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Crustal deformation at Grímvötn volcano: Constraints on magma flow in relation to eruptions of 1998, 2004 and 2011, and location of a shallow magma chamber

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Time series of displacements of Mt. Grímsfjall have been collected by Global Positioning System (GPS) geodetic measurements, with increasing detail since 1997. The measurements provide unique constraints on magma flow in relation to the 1998, 2004 and 2011 eruptions of Grímsvötn, and on location of a shallow magma chamber beneath the complex of three calderas at Grímsvötn. The observed displacements 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 segments of continuous GPS-monitoring are available from before the 2004 eruption. During inflation periods the vertical displacements are a result of 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 displacements of the GPS-site on the caldera rim are directed outward during inflation and inward (directly opposite) during 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. Although erupting vents in 1998, 2004 and 2011 were located at the foot of the southern Grímsvötn caldera rim, the inferred pressure centre of a shallow magma chamber is under the centre of the overall caldera complex. Earthquake patterns were 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. Time series from the continuous GPS station on Grímsfjall suggest a fast pressure recovery of the shallow magma chamber following the eruption in 2011, similar to observations after the 1998 and 2004 eruptions. 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 depth that results in eruptions when the strength of the crust is overcome by the magma pressure.

During the 2011 Grímsvötn eruption high rate geodetic measurements gave information on displacements at sub second intervals, revealing details of surface deformation associated with magma movements during the eruption. A 5 Hz GPS station and an electronic tilt meter were in operation at Grímsfjall during the eruption. The colocation of these instruments allows us to relate the observed surface deformation to pressure change in a magma chamber assuming a simple Mogi source within an elastic half space. Continuous stream of data was transmitted during the eruption to Reykjavík, despite the strong eruption plume and lightning. The tiltmeter measures N-S and E-W components of tilt, with the N-S component recorded at 100 samples per second (sps) but the E-W component at 4 sps. The high rate data from the GPS station at Grímsfjall (GFUM) were analyzed using the Track part of GAMIT/GLOBK. We produced kinematic solutions at 5 Hz and 1 Hz intervals using reference stations in 40-120 km distance of the volcano. To minimize multipath effects we applied sidereal filtering and stacked the individual solutions to further improve the signal to noise ratio. The resulting deformation time series suggests a rapid pressure drop starting about 50 minutes prior to the onset of the eruption when over 20 km high plume formed. The characteristics of the GPS and tilt data time series suggests that the main signal was induced by a single source of fixed location and geometry throughout the eruption; a shallow magma chamber. Small deviations in displacement direction prior to the onset of the eruption can be explained by the opening of the feeder dike. We see a total displacement of 57 cm in direction N38.5°W and down at the GPS station, suggesting a source depth of 1.8 +/- 0.2 km and a total volume contraction of the shallow magma chamber of (38 +/- 4) x 106 m3. About 20% of the displacement preceded the eruption and more than 95% took place within 24 hours of the onset of deformation. The data show that magma feeding the eruption drained from a shallow magma chamber under the Grímsvötn caldera, and from the GPS record we can infer the pressure drop history in the 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 mostly exponentially.

The inferred pressure change can be compared to the vigor of the eruption and measurements of plume heights. The eruption produced an initial plume reaching a height of about 20 km, rapidly declining over several days. Plume height was measured by a 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. 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 5-10 times smaller than the suggested DRE volume from the integration of plume heights. The difference can be related to expansion of magma residing in the shallow chamber, due to its compressibility.