Volcano geodesy and magma dynamics in Iceland

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Abstract

Here we review the achievements of volcano geodesy in Iceland during the last 15 years. Extensive measurements of crustal deformation have been conducted using a variety of geodetic techniques, including leveling, electronic distance measurements, campaign and continuous Global Positioning System (GPS) geodesy, and interferometric analysis of synthetic aperture radar images (InSAR). Results from these measurements provide a comprehensive view of the behavior of Icelandic volcanoes. Between inflation, intrusion, and eruption episodes, volcanoes are likely to deflate or show no sign of seismic activity. Subsidence rates are often in the range of a few millimeters to a few centimeters a year, reducing progressively with time since the last eruption or intrusion at the volcano. Subsidence can be caused by cooling and contraction of magma, outflow of magma, it can be related to plate spreading. Volcano subsidence or lack of deformation is often interrupted by episodic magma flow towards near-surface locations. Such magma recharge has been observed geodetically at Hengill, Hekla, Eyjafjallajökull, Katla, Grimsvötn, and Krafla volcanoes, with inflow inferred to last from a few months up to two decades. In the last 15 years, five volcanic eruptions, three intrusive events and two M6 earthquakes have occurred. In recent years, the Grimsvötn and Katla volcanoes have exhibited continuous inflation of a few centimeters per year, which at Grimsvötn culminated in an eruption on 1 November 2004. Hekla and Torfajökull volcanoes have inflated at rates an order-of-magnitude less. Subsidence is occurring presently at the Askja and Krafla volcanoes. Within the period of geodetic measurement, signals consistent with no deformation are typical for most of the 35 active volcanoes in Iceland.
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1. Introduction

The Icelandic landmass, being the product of a hotspot located at a divergent plate boundary, provides an unusual display of volcano types, ranging from rift zone volcanoes of tholeiite petrology to off-rift and even intraplate volcanoes of more evolved products. Even rhyolitic products are found, sometimes almost exclusively. The crustal thickness of 25–40 km (Darbyshire et al., 2000) suggests that the hotspot amplifies the normal magmatic output of the divergent plate boundary by a factor of 5–8. About 35 active volcanic systems exist in Iceland (Figs. 1 and 2). The centre of the hotspot is currently thought to be located near the junction of the EVZ and the NVZ in Central Iceland (Wolfe et al., 1997). The large variability of volcanic manifestations in Iceland calls for flexibility in monitoring methods. External conditions are also highly variable as several of the volcanoes are subglacial. Jökulhlaups (glacial water floods), explosive activity, lahars, and even tsunamis may result from magma–water interactions. The high rate of volcanism in Iceland makes volcano monitoring a high-priority issue. Since the settlement of Iceland in the ninth century 230 eruptions have been documented.

The high volcanic activity in Iceland in the last decades has provided numerous opportunities to study deformation of volcanoes. Eysteinn Tryggvason, the pioneer of Icelandic deformation studies of volcanoes, installed the first leveling profiles in 1966 at the Askja volcano. Since then the volcanoes Hekla, Vestmannaeyjar, Krafla, and Grímsvötn have had several eruptions, and a large eruption occurred at Gjálp, an eruptive fissure located between Bárðarbunga and Grímsvötn volcanoes. Furthermore, Askja, Eyjafjalla-

Fig. 1. Map of Iceland with the general outline of the volcanic systems (in yellow, from Einarsson and Sæmundsson, 1987) along the plate boundary (dashed red line), which is offset by two transform fault systems (black lines). The neovolcanic zone across Iceland is divided into the northern volcanic zone (NVZ), the western volcanic zone (WVZ) and the eastern volcanic zone (EVZ). The EVZ and the WVZ are parallel and connected by the south Iceland Seismic zone (SISZ) transform fault zone. In the north, the NVZ connects with the Kolbeinsey ridge by the Tjörnes fracture zone (TFZ). The continuous GPS stations are shown by red hexagons and the volumetric strain meters are shown by green rhombuses. Note the location of the OLKE GPS station, which is located close to the Hengill volcano. The campaign GPS station at Jökulheimar (JOKU), which is used as the reference station in the campaign GPS measurements at Grímsvötn, is also indicated. Boxes show the location of Figs. 3 and 5.
jökull, Katla and Hrómundartindur have shown measurable deformation interpreted as the result of magma movements at depth. Eysteinn Tryggvason initiated several important time series in the mid-late sixties that are still continued today. The aim of this paper is to provide a summary of recent deformation result. We will address the volcanic systems and eruptions that are currently studied by geodetic measurements of crustal deformation, i.e., Hengill/ Hrómundartindur, Hekla, Eyjafjallajökull, Katla, Torfajökull, Grímsvötn, Askja, Krafla, and Gjálp.

2. Geodetic techniques

2.1. Early techniques

The first geodetic project specifically aimed at monitoring of a volcano in Iceland was the establishment of a leveling line at Askja in 1966 (Tryggvason, 1989). This technique was subsequently applied to several volcanoes, including Surtsey, Hekla, Katla, Hengill, and Krafla. A related technique, optical tilt measurements (or “dry tilt”), has also been widely applied at some of these volcanoes. Eysteinn Tryggvason installed benchmarks around several lakes in Iceland and utilized lake surfaces as tiltmeters (Tryggvason, 1987). By the time of the Hekla 1970 and 1980–81 eruptions, electronic distance measuring (EDM) instruments were available (e.g., Decker et al., 1971; Kjartansson and Grönvold, 1983). EDM was also used extensively during the volcano–tectonic events at Krafla in 1975–1984. Electronic tiltmeters were designed and applied for continuous monitoring of tilt changes (e.g., Tryggvason, 1986). Extensometers were installed across fractures to monitor changes in their width (Hauksson, 1983). Additionally, gravity measurements were applied to monitor the extensive vertical movements at Krafla (Johnsen et al., 1980).

