# Volcanological Workshop - Presentations

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# Abstracts

## FLIR observations of the Eyjafjallajökull flank eruption

Talfan Barnie*, Evgenia Ilyinskaya, Amy Donovan, Clive Oppenheimer, CVG
Department of Geography, Cambridge University, UK, *tdb29@cam.ac.uk

We present time series of FLIR images of the Eyjafjallajökull flank eruption, collected on the 28th of March and 1st,4th and 7th of April 2010. Presented as time lapse video, the images show the geomorphological evolution of the lava flows and scoria cones over short timescales during different phases of the eruption. A number of volcanic processes are captured, including scoria cone construction and deformation and lava front advance, collapse and inflation. The images also provide a useful record of the temperature distribution on different volcanic surfaces that can be integrated with aerial and orbital thermal images to better describe the evolution of the eruption.

## Intrusive activity beneath Eyjafjallajökull 1991-2010 from analysis of earthquake data

Bryndís Brandsdóttir[1], Jon Tarasewicz[2], Martin Hensch[1] and Bergþóra Þorbjarnardóttir[3]

1 Institute of Earth Sciences, University of Iceland
2 Bullard Laboratories, University of Cambridge
3 Icelandic Meteorological Office

The Eyjafjallajökull stratovolcano is located at the western border of the Eastern Volcanic Zone (EVZ) in South Iceland, west of Mýrdalsjökull (Katla). The EVZ is propagating southwestwards into older oceanic crust. Situated near the tip of the propagating zone, Eyjafjallajökull and Katla are interconnected by east- west-striking faults and eruptive fissures. Katla is one of the most active volcanoes of the EVZ, whereas only three eruptions have been documented in Eyjafjallajökull before 2010, in 920, 1612 and 1821-1823. Prior to 1991 the volcano was seismically quiet for at least 20 years.

Enhanced seismic activity beneath Eyjafjallajökull, detected in 1991-1992, was followed by persistent microearthquake activity during the next decade with intense seismic swarms beneath the northeastern and southeastern flanks in 1994 and 1999 and a smaller swarm beneath the summit crater in 1996. Following this decade of unrest the volcano was relatively quiet until March 2009 when a few earthquakes were recorded beneath the northeastern flank. Gradually increasing seismic activity throughout the year culminated in an intense swarm in February-March 2010. Simultaneous inflation observed by GPS and InSAR data confirmed magmatic accumulation within the volcano and heralded the subsequent eruptions.

Following a prolonged period of escalating seismicity we deployed six temporary, three-component, semi- broadband seismometers around the Eyjafjallajökull volcano in early March. Data from these seismometers were augmented by data from the permanent network operated by the Icelandic Meteorological Office (IMO). Using an automated earthquake location process by Coalescence Microseismic Mapping (CMM) we have located over 9,000 earthquakes prior to the Fimmvörðuháls fissure eruption at the northeastern flank of Eyjafjallajökull. During March 2010, sustained seismic activity was concentrated primarily between 3-6 km depth under the northeastern flank of the volcano. During the two weeks prior to the Fimmvörðuháls eruption, seismicity migrated eastwards along the flank, away from the Eyjafjallajökull summit crater. Spatial and temporal variations in seismicity, reflect complicated intrusive activity along the northeastern flank, rather than a single dyke propagating towards the Fimmvörðuháls eruption site. Seismic activity decreased markedly in the two days prior to the onset of the fissure eruption on March 20th.Preliminary focal mechanisms indicate E-W striking nodal planes with both thrust and normal faulting movements, reflecting an E-W elongated intrusion beneath the northeastern flank, as in 1994. The Fimmvörðuháls eruption continued until 12th April and was a pre-cursor to the more explosive, sub-glacial Eyjafjallajökull eruption which started on 14th April in the summit crater. Seismicity significantly increased again on the day before the second eruption, this time located beneath the summit crater.

## Observing the 2010 Eyjafjallajökull, Iceland, Eruptions with NASA's *EO-1* Spacecraft – Improving Data Flow In a Volcanic Crisis Through Use of Autonomy

A. G. Davies[1], S. Chien[1], J. Doubleday[1], D. Tran[1], M. T. Gudmundsson[2], I. Jónsdóttir[2], A. Hoskuldsson[2], T. Thordarson[3], S. S. Jakobsdóttir[4] and R. Wright[5]

1 Jet Propulsion Laboratory-California Institute of Technology, Pasadena, CA, USA (tel: 818-393-1775; email: Ashley.Davies@jpl.nasa.gov)
2 Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland
3 University of Edinburgh, Edinburgh, UK
4 Icelandic Meteorological Office, Reykjavik, Iceland
5 University of Hawai'i, Honolulu, HI, USA

Eyjafjallajökull volcano, Iceland, erupted from 20 March to 12 April 2010 (a flank eruption) and again from 14 April to 23 May 2010. The latter eruption heavily impacted air travel across much of northern Europe, and highlighted the need to monitor and quickly react to new eruptions. The NASA Earth Observing 1 spacecraft (*EO-1*), which is managed by the NASA Goddard Space Flight Center, obtained over 50 observation pairs with the Hyperion hyperspectral imager and ALI (Advanced Land Imager) multispectral camera. *EO-1* is the remote-sensing asset of a globe-spanning Volcano Sensor Web [1], where low spatial resolution data (e.g., MODIS) or alerts of ongoing or possible volcanic activity are used to trigger requests for high resolution *EO-1* data. Advanced resource management software, developed in part for flight onboard *EO-1* as part of the Autonomous Sciencecraft [2, 3] is now used to task *EO-1*. This system allowed rapid re-tasking of *EO-1* to obtain both day and night data at high temporal resolution (on average every 2 days), unusual for such high spatial resolution imagers (Hyperion and ALI at 30 m/pixel, with an ALI panchromatic band at 10 m/pixel). About 50% of the data were impacted by cloud. Advances in data handling and communications during the last two years means that Hyperion and ALI data are typically on the ground and ready for analysis within a few hours of data acquisition. Automatic data processing systems at the NASA's Jet Propulsion Laboratory process Hyperion data to (1) correct for atmospheric adsorption; (2) remove the sunlight component in daytime data; (3) identify hot pixels; (4) fit unsaturated data to determine temperature and area of sub-pixel thermal sources; (5) calculate total thermal emission and, from this, an effusion rate; (6) generate geo-located data products. The entire process is autonomous. Data products, as well as images generated, were sent to volcanologists in the field to aid in eruption assessment. The JPL group is now working with Icelandic scientists to develop a mechanism for triggering *EO-1* observations from Icelandic Meteorological Office and University of Iceland *in situ* instruments. References: [1] Davies, A. G., et al., 2006, *Eos*, 87 (1), 1&5. [2] Chien, S. et al., 2005, *J. Aerospace Computing, Information, & Communication*, 2005, AIAA, 2, 196-216. [3] Davies, A. G. et al., 2006, *Rem. Sens. Environ*., 101, no. 4, 427-446. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

## Dynamics of two-magma eruptions

John C Eichelberger, U.S. Geological Survey, Reston, VA, 20192 USA,
jeichelberger@usgs.gov

Two-magma eruptions, such as the March-April 2010 Eyjafjallajokull event in Iceland, are remarkably common. They include not only basalt – andesite pairs (e.g., Eyjafjallajokull 2010, Karymsky 1996, Gorely 1737, Miyakejima 2000), but also basalt – basalt (Tolbachik 1975-1976), rhyolite – rhyolite (Inyo Domes, ~1400 CE), andesite – rhyolite (Katmai 1912), and basalt – rhyolite (Askja 1875). The contrasting magmas may emerge separately from widely spaced vents or together from the same vent, either simultaneously or closely spaced in time.

