical discharges, therefore affecting the time resolution of the plume detection.
Here, electrical discharges were recorded in situ at the Minamidake crater of Sakurajima volcano, Japan, using two Biral Thunderstorm Detectors (BTD-200) deployed within few kilometres of the crater. These observations were combined with detections from three wideband sensors from the Earth Networks Total Lightning Network (ENTLN). Since the ENTLN stations were located at much greater distances from the volcano, lightning interferometry was applied to the data to enhance detection of the signals originating from the volcano. Additionally we used Thermal Infrared (TIR) and visible high-speed videos and Doppler radar measurements to further constrain the dynamics of the observed plumes.
The BTDs were able to detect most of the explosions at Minamidake regardless of weather conditions and plume height, thus proving its suitability to monitor active volcanoes at proximal to medial distances. Lightning interferometry revealed to be a valuable method in detecting volcanic lightning at greater distances, even when the signals were not clearly visible in the raw data. Cross-correlation between the two signals shows strong correlated peaks shortly after the start of larger explosions. Also the peak particle ejection velocity measured by the Doppler radar corresponds well to the timing of electrical discharges and allows to distinguish between consecutive explosive pulses. The TIR images show a positive correlation between the plume height of the eruptions and the amount and magnitude of electrical discharges. These findings show that volcanic lightning cannot only be used as a monitoring tool at active volcanoes, but can also give a first-order estimation of the magnitude of the eruption.

Imaging the 2013 explosive crater excavation and new dome formation at Volcán de Colima with TerraSAR-X, time-lapse cameras and modelling

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The summit region of steep volcanoes hosting lava domes often displays rapid geomorphologic and structural changes, which are important for monitoring the source region of hazards. Explosive crater excavation is often followed by new lava-dome growth, which is one of the most dynamic morphometric changes that may occur at volcanoes. However, details of these crater formations, and the ensuing new dome growth remain poorly studied. A common problem is the lack of observational data due to hazardous field access and the limited resolution of satellite remote sensing techniques. This paper describes the destructive-constructive crater activity at Volcán de Colima, Mexico, which occurred between January and March 2013. The crater geometry and early dome formation were observed through a combination of high-resolution TerraSAR-X spotmode satellite radar images and permanently installed monitoring cameras. This combined time-lapse imagery was used to identify ring-shaped gas emissions prior to the explosion and to distinguish between the sequential explosion and crater excavation stages, which were followed by dome growth. Crater formation and dome growth is first observed by the TerraSAR-X data. By means of particle image velocimetry, the digital flow field is computed from consecutive camera images, showing that vertical dome growth is dominant at the beginning. The upward growth is found to grade into spreading and a lateral growth domain. After approximately two months of gradually filling the excavated craters with new magma, the dome overflows the western margin of the crater and develops into a flow that produces block and ash flow hazards. We discuss and compare the observations to discrete element models, allowing us to mimic the vertical and lateral growth history of the dome and to estimate the maximum strength of the bulk rock mass. Moreover, our results allow a discussion on the controls of a critical dome height that may be reached prior to its gravitational spreading. This study, for the first time, provides a detailed view into explosive crater formation and new dome formation at Volcán de Colima, with important implications for other dome-building volcanoes.

Bromine monoxide/Sulphur dioxide molar ratios in volcanic plumes from S5-P/Tropomi

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In this presentation, the potential of the recently launched Tropomi instrument to detect bromine monoxide (BrO) in volcanic plumes is investigated. So far BrO in volcanic plumes has been successfully retrieved from satellite only during major eruptions. The higher spatial resolution of S5-P/Tropomi (3.5x7km^2) and the daily coverage allows for an investigation of volcanic BrO during smaller eruptions and even during continuous passive degassing. The continuous observation of passive degassing volcanoes yields the potential for long-term monitoring of volcanoes from satellite. Also, it is expected that the volcanic plumes can be tracked over larger distances.
BrO is a halogen radical altering – inter alia – the atmospheric ozone chemistry. BrO and in particular the molar BrO/SO2 ratios in volcanic gas emissions have been suggested as proxy for monitoring volcanic activity on several accounts.
In this study, we present BrO column densities as well as SO2 column densities retrieved using Differential Optical Absorption Spectroscopy (DOAS) and BrO/SO2 molar ratios in volcanic plumes with varying emission strength from Tropomi data. By deriving a time series, we investigate the variation of the BrO/SO2 molar ratio of various volcanoes, in order to investigate plume chemistry and emission composition.

How does lava fountaining and vent morphology influence each other? A case study 2014-2015 Holuhraun fissure eruption

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At fissure eruptions, both lava fountains with complex venting activity in pulsating form and the development of characteristic morphological features occur. Recent studies based mainly on analyses of old structure and hence, are not related to direct observations and systematic vent activity records.
Here, we analyze the 2014-2015 Holuhraun eruption site, Iceland, to study the location and evolution of these cones and their relationship to venting dynamics. Therefore, we analyze video records from lava fountain activity at distinguished vents during the first days of the eruption and compare them with the morphology of spatter cones that developed. The cone morphology was provided by our fieldwork mapping project which combines terrestrial laser scanning (TLS) and unmanned aerial vehicle (UAV) aerophoto techniques.

