deformation. GPS and InSAR observations are available throughout the period, with a strongly enhanced data quality and quantity during the most recent unrest episode spanning 2009-2010. A set of inverse models calculated from the entire set of pre-eruptive, and co-eruptive surface deformation data has revealed a complexity of the subsurface magma plumbing, consisting of a network of sills and melt pockets at 4-7 km depth, as opposed to a single crustal magma chamber.

UV4-02

Deformation cycle of the Grímsvötn sub-glacial volcano, Iceland, measured by GPS

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The subglacial Grímsvötn volcano in Vatnajökull ice cap erupted in 1998, 2004, and 2011. We present results of Global Positioning System (GPS) geodetic measurements since 1997 conducted at one site on the volcano's caldera rim, which protrudes through the ice cap. The volcano contains a complex of three calderas (<12 km^2 each). The observed displacement can be attributed to several processes: i) transport of magma in and out of a shallow chamber under the center of a caldera complex (inflation, deflation, accompanied by in- and outward horizontal displacements), ii) isostatic uplift due to gradual thinning of the ice cap, iii) annual variation in snow load, iv) crustal plate movements. Annual GPS measurements started after the 1998 eruption and a continuous GPS-monitoring station has been operative shortly before the 2004 eruption. During inflation periods the vertical displacement is a joint result of a glacial isostatic adjustment due to thinning of the glacier and inflow of magma to a shallow magma chamber, while the horizontal displacement component is predominately attributed to magma pressure changes. The horizontal displacement of the GPS-site on the caldera rim is directed outward during inflation and inward (directly opposite) accompanying the eruptions. This pattern has been repeated for each eruption cycle, pointing to location of one and the same magma chamber in the center of the caldera complex. Erupting vents in 1998, 2004 and 2011 were located at the foot of the southern Grímsvötn caldera rim. The earthquake pattern was similar prior to the two most recent eruptions: a slow increase in number of events during the years before the eruptions and practically none following the eruptions. The continuous GPS data after the eruption in 2011 suggest a fast pressure recovery of the shallow magma chamber similar to that following the 1998 and 2004 eruptions, although the 2011 eruption is the best observed. The regularity of the crustal deformation and the earthquake pattern prior to the past two eruptions led to both successful long- and short-term predictions and warning of the events. Grímsvötn volcano has shown to be in a state of continuous magma accumulation at shallow depths that results in eruptions when the strength of the crust is overcome by the magma pressure.

UV4-03

Grímsvötn 2011 Explosive Eruption, Iceland: Relation between Magma Chamber Pressure Drop inferred from High Rate Geodesy and Plume Strength from Radar Observations

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We demonstrate a clear relation between the vigor of an explosive eruption and inferred pressure change in a magma chamber feeding the eruption, based on near-field records of continuous GPS and ground tilt observations. The explosive mostly phreatomagmatic VEI4 eruption of the subglacial Grímsvötn volcano in Iceland, 21-28 May 2011, produced an initial plume reaching a height of about 20 km. Magma feeding the eruption drained from a shallow magma chamber under the Grímsvötn caldera. A continuous GPS site on the caldera rim sampling data at 5 Hz has allowed the reconstruction of the pressure drop history in this magma chamber. The pressure dropped at a fast rate about an hour prior to the eruption while a feeder dike formed. Throughout the eruption the pressure continued to drop, but decayed exponentially. These observations are compared to measurements of plume heights, based on C-band radar located 257 km from the volcano and a mobile X-band weather radar placed at 75 km distance from the volcano after the eruption began. The radar further away has height resolution steps of 5 km at the location of Grímsvötn above 10 km elevation, and the one closer has resolution steps of 2-3 km. The measurements reveal plume heights often above 15 km between 19:21 on 21 May and 17:35 on 22 May (local time same as GMT). Peak elevation values of about 20-25 km for about 30 minute intervals were observed a few times between 21:25 on 21 May and 06:40 on 22 May. The initial strong plume was followed by pulsating but generally declining activity. After 04:55 on 23 May the measurements indicate a fluctuating plume mainly below 10 km. In order to generate a continuous curve of plume elevation we average all available plume elevation information for each hour. The resulting plume height is then related to magma flow rate using an

empirical formula from Mastin et al. (2009). Integrating these flow rates yields an estimate of accumulated volume of eruptive products calculated as dense rock equivalent (DRE). Despite large uncertainties on the inferred magma flow rate, the shape of the curve of inferred accumulated DRE and the pressure drop are similar. For this eruption, we see a clear link between the strength of an eruption plume and pressure change in the feeding magma chamber, measured by high rate ground deformation studies. Hence we can conclude that magma flow inferred from plume height correlates with the pressure change, which demonstrates the potential of real time high rate geodesy to foresee both onset and evolution of explosive eruptions and their plumes. The inferred volume change of the underlying magma chamber, modeled as a Mogi source, is about 5-8 times smaller than the suggested DRE volume from the integration of plume heights, which we relate to the effects of magma compressibility.