Traditionally, such eruptions have often been interpreted as products of chemically zoned magma chambers, wherein zoning developed over time through magmatic differentiation. That interpretation is precluded by heat and mass transport considerations, at least for cases where there is a clear gap in storage temperature and melt composition of the magma pairs. More likely, these eruptions represent disruption of a shallow, long-lived magma body by a rising dike of new magma. Although the magmas may share a common heritage, they have no direct relationship to each other except for being coincident in space and time.

## The 1992 eruption of Crater Peak, Mount Spurr, Alaska: an eruptive sequence with unique seismological and geological attributes

Cynthia Gardner, U.S. Geological Survey, 1300 SE Cardinal Court, Vancouver, Washington 98683, USA (cgardner@usgs.gov; 360-993-8914)

In 1992, Crater Peak, a Holocene satellite vent of Mount Spurr in south-central Alaska, erupted after almost 40 years of quiescence. The previous eruption in 1953 consisted of a single sub-plinian event of several hours duration, whereas the 1992 eruption consisted of three sub-plinian events notable for their similarity in duration, eruptive volume, gas emission, distinctive tephra-fall deposits and eruptive style. Precursory seismicity and gas emissions were noted in advance of the first eruptive event on 27 June 1992, which enabled the Alaska Volcano Observatory to warn about an impending eruption. An immediate decrease in shallow seismicity and gas emission rates to background levels in the days following the 27 June event suggested that the 1992 eruption would be a simple repeat of the 1953 eruption. However, the volcano erupted again on 18 July with no notable increase in seismicity prior to a short-lived (several minutes) emission approximately 1 hour before the sub-plinian phase of the eruption. After this second eruptive event, seismicity and gas again fell to near background levels although the third and final eruptive event (16-17 September) was preceded by almost 4 hours of shallow low-level seismicity. The sub-plinian events primarily produced tephra-fall deposits with negligible pyroclastic-flow deposits. The lowermost two-thirds of the tephra-fall deposits of each event were medium tan in color with the uppermost third, medium gray in color: all clasts were basaltic andesite and identical in composition. The color change is correlative with an increase in density and in microlite crystallization suggested to be the result of syn-eruptive decompression. A notable feature of the 1992 eruption is that the seismic energy release increased dramatically after the third sub-plinian event. This increase was due to a strong swarm of earthquakes that followed the September eruption and a smaller but still notable swarm in November 1992. These post-eruptive swarms are likely due to post-eruptive magmatic intrusions that failed to culminate in an eruption.

## Properties of the Eyjafjallajökull volcanic ash, and chemistry of floods and surface waters during and "after" the Eyjafjallajökull eruption 2010

S.R. Gislason[1], S.L.S. Stipp[2], E.S. Eiriksdottir[1], H.A. Alfredsson[1], T. Hassenkam[2], S. Nedel[2], N. Bovet[2], C.P. Hem[2], Z.I. Balogh[2], K. Dideriksen[2], N.Ö. Óskarsson[1], B. Sigfússon[3], G. Larsen[1], A. Leth[1,2], J. Olsson[1,2], G. Sigurðsson, H. Hródmarsson, Ó. Þórarinsson and S. Zóphóníasson.

1 Institute of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavik, Iceland
2 Nano-Science Center, Department of Chemistry, University of Copenhagen, Denmark
3 Reykjavik Energy, Baejarhalsi 1, 110 Reykjavik

The recent volcanic activity in Eyjafjallajökull began 20 March 2010. Lava flowed from a fissure on the ice free flank of the Eyjafjallajökull volcano, but ashfall was insignificant. After a hiatus of ~2 days, eruption recommenced 14 April, this time from within the caldera, under 100 to 300 m of ice. Jökulhlaups, floods of meltwater, flowed down the northern and southern slopes. This second phase was explosive, sending exceptionally fine grained ash all the way to Europe. Effusion rate was at maximum during the first few days of the explosive phase. After 18 April, meltwater no longer reached the crater and ash production decreased.

In this talk we report on the grains size distribution of ash samples from 15 April and 27 April. Their specific surface area, bulk mineral and chemical composition, surface composition and we have conducted ash/water, ash/acid water and ash/seawater dissolution experiments in the laboratory to study the surface properties of the ash and its dissolution rate in aquatic solutions of variable composition. Furthermore we have measured the chemistry and fluxes of dissolved and suspended matter in the floods of 14 April, and the pollution of surface waters following the first rain on the ash and the ensuing mud flow (lahar).

# Eyjafjallajökull eruption in April-May 2010: variable vent discharge, plume height and preliminary height-discharge correlations

Magnús T. Gudmundsson, Björn Oddsson, Þórdís Högnadóttir, Eyjólfur Magnússon, Guðrún Larsen, Ármann Höskuldsson, Institute of Earth Sciences, University of Iceland (mtg@hi.is)
Thorvaldur Thordarson, University of Edinburgh, UK

The explosive eruption of Eyjafjallajökull in April-May 2010 went on for 39 days, producing a sustained volcanic plume that rose 3-8 km over the vent. Although there was some pulsation in activity, temporary breaks in magma flux into the vent (typically lasting minutes) occurred only occasionally. The main craters were located in the western part of the summit caldera, where ice thickness was 170-200 m before the eruption. Initially, ice melting had considerable effect on plume activity. This effect was manifested in magma-water interaction during the first four days (14-17 April). In addition, the ice melting took up a considerable fraction of the eruption energy during 14 and 15 April. Airborne monitoring using SAR radar, still photography, videos, and thermal imagery was applied to assess activity. Plume height was estimated whenever possible, both from the air and the ground. The long duration of the eruption with periods of both high and low activity provides a detailed series where plume transport, as calculated from plume height, can be compared to the actual measured tephra fallout. This work has only just began, but it should provide an opportunity to significantly expand the empirical data set used to produce plume height/magma discharge correlations. As predicted by theory and the empirical correlations, plume height is the single most important parameter to assess plume transport. It is, however, only a very approximate tool to assess plume transport and considerable deviations are to be expected. Preliminary results of correlations between measured fallout volume in different phases will be presented and discussed.