A network of volumetric strainmeters (Sacks et al., 1971) was installed in the South Iceland Seismic Zone in the late seventies for continuous monitoring of strain loading of the seismic zone. These instruments have shown strain changes associated with the recent Hekla eruptions and have proven to be very important in the monitoring of Hekla (e.g., Linde et al., 1993).

Advances in geodetic methods in the last decade have brought new techniques that turn out to be very valuable in volcano monitoring in Iceland. These include GPS-geodesy (both campaign and continuous GPS), InSAR, and micro-gravity measurements. Older techniques, such as optical tilt and leveling, are also still widely applied.
2.2. GPS (campaign)

The first GPS-campaign in Iceland was performed in 1986 when a regional network covering most of Iceland was established. The purpose of the network was mainly to monitor plate spreading (Foulger et al., 1987). The first GPS survey of an individual volcano in Iceland was conducted in 1991 around Hekla (Sigmundsson et al., 1992). The GPS network has since been expanded to cover most volcanoes showing signs of activity.

2.3. CGPS (Continuous GPS)

Crustal deformation in near real-time is currently recorded at 17 CGPS sites in order to monitor plate spreading, volcanic deformation and co-seismic displacements. The stations are concentrated around the plate boundary (Fig. 1). The CGPS data are automatically downloaded and processed on a daily basis using predicted satellite orbits and reprocessed with final orbits when they become available. The results are available on the IMO website for public viewing (http://www.vedur.is/ja). The time series from the CGPS stations are mostly dominated by plate spreading, but deviations are observed at stations close to individual volcanoes (Geirsson, 2003). The CGPS stations give excellent time resolution of volcanic activity, but due to high installation and operating costs their spatial coverage is necessarily much sparser than that provided by campaign GPS.

2.4. InSAR

Application of interferometric synthetic aperture radar images (InSAR) in crustal deformation studies has been gaining popularity since the early 1990s (e.g., Massonnet and Feigl, 1998; Dzurisin, 2003). Interferometric processing of two SAR images acquired from about the same orbital position but at separate times may reveal a phase interference pattern caused by a change in distance from ground to satellite within this time span (Fig. 3). A fringe pattern emerges with each fringe corresponding to a phase

Fig. 3. A) InSAR image showing surface uplift at the Eyjafjallajökull volcano modified from Pedersen and Sigmundsson (2004). The interferogram covers the time period 6 Sep. 1992 to 15 Aug. 1995 and shows deformational fringes due to an intrusion event in 1994. One full color fringe corresponds to 2.8 cm of range change. Location of the study area is shown in Fig. 1. The outline of the Eyjafjallajökull ice cap is given in black. The interferogram is overlain on a SAR amplitude image. B) The fringe pattern that is predicted by a sill with variable opening up to 0.36 m. A green star denotes the alternative optimal Mogi source. Grey circles shows the best located earthquakes from the swarm in 1994. C) Residual interferogram, the difference between (A) and (B).
difference of $2\pi$ which for the ERS satellites is 2.8 cm. In Iceland, utilization of the technique has yielded good results (e.g., Vadon and Sigmundsson, 1997; Pedersen et al., 2003; de Zeeuw-van Daljes et al., 2004a). Combining three component GPS data with the spatial coverage of InSAR data is currently the most powerful tool in volcano geodesy.

2.5. Micro-gravity

Micro-gravity techniques can be used to identify sub-surface mass redistributions related to volcanic activity (Rymer, 1996). To be able to interpret the results unambiguously, it is essential that height changes are known at least with centimeter precision. The combination of micro-gravity with geodetic data forms a powerful tool to get better insight into volcanic systems, rather than with any of the two techniques alone. Repeated micro-gravity measurements have been conducted within the Askja volcano since 1988 (Rymer and Tryggvason, 1993; de Zeeuw-van Daljes et al., 2004b) and at Krafla volcano since 1975 (Johnsen et al., 1980; Rymer et al., 1998). The resulting data are among the most extensive micro-gravity data sets in the world.

3. Recent magmatic activity and geodetic observations

Since the early nineties, installation of an extensive GPS network and introduction of InSAR technology, have improved the ability to measure magma movements. More data has resulted in a more complete picture of volcano deformation in the active volcanic zones. Three volcanoes in Iceland dominate the eruption statistics and are the most active: Grímsvötn, Hekla and Katla (Fig. 2). Since 1990 there have been measurable movements at nine volcanoes, 5 confirmed eruptions, 3 inflation episodes, and several events suspected to be small subglacial eruptions. Three volcanoes are currently inflating, two of them at a rate of several centimeters a year.

3.1. Krafla

The episode of magmatic and rifting activity within the Krafla volcanic system from 1974 to 1989 offered a multitude of opportunities to study crustal deformation associated with magma movements. Located in the Northern Volcanic Zone, the Krafla system consists of a central volcano with a caldera and a trans-ecting fissure swarm. High-temperature geothermal systems are located within the Krafla caldera, providing energy for the Krafla power plant. The 1974–1989 rifting activity affected a 100 km long section of the plate boundary (see e.g., Björnsson et al., 1977; Einarsson, 1991a; Tryggvason, 1995). During most of this time magma infow into a shallow-level magma chamber beneath the caldera caused inflation of the caldera region. This inflation was interrupted by sudden deflation events when the walls of the chamber were breached and dykes were injected into the adjacent fissure swarm (Tryggvason, 1980; Einarsson and Brandsdóttir, 1980; Brandsdóttir and Einarsson, 1979). Large scale rifting occurred within the fissure swarm during these events. In nine out of twenty cases the dyke reached the surface and produced basaltic fissure eruptions. Extensive geodetic measurements have been conducted at Krafla, utilizing most available methods.