First, we find a decrease in the number of active vents producing lava fountains from 57 along the whole line of fire to 10 lava fountains at distinct vents during the first five days of the eruption. Thereby the locations where spatter cone morphology developed, are where the strongest and the highest lava fountains were recorded. Accordingly, the sites that eventually developed moderate or weak cone morphologies were identified as less active lava fountain locations. Secondly, the comparison of our topographic datasets shows that the spatter cones remained similar in shape but increased in size as the eruption progressed. We suggest that the observed changes in morphology are related to lava ponding in the crater, which in turn strongly influenced the lava fountain heights. In our lava fountain height model, we show the effect of entrainment due to lava ponds on the height.

Based on this study we are able to demonstrate the close relationship between cone morphology and lava fountain activity at the onset of an eruption.

Fluid migration, fast and slow

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Monitoring gas discharge and composition is a standard component in many volcano surveillance programs. The logic behind is that rising magma depressurizes while ascending to the surface and thus releases gases, which then can travel faster to the surface than the magma itself. But how fast is fast? Are some gases traveling faster than others? This review compiles fluid migration studies - velocities are hardly reported - from various crustal environments and compares the findings with theoretical velocity models provided e.g. by Dahm (2000) or Etiope & Martnielli (2002). Selected case studies are presented, including injection experiments with He and CO2. Another case is related to the El Hierro submarine eruption on 12 October 2001. Total Helium, 3He/4He, CO2 and H2S showed precursory signatures. Guess, which of the gases was the fastest.

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Geochemical constraints on physical models of the Laacher See Magma system

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Petrological, geochemical and geochronological data constrain the location, volume and architecture of the Laacher See magma system as well as its thermal evolution and unrest events that eventually triggered the eruption 13.000 years ago.
A minimum volume of ca. 60 km3 of basanite melt derived by low degrees of partial melting of the asthenospheric mantle below the East Eifel volcanic field gave rise to the erupted evolved phonolite magma through fractional crystallization(1,2). Crustal contamination is minor and has no impact on erupted volumes(3).
The composition of erupted phonolite tephra deposit represents compositional stratification of the magma reservoir from mafic, crystal-rich phonolite at the bottom of the magma reservoir to phenocryst-free, highly evolved melt enriched in incompatible elements towards its top(1). The final erupted products from the base of the magma reservoir are characterized by mixing and mingling between contrasting phonolite and basanite magmas(4), which clearly proves that new, fresh basanite magmas had ascended and was replenishing the Laacher See magma reservoirs as late as 13 kyrs ago.
Pressure estimates combined with solubility data determined experimentally and the observed decrease in Cl towards to top magma layer indicates that the phonolite magma was actively degassing prior to eruption(2,5). High volatile contents (>5% H_2O, 0,3% Cl, up to 0,7% F) and enrichment in alkali elements (Na, K) result in low magma viscosities (4 – 5 log poise) and densities (<2,5 g/cm3).
Petrological investigations and studies of crustal xenoliths suggest the emplacement of the Laacher See phonolite magma chamber at a depth between 5 and 15 km(2,6). Cognate crystal-rich cumulates and carbonate-bearing syenite are witness of the formation of a crystal-rich carapace and a complex of layered cumulates that developed over time around the shrinking liquid core of the reservoir(7,8,9). Thermally metamorphosed and often partial molten crustal xenoliths indicate the development of an extensive thermal aureole within rocks of the Devonian crustal section down to the metamorphic basement.
U-series dating of phonolitic phenocrysts from the pumice and cumulate rocks(10) as well as zircon from the syenites(8,9) indicate that batches of highly evolved phonolite magma existed and began crystallizing about 20 kyr prior to eruption. The magmatic evolution from the parent basanite to the evolved phonolite with its surrounding carapace must have occurred well before that (>33ka) and possibly dates back to the last basanite activity in the region about 100 kyrs ago.
Late-stage heating events within the magma reservoir occurred prior to eruption and are recorded in diffusion gradients in feldspars of the phonolite, cumulates and syenites(11,12). Modelled diffusion times indicate thermal disturbances around 1500 to 3000 years prior to eruption, which, however, did not trigger an eruption. More recent phonolite-basanite mixing occurred about 4 to 7 years (maximum estimate) before eruption. The crystal-rich carapace and the lower more mafic magma layers where thermally disturbed by heating only within 40 to 50 days prior to eruption(11, 12). Thus the initial unrest events may have started several years before but the actual eruption trigger occurred very shortly before eruption.

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The extrusion of spines during lava dome growth using analogue experiments

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The production of spine domes is a commonly observed and hazardous phenomenon during lava dome growth at stratovolcanoes such as Mt. Pelée, Soufrière Hills, Mt. St. Helens or Mt. Unzen, yet many aspects controlling the formation of spines are only partially understood. Here, we provide new and detailed insight into the production of vertical spines during lava dome growth using a set of analogue experiments, extruding a sand-plaster mixture from a fixed conduit. Maintaining purely brittle behavior, results initially show endogenous dome growth through gradual intrusion of new material and slumping of oversteepening slopes, forming a talus. Once a greater depth level of the magma analog in the conduit reaches the surface, solid spines start extruding out the dome top and start a cycle of spine growth and collapse. Due to the appearance of spines on domes after prolonged extrusion already took place, we attribute their production to compaction of the conduit material at depth through shearing during the extrusion as well as load compaction due to the overlying conduit material and dome. This significantly increases cohesion and thus rock strength of the material and allows for the formation of solid spines. We also note that the diameter of the spines is significantly smaller than the diameter of the underlying conduit, thus the extrusion shear faults of spine domes are not representative of the conduit wall faults. Our findings translate well in to real spine growth scenarios, where compaction can be achieved by vesicle collapse and increased degassing due to overburden and magma pressure. They further highlight the relevance of experimental analysis of lava domes and spines, as they remain one of the most hazardous and unpredictable volcanic features.