## The Eyjafjallajökull eruption April to May 2010: Magma fragmentation, plume and tephra transport, and course of events.

Ármann Höskuldsson, Guðrún Larsen, Magnús T. Gudmundsson, Björn Oddsson, Eyjólfur Magnússon, Olgeir Sigmarsson, Níels Óskarsson, Ingibjörg Jónsdóttir, Freysteinn Sigmundsson, Páll Einarsson, Sigrún Hreinsdóttir, Rikke Pedersen, Þórdís Högnadóttir, *Jarðvísindastofnun Háskóla islands*
Thor Thordarson, Chris Hayward, Margaret Hartley, Rhian Meara, *University of Edinburgh*
Þórður Arason, Sigrún Karlsdóttir, Guðrún Nína Petersen, *Icelandic Met Office*

The Eyjafjallajökull eruption began in the first hours of April 14th 2010. The eruption can be broadly divided into three periods of activity, Phase I from 14th to 17th of April, Phase II from 18th to 4th of May and finally Phase III from 5th to 22nd of May.

Phase I was characterised by the breaking through the ice and densely ash laden plumes. During this phase phreatomagmatic activity was most intense, although magmatic fragmentation was a major tephra producing factor. During Phase I the plume rose highest, up to 9 km, following intense phreatomagmatic activity forming steam rich and ash poor plume. However, most of the time plume was lower than 6 km and rich in ash. Activity was intermittent during this phase and could be low or quiescent for several hrs to minutes between pulses. Ash production was most intense during this phase.

Phase II was characterized by high eruption tremor and lava flowing down the Gígjökull outlet glacier. During this phase eruption plumes were weak and ash poor. Only on the 28th did the plume rise above 7 km. Activity was pulsating with small discrete explosions taking place at intervals of several seconds. During phase II tephra grains of fluidal shape where common, indicating magmatic fragmentation and decrease in viscosity of the erupting magma.

Phase III began as tremor diminished and lava stopped advancing. During this phase plume activity picked up again with ash rich plumes rising commonly up to 5 km. Magma fragmentation during this period was altering between magmatic and phreatomagmatic, with abundant ballistic bombs in the proximal area. Tephra deposited in the Þórsmörk region during Phase III developed sulphur crystals on its surface, which had not been observed on other tephra deposits during the eruption.

Total amount of tephra produced in the eruption is about 0.11 km$^3$ and that of lava 0.025 km$^3$ DRE. Average discharge rate in the eruption was about 40 m$^3$/s DRE or about 4 times that of Fimmvörðuháls eruption.

## Airborne monitoring of vent activity in the Eyjafjallajökull eruption in April-May 2010, data collection and methods.

Björn Oddsson[1], Magnús Tumi Guðmundsson[1], Eyjólfur Magnússon[1], Þórdís Högnadóttir[1] and Friðrik Höskuldsson[2].

1 Institute of Earth Sciences, University of Iceland (bjornod@hi.is)
2 Icelandic Coast Guard

Data collected during over flights of the eruption in Eyjafjallajökull 2010 are photographs, videos, radar images, infrared images (scaled and none scaled) and notes from visual inspection. The methods of data collection depended on the aircraft used each time. Three types of aircrafts were used. The largest aircraft was a twin turbo-engine Dash 8 of the Icelandic Coast Guard. It is equipped with a Synthetic Aperture Radar (SAR), an infrared/TV daylight camera and large windows for video and photography. Many over flights were done using a small Cessna 207 with a possibility to open a window allowing usage of the hand-held infrared cameras. Coast Guard helicopters were used occasionally, allowing closer inspection and landing near the craters under favourable conditions.

In the beginning phase of the eruption, the most important task was to locate the eruption site to be able to make assessment of flooding danger which is a regular feature of eruption within glaciers. Due to bad weather, no visibility was on the glacier until the fourth day of the eruption but the location of ice cauldrons forming in within the caldera and monitoring of their growth was possible with the SAR radar. The SAR images are acquired at flight altitude of 18-20,000 feet, along flight lines 15-20 km away from the volcano. This makes their acquisition possible under poor weather conditions and outside the reach of the volcanic plume. In the following weeks radar images were produced as often as possible allowing us to record the growth of the ice cauldrons. During the mixed explosive/effusive phase April 21 - May 4 the radar images showed the advance of the lava front which ran down Gígjökull.

During all the flights, a large amount of photographs and videos were taken to capture the status of the eruption at every time and for further estimation of the level and style of activity. A hand held FLIR camera and video recorder was used when conditions allowed. These data provided estimates of plume and vent ejecta temperatures, and recorded the progression of the lava stream.

## Monitoring the Eyjafjalljokull ash eruption with a near-source Infrasonic Array

M. Ripepe, G. Lacanna, D. Delle Donne, A. Höskuldsson, E. Marchetti.

1 Dipartimento Scienze della Terra, Università di Firenze, via LaPira, 4, 50121 Firenze, Italy
2 Institute of Earth Science, University of Iceland, Sturlugata 7, 101 Reykjavik Iceland

Volcanoes are efficient radiators of infrasonic waves, as gas volumes rapidly expanding in the atmosphere generate pressure perturbations able to propagate up to thousands of kms away. The intensity of infrasound produced can range from very low amplitude pressure signals (mPa) to violent shock waves (MPa) and its frequency content as well can span 5 orders of magnitude (10-3-102 Hz), from sustained long lasting signals to discrete sharp transients. Here, the recorded infrasound can provide valuable insights into eruption and plume dynamics and thus represents a valuable information to describe the eruptive scenario.

We recorded the ash plume activity of Eyjafjalljokull with a 4-elements small aperture (150 m) infrasonic array, located ~7 km south of the volcano. The sustained volcanic plume ejected into the atmosphere large quantities of hot ash and debris, inducing pressure perturbation with frequency content ranging from 0.1-4 Hz down to 1-2 mHz typical of acoustic-gravity waves. The array fully recorded the time history of the excess pressure fully coherent in the 0.03-2 Hz band that allowed us to track the evolution of the ash plume, and the emission of the explosive gas emission driving the plume height.

Infrasound provided important information for the analysis of eruptive dynamics and could be successfully used as input parameters in the simulations of the ash cloud dispersal in the atmosphere, thus contributing to a correct risk assessment.