The Krafla power plant was under construction when the activity started in 1974. The foundation of the new power station building had been surveyed by precise leveling in order to monitor its settling during construction. The Krafla station turned out to be ideally located for monitoring of tilt variations associated with the Krafla magma chamber. A water tube tiltmeter was installed in the building in August 1976 and two readings taken per day during the next 11 years. This instrument was complemented by an electronic pendulum tiltmeter in August 1977 (Tryggvason, 1995). The tilt record in Fig. 4 is a composite of data obtained by these three methods, i.e., leveling the foundation, water-tube tiltmeter and pendulum tiltmeter. The tilt parameter can be used as a proxy for the pressure in a magma chamber throughout a whole eruptive and intrusive sequence. Leveling and tilt data from Krafla, both during inflation and deflation periods, have been used by several authors to derive the location and depth of a magma chamber (e.g., Björnsson et al., 1979; Tryggvason, 1980; Ewart and Voight, 1991). The principal conclusions of these studies are that the pressure source is located near the centre of the caldera at slightly less than 3 km. Seismic studies reveal a body of S-wave attenuation and low P-wave
velocity within the Krafla caldera (Einarsson, 1978; Brandsdóttir et al., 1997). Several lines of evidence suggest a deeper magma chamber at Krafla in addition to the one at 3 km depth. The continuous flow of magma towards the shallow chamber for over a decade during the Krafla fires suggest magma was transported from a localized reservoir or magma storage area at a deeper level in the crust or mantle. The location of it is uncertain, but geodetic data shows that deformation on the surface cannot fully be explained by the 3 km deep chamber. The deformation field is wider than expected. Tryggvason (1986) interpreted records from tiltmeters during the September 1984 eruption in terms of three stacked magma chambers, but location of the two deeper ones was not well resolved. The role of two deeper sources, rather than one, in the 1984 eruption, is also not certain. Árnadóttir et al. (1998) interpreted EDM and leveling data from the 1984 eruption and confirmed that magma was drained from a deeper source in addition to the 3 km deep source, to form a 1 m wide, 9 km long dyke, extending from the surface to about 7 km depth, and lava flows on the surface. The location of the deeper source was constrained to be deeper than 5 km, but narrow aperture of the geodetic network did not allow further resolution of its depth. The deformation associated with dyke intrusion events during the Krafla fires is for most events not well constrained. Leveling profiles crossing the fissure swarm in two places (Sigurdsson, 1980; Kamngiesser, 1983) show how the flanks of the fissure swarm were uplifted while a central block above the dikes was downfaulted.

The caldera region inflated after the last eruption (1984) until the pre-eruption level was approached. Then the inflation became intermittent. The last inflation period occurred in the summer of 1989. After that the caldera region has been slowly subsiding, a few centimeters per year, as determined by InSAR (Sigmundsson et al., 1997a) and a combined geodetic and micro-gravity study (Rymer et al., 1998). In the post-rifting period, GPS revealed higher than average spreading rates. The post-rifting deformation is fit by an elastic upper crust overlying a visco-elastic lower crust and even weaker visco-elastic upper mantle (e.g., Foulger et al., 1992; Pollitz and Sacks, 1996).

A recent InSAR study (de Zeeuw-van Dalfsen et al., 2004a) has revealed uplift over an about 50-km-wide area at the Krafla volcanic system (8 cm from 1993 to 1999), in addition to deformation caused by subsidence above the shallow magma chamber, and effects of plate spreading and post-rifting adjustment (Fig. 5). The favored explanation of de Zeeuw-van Dalfsen et al. (2004a) for the widespread uplift is that it results from magma accumulation at the crust–mantle boundary at 20 km depth, rather than being caused by post-rifting adjustment.

3.2. Askja

The Askja volcano in the Northern Volcanic Zone (Fig. 1) has three overlapping and nested calderas. The main caldera, formed in the early Holocene, is 8 km in diameter. An older caldera is discernable but it has been filled by later lava flows. The most recent caldera, Óskjuvatn, is 4.5 km in diameter and is filled by a lake. It was formed after the Plinian eruption of 1875. The most recent eruption of Askja took place in 1961 when a short E–W fissure opened up near the eastern caldera fault of the main caldera. A short leveling line was installed in the main caldera in
1966. The line was extended to 1.7 km length (Fig. 6) in 1968 and measured annually until 1972. Annual measurements were resumed in 1983 and the line was also extended. Because not all benchmarks are found every year due to snow cover, and because the entire line lies within the deformation field of the volcano, benchmark 404 is arbitrarily set to zero. This point has in recent years been measured annually by GPS.