II
Poster Presentations

Table of Contents (poster presentations)

Characterizing the degassing of Petroa and Copahue, two Andean volcanoes, Argentina, 2018

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The two active stratovolcanoes, Peteroa (35.240ºS, 70.570ºW, 3603 m a.s.l.) and Copahue (37.856°S, 71.159°W, 2997 m a.s.l.), are both located at the border between Argentina and Chile. Peteroa volcano is part of the NNE-oriented Planchón-Peteroa-Azufre Volcanic Complex. The about 5 km wide caldera at the Peteroa summit is partially covered by glaciers and consists of four craters hosting acidic lakes and one scoria cinder cone. Copahue volcano is situated on the rim of the large, about two million year old Caviahue caldera with an extension of ca. 6.5 x 8.5 km. The eastern currently active summit crater hosts a cold melt water lake, a hyperacidic lake and a spattering mud pool (observation March 2018). The crater is surrounded by walls of phreatic debris and glacier ice. The activity of both volcanos is characterized by phreatic and phreactomagmatic eruptions.
During February-March 2018, new emission flux and gas composition measurements at volcano Peteroa and volcano Copahue were undertaken. Measurements of the SO2 flux were performed with a scanning DOAS instrument. Using the wind speed measured at the crater and the distance of the instrument to the plume, the SO2 flux was calculated from the retrieved SO2 CDs of a series of scanning angles. The SO2 flux at Peteroa was 188(±28) tSO2/d and the SO2 flux at Copahue was determined to 1294 ± 377 tSO2/d. Both values are similar to earlier reported SO2 fluxes on Peteroa and Copahue, respectively.
Simultaneously to the SO2 fluxes, the CO2/SO2 ratio was determined inside the plumes with a PITSA instrument by measuring at the crater rim of crater 4, the only significantly degassing crater at Peteroa as well as on the crater rim of Copahue. The CO2/SO2 ratio for Peteroa on all three measurement days varied only slightly between 1,44 and 1,81 meaning that the CO2 flux of Peteroa plume was about 300(±72) tCO2/d.
At Copahue, the CO2/SO2 ratio lies between around 1 and 60. The large scatter in the CO2/SO2 ratio of Copahue's plume most likely originates from mixing of emissions from the closely located sources. The lowest values of the CO2/SO2 ratio (CO2/SO2 = 1) were assigned to the plume from the spattering mud pool, which has therefore a CO2 flux of 1294 ± 377 tCO2/d. This is however only a lower limit to the CO2 flux of Copahue since the CO2 emissions from e.g. the bubbling lake (where most of the SO2 might be scrubbed and therefore cannot be used for tracing plume CO2) are not taken into account.
In addition, the DOAS spectra for halogen species was evaluated. We could not detect any BrO or OClO above our column density detection limits of 2e13 molec cm-2 for both species and volcanoes. This means, assuming a plume diameter of 200 m for Peteroa that the maximum mixing ratios of BrO and OClO were below 57 ppt, and assuming a plume

diameter of 1300 m for Copahue, maximum mixing ratios of BrO and OClO were below 8 ppt .
Furthermore, a comparison between soil and plume emission was carried out for the first time at Peteroa. This comparison leads to the result that the major emission of CO_2 is focused on a “point source” – the lake inside crater 4. With the current data available from Peteroa, only about 2 % of the total calculated CO2 output are degassed by diffusive soil degassing in the crater region. Certainly, further studies in the surroundings are still necessary to assure no missing emission source on the flank of the volcano.

Exhibition of experimental test bed for investigation of damaging effects of volcanic ash to aircraft turbines

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The testbed shows a micro gas turbine to investigate damaging effects on thermal barrier coatings induced by volcanic ash. Volcanic ash particles mixed with turbine inlet air melt in the combustion chamber. Turbine blades and there thermal barrier coatings were stressed due to molten volcanic ash particles. Particle sampling in the exhaust gas jet shows molten Particles and not molten particles depending by engine throttle. Different damaging processes could be analysed. Strategies to reduce damages induced by volcanic ash were developed.

Artificial production of fulgurites and lightning-induced volcanic spherules

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Fulgurites and lightning-induced volcanic spherules (LIVS) are both natural occurrences produced by lightning strikes on ashy or sandy material, a process that is yet to be completely understood. To provide a better understanding of the melting mechanism and consequent physico-chemical modifications, several experiments under variable controlled conditions were performed, aiming to artificially produce fulgurites and LIVS. The starting material consisted of two types of glassy sand: natural volcanic ash from the Laacher See eruption (approximate diameter of 90 µm) and industrial E-type glass fibers (nominal length of 180 µm and diameter of 14 µm). Tests were carried out under the same conditions on both materials, changing the volume of sand at impulse durations of approximately 200, 500 and 900ms. Fulgurites and LIVS were successfully produced and studied, focusing on their morphological and chemical characteristics. The fulgurites are up to 20 mm on the longest axis and the spherules have a diameter up to 9 mm. Results show that the type of material is the main control that influences the proportion of fulgurites and LIVS in each experiment. The experimental material and the impulse duration both affect the size of the resulting fulgurites and LIVS – a longer impulse duration leads to the production of larger fulgurites and LIVS. Pristine material is commonly covering fulgurites and LIVS. Crystals such as quartz and feldspar from the Laacher See ash remain only partially molten and was identified both inside the glassy mass or covering it, and therefore are more resistant to transformations due to lightning strike than glass particles. At least two different compositions of glass have been identified in the spherules produced with the E-type glass fibers, due to contamination from the electrode. Scanning Electron Microscope analysis in a Laacher See ash fulgurite revealed the presence of an incipient barred-like texture in oxides, similar to the barred-olivine found in chondrules, with long fibers intersecting each other almost perpendicularly. Degassing processes were also observed through the presence of bubbles, mostly on the edges of the LIVS.