## Dynamic magma mixing revealed by the 2010 eruption of Eyjafjallajökull, Iceland.

Sigmarsson, O.[1,2*], Vlastelic, I.[2], Andreasen, R.[3] , Bindeman, I.[4], Devidal, J.-L. [2], Moune, S. [2], Jakobsen, J.K.[5], Larsen, G.[1], Höskuldsson, A.[1], and Thordarson, Th.[6]

1 Institute of Earth Sciences, University of Iceland, 101 Reykjavik, Iceland
2 Laboratoire Magmas et Volcans, CNRS-Université Blaise Pascal-IRD, 63038 Clermont-Ferrand, France
3 Department of Earth Science and Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
4 Department of Geological Sciences, 1272 University of Oregon, Eugene, OR, USA
5 GeoForschungsZentrum Potsdam, Telegrafenberg, 14473 Potsdam, Germany
6 School of GeoScience, University of Edinburgh, Grant Institute, Edinburgh EH9 3JW, UK

Injection of basaltic magmas into silicic crustal holding chambers and subsequent mixing of the two components is a process that has been recognised since the late seventies to have resulted in explosive eruptions[1-2]. Detailed reconstruction and assessment of the mixing process caused by such intrusion is now possible because of the exceptional time-sequence sample suite available from the tephra fallout of the 2010 summit eruption at Eyjafjallajökull volcano in South Iceland. From 14 to 19 April the tephra contains three glass types of basaltic, intermediate, and silicic compositions recording rapid magma mingling without homogenisation, involving evolved FeTi-basalt and dacite with composition identical to that produced by the 1821-23 AD Eyjafjallajökull summit eruption. The time-dependent change in the magma composition is best explained by a binary mixing process with changing end-member compositions. On 5 May, after a new injection of deep-derived basalt, the silicic mixing end-member changed from pre-existing melt to the solid carapace of the magma chamber. Increasing whole-rock Mg-number during the eruption strongly suggests that not only the silicic end-member varied with time but that the injected basalt became more primitive as well. Finally, decreasing proportions of the mafic end-member with time in the erupted mixed-magma, suggest that explosive silicic eruptions and corresponding tephra production can be expected from Eyjafjallajökull volcano in the future.

1. Sparks, S.R.J., Sigurdsson, H. & Wilson, L. Magma mixing: a mechanism for triggering acid explosive eruptions. *Nature* **267**, 315-318 (1977).

2. Eichelberger, J. C. Vesiculation of mafic magma during replenishment of silicic magma reservoirs. *Nature* **288**, 446-450 (1980).

## Role of crustal deformation studies to infer magma movements – observations from Eyjafjallajökull

Freysteinn Sigmundsson[1], Sigrún Hreinsdóttir[1], Andy Hooper[2], Thóra Árnadóttir[1], Rikke Pedersen[1], Matthew J. Roberts[3], Níels Óskarsson[1], Amandine Auriac[1], Judicael Decriem[1], Páll Einarsson[1], Halldór Geirsson[3], Martin Hensch[1], Benedikt G. Ófeigsson[1], Erik Sturkell[4], Hjörleifur Sveinbjörnsson[3], Kurt L. Feigl[5].

1 Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland.
2 Delft University of Technology, The Netherlands.
3 Icelandic Meteorological Office, Reykjavik, Iceland.
4 University of Gothenburg, Sweden.
5 University of Wisconsin-Madison, USA.

Monitoring of eruption precursors, such as increased seismic activity, enhanced rates of crustal deformation and emission of heat and gas, is important for understanding volcanoes and for improved air safety. Seismic observations provide primary information, but observations of how volcanoes deform can provide invaluable additional information. When magma intrudes volcano roots it induces displacements at the surface of the Earth, typically on the scale of centimetres. Such movements can be precisely measured by two complementary space geodetic techniques: Global Position System (GPS) geodesy, and satellite radar interferometry (InSAR) by combining synthetic aperture radar images acquired by satellites. With these techniques we have mapped deformation at Eyjafjallajökull in details during 18 years of intermittent unrest prior to the 2010 eruptions. From these observations the shape and volume of extensive repeated magmatic intrusions occurring in 1994, 1999 and 2010 can be inferred. More than two months prior the 2010 eruptions of Eyjafjallajökull seismicity and deformation began at enhanced rates. Continuous GPS measurements reveal how daily rate of deformation exceeded 5 mm/day. The spatial extent of deformation was well mapped by images from the TerraSAR-X satellite of the German Space Agency. These measurements allow mapping of the intrusion that grew in the roots of the volcano prior to the flank eruption of basalt March 20 – April 12. The subsequent explosive eruption of trachyandesite beginning on April 14 was then associated with pressure decrease in another source under the summit of the volcano. Our observations provide a good case for improving monitoring of volcano deformation worldwide, as a wealth of information was provided by these observations on subsurface activity taking place at Eyjafjallajökull.

The present techniques for automated geophysical monitoring of subsurface magmatic activity may provide insights for improvements in eruptive monitoring. Geophysical sensors such as seismometers and GPS-receivers are used to continuously map the consequences of earthquakes and intrusions. These data can be modelled in near real time to provide information on origin of recorded signals. In an analogues manner, development of automated instruments to map fallout from eruption plumes and its characteristics could, together with near-real time advanced modelling, help provide timely information on mass of tephra/ash ejected into eruption plumes.

## Volatile budget of Eyjafjallajokull magmas

Haraldur Sigurdsson[1], Charles W Mandeville[2]

1 Graduate School of Oceanography, University of Rhode Island, Narragansett, RI, United States.
2 Department of Earth and Planetary Sciences, American Museum of Natural History, New York, NY, United States.

Volatile elments played a critical role in the style of activity during the 2010 eruptions of the glacier-covered Eyjafjallajokull volcano in Iceland. The alkali basalt flank eruption at Fimmvorduhals was dominated by vigorous fire fountaining that produced dominantly spatter-fed aa lava flows. Production of fine ash during the subsequent summit eruption has been variously attributed to magma fragmentation, either due to water-ice-magma interaction related to the 250 m thick glacier cover over the crater, or juvenile volatile content of the magma. Considering the great impact of the ash dispersal on trans-North Atlantic aviation, knowledge of the fragmentation mechanism and the relative roles of juvenile magmatic gases versus phreatomagmatic fragmentation is of prime significance. To evaluate the potential importance of juvenile components, the concentrations of volatiles in magmas erupted in 2010 from Eyjafjallajokull volcano in Iceland have been measured. Analysis of glass inclusions in olivine Fo 77-85 and plagioclase phenocrysts in the alkali basalt magma erupted at Fimmvorduhals flank eruption contain high total volatiles in the range 0.96 – 2.12 wt.%, and sulfur 0.10 – 0.16 wt.%. These glass inclusions are comparable to major element bulk composition of Fimmvörduháls alkali basalt lavas. In contrast, tephra from the explosive summit crater eruption are trachy-andesitic. This magma contains a rather wide range of olivine and plagioclase phenocrysts of Fo48-79 and An 69-81, with both basaltic and andesitic glass inclusions. This diversity is also reflected in a much wider range of total volatile content from 0.1 – 2.88 wt.% and sulfur 0.1 – 0.24 wt.%. At the basic end, the glass inclusions are comparable to the Fimmvorduhals alkali basalt lava, but some have andesitic composition. The highest volatile content is observed in the andesitic glass inclusions in plagioclase An78. Further analysis of glass inclusions and matrix glass by FTIR and ion probe is in progress.