To visualize the changes along this line we have plotted the height difference between the end points, A429 and A406, as a function of time (Fig. 7). Station A406 is 1 km closer to the caldera centre than A429. The data show that the volcano was inflating during 1970–1972. This had turned to deflation when measurements were resumed in 1983, a trend that has continued since. The deflation follows an exponential curve with a decay constant of 39 years (Sturkell et al., submitted for publication). The geodetic data have been modeled and interpreted in terms of a single Mogi-type pressure source (Mogi, 1958) located close to the centre of the main Askja caldera (Tryggvason, 1989; Rymer and Tryggvason, 1993; Sturkell and Sigmundsson, 2000). All these authors placed the point source at 1.5 to 3.5 km depth. This model
accounts for most of the observed displacements in the main caldera and its immediate vicinity. At a greater distance, however, displacements observed with GPS do not show the same good fit. A more elaborate model is presented by Sturkell et al. (submitted for publication) who invoke two Mogi sources to account for the far field displacements (Fig. 6). The shallow source at 3 km depth and the deeper at 16 km depth. The shallow source contributes to an estimated annual subsidence of 4.2 cm and the deeper source about 1.0 cm. This model was also applied to the results of a micro-gravity study for the period 1988–2003. A sub-surface mass decrease of $1.6 \times 10^{11}$ kg is derived (de Zeeuw-van Dalfsen et al., 2004b) indicating that magma drainage is an important contributor to the subsurface mass decrease and therefore to the surface deflation. Interferometric analysis of synthetic aperture radar images from radar satellites (InSAR) have also been conducted (Pagli et al., 2003), and show clearly the ongoing subsidence at Askja. The InSAR data are being further analyzed. The geometry of the deeper pressure source has not been resolved.

Sturkell et al. (submitted for publication) suggest that the onset of deflation at Askja in 1973 is causally related to the beginning of magma flow into the Krafla magma chamber about 75 km to the north which preceded the rifting episode of 1975–1984. We also point out that a series of large earthquakes began at the Bárðarbunga volcano in 1974 that lasted until 1996. The reverse faulting mechanisms of these events were interpreted by Einarsson (1991b) as the expression of deflation of Bárðarbunga. The temporal correlation of deflation of Bárðarbunga and Askja and the beginning of activity at Krafla suggests links between the volcanoes, eventually by pressure connection through the lower ductile crust in Iceland (Einarsson, 1991b).

3.3. Grímsvötn

This highly active volcano most recently erupted in December 1998 and November 2004. Grímsvötn is a subglacial volcano, and deformation can only be measured at a campaign GPS station located at the sole nunatak on the caldera rim. Fig. 8 shows vertical displacement of the GPS point at Grímsvötn (GRIM). GPS measurements showed uplift before the 1998 eruption, followed by subsidence as the pressure dropped in the magma chamber. Measurements were fitted to a Mogi model with the assumption that the source was located under the centre of the Grímsvötn caldera complex at a depth of at least 1.6 km (Sturkell et al., 2003a). Inflation resumed at Grímsvötn following the 1998 eruption and it was assumed that the pressure of the Mogi-source would have to surpass a critical level before a new eruption was to be expected. The critical level of the vertical component of the GRIM station was suggested to be at least 0.15–0.20 m above the minimum height obtained immediately after the 1998 eruption (Sturkell et al., 2003a). A measurement in September 2004 showed that the inflation had exceeded this level. Seismic activity increased markedly in the latter half of the year 2003 (Fig. 9) showing that the stress in the magma chamber roof had increased. Further increase of seismicity in late October and the onset of a jökulhlaup (a flood of melt water) from the Grímsvötn caldera lake on October 27 suggested that an eruption might be imminent, triggered by the pressure release of the flood. An eruption began in the evening of
November 1 as indicated by the appearance of low-frequency eruption tremor on nearby seismographs. The eruption onset was preceded by an intense swarm of earthquakes. The geodetic and seismic precursors to the eruption were recognized and formed the basis for rather detailed eruption warnings issued to the civil defense authorities, both in the long-term (months and year), intermediate-term (weeks and days) and short-term (hours) (Vogfjörd et al., 2005).

3.4. Gjálp

In the beginning of October 1996, a sub-glacial eruption started on a fissure between the Bárðarbunga
and Grímsvötn volcanoes (Fig. 1). This eruption fissure was termed Gjálp (Gudmundsson et al., 1997). The eruption began on a 7 km long N–S fissure after 36 h of intense seismic activity at Bárdarbunga. The seismicity propagated towards the eruption site suggesting that the eruption was fed from Bárdarbunga (Einarsson et al., 1997). The eruptive products were basaltic andesites, different from recent eruptive products of both Bárdarbunga and Grímsvötn. The similarity of the isotope characteristics with those of Grímsvötn has led to suggestions that the eruption was fed by Grímsvötn volcano (Sigmarsson et al., 2000). The eruption lasted for thirteen days. In early November a jökulhlaup of approximately 3.8 km$^3$ of meltwater was released over Skeiðarársandur, shown in Fig. 1 (Gudmundsson et al., 1997).

3.5. Hekla

Hekla volcano has had 18 summit eruptions and five in its direct surroundings during historic time, the last 1100 years. Precursory events have been detected prior to recent eruptions. Generally, eruption related earthquakes begin less than two hours before the eruption starts (Soosalu et al., in press). Hekla was the first volcano in Iceland to be studied by a local GPS-network. Measurements before and after the 1991 eruption revealed contraction towards the volcano (Sigmundsson et al., 1992). The data suggested a magma reservoir at 9 km depth, but uncertainties on this estimate were large because of absence of GPS stations close to the volcano (the closest being at about 13 km distance). Measurements prior to the 2000 eruption were conducted in 1996. After the eruption measurements have been conducted annually at selected points. The 1996–2000 displacement reveal clearly deformation associated with the feeder dyke for the 2000 eruption (amounting to several tens of cm). Further modelling of these data are needed, in particular to constrain eventual inflation/deflation cycle at the volcano. GPS data combined with all other geodetic data from Hekla, including InSAR and optical leveling tilt has the potential to provide improved constraints on the magma plumbing system under Hekla (Sigmundsson et al., 2001).