Trace gas imaging with Fabry-Perot Interferometer Correlation Spectroscopy

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Optical remote sensing of atmospheric trace gases in the UV and visible spectral ranges provides insights in chemical and physical processes of the atmosphere. Especially the fast and widespread evolution of atmospheric gas distributions in volcanic plumes can be studied on a comprehensive and more representative scale than by classical in-situ measurements.
Conventional ground based remote sensing observations are often limited to a single viewing direction or to a single spatial dimension (e.g. Differential Optical Absorption Spectroscopy DOAS) where the acquisition of images requires time-consuming spatial scanning. Full frame imaging techniques use non-dispersive wavelength selecting elements. The application of band pass filters (as used e.g. in the sulphur dioxide (SO2) camera) are limited to particular trace gases and can only be used under very specific measurement conditions due to cross interferences with the background sky.
Here we present a novel remote sensing technique based on the periodic transmission profile of a Fabry-Perot interferometer (FPI). The ability of tuning the FPI yields the opportunity to use two spectral channels where the first one correlates and the second one anticorrelates to the transmission profile of the target gas spectral absorbance, which exhibits approximately periodic variation with wavelength. This allows to quantify the differential optical density of trace gases and thus their column density with a high selectivity and sensitivity.
Using FPI Correlation Spectroscopy (FPI-CS) reduces the impact of broad band extinction processes in SO2 camera measurements. Moreover, it allows to image further trace gases including bromine monoxide (BrO) and chlorine dioxide (OClO). The latter species are both important for understanding the chemistry of volcanic plumes.
After first lab studies of a one-pixel device we present extensions to a FPI-CS 2-D imaging setup. First technical implementations for imaging and model simulations of the sensitivity and selectivity of the FPI-CS technique are presented.

Remote and in-situ gas measurements at Santa Ana volcano, El Salvador

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Volcanoes release large amounts of reactive trace gases including sulfur and halogen-containing species as well as and non-reactive gases (e.g., carbon dioxide) into the atmosphere. The relative abundance of carbon and sulfur in volcanic gas as well as the total sulfur dioxide emission rate from a volcanic vent are established parameters in current volcano-monitoring strategies, and they oftentimes allow insights into subsurface processes.

Santa Ana volcano, also known as Ilamatepec, is the most active volcano in El Salvador. The 2,381 m high Santa Ana volcano, is part of the Coatepeque-Izalco-Santa Ana volcanic complex. Its last eruption occurred in October 1st 2005 and, since 2008, its SO2 emissions are monitored within the Network for Observation of Volcanic and Atmospheric Change (NOVAC), with SO2 fluxes varying between 11 - 609 tons per day and an average of 221 tons per day during 2018. However, its volatiles emissions has not been extensively studied and only a few published gas data exist, usually just SO2 emissions (Rodriguez et al. 2004, Olmos et al. 2007, Barrancos et al. 2008, Colvin et al. 2013, Laiolo et al. 2017). Recently, Hasselle et al. 2017 presented the first compositional data for Santa Ana's gas plume (CO2, SO2, H2S and H2), measured in March 2017. As preliminary results a CO2/SO2 ratio between 21 and 99 (plateau and lake shore, respectively), and a H2/SO2 ratio between 0.34 (lake shore) and 2.44 (plateau) were reported.

In this study, we present SO2 long-term data of Santa Ana obtained from the NOVAC stations (2008 - 2018) and a description of the sampling techniques used during a field campaign in El Salvador in January - February 2019. The aim of the study is an improved characterization of Ilamatepec and therefore the forecasting possibilities. The extended data set will be discussed in context with former reported data and visual volcanic activity observations.

Changing magma stagnation depths related to oceanic volcano growth at Cape Verde

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Mafic magmas at ocean islands typically stagnate and partly crystallize in the upper mantle, and thereafter intermittently reside in the lower crust prior to further ascent1. We have performed clinopyroxene (cpx)-melt thermobarometry2 and fluid inclusion barometry on mafic alkaline rocks from submarine volcanoes in the Cape Verde Archipelago, comprising the morphologically young and possibly active Sodade Seamount and Charles Darwin Volcanic Field, both located in the northwest at more than 3 km water depth, and additionally from the submarine flanks of the active Fogo volcano at about 1.5 km depth. The host rocks comprise basanites, olivine nephelinites and olivine melilitites.
Most cpx-melt pairs reflect a comparatively deep early crystallization at pressures higher than 550 MPa, i.e. within the uppermost mantle. This overlaps with pressure estimates from a subset of the CO2-dominated fluid inclusions. At all locations, the remaining CO2-dominated fluid inclusions, and also some cpx-melt pairs, reflect a well constrained stagnation level at
similar data from Fogo island3. These pressures translate into depths of about 9.5 to 15.5 km. Considering the variable depths to Moho ranging from about 14 km for the young seamounts, through 16 km for the submarine Fogo flank volcanoes, to 19 km for the eruptions on Fogo island, the mafic magmas effectively stagnate at different crustal levels according to volcano size and age. Thus the mafic magmas at small and young seamounts pond close to Moho, while those at more mature and larger volcanoes rather stagnate within the lower crust.