## Posters

Uni Árting and Bartal Højgaard: **Collecting ash samples from the Eyjafjallajøkull eruption (April-May 2010) on the Faroe Islands**

Chang-Hwa Chen, and Teh-Quei Lee: **Dome collapse eruption in Tatun Volcanic Group near metropolitan Taipei, Taiwan at ~6 kyrs eruption**

Páll Einarsson: **Short-term seismic precursors to Icelandic eruptions**

Galen R. Gisler: **Simulating explosive volcanic eruptions**

Chris Hayward et al.: **The 20 March - 12 April 2010 Fimmvorduhals eruption, Eyjafjöll volcano, Iceland: Volatile contents and magma degassing**

Ármann Höskuldsson et al.: **The 20 March to 12 April basaltic Fimmvorduhals flank eruption at Eyjafjallajökull volcano, Iceland: Course of events**

Ingibjorg Jonsdottir et al.: **Near-field tephra dispersal monitoring by satellites**

Larry Mastin et al.: **Why do models predict such large ash clouds? An investigation using data from the Eyjafjallajőkull eruption, Iceland**

Björn Oddson et al.: **Eyjafjallajökull 2010: Monitoring the eruption site and changes in vent activity from aircraft**

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# Abstracts

## Collecting ash samples from the Eyjafjallajøkull eruption (April-May 2010) on the Faroe Islands

Uni Árting and Bartal Højgaard
Jarðfeingi, Brekkutún 1, P.O. BOX 3059, FO-110 Tórshavn, Faroe Islands, ua@jardfeingi.fo

Since the renewed eruption started on 14 April 2010 areal (0.053 m2) bulk samples have been collected in Hoyvík, Streymoy, using the simplistic method of positioning a standard bucket in a relatively open location over a set period of time. This method was repeated the following week with varying results, but mainly providing very small amounts of ash that were difficult to accurately measure (<0.01 g).

Additional samples were collected from snow covered areas the following days and some surface samples from roofs were added to the collection.

Preliminary grain sizes have and are still being measured using a polarizing microscope. The initial results show that both fine and coarse ash particles have been detected up to 1.5 mm across.

## Dome collapse eruption in Tatun Volcanic Group near metropolitan Taipei, Taiwan at ~6 kyrs eruption

Chang-Hwa Chen, and Teh-Quei Lee, Institute of Earth Sciences, Academia Sinica, P.O. Box 1-55, Nankang, Taipei, Taiwan

The Tatun Volcanic Group (TVG) is located in the north of metropolitan Taipei, Taiwan. Over 6 million inhabitants are living in Taipei City and suburban area. Another critical issue is an international airport and two nuclear power plants are lying at the foot of the TVG. If the TGV will be re-active, the serious hazard for human lives and economies in this area will definitely occur. Understanding the youngest eruption history of the TVG will be much important for prediction the future activity of eruption.

The core was collected from the Dream Lake at the eastern slop of Cising Mt.. Total 21 samples from depth 190 cm to 231.5 cm have been tested. Comparison of chemical compositions of glass and minerals in the volcanic clasts with those of lava around TVG, they clearly showed that the volcanic clasts can be correlated with the eruption of the closest Cising Mt. According to the radiocarbon (C-14) age of core sample at the depth 225 cm, the age was extrapolated around 6150 yrs ca. C-14 B.P.. Moreover, the respiratory cristobalite in the volcanic clasts were firstly identified by the identical morphology, chemical composition and Laser Raman Spectrometry (LRS). The crystalline silica was produced by vapor-phase crystallization and devitrification in the andesite lava dome and volcanic ash generated by pyroclastic flows formed by lava dome collapse in Soufriere Hills volcano, Montserrat (Baxter et al.,1999).

These new evidence demonstrated that there would probably have the lava dome collapse eruptions in the TVG in the last 6 kyrs. The result in this paper also sustained that the landslide caused by the weak phreatic eruption within the last 6000 yrs in the TVG (Belousov et al., 2010). It must further be noted that an efficient program of the volcanic hazard reduction should be practiced for the metropolitan Taipei and suburban area.

## Short-term seismic precursors to Icelandic eruptions

Páll Einarsson, Institute of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland

Networks of seismographs of high sensitivity have been in use in the vicinity of active volcanoes in Iceland since 1973. During this time 19 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 34 hours. In half of the cases the precursor time was less than 2 hours. Two eruptions stand out for their long precursory time, Heimaey 1973 with 30 hours and Gjálp 1996 with 34 hours. 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. Although all 19 eruptions since 1973 had detectable precursors only 12 of them 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 the eruption was seen or detected before the seismic precursor was verified.

## Simulating explosive volcanic eruptions

Galen R. Gisler
[1]Physics of Geological Processes, University of Oslo, Norway, galen.gisler@fys.uio.no

Explosive volcanic eruptions represent a significant geological hazard. Depending on the setting and the circumstances of the eruption, the hazard may consist of pyroclastic flows, ash falls from plumes, lahars, or floods from sudden melting of glaciers. Numerical modelling of volcanic eruptions is an art still in infancy, but notable strides have been made in the last few years. We list four distinct recent approaches. Pelanti and Leveque (2006) used a finite-volume code to simulate the hot dusty gas of an explosive volcanic jet by coupling the compressible fluid equations of a gas to equations for the pressure-less flow of dust. Dartevelle and Valentine (2007) modelled an explosive eruption that occurred through a geothermal borehole as an analogue of natural volcanic eruptions, using a multiphase gas-particle code. Ogden, Glatzmeier and Wohletz (2008) used a single-fluid Eulerian code to model unsteady flow in an overpressured column. These four different numerical approaches have different realms of applicability and respective advantages and disadvantages. We will discuss some of these, and will also present some all-new simulations with the adaptive-mesh multi-material finite-volume code Sage. We have simulated an erupting column of magma arising from depth, penetrating layered media, and emerging at the surface. When pockets of water are encountered at depth and heated suddenly, the resulting supercritical fluid aids the vertical penetration, eventually exploding violently at the surface. When a dry magma column encounters water or ice at the surface, explosive fragmentation is also observed.

## The 20 March - 12 April 2010 Fimmvorduhals eruption, Eyjafjöll volcano, Iceland: Volatile contents and magma degassing

Chris Hayward[1], Severine Moune[2], Margaret Hartley[1], Thor Thordarson[1], Olgeir Sigmarsson[2], Armann Hoskuldsson[3], Magnus Gudmundsson[3], Freysteinn Sigmundsson[3].

1 School of Geosciences, University of Edinburgh, Edinburgh, UK
2 LMV, CNRS, Clermont Ferrand, France
3 IES, University of Iceland, Reykjavik, Iceland

The 2010 March to April mildly alkalic basaltic fissure eruption on the east flank (Fimmvorduhals) of the Eyjafjoll volcano, Iceland, was a precursor to the main summit eruption that followed on April 14. It most likely represents the mafic magma that triggered the summit eruption by intrusion into and mixing with a silicic magma body residing at shallow levels within the volcano. The Fimmvorduhals eruption took place on a 300 m-long radial fissure, featuring up to 150 m-high lava fountains that produced an a'a lava flow field with a mean thickness of 20m, area of 1.3 $km^2$ and a volume of 0.025 $km^3$. The average magma discharge for the eruption is 13 m3/s.

