# Overview of results from continuous GPS observations in Iceland from 1995 to 2010

Short title: 15 years of CGPS in Iceland

Halldór Geirsson (1,2), Thóra Árnadóttir (3), Sigrún Hreinsdóttir (4,3), Judicael Decriem (3), Peter C. LaFemina (2), Sigurjón Jónsson (5,6), Richard A.Bennett (4), Sabrina Metzger (5), Austin Holland (4), Erik Sturkell (7), Thierry Villemin (8), Christof Völksen (9), Freysteinn Sigmundsson (3), Páll Einarsson (10), Matthew J. Roberts (1), Hjörleifur Sveinbjörnsson (1)

(1): Division of Processing and Research, Icelandic Meteorological Office, Reykjavík, Iceland
(2): Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania, USA
(3): Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland
(4): Department of Geosciences, University of Arizona, Tucson, Arizona, USA
(5): Institute of Geophysics, ETH Zurich, Switzerland
(6): Division of Physical Sciences and Engineering, King Abdullah University of Science and Technology, Jeddah, Saudi Arabia
(7): Department of Earth Sciences, University of Gotenburg, Göteborg, Sweden
(8): EDYTEM, Universite de Savoie and CNRS, Le Bourget du Lac, France
(9): Bayerische Kommission für die Internationale Erdmessung, München, Germany
(10): Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

Email addresses:
Halldór Geirsson (hzg5036@psu.edu), Thóra Árnadóttir (thora1@hi.is), Sigrún Hreinsdóttir (runa@hi.is), Judicael Decriem (judicael@hi.is), Peter C. LaFemina (plafemina@psu.edu), Sigurjón Jónsson (sigurjon.jonsson@kaust.edu.sa), Richard A.Bennett (rab@geo.arizona.edu), Sabrina Metzger (smetzger@erdw.ethz.ch), Austin Holland (holland.austin@gmail.com), Erik Sturkell (erik.sturkell@gvc.gu.se), Thierry Villemin (thierry.villemin@univ-savoie.fr), Christof Völksen (voelksen@bek.badw.de), Freysteinn Sigmundsson (fs@hi.is), Páll Einarsson (palli@hi.is), Matthew J. Roberts (matthew@vedur.is), Hjörleifur Sveinbjörnsson (hs@vedur.is)

## Abstract

Iceland is a natural laboratory for a variety of processes associated with crustal deformation, such as earthquakes, magmatic events, tectonic plate motions, and glacial load changes. Continuous GPS (CGPS) measurements started in Iceland in 1995, and since then data from the network have helped to shed light on a variety of active deformation processes. The number of CGPS sites in Iceland tripled during 2006-08, as a result of an international collaborative effort coordinated by Icelandic scientists, and by early 2010 their number had reached 64, located primarily around and within the plate boundary zone. Since its initiation, the CGPS network has played an important role in monitoring volcanoes and seismogenic areas, most notably during the 2009-2010 Eyjafjallajökull unrest. Plate spreading of up to 2 cm per year usually dominates the horizontal motion observed at the CGPS sites, while uplift is observed at many of the stations due to recent retreat of the Icelandic ice caps. Co-seismic and post-seismic deformation of the largest earthquakes in 2000 and 2008 in the south Iceland seismic zone was captured by the network and high-rate (1Hz) CGPS observations helped to identify two magnitude 6 mainshocks in 2008 that were separated in time by only 2-3 seconds. The CGPS network has enabled us to monitor deformation occurring over days to months caused by migration of magma or fluids, post-seismic transients as well as rapid deformation caused by earthquakes and eruptions.

## 1. Introduction

Iceland is a sub-areal exposure of the mid-Atlantic ridge, and the interaction of the plate boundary to the Icelandic hotspot makes the 100 thousand km$^2$ island effectively a natural laboratory for a wealth of geophysical and geological processes. Many pioneering studies of crustal deformation have been conducted in Iceland since the first geodetic network was established in 1938 to test Wegener's hypothesis of continental drift and subsequent theories of plate tectonics (Einarsson et al., 2006 and references therein). Iceland was one of the first (1986) countries in the world where GPS was used for precision geodetic studies of crustal deformation (Foulger et al., 1993). Before the first continuously operating GPS site in Iceland was installed in 1995, a number of GPS campaigns had already been performed, observing geodetic benchmarks for hours or days to obtain a position in time to estimate surface deformation caused by plate spreading, earthquakes and magma movements.