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Artificial Fulgurites: Chemical and Textural Alterations, and a Comparison to Natural Samples

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Lightning is a transient, high-current electric discharge that most commonly occurs in thunderstorm clouds but is also frequently observed in volcanic plumes during large explosive eruptions. Lightning discharges can reach extreme temperatures of up to 104 – 105 K, being able to geochemically and morphologically significantly alter volcanic rocks in eruption plumes and on the ground, forming fulgurites [Mather & Harrison, 2006; Pasek et al., 2012, Genareau et al., 2015].

Aim of this study was to test the applicability of an experimental setup developed by Mueller et al. [2018] with respect to its ability to simulate fulgurite-forming conditions in the laboratory. For this purpose, natural fulgurites collected from South Sister Volcano, USA are compared to artificial fulgurites, produced by exposing a 7 mm rock cylinder to a 50 A electric arc in an Argon-rich atmosphere.

Textural and chemical properties of the fulgurites were investigated via secondary electron imagery combined with electron microprobe measurements. Comparisons revealed remarkable textural and geochemical similarity between the natural and artificial fulgurites. Key characteristics present in both fulgurite types are: I) the occurrence of at least three geochemically distinguishable melts; II) distinct mixing and mingling processes of the different phases, III) intense bubble formation, generating strong turbulences within the melt during flash-melting and IV) considerable mineral melting processes, including the formation of monomineralic melts, incongruent melting and dendritic growth structures.

The successful reproduction of the previously mentioned characteristics in the artificial fulgurites supports the applicability of our experimental setup for simulating alteration of volcanic rocks by lightning.

Drone-deployed sensors capture multi-parameter perspective of explosions at Stromboli volcano

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Explosive volcanic eruptions are comparably short-lived events with potentially catastrophic consequences and long-term impact. Volcanic hazard assessment relies on detailed mechanistic understanding of the associated physical processes (magma ascent, priming, and eventually fragmentation), which are not directly observable.
A series of acoustic and pressure sensors were deployed in September 2018 near active vents at Stromboli volcano (Italy) to better constrain the physical processes of mildly to moderately energetic explosions. Five out of the eight active vents displayed explosive activity, which ranged in intensity, duration, and ash content. We used six time-synchronized microphone arrays with double sensors and a range of 1-200Hz and 10-10000Hz, respectively. Additionally, three infrasound arrays and twelve drone-deployed sensors, which measured temperature, humidity, electric potential, pressure, and sound. The arrays were deployed 200-500 m (horizontal distance) from the active vents, whereas the sensors were positioned directly adjacent to them. The location of each sensor was determined by the drone's GPS measurements (at 10Hz). Close observations of eruptive activity over 5 days allowed for a complete correlation of time, duration, and source vent of 100 explosions.
Selected Strombolian explosions were analysed for the distance-dependent acoustic and pressure signals to allow for 1) revealing the radial dissipation of signals from explosive eruptions, 2) better constraining conduit conditions (depth, open/closed), and 3) correlating these features to different types of explosive events. Enhanced understanding of the spatial shift of the acoustic signal produced by explosive eruptions will increase the reliability of volcano monitoring based on long(er) distance measurements.

Quantification of Hydroxyl Radicals (OH) in Volcanic Gases

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Hydroxyl free radicals (OH) are of central importance in many reaction systems (e.g. atmosphere, combustion) and are an essential factor for the understanding of volcanic plume chemistry. Simple stationary state calculations predict extremely high amounts of OH emitted from volcanic vents with concentrations up to $2 \cdot 10^{13}$ molec/cm3, several orders of magnitude higher than in other atmospheric environments. Today those values are the base of modelling atmospheric chemistry process in and around volcanic plumes. However, neither direct measurements of OH in volcanic plumes exist nor can a high OH abundance be evidently derived from secondary observations and the current knowledge of volcanic plume chemistry.
We propose a novel, compact setup for direct quantification of volcanic OH. The already established differential optical absorption spectroscopy (DOAS) method is combined with a Fabry-Perot interferometer (FPI). A novel 2D-approach allows to achieve the required high spectral resolution (ca. 2 pm) in the UV (around 308 nm) and thus to replace the traditional bulky grating spectrometers with a very compact and portable set-up. Further, UV-LEDs will serve as light sources replacing complicated laser systems. We present sample calculations and first laboratory studies of our spectrograph setup

Volcanoes and Climate

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Since a long time it is known that volcanic eruptions influence weather and climate. Firstly Plutarch was the first one who mentioned 2000 years ago an effect on weather and climate by volcano eruptions after the eruption of Etna in 44 BC. In contrast to earthquakes and many other natural hazards stronger volcano eruptions are able to generate a glo¬bal impact. This is true especially for strong explosive events if the eruption products are transported into the stratosphere. Known are volcanic eruptions with definitely more than 1,000 cubic kilometer eruptive material involved, but, not much is known about their impact on climate, fauna, and flora as well as on human life. Historically evident is one eruption with global influence only. The explosive eruption of Tambora, Sumbawa, in 1815 with an estimated erupted volume around 100 km^3. This southern hemisphere eruption led 1816 on the northern hemisphere to the so called »year without summer«. Only a few decades ago it was believed that fragmented fine lava, ash particles, have the main influence on the incoming radiation. But, only in the 2nd half of the last century it was found out that not the ashes are responsible for the influence on weather and climate, but, released gases like the sulfur dioxide which reacts with water vapor to ultra-fine sulfuric acid droplets which lead to an aerosol layer that can stay in the stratosphere for some years, changing the albedo of the earth. Unfortunately, our knowledge about the development and generation of giant eruptions or so called mega eruption is still small. However, as the driving forces for geodynamic processes have not changed over millions of years and will continue in the future, we have to expect volcanic events that will exceed the impact of the Tambora eruption many times.