Here we present results on major element composition and initial and residual volatile (S, Cl, F, $H_2O$, $CO_2$) concentrations in the Fimmvorduhals magma as determined by analysis of 87 melt inclusions (MI) and 177 analysis of glass groundmass obtained from a suite of 9 samples representing the first 14 days of the eruption. The groundmass glass ($TiO_2$ = 4.91±0.2 wt%; FeO = 14.52±0.46 wt%) and the MIs ($TiO_2$ = 4.91±0.2 wt%; FeO =13.12±1.77 wt%) have very similar FeTi basalt composition, although the MIs (MgO = 5.39±0.90 wt%) are slightly less evolved than the groundmass glass (MgO = 4.7±0.20 wt%). The data defines distinct trends on bivariate plots consistent with evolution by fractional crystallization. Volatile measurements in the MIs gave the following results: 0.148±0.041 (range 0.016–0.254) wt% S, 0.071±0.031 (range 0.022–0.240) wt% Cl and 0.095±0.042 (range 0.032–0.299) wt% F, 0.54±0.25 (range 0.20–0.88) wt% $H_2O$, 0.19±0.09 (range 0.04–0.32) wt% $CO_2$. MIs with the highest volatile concentrations are situated in the core of the pheneocrysts, those with lower and more variable volatile contents are typically located near their edges. We interpret this to indicate progressive entrapment of MIs into phenocrysts, first in the magma holding chamber and then during magma ascents, where additional growth is facilitated by the low magma discharge. Thus, only MIs from the core contain information on the initial volatile concentration of the magma at depth, the remainder records magma parcels degassed to variably degree during ascent and prior to entrapment. Consequently, the pre-eruption concentrations of dissolved volatiles in the Fimmvorduhals magma at depth are indicated by the highest values, giving the following estimate for the initial volatile values: 0.224±0.021 wt% S, 0.074±0.018 wt% Cl and 0.112±0.041 wt% F, 0.87±0.01 wt% $H_2O$, 0.294±0.02 wt% $CO_2$. This gives a total pre-eruption volatile content of 1.5±0.15 wt% for the Fimmvorduhals magma. The corresponding groundmass (residual) values are 0.047±0.012 wt% S, 0.068±0.008 wt% Cl and 0.118±0.018 wt% F, 0.07±0.02 wt% $H_2O$, 0.012±0.05 wt% $CO_2$. These data indicate that about 80% of the volatiles escaped into the atmosphere upon venting. The total mass of sulphur released into the atmosphere by the Fimmvorduhals eruption is therefore about 3 megatons.

## The 20 March to 12 April basaltic Fimmvorduhals flank eruption at Eyjafjallajökull volcano, Iceland: Course of events.

Armann Hoskuldsson[1], Thor Thordarson[2], Eyjolfur Magnusson[1], Magnus T. Guðmundsson[1], Freysteinn Sigmundsson[1], Olgeir Sigmarsson[1]

1 Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland
2 School of Geosciences, University of Edinburgh, Edinburgh, UK

At 11:30 PM on March 20, reports were received of an eruption in the region of the Fimmvorduhals pass between the glaciers of Eyjafjallajokull and Myrdalsjokull. A surveillance flight at daybreak on 21 March showed that a basaltic eruption was underway on a radial fissure on the east flank of the Eyjafjallajökull volcano, featuring a 300 m-long curtain of lava fountains feeding small lava streams. The onset of the eruption was unusually calm. Seismicity did not intensify immediately prior to the eruption despite the fact that in the week leading to the eruption, an earthquake swarm migrated towards the surface from depth of >14 km indicating rise of magma from depth. Only very weak seismic tremor was detected around 10:30 PM on the 20th, gently increasing through the night.

At the beginning the eruption featured as many as 15 lava fountains with maximum height of 150 m. On March 24 only four vents where active with fountains reaching to heights of 100 m. On March 31 and April 1 the activity was characterized by relatively weak fountaining through a forcefully stirring pool of lava. The vents were surrounded by 60-80 m high ramparts and the level of lava stood at approximately 40 m. This high stand led to opening of a new fissure trending northwest from the central segment of the original fissure. As activity on the new fissure intensified, the discharge from the original fissure declined and stopped on April 7.

The intensity of the lava fountains varied significantly on the time scale of hours and was strongly influenced the level of the lava pond in the vents, producing narrow, gas-charged, piston-like fountains during periods of low lava levels, but spray-like fountains when the lava level was high and dampened the rate of atmospheric venting of volatiles.

The eruption produced a fountain-fed lava flow field with an area of about 1.3 km$^2$. Initially (20-25 March), the lava advanced towards northeast, but on March 26 the lava began advancing to the west and northwest, especially after April 1 when the activity became concentrated on the new fissure. The flow field morphology is dominantly a’a, but domains of pahoehoe and slabby pahoehoe are present, particularly in the western sector of the flow field. The advance of the lava from the vents was episodic; when the lava stood high the lava surged out of the vents, but at low stand there was a lull in the advance. The lava discharged from the vents through open channels as well as internal pathways. The open channels were the most visible part of the transport system, feeding lava to active a’a flow fronts and producing spectacular lava falls when cascading into deep gullies just north of the vents. The role of internal pathways was much less noticeable, yet an important contribution to the overall growth of the flow field as it fed significant surface breakouts emerging on the surface of what otherwise looked like stagnant lava. When activity stopped on April 12 the fissure had issued about 0.025 km$^3$ of magma, giving a mean discharge of 13 m$^3$/s.

## Near-field tephra dispersal monitoring by satellites

Ingibjorg Jonsdottir[1], Gudrun Larsen[1], Thor Thordarson[2], Armann Hoskuldsson[1], Fridrik Hoskuldsson[3], Ashley Gerard Davies[4]

1 Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland
2 School of Geosciences, University of Edinburgh, Edinburgh, UK
3 Icelandic Coast Guard, Reykjavik, Iceland
4 Jet Propulsion Laboratory-California Institute of Technology, Pasadena, CA, United States

Various satellite images were used to monitor the eruption plume from Eyjafjallajökull central volcano in real time from April 14 and throughout the eruption, which stopped, at least temporarily, on May 22. The main object was to study the dispersion of the ash; it‘s extent and direction, for scientific purposes as well as for public safety. The work included a detailed examination of the characteristics of the plume; it‘s content, height and density. Some effort was made to distinguish the plume from dust storms of remobilized ash that prevailed during part of the period.

MODIS and MERIS images, with a number of channels and geometric resolution in the optical channel of 250m and 1km in thermal bands, along with NOAA images with 1km resolution, provided over 15 observations from space daily, although not with equal intervals. ASTER, EO-1 and ENVISAT ASAR images were used when available for comparison and additional information.