Continuous monitoring of crustal deformation in the South Iceland seismic zone (including Hekla) is done by six continuously recording borehole strainmeters operated by the Icelandic Meteorological Office. The permanent strainmeters are located 15–45 km from Hekla and gave a clear strain signal prior to the eruptions of 1991 and 2000 (Fig. 10). The closest volumetric strain meter (15 km distance, at Búrfell in BUR in Fig. 10) detected compression due to dyke injection 30 min before magma reached the surface and the eruption started on February 26, 2000 (Fig. 10). However, it had long been suspected that large strain excursions at BUR were accompanied by localized recovery, which may bias estimates of magma source depth. This was confirmed by strain records for the Mw 6.5 South Iceland earthquakes (the first occurring on 17 June and the second on 21 June, 2000). The original interpretation of the strain data at BUR associated with the 1991 and 2000 eruptions of Hekla gave too shallow a source depth. By considering the localized strain recovery, Jónsson et al. (2003) prefer a deeper location than the 6.5 km suggested by Linde et al. (1993) for the magma source. The most recent estimate based on re-interpretation of strain data places the magma chamber at 11 km depth (Kristján Ágústsson pers. com. 2004). Despite these complications, the combination of seismic and volumetric strain monitoring has given strong evidence of magma propagation towards the Earth’s surface and was used to issue a warning prior to the 2000 eruption.

Seven short leveling arrays (“dry-tilt” stations) are surveyed repeatedly around Hekla. The best station, Næfurholt, is located 11 km west of the summit, allowing for easy monitoring of E–W tilt. The tilt signal from the Næfurholt station is rather small but is still significant (Fig. 11). It suggests inflation beginning directly after the 1991 and 2000 eruptions. Eastward upward tilt generally increases with time, as the volcano builds up pressure for the next eruption, when a co-eruptive pressure decrease occurs. The most recent measurement (18 Nov. 2004) of the tilt station at Næfurholt shows upward tilt towards Hekla (Fig. 11). The east component indicates that a pressure increase under the volcano is of the same scale as prior to the 1991 and 2000 eruptions. It should be pointed out that one tilt station gives only an indication of possible magma accumulation under a volcano, and it should spur some additional measurements.
Fig. 11. Data from the Næfurholt tilt station located 11 km directly west of the Hekla volcano. Its east–west tilt shows the radial tilt component of deformation of the volcano. The observed tilt pattern repeats itself, suggesting a cyclic pattern, with upward tilt in the direction of the Hekla volcano prior to the eruptions, followed by subsidence as magma drains from beneath the volcano. The most recent measurement (18 Nov 2004) indicates that the east–west tilt is close to the critical value.
3.6. Katla

Katla volcano has had 20 eruptions since the settlement period in 874 AD. (Larsen, 2000). Its caldera, which is 600–700 m deep and encircles an area of 100 km² (Björnsson et al., 2000) is covered by the Mýrdalsjökull ice cap. The initial phase of its eruption is phreatomagmatic due to its occurrence at the base of the ice cap. Meltwater from the eruption site is released as a jökulhlaup at the ice margin. Such floods are characterized by a rapid rise to maximum discharge within a period of a few hours (Roberts et al., 2003). The most recent large eruption took place in 1918, generating a massive jökulhlaup. In 1955 a smaller jökulhlaup emerged from the eastern side of Mýrdalsjökull and two cauldrons were formed in the ice cap (Rist, 1967). Guðmundsson et al. (2000) suggested that the jökulhlaup was caused by a small sub-glacial eruption that did not break the ice surface. In July 1999 a sudden jökulhlaup occurred at the Sólheimajökull outlet glacier (Fig. 12) on the south side of the Mýrdalsjökull ice cap (Sigurðsson et al., 2000). This was preceded by changes in earthquake activity and accompanied by tremor bursts (Einarsson, 2000). A minor sub-glacial eruption or a shallow intrusion could have triggered this jökulhlaup (Guðmundsson et al., 2000).

The Katla area has shown persistent seismic activity since the beginning of seismograph observations in the first half of the last century. Einarsson and Brandsdóttir (2000) analyzed seismic data from the period 1978 to 1985, and found that the seismicity was mostly located in two areas, one within the caldera and the other in the Goðabunga area to the west of the caldera (Fig. 12). The seismicity has a distinct seasonal pattern, particularly in the Goðabunga cluster (Fig. 13), with a large majority of earthquakes occurring in the second half of the year. This pattern has persisted for at least four decades. The autumn activity in 2001 was intense but within normal limits. Seismic activity, however, did not stop in the winter of 2002 as it would have in a normal year and seismicity has been high ever since. In a recent study by Soosalu et al. (in press) a local seismic net was set up on and around the...
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Fig. 13. Accumulated seismic moment release from 1997 to 2004 in the Katla volcano. The area is divided into two sub-areas; the Katla caldera and the area west of the caldera, the Goðabunga area. The division is drawn along a north–south line at 19° 15' W (see Fig. 12). The moment–magnitude relation log $M_0 = M_l + 10$ from Slunga (1991) is used, where $M_0$ is the moment (in Nm) and $M_l$ the magnitude, for the 2775 earthquakes with $M_l > 1.7$ recorded since the beginning of 1997 (2554 eq. in Goðabunga, 221 in the caldera). The earthquakes under Goðabunga show a clear seasonal correlation with a distinct activity during the autumn. This pattern changed in 2002 to more continuous activity. The earthquakes in the caldera have a swarm character, and the largest earthquakes occur there.

glacier, with one station directly above the center of the activity in the Goðabunga area. This study gave a much better depth constraint for the hypocentral locations and suggests that the Goðabunga cluster is an expression of an ascending, dome-shaped structure created by accumulation of viscous magma at shallow depth (cryptodome).