Hazards related to subsoil alteration and degassing in the Rotokawa geothermal field, New Zealand

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Surface expressions of hydrothermal systems such as mud pools, fumaroles, and collapse or explosion craters are diverse, complex, and highly variable in space and time. These features often become tourist attractions (e.g. in Yellowstone, USA, or Wai-o-Tapu, NZ), and may be present in operating geothermal fields. One example of these systems is the Rotokawa geothermal field, which contains varied and extensive hydrothermal surface features, including Lake Rotokawa. Lake Rotokawa lies within the crater of New Zealand's largest hydrothermal eruption, which occurred approximately 6000 years ago. Important energy infrastructure, specifically the Nga Awa Purua Geothermal Power Plant is also located in the area.
A field campaign was carried out to assess the surface distribution of temperature and hydrothermal features, as well as the physical and mechanical properties of near-surface subsoils and the resulting hazards created by variable alteration. Field-scale faults, coincident with the orientation of the Taupo Volcanic Zone, are a controlling factor in permeability within the Rotokawa geothermal field. The surface lithology is dominated by the pumice-rich Taupo Ignimbrite deposit and reworked material from sulfur mining in the 20th century. Porosity measurements and rapid decompression experiments were performed in the laboratory. Four distinct soil domains were identified, each with specific associated hazards, including 1) undisturbed Taupo soil units, 2) excavated areas with sulfur-cemented crusts and hummocks, 3) areas dominated by mud and heated pools, and 4) areas of active sinter deposition.
The spatial distribution of these soil domains suggests that degassing is controlled by structures on a field-scale and a local scale (<10 m), and by permeable contacts and layers within the subsoil. Surface temperatures range from approximately 10 to 100◦C, with the hottest temperatures measured in water pools or in close proximity to sulfur-encrusted areas. Sinters, mud, and sulfur crusts may allow for the buildup of gases and pressure beneath these low-permeability surface units, especially in areas where significant degassing occurs. Dissolution of subsurface pumice layers in Taupo soils create a subsoil environment that may be prone to collapse, and shows no immediate surface expression of the deeper alteration. Ground collapse is the most likely hazard in the Rotokawa geothermal field, but the hazard of a hydrothermal eruption, which could result in loss of property and potentially lives, cannot be ruled out.

The DEEP-TEE Seismological Experiment:
Exploring Micro-Earthquakes in the East Eifel Volcanic Field

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The East Eifel Volcanic Field in Germany is an active magmatic region where monitoring is important for hazard assessment and scientific analyses. Following two unusually deep micro-earthquakes in September 2013 (about 40 km depth), detected at about 10 local stations, an improved seismological recording network was installed to better monitor and locate local seismic events. The motivation was to enhance our understanding of the seismicity, magmatism and dynamics of the volcanic field. This seismological experiment is called Deep Eifel Earthquakes Project - Tiefe Eifel Erdbeben (DEEP-TEE). It started in July 2014 in and around the East Eifel Volcanic Field (network centre ca. 50.4N, 7.3E).
During Phase 1, from July 2014 until August 2016, ten short-period seismic recording stations provided by the Geophysical Instrument Pool Potsdam (GIPP) and three broadband stations provided by the KArlsruhe BroadBand Array (KABBA) were placed between the permanent stations of the local state earthquake surveys (LGB-RLP and GD-NRW). Since August 2016 (Phase 2), the network is continuously reconfigured und updated by KIT and LGB, including up to eight KABBA stations. Data are transferred to Freiburg (LED) where a real-time detection and location procedure is performed. More detailed data analysis is currently done at GFZ, KIT, and LED-BW. The recordings allow to study the seismicity in many aspects, including the identification of deep low-frequency micro-earthquakes related to magmatic injections below the Laacher See volcano (Hensch et al., GJI, 2019).
We thank the GFZ-GIPP and the KIT-KABBA for providing instruments. Part of the data is stored at GFZ (doi:10.14470/6C709520).

Hydrothermal eruptions at unstable crater lakes - findings from field investigations at the Boiling Lake, Dominica, Lesser Antilles

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The Boiling Lake, an unstable volcanic crater lake, is located in the midst of a hydrothermal highly active area at the southern part of Dominica. This island has one of the highest concentrations of potentially active volcanoes worldwide.
The very popular and frequently visited Boiling Lake is characterized by irregularly occurring drainage events, where the lake water drains about 10 - 12 m until the local water table. These events are sometimes followed by hydrothermal eruptions and toxic gas emission that seriously endanger lake visitor's health and life.
Combined field- and laboratory- based approaches were carried out in order to i) characterize the properties of the dominant crater wall lithology, ii) determine the influence of ongoing alteration on petrophysical properties (porosity, permeability,…) and rock strength iii) assess how water-saturated, unsolidified wall rock material behave when rapidly decompressed from low pressure and low temperature conditions such as during hydrothermal explosions.
Two kinds of experimentally simulated scenarios were conducted in this study: i) mimicking a small hydrothermal eruption occurring after lake drainage events (decompression from low pressure conditions) ii) simulation of a more energetic hydrothermal eruption (medium pressure condition) showing rapid decompression triggered by capping and overpressurization of the vent area following landslide episodes.
Ejection velocities obtained from conducted experiments were used for ballistic trajectory calculations whose results allow an estimation of the potential area impacted by ejected debris.
Our results contribute to a better understanding of the hazard potential for future hydrothermal eruptions at the Boiling Lake as well as at similar hydrothermal active areas worldwide.