A number of analyses were performed on the data, to enhance the images, classify the plume into different severity categories and to estimate the amount of ash in the atmosphere. Other methods included calculations of plume height and data merging in Geographical Information Systems.

Other independent sources of information were used for comparison of the satellite data, such as observations of the eruptions plume from the Icelandic Coast Guard reconnaissance flights, surveying from the ground, web cameras and measurements of the ash distribution, qualities and thickness on the ground.

The results are daily maps of the eruption plume, indicating the extent and severity of the plume at all orbit times. Satellite images, though not a continuous observation method, did record significant changes in the eruption behavior.

In conjunction with in situ investigations, the remote-sensing dataset from the Spring 2010 eruption is a valuable resource which is being used to refine image interpretation techniques and to improve the use of future satellite data of volcanic activity to assess volcanic risk and hazard.

## Why do models predict such large ash clouds? An investigation using data from the Eyjafjallajőkull eruption, Iceland

Larry G. Mastin, USGS, Cascades Volcano Observatory
Hans Schwaiger, USGS, Alaska Volcano Observatory, Anchorage
Roger Denlinger, USGS, Cascades Volcano Observatory

The 2010 eruption of Eyjafjallajökull volcano, Iceland caused unprecedented disruption of European air operations and a rethinking of current practices on avoidance of volcanic ash by aircraft. During eruptions, Volcanic Ash Advisory Centers (VAACs) are responsible for tracking and communicating ash-cloud location and movement to the aviation community. VAACs rely on numerical models to forecast ash-cloud movement, but models tend to predict larger ash clouds than are observed in satellite images, suggesting sometimes unnecessarily large areas of hazard. This discrepancy led to controversy during the Eyjafjallajökull eruption as pressure to open airspace increased and sporadic airborne measurements failed to find ash at some locations where models predicted it.

We compare ash-cloud model simulations from our new Eulerian finite-volume model, Ash3d, with satellite, air, and ground-based measurements obtained by others during the Eyjafjallajökull eruption. Our objective is to examine the discrepancy between observed and modeled ash-cloud size and to consider possible causes. We used wind data from the NOAA Global Forecast System model, and modeled the period April 14-16 2010 using a plume height of 10 km, eruption rate of $2.5\times10^4$ kg/s, and a single grain size having fall velocity of 0.01 m/s. We did not calculate diffusion, meaning that all downwind widening of the plume occurred through wind advection and “numerical diffusion”, an artifact in which ash is smeared across cells in the model. Our model results are similar to others that have been publicly released. On April 16, satellite images show the migration of an east-west-oriented crescent-shaped, concave-northward cloud from southern Norway and Sweden southward toward Poland and Germany. By 1800UT, the cloud extended from near the German-Dutch border across the Czech Republic toward the northeast corner of Poland—an area of $\sim1\times10^5$ $km^2$ where ash load exceeded 0.1 $T/km^2$. In contrast, the modeled cloud in map view at this time resembles an inverted mushroom whose cap coincides with the crescent-shaped cloud but whose stem extends northward over Denmark and Norway back to Iceland. Its area with ash load >0.1 $T/km^2$ is $\sim6\times10^6$ $km^2$. By greatly reducing eruption intensity on April 16, simulations produce the mushroom cap without the stem, reducing area by ~20%. Decreasing numerical diffusion by reducing nodal spacing from 0.33° to 0.1° reduces cloud area by another 50%. Reducing erupted mass 10x does not decrease cloud area significantly. Large diffuse clouds of ash whose concentration lies below satellite detection limits may account for some of the discrepancy, but LiDAR measurements in Leipzig and Munich show that the April 16 ash cloud had sharp boundaries with relatively clear air outside. From these results we infer that the discrepancy may reflect at least three processes: (1) ash removal from the atmosphere through formation of aggregates and hydrometeors; (2) details in the eruption source history; and (3) numerical diffusion or “smearing” of ash across cells of finite size.

## Eyjafjallajökull 2010: Monitoring the eruption site and changes in vent activity from aircraft

Björn Oddsson[1], Magnús Tumi Guðmundsson[1], Eyjólfur Magnússon[1], Þórdís Högnadóttir[1] and Friðrik Höskuldsson[2].

1 Institute of Earth Sciences, University of Iceland (bjornod@hi.is)
2 Icelandic Coast Guard

The vent area of the eruption in Eyjafjallajökull was monitored by overflights as often as possible during the main activity and with less frequent flights in the first weeks after the eruption declined. Three types of aircrafts were used; TF-SIF(Dash 8 Q300 airplane) and TF-GNÁ ( Aerospatiale Super Puma AS-332L1 helicopter) operated by the Icelandic coast guard and a small propeller driven Cessna 207 from Eagle Air, a private air service. The purpose for these overflights was to monitor any changes in volcanic activity and estimate possible hazards caused by the volcano (jökulhlaups, plume fallouts, possible pyroclastic flows, etc.). Changes in definitions of a no-fly zone during the eruption made flight monitoring more complicated as the eruption progressed; as it restricted the use of turbo-engined planes and helicopters.

TF-SIF is equipped with Synthetic Aperture Radar- radar (SAR), infrared/TV daylight camera and large windows for visual inspection and photography. It is most useful when visibility is low, since cloud and eruption plume are transparent to the SAR radar. The SAR images allow the monitoring of changes in the ice cauldrons, progress of a lava field and build up of crater cones within the Ice cauldrons. During the morning of April the 14 when the eruption started, this was the only way to locate the vents and monitor the evolution of ice cauldrons forming within the caldera. The aircraft cannot enter the no-fly zone, but the radar images are acquired at 18-20,000 feet along flight lines 15-20 km away from the target, making monitoring from outside the no-fly zone possible.

TF-GNÁ was used when visibility was good, and it was possible to fly close to the eruption site. It has an infrared camera on board (no absolute scale). Having the possibility of opening a large side door and hovering gave chances to focus on one target at a time, e.g. when using the hand--held infrared camera. The helicopter cannot enter the no-fly zone, but during the effusive phase in late April, it was possible to approach the eruption site and inspect the outlet glacier to learn more about the floodwater path and the progression of the lava. After the increase in explosive activity in early May, the helicopter was not used for monitoring due to the no-fly zone.

The Cessna 207 was the most used aircraft for monitoring the changes in the volcanic activity. It was allowed to enter the no-flight zone and it was possible to come quite close to the eruption site.

The data collected were videos, photographs, infrared images, radar images and observations by visual inspections.

## Riverine $CO_2$ fluxes from the Eyjafjallajökull volcano

Olsson J.[1,2] and Gislason S. R.[1]

1 Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavik, Iceland
2 Nano-Science Center, Department of Chemistry, University of Copenhagen, Denmark.