UV4-04

Resonating eruptive flow rate during the Grímsvötn 2011 volcanic eruption

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The Grímsvötn volcano in Iceland erupted 21-28 May 2011 at a similar place (64°23.9’N, 17°23.1’W, about 1450 m a.s.l.) under the SW caldera rim as the last eruption in November 2004. The eruption started at or just before 19:00 UTC on 21 May. During the first night the plume reached 20-25 km altitude over a 10 hour period, after which the strength of the eruption appeared to decrease exponentially.

Two weather radars monitored the plume during the eruption; a fixed C-band radar in Keflavík and a mobile X-band radar at Kirkjubæjarklaustur, 257 and 75 km from the volcano, respectively. The plume height of the radar time-series was used to calculate the mean eruptive flow rate. The calculations indicate that about 90% of the total mass erupted during the first 21 hours. The estimates of eruptive flow rate show very strong regular oscillations with periods of about 5 hours. During the first 12 hours the 1 hour mean dense rock equivalent flow rate oscillated between about 1000 and 8000 m^3/s (2 and 20 million kg/s).

During the eruption, over 16 000 lightning strikes were recorded near Grímsvötn by the ATDnet (Arrival Time Difference) network of the UK Met Office. Peculiar variations in the rate of lightning occurrence became evident during real-time monitoring of the ATDnet lightning data during the first night of the eruption. The calculated flow rate oscillations agree well with the observed lightning oscillations, both in phase and relative amplitude. The same oscillations can also be seen in tiltmeter data from Grímsfjall, about 6 km East of the vent. In hindsight, there also appear to have been some regular long period oscillations in lightning rate and plume height during the Grímsvötn 2004 eruption.

We can only speculate on the causes of the apparent volcanic resonance. (a) The magma chamber and feeding dykes of the volcano might act like a Helmholtz cavity resonator. However, the observed period is considerably longer than one might expect. (b) The oscillations might reflect an interaction between quenching of the feeding dykes to the surface and boiling of the geothermal fluids in the geothermal system above the magma chamber. (c) A small shallow magma chamber might be emptied in a few hours and a larger deeper source might take similar time to refill the shallow magma chamber. Possibly, such a two chamber system might resonate with the observed period.

UV4-05

Inferring volcanic plumbing systems from ground deformation: what we learn from laboratory experiments

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Active volcanoes experience ground deformation as a response to the dynamics of underground magmatic systems. The analysis of ground deformation patterns may provide important constraints on the dynamics and shape of the underlying volcanic plumbing systems. Nevertheless, these analyses usually take into account simplistic shapes (sphere, dykes, sills) and the results cannot be verified as the modelled systems are buried. In this contribution, I present new results from experimental models of magma intrusion, in which both the evolution of ground deformation during intrusion and the shape of the underlying intrusion are monitored. The models consisted of a molten vegetable oil, simulating low viscosity magma, injected into cohesive fine-grained silica flour, simulating the brittle upper crust; oil injection resulted is sheet intrusions (dykes, sills and cone sheets). The initial topography in the models was flat. While the oil was intruding, the surface of the models slightly lifted up to form a smooth relief, which was mapped through time. After an initial symmetrical development, the uplifted area developed asymmetrically; at the end of the experiments, the oil always erupted at the steepest edge of the uplifted area. After the experiment, the oil solidified, the intrusion was excavated and the shape of its top surface mapped. The comparison between the uplifted zone and the underlying intrusions showed that (1) the complex shapes of the uplifted areas reflected the complex shapes of the underlying intrusions, (2) the time evolution of the uplifted zone was correlated with the evolution of the underlying intrusion, and (3) the early asymmetrical evolution of the uplifted areas can be used to predict the location of the eruption of the oil. The experimental results also suggest that complex intrusion shapes (inclined sheet, cone sheet, complex sill) may have to be considered more systematically in analyses of ground deformation patterns on volcanoes.