Virtual Experiments: Targeting the volcanic conduit using TEM

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Investigation and monitoring of volcanoes is crucial in understanding volcanic processes and, therefore, in estimating volcanic risk. Among these processes, those inside volcanic conduits are of prime interest since they control the final rise of magma prior to an eruption. Unfortunately, they cannot be observed directly. For example, Strombolian eruptions are assumed to be driven by gas slugs. These slugs ascend within the magmatic conduit and burst at the magma-air interface. This would further help constraining the final rise of gas slugs prior to strombolian eruptions.
The transient electromagnetic method (TEM) is a promising geophysical method for imaging fast changes in conductivity distribution as expected by gas slugs (<10 s). The conductivity ratio magma to gas of approximately 10e8 is regarded highly significant. Within a measurement series, the instruments' time range with a maximum of 10 ms allows for numerous subsequent measurements during the final rise of the gas slug. Due to the high temporal resolution down to less than 1 µs and variety regarding transmitter-receiver configurations,
TEM covers a variety of penetration depths.
We present the results of our full 3D TEM simulation on a simple volcanic model including a conduit structure as well as topography. The calculated quantities are both the electrical field and the time derivative of the vertical component of the magnetic flux density dependent on the subsurface conductivity distribution. We
demonstrate the effect of topography and conductivity changes within the volcanic conduit on synthetic TEM measurements. The conducted virtual experiments are used to determine an ideal measurement configuration for a future field experiment at Stromboli volcano.

Glacier cave research on volcanoes of the Cascade Volcanic Arc – chances to improve forecasting volcanic hazards?

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The Cascade Volcanic Arc - ranging from Mt. Garibaldi in British Columbia to Lassen Peak in the northern part of California - represents a subduction zone with plenty of active volca-noes. Most of them are covered with huge glaciers and ice masses. Besides the importance of these glaciers for environmental aspects, fresh water supply or tourism, there are still multiple hazards which ought to be considered. Based on volcanic activity as well as atmospheric conditions, volcanic glaciers often lead to lahars, mudflows or avalanches. These hazards endanger several millions of people who are living in the agglomerations of Washington and Oregon, with tendency to rise. Since population growth, global warming and land use conflicts are a daily occurrence, discussions about forecasting natural hazards or effects of climate changes become even more important. Glacier caves, up to now a rather unknown object of investigation, may lead to a better understanding of these sensitive issues. Therefore, glacier caves on Mt. Hood, Mt. St. Helens and Mt. Rainier were investigated.

Towards 3D geodynamic modelling of the Altiplano-Puna Magma System

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The Altiplano-Puna Magma Body (APMB) in the central Andes is considered to be the largest active melt zone in the Earth's crust today. For the past decades, multiple research projects have looked at the uplift rates above the APMB and successfully reproduced the observations with 2D or 3D numerical models, using simplified (elastic) rheologies and/or source geometries.
Yet, rocks are not just elastic but have a temperature-dependent viscoelastic rheology. Here, we therefore develop 3D models of the system using such more realistic rheologies, while also taking observed gravity anomalies into account. By forward modelling the gravitational effect of the APMB and the thickened Andean crust, we try to unite geometries inferred from S-wave tomography with crustal density models and bouguer data. The resulting 3D setup and the 3D thermo-mechanical finite difference code LaMEM is then used to make predictions about surface deformation which can be compared to observations made by InSAR and GPS studies. The ultimate goal is the creation of a numerical model which is consistent with a large amount of geophysical data and can be used to better constrain the geometry and geophysical properties of the APMB as well as to understand why uplift rates at the surface above it have decreased since the mid-2000s.

Interpreting Vulcanoes and Vulcanism : 'explosive' potential ... ?!

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Vulcanoes do have their ‘inherent‘ fascination – as do dinosaurs – nevertheless, relating this (worldwide) phenomenon in different ‘proximities‘/neighborhoods/concerns/ “Betroffenheiten“ to a (still) broader public – and to transformative learning/“ESD“* towards the goal of ‘future-ability‘ (Zukunftsfähigkeit) and the “AGENDA2030“-“SDGs“** : some additional inspirations and instrumentative tools from the “Art of Interpretation“*** might be considerable or helpful … (and result in some ‘added value‘)

*ESD = Education for Sustainable Development (UNESCO and VENRO, among others); **SDG = Sustainable Development Goals (of the UN); ***original author: Freeman TILDEN, 1962

Xenoliths from the Weinfelder Maar and Meerfelder Maar, West Eifel Volcanic Field: Crustal provenance and pyrometamorphism revealed by petrology and high spatial resolution zircon geochronology