The July 1999 event at Katla spurred both tilt and campaign GPS measurements. Tilt measurements showed no detectable displacements at the Katla volcano, but the stations are located ≥12 km from the center of the Katla caldera. However, inflation of the neighboring volcano Eyjafjallajökull was detected (see the Eyjafjallajökull section). Campaign GPS measurements on nunataks in the ice cap, the ENTA and AUST sites (Fig. 12), have provided important results. The first campaign measurements that include the nunatak stations were performed in 1993, and repeated for the first time in July 2000. The two stations displayed outward displacement from the center of the caldera, during this period, indicating that magma accumulation had started (Sturkell et al., 2003b). The nunatak sites have been visited annually since year 2000, and recently twice a year. The GPS measurements for the period 2001 to 2003 is shown in Fig. 12 and display uplift and outward horizontal displacement from the centre of the sub-glacial caldera. These displacements fit well with a point source at 4.7 km depth within the caldera and give an uplift rate of about 2 cm/a since 2000 at the GPS point AUST (Sturkell et al., 2003c).

The Katla GPS-network is complemented by two continuous GPS-stations, (SOHO and HVOL), which were installed in the autumn of 1999, at the southern flank (Fig. 12). After considering expected plate movements, they display residual outward displacements (southward) from the volcano centre (Fig. 14). This southward displacement has been observed since the year 2000. The southward displacement observed from the continuous stations is not uniform in time and shows periods with accelerated southward displacements. This suggests eventual annual component of deformation related to variable ice loading. Altogether, the geodetic data suggest progressive caldera inflation over time. From 2000, the measured sub-
surface volume increase is \( \sim 0.011 \) km\(^3\). In comparison, the eruptive volume of the 1918 Katla eruption was of the order of 1 km\(^3\). In summary there are seismic, geodetic and geothermal indications that Katla has entered an agitated state that most likely began in 1999. The most recent GPS measurements (from March 2003 to January 2004) confirm that the unrest at Katla continues with the same rate.

Fig. 14. Time-series plot of the continuous GPS station SOHO, located at the southern edge of Myrdalsjökull ice-cap covering the Katla volcano, relative to REYK (the continuous GPS station in Reykjavik). Times of the Hekla eruption in February 2000 and the June 2000 south Iceland seismic zone earthquake sequence are noted with vertical lines. For reference, the predicted movement of SOHO from the NUVEL1-A model (DeMets et al., 1994) is shown with solid lines. Outliers have been removed and error bars are at the 2 \( \sigma \) level.
3.7. Eyjafjallajökull

The volcano Eyjafjallajökull has an ice cap with the same name. No volcanic activity is known from the time of settlement (874 AD) until 1612. Annals for that year mention an eruption in Eyjafjallajökull or Katla, but it is not clear whether one volcano or both were active. A small eruption occurred in 1821–1823 (Larsen, 1999). Prior to 1991, the Eyjafjallajökull volcano showed insignificant seismic activity for at least three decades (time of seismic coverage). An increase in activity started near the end of 1991 and peaked with an earthquake swarm in 1994. Unrest continued, and a second earthquake swarm occurred in 1999. The seismic activity that started in the early nineties continues with a higher background level than before 1991 (Fig. 15).

The 1994 and 1999 seismic episodes at Eyjafjallajökull were associated with significant inflation of the volcano indicating intrusions under its southern flank. The timing of the deformation is bracketed by tilt and GPS measurements (Sturkell et al., 2003b) for both the intrusive events (Fig. 15). The deformation data from 1999 are modelled by a point pressure source at 3.5 km depth beneath the flank of the volcano, about 4 km south of the summit crater. Maximum uplift of the model is 0.35 m (Sturkell et al., 2003b). A similar model also explains deformation associated with the 1994 seismic crisis. However, its location is not that well constrained because only two GPS stations and one tilt station recorded the event. The 1994 intrusion has also been modeled by Pedersen and Sigmundsson (2004) using InSAR images. Their study suggests that a sill with varying thickness accommodates the deformation signal better than a single point pressure source (Fig. 3). A similar sill model can be applied to the 1999 event (Pedersen et al., 2004). The earthquake activity associated with the intrusions began a few months before measurable deformation occurred. A large part of it was located below the northern flank of the volcano (Dahm and Brandsdóttir, 1997) and at larger depth than the inferred intrusions. We suggest that this activity is related to the feeding channel of the intrusions.