Significant amount of $CO_2$ can be dissolved in river and flood waters associated with volcanic eruptions (e.g. Gislason et al. 2002; Flaathen et al. 2009). Before the eruption of Eyjafjallajökull in 2010, $CO_2$ riverine fluxes were measured occasionally from 1993, covering two intrusive events within the volcano in 1994 and 1999 (Gislason et al 1995; Pedersen et al.; 2004; 2006). The main dissolved $CO_2$ flux from the volcano has been via River Jökulsá draining the summit caldera. The partial pressure of $CO_2$ in the waters has been up to 90 times that of the atmosphere. The riverine flux in 1993-94 was of the order of 0.1 to 1 kg $CO_2$ per second. An order of magnitude smaller, than water dissolved $CO_2$ fluxes from the Hekla and Grimsvötn volcanoes in Iceland (Agustdottir and Brantley 1994; Flaathen et al. 2009).

Conductivity, temperature and water level in Jökulsá have been continuously monitored by the (Icelandic Meteorological Office, 2010) since 1999 and few water samples have been analysed in order to correlate conductivity with water chemistry. Conductivity increases with total concentration of charged dissolved constituents. Since 1999 the conductivity of Jökulsá has remained much higher than the neighbouring rivers.

The conductivity of several rivers in the vicinity of the Eyjafjallajökull was studied following the first phase of the eruption 20 March to 12 April 2010. The conductivity of the Jökulsá remained high but the change in conductivity of other rivers was mostly associated with direct contact of surface waters with lava or ash. There was no indication of deep degassing into these rivers, as into Jökulsá.

However, in July 2010 there were two main outlets of riverine $CO_2$ on the north side of the volcano, via the Jökulsá, and Hvanná/Hrunaá rivers. The first phase of the eruption, 20 March to 12 April, was within the river catchments of the Hvanná and Hruná rivers. The concentration of dissolved constituents was remarkably high in Hvanná in July 2010. The conductivity was in the range of 1000 to 3000 µS/cm, alkalinity higher than 20 meq/kg, temperature was 2-4°C and the pH was relatively high 6.5-8, indicating significant water rock interactions during and after $CO_2$ addition to the waters. The partial pressure of $CO_2$ in the river was greater than the atmosphere, leading to degassing of the waters, resulting in carbonate precipitation for hundreds of meters downstream.

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# The 14 April - 22 May 2010 summit eruption at Eyjafjöll volcano, Iceland: Volatile contents and magma degassing.

Thor Thordarson[1], Chris Hayward[1], Margaret Hartley[1], Olgeir Sigmarsson[2], Armann Hoskuldsson[2], Magnus Gudmundsson[2], Freysteinn Sigmundsson[2]

1 School of Geosciences, University of Edinburgh, Edinburgh, UK
2 Institute of Earth sciences, University of Iceland, Reykjavik, Iceland

The unexpected disruption to aviation over Europe during the 14 April-22 May 2010 explosive eruption at the Eyjafjöll volcano, Iceland, was primarily caused by the large proportions of fine ash generated by the event and consistent westerly airflow over |Iceland during the 39 days of activity. The 2010 summit eruption produced about 0.1 $km^2$ (DRE) of trachyandesite tephra containing between 10-20% of extremely fine ash (≤10 micrometers). Three main phases are identified in the eruption: a) an initial intraglacial phase lasting from 14-19 April, featuring semi-continuous phreatomagmatic and magmatic Vulcanian-type explosions; b) about 14 day-long (19 April-3 May) phase of weak magmatic explosions and lava emission; and c) a renewed moderately intense, intermittent Vulcanian-type explosions lasting another 21 days. In order to fully understand fragmentation processes that produce large amounts of fine ash, it is important to assess role of magmatic volatiles and degassing mechanism.

Here we present results on major element composition as well as initial and residual volatile (S, Cl, F, $H_2O$, $CO_2$) concentrations in the Eyjafjoll summit eruption as determined by analysis of 14 melt inclusions (MI), hosted by plagioclase, olivine and pyroxene pheneocrysts, and 78 analysis of glass groundmass obtained from a suite of 7 samples representing the initial phase (first 7 days) of eruption. The composition of the groundmass glass of the tephra ($SiO_2$ = 61.13±1.08 wt%) and the MIs ($SiO_2$ = 58.59±2.52 wt%) is trachyandesite. Volatile concentrations in the MIs are 0.063±0.024 wt% S, 0.269±0.026 wt% Cl and 0.168±0.0418 wt% F, 1.7 wt% $H_2O$ and the $CO_2$ content ranges from 0.11 – 0.13 wt%. The corresponding groundmass (residual) values for the trachyandesite grondmass glasses are 0.031±0.006 wt% S, 0.277±0.019 wt% Cl and 0.171±0.019 wt% F, 0.58±0.17 wt% $H_2O$ and 0.014±0.014 wt% $CO_2$. This data indicates that 50-60% of the sulfur and $H_2O$ and about 90% of the $CO_2$ was realest upon venting. Cl and F do not appear to have been released in any significant amounts. This data indicates that the total mass of sulphur released into the atmosphere by the initial phase of the Eyjafjoll summit eruption was ≤0.1 megaton.

## Aircraft based optical in-situ measurements of the distribution of the Eyjafjallajökull´s volcanic ash particles over north-western Germany with a light sport aircraft and an optical particle counter

WEBER, Konradin, POHL, Tobias, VOGEL, Andreas, FISCHER, Christian, VAN HAREN, Günther, Duesseldorf University of Applied Sciences, Environmental Measurement Techniques, Josef-Gockeln-Str. 9, 40474 Duesseldorf, Germany

The eruption of the volcano Eyjafjallajökull (Iceland) in 2010 has caused a transportation of an ash plume over large areas of Europe. In April 2010 the airspace over Europe was closed for several days because of the volcano ash plume. The VAAC (Volcanic Ash Advisory Center), London, has continuously published graphics of the predicted spread and dispersion of the volcanic ash plume, which were partly basis for the air traffic restrictions in Germany.

In this situation the Laboratory for Environmental Measurement Techniques of the University of Applied Sciences in Duesseldorf has performed 14 measurement flights from April 24 to May 21 2010 in order to get realtime measured information about the distribution of the ash plume. Within these measurement flights real airborne in-situ particle measurement data over a part of Germany (north-western Germany) were obtained and could be compared with the predicted ash dispersion model data of the VAAC.

For these measurements a laser based optical particle counter (OPC, Model Grimm 1.107) has been used, which was mounted in a light sport aircraft (Model CT Shortwing). With this OPC in-situ and on-line measurements of particles in a range of sizes between 250 nm and 32 µm were possible. The OPC was combined with an isokinetic sampling device. Airborne particle measurements were performed during flights up to a maximum altitude of nearly 4500 m. The results of the airborne optical particle measurements were compared with the model dispersion predictions for the ash plume by the VAAC and with European limit concentrations. During this study it turned out, that the volcanic ash plume over north-western Germany had a strong temporal variation as well as a very inhomogeneous spatial structure and distribution within the atmosphere during the measurement period and within the sampling area.