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Xenoliths brought to surface by rising magma provide valuable information on deep crustal structures, particularly in regions where no outcrops of basement rocks exist, such as the Eifel (Germany). Petrological investigation of crustal xenoliths can determine their crustal provenance, and reveal major magmatic or metamorphic events during crustal formation. Geochronological analysis at zircon in crustal xenoliths can further the timing of these events. This permits integration of the regional xenolith record into a broad geodynamical context.
The Quaternary Eifel volcanic field as the youngest part of the Cenozoic European Volcanic Province (CEVP) is located within the Paleozoic tectonic block of the Rhenish Massif. The basement rocks of the Eifel form part of the Paleozoic Avalonia terrane, which underwent several phases of magmatic and metamorphic events. Detrital zircon ages from sedimentary rocks of the Rhenish Facies reflect Gondwanan, Baltican and Cadomian provenance with Proterozoic to Paleozoic ages, whereas regional metamorphism during the Variscan orogeny affecting the Rhenohercynian crust is recorded in metamorphic zircon crystallization.
In pyroclastic deposits of the West Eifel volcanic centers Meerfelder Maar and Weinfelder Maar, felsic crustal xenoliths of both igneous and sedimentary origin are abundant along with peridotite and mafic cumulate xenoliths. Juvenile components of both maars are foiditic to basanitic. Three of the analyzed samples represent mid- to lower crustal para- and orthogneisses, which were variably affected by Variscan metamorphism. Zircon from meta-sedimentary rocks show wide age distributions ranging from 300 Ma to 1.9 Ga. A forth xenolith investigated here is magmatic origin and based on a concordant zircon rim age of 270 Ma coeval with post-collisional volcanism during the Late Carboniferous/Permian. All samples show variable pyrometamorphic overprint related to the Quaternary volcanism reflecting different residence times in the magma, but zircon rims are unaffected by pyrometamorphism.

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SAR Interferometric time series on the 2005 and 2010 eruption deposits of Shiveluch volcano Kamchatka

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Deformation is a signal commonly used for monitoring and early warning of active volcanoes. Here we investigate the importance and degree of deformation associated with very shallow processes, located on the flanks of an active volcanoes. Shiveluch is one of the most active and largest volcanoes in Kamchatka Peninsula. It lays directly on the Kiril-Aleutian arcs junction, the north-western corner of the Pacific subduction plate. Shiveluch produces also some of the largest dome-collapse-driven block-and-ash (BAF) deposits worldwide consequent of erupt episodes in 2005 and 2010, and is the site of lahars and rock avalanches. The BAF deposits are formed by heterogeneous dome materials characterized by different degree of fragmentation and this diversity is visible in differing surface morphologies. In this study we perform a SAR interferometric time-series analysis exploiting a data set of 19 images acquired between 2016 and 2018 with the main focus to detect possible flank deformations. From this data set we identify a large subsidence displacement over the central part of the 2010 BAF deposits with maximum mean rate per year of around 6 cm in line-of-sight direction. In addition a low prominent displacement was detected over a small section of the 2005 BAF deposits with a maximum mean rate per year of around 2 cm. A number of other deformation sources was identified, located at prominent rock fall valleys, and locations of lahar deposits. The diversity of displacement rate over the deposits reflects their heterogeneous composition, which will be further analysed using morphological and available stratigraphical data. This work shows the great potential of SAR interferometric techniques for volcano processes detection and monitoring over time, and underlines complex deformation occurrence affecting the volcano flanks.

Bromine monoxide/Sulphur dioxide molar ratios in volcanic plumes from S5-P/Tropomi

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In this presentation, the potential of the recently launched Tropomi instrument to detect bromine monoxide (BrO) in volcanic plumes is investigated. So far BrO in volcanic plumes has been successfully retrieved from satellite only during major eruptions. The higher spatial resolution of S5-P/Tropomi (3.5x7km²) and the daily coverage allows for an investigation of volcanic BrO during smaller eruptions and even during continuous passive degassing. The continuous observation of passive degassing volcanoes yields the potential for long-term monitoring of volcanoes from satellite. Also, it is expected that the volcanic plumes can be tracked over larger distances.

BrO is a halogen radical altering – inter alia – the atmospheric ozone chemistry. BrO and in particular the molar BrO/SO2 ratios in volcanic gas emissions have been suggested as proxy for monitoring volcanic activity on several accounts.

In this study, we present BrO column densities as well as SO2 column densities retrieved using Differential Optical Absorption Spectroscopy (DOAS) and BrO/SO2 molar ratios in volcanic plumes with varying emission strength from Tropomi data. By deriving a time series, we investigate the variation of the BrO/SO2 molar ratio of various volcanoes, in order to investigate plume chemistry and emission composition.

Set-up of a testbed for the investigation of the impact of real volcanic ash from Icelandic volcanoes to microgas turbines

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Volcanic ash clouds, which are emitted from erupting volcanoes, are a danger for the aviation. The volcanic ash particles can damage the turbine blades and their thermal barrier coatings as well as the bearings of the turbine. For a detailed investigation of these damaging effects a testbed was designed and constructed, which allowed the study of the detrimental effects of real volcanic ash to a microgas turbine. The microgas turbine served as a model turbine for big jet engine turbines, which are used in commercial aviation. The application of this microgas turbine had the advantage that it delivered near reality conditions, using kerosene and operating at similar temperatures as big turbines, but at a very cost effective level.
The testbed comprised a disperser for the real volcanic ash, optical particle counters (OPCs) for the measurements of ash particles and all the equipment needed to control the micro gas turbine. The OPCs enabled the online measurement of the concentration and particle size distribution of the volcanic ash at the intake and within the exhaust stream of the microgas turbine. The OPC at the intake was combined with an isokinetic sampling unit in order to get reliable results. Moreover, within the exhaust stream of the microgas turbine ash particles were caught with an impactor additionally to the OPC measurements. This enabled the later analysis of the ash particles with an electron microscope concerning the morphology to verify possible melting processes. This testbed proved its capability for detailed investigations of the impact of volcanic ash to jet turbines and appropriate countermeasures.