3.8. Hengill–Hrómundartindur

In mid-1994 a very intense earthquake swarm started at the Hengill triple junction where the Reykjanes Peninsula oblique rift, The Western Volcanic Zone and the South Iceland Seismic Zone meet. The activity was concentrated 5 km east of the Hengill volcanic system, in the less pronounced Hrómundartindur volcanic system. This enhanced earthquake activity continued until 1998. During the 1994–1998 period about 85,000 earthquakes were recorded (Jakobsdóttir et al., 2002; Árnadóttir et al., 1999), and still the Hengill triple junction is one of the most persistent source of microearthquakes in Iceland. The increased earthquake activity was associated with 2

![Graph showing magnitude of earthquakes in Eyjafjallajökull volcano as a function of time, spanning the interval 1 Jan. 1990 to 31 Aug. 2004, including all events above magnitude 1.0. The seismic activity started in the autumn 1991 and it has continued with varying intensity, culminating in a swarm that started in the beginning of 1999. This swarm continued into 2000 and thereafter the earthquake activity has settled at a higher background level. The 1994 and 1999 periods of crustal deformation (intrusion) are shown as shaded bars (Sturkell et al., 2003b).]
cm/a of uplift and horizontal displacement between 1993–1998, interpreted to be caused by magma accumulation at about 7 km depth (Sigmundsson et al., 1997b; Feigl et al., 2000). Hreinsdóttir (1999) measured a maximum uplift of 8 cm and outward horizontal displacement from the centre of Hrómundartindur volcanic system by GPS-geodesy. The geodetic monitoring of the Hengill triple junction utilized leveling, tilt, GPS and InSAR. An extensive GPS network is installed in the area. The unrest in this area (which is located about 50 km east of the capital, Reykjavík) spurred the installation of 4 continuously recording GPS stations, that were up and running in the spring of 1999, transferring the data daily to the Meteorological Office in Reykjavík. The activity culminated in 1998 with a couple of magnitude 5 earthquakes (Clifton et al., 2002) after which the unrest terminated.

3.9. Torfajökull

The Torfajökull volcano is located at the rift–transform intersection where the Eastern Volcanic Zone meets the South Iceland Seismic Zone. It is unique among Icelandic volcanoes because of its abundance of acidic lavas (e.g., Gunnarsson et al., 1998). Eruptions are sometimes triggered by lateral injection of basaltic dykes from the rift zone to the NE, the Veíðivötn fissure swarm of the Bárdarbunga volcanic system (McGarvie, 1984). This appears to be true for the last two eruptions, those of 871 and 1477 AD (McGarvie, 1984; Larsen, 1984). Torfajökull is a persistent source of small earthquakes, both high and low frequency. The distribution of the hypocenters of the high-frequency events led Soosalu and Einarsson (1997) to suggest that they were caused by the cooling of a hot body centered at 8 km depth beneath the 12 km wide Torfajökull caldera. Tilt measurements seem to support this as slow deflation is discernible for the period 1991–2002. Our measurement of the tilt stations in 2003, however, shows that the subsidence has turned to inflation.

4. Discussion

Crustal deformation studies of active volcanoes in Iceland were initiated by Eysteinn Tryggvason in 1966, when he set out the first part of the leveling line at the Askja volcano. In the following years, he installed short leveling lines at the Katla volcano and started to use mobile water-tube tilt meters at Hekla. The profile at Askja was extended in 1968 to 30 benchmarks. Eysteinn concluded after a few years of experiences with mobile water-tube tilt meters that optical leveling gave the same precision and the measurements were much easier to perform (Tryggvason, 1994). With the start of the Krafla rifting episode 1975–1984, crustal deformation studies became one of the most important means to monitor the state of the volcano, and its shallow magma chamber. The installation of the water-tube tilt meter (Fig. 4) in the main building of the Krafla power station then gave a time-series of 11 years for the volcano.

The installation of leveling lines and tilt stations since the mid-sixties has made it possible to observe long time series at active volcanoes. Eysteinn Tryggvason installed several long leveling lines and more than fifty optical tilt stations (dry-tilt) around volcanoes in Iceland. Over the years some leveling lines and tilt stations have proved to be more sensitive to magma movements under volcanoes than others. A good example is the tilt station Næfurholt (Fig. 11) 11 km due west of Hekla volcano, which shows inflation/deflation events clearly. Some tilt stations are not particularly sensitive or are unstable with local conditions masking volcano signals. With the introduction of GPS and later InSAR techniques the studies of crustal deformation on volcanoes have taken a step forward. Those techniques have much better spatial and temporal resolution and they are less weather dependent.

In the Hengill volcano a persistent swarm of about 85,000 earthquakes were recorded in 1994–1998. In May 1999 a permanent GPS station (OLKE in Fig. 1) was installed close to the measured center of uplift in Hengill as determined by campaign GPS (Hreinsdóttir, 1999). At the time the continuous GPS-station at OLKE became operational in May 1999, crustal deformation ceased. Based on tilt and GPS measurements it has been revealed that intrusion events occurred within the Eyjafjallajökull volcano in 1994 and 1999 (Sturkell et al., 2003b). The two permanent GPS stations at the southern edge of Mýrdalsjökull that covers the Katla volcano have detected displacements (Fig. 14) that are attributed to magma inflow under the Katla volcano (Sturkell...
et al., 2003c). The Icelandic Meteorological Office provides online access to real-time geophysical data, (see http://www.vedur.is/ja). Epicenters and strain data are displayed on this homepage and are uploaded automatically.

Of the 35 active volcanic systems in Iceland, deformation due to magma movements has been measured at eight of them in the last 15 years. Using a combination of the different geodetic techniques we have been able to locate magma chambers with a better precision. The Askja, Krafla, Grimsvötn and Katla volcanoes appear to have a shallow magma chamber at about 3 km depth. Recent observations suggest that at least the Askja and Krafla volcanoes have deeper magma reservoirs, suggested to be at 16 and 20 km depth, respectively (Sturkell et al., submitted for publication; de Zeeuw-van Dalfsen et al., 2004a,b). The location of the magma chamber under the Hekla volcano has been debated and depth estimates range from 6.5 to 11 km depth. Petrological observations suggest a magma reservoir under Hekla, as magma undergoes differentiation with time. However, a study of the attenuation of seismic waves beneath Hekla suggests that a significant volume of magma does not exist above 14 km depth (Soosalu and Einarsson, 2004). The discrepancy between these data is the subject of ongoing research.

Comparison of seismicity and deformation during volcanic unrest demonstrates great variability. In the Hengill area 85,000 earthquakes were recorded during inflation, but the total uplift was 8 cm during the same time period. The uplift in the Katla caldera since 1999 has been 12 cm but only 221 earthquakes Mw > 1.7 were recorded within the caldera (Fig. 13). In the neighboring volcano Eyjafjallajökull, which experienced intrusion events in 1994 and 1999, the earthquake activity began before the intrusion events. This pattern could be observed for both intrusions (Fig. 15). These observations suggest volcanoes behave individually, e.g., depending on prevailing stress fields.

Over this period (the last 15 years), the volcanoes Hengill, Hekla, Katla, Eyjafjallajökull, Torfajökull and Grimsvötn had inflow of magma from depth into shallow-level magma chambers (Fig. 2). The Grimsvötn volcano was the fastest inflating volcano with a rate of 3 cm/a at the closest GPS point (Fig. 8) until it erupted 1 November 2004. It is likely the volcano will start to re-inflate after the eruption in a similar way as happened in 1998. The Grimsvötn caldera hosts a lake that can contain up to 2–3 km³ of water and can be drained in one flood (Björnsson, 2002). Removing such amount of mass directly above an inflating magma chamber may serve as an eruption trigger. The eruption of Grimsvötn on November 1, 2004 was preceded by a jökulhlaup that began on October 27, suggesting that a pressure drop equivalent to 15 m of water was sufficient to trigger an eruption from the inflated magma chamber. The center of the Katla volcano inflates with a steady rate of 3 cm/a. The extraction and increased water circulation may contribute to the cooling of the shallow magma body. Volcanic geodesy allows observations of this subsidence and shows its decay rate. Combined with micro-gravity, it gives an estimate of the amount of crystallization and the amount of draining from the shallow magma chamber (Soosalu et al., submitted for publication).

Subsidence takes place at present time at the Krafla and Askja volcanoes. Cooling and consequent crystallization of magma cause a volume reduction of 10–11%. This process is probably the most dominating for the 3 km deep magma chamber at Krafla, but also magma draining may be a contributing factor. The Krafla volcano began to subside in 1989, initially at a rate of a few cm/a. Since around 2000 the subsidence rate has decreased to a few mm/a. Currently the largest subsidence signal is caused by the extensive exploitation of the geothermal field. The extraction and increased water circulation may contribute to the cooling of the shallow magma body. Volcanic geodesy allows observations of this subsidence and shows its decay rate. Combined with micro-gravity, it gives an estimate of the amount of crystallization and the amount of draining from the shallow magma chamber (de Zeeuw-van Dalfsen et al., in press). The Askja volcano has subsided for over twenty years, and extrapolation of the vertical change into the 1972–1983 period suggests a total subsidence from 1973 to 2003 of 1.9 m at the Askja center (Sturkell et al., submitted for publication). A combination of magma drainage and cooling and contraction of the shallow magma reservoir at 3 km and the deeper one at 16 km depth is our favoured model, and is consistent with the integrated micro-gravity and deformation observations (de Zeeuw-van Dalfsen et al., 2004b; Sturkell et al., submitted for publication). We suggest that exten-
sional tectonic forces generate a pressure drop in the lower and ductile part of the crust to accommodate ongoing magma drainage from the shallow magma chamber.

A combination of different monitoring methods is essential to obtain the best possible information on magma sources and movements within volcanoes. Today, the real-time network in Iceland consists of 40 seismic stations, 17 permanent GPS stations and six volumetric strainmeters. Five analogue seismic stations maintained by the Science Institute at the University of Iceland complement these networks. Both networks play an important role in eruption prediction. Data from volumetric strain meters have enabled detection and monitoring of dyke propagation preceding eruptions of Hekla. The initial sign of a forthcoming eruption of Hekla in 2000 was the onset of small earthquakes, known from previous eruption to be associated with opening of a dike under the volcano. The BUR strain station then recorded contraction (Figs. 1 and 10) beginning 30 min before the eruption, and was at that time recognized as resulting from a dike propagating to the surface (Agustsson et al., 2000). It was used along with the seismic data in a successful prediction of the eruption that was issued to the civil defense authorities and broadcast as well to the public.

5. Conclusions

Crustal deformation measurements in Iceland have significantly advanced our understanding of volcanic processes, with new geodetic techniques allowing increasingly detailed views of magma dynamics. Seismic methods complemented with various geodetic methods, including leveling, GPS, volumetric strain and InSAR, have provided the most important data. The longest time series extend from the mid-sixties to the present time. Forecasting volcanic activity is challenging, but geodetic measurements are providing useful constraints (location, amount and timing of magma movements), which can be interpreted along with other data. The most successful monitoring programs are based on a combination of seismic and deformation methods, as the recent eruptions in Grimsvötn demonstrated. In recent years Katla and Grimsvötn have shown the highest inflation rates with ca. 3 cm/a. and tilt data from Hekla suggest that magma accumulation is taking place. At Katla, continued uplift coincides with elevated seismicity. If uplift and internal pressure build-up continues at these volcanoes, eruptive activity is a likely consequence within several years.

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