Crustal deformation in Iceland is due to many different processes, acting at different spatial and temporal scales. A range of deformation signals have been detected by the continuous GPS (CGPS) network. These include plate motion, co- and post-seismic deformation in the south Iceland seismic zone and the Reykjanes peninsula, time-varying deformation due to intrusive activity in Eyjafjallajökull and Upptyppingar-Álftadalsdyngja area, magma accumulation in Hekla and Katla, uplift and subsidence in geothermal areas in Krísuvík and Hengill, seasonal signals due to snow loading in winter and melting in summer, and high rates of uplift in central Iceland due to melting of the ice caps.

The general purpose of this paper is to present a summary of results and observations from continuous GPS measurements in Iceland during 1995 to 2010. This paper is not intended to be an in-depth study of any of the processes or events encountered, rather it serves as a summary of recent and previously published results obtained so far.

## 2. The CGPS Network

As of the beginning of 2010, there were 64 CGPS stations in operation in Iceland, mostly located within and around the plate boundary (Figure 1). Continuous GPS measurements began in Iceland in 1995 when the IGS (International GNSS Service) station REYK was installed in Reykjavík, followed by a second IGS station, HOFN, in 1997. In 1999 the CGPS network expanded significantly when six stations were installed as part of a collaborative effort between the Icelandic Meteorological Office (IMO) and the University of Iceland (Geirsson et al., 2006). The Icelandic CGPS network has been expanding rapidly since, with 16 more stations added to the network between 2000 and 2005, and more than 40 stations installed between 2006 and 2009.

Most of the network expansion during 2006 – 2009 resulted from a joint effort of several research groups in Iceland, the United States and Switzerland. The projects are funded by the Icelandic Research Council, the US National Science Foundation (NSF), ETH Zurich, University of Arizona, and Pennsylvania State University. The new CGPS stations form sub-networks that have been installed in co-operation with the IMO, who operate a large part of the CGPS sites in Iceland. The network operated by IMO is called the ISGPS (Icelandic GPS) network. The sub-networks are: (1) The North Iceland network, with 10 CGPS stations installed by the group from ETH Zurich; (2) The Central Highland of Iceland (CHIL) network, with 14 stations installed by the group from the University of Arizona; (3) The Hekla network with 6 stations installed by the groups from Pennsylvania State University and the Nordic Volcanological Center; (4) The South Iceland Seismic Zone and Reykjanes Peninsula networks with 5 new stations installed by the groups from the Nordic Volcanological Center and University of Arizona.

The National Land Survey of Iceland also operates a network of five CGPS stations, including the IGS sites. These data are included routinely in our data processing. In addition, there are private and governmental single- and dual-frequency networks in continuous operation intended primarily for cadastrial surveys and navigation of airplanes, ships, and other vehicles. These sites are not routinely included in our data processing of daily solutions, nor do we count them in our numbers for CGPS sites in Iceland. However, data from one such site in south Iceland were used for high-rate processing of data from the May 2008 earthquake sequence and and helped constraining source parameters and timings for these events (see below). The data from the CGPS network has been utilized for cadastrial surveys as well, where the stations have served as base stations for a variety of mapping projects. In addition, the atmospheric delay imposed on the satellite signals observed at the stations is being used as an input to meteorological models.

Good coupling of the antenna to solid bedrock by the GPS-monument is important to eliminate possibilities of monument movement in the interpretation of the results. Most of the CGPS stations in Iceland have one of two kinds of monuments: (a) a 1 meter high stainless steel quadripod anchored to bedrock by drilling and cementing eight threaded rods typically 12-50 cm into decent bedrock; this we term the ISGPS monument; (b) the short-braced UNAVCO Plate Boundary Observatory (PBO) monument, where four one inch thick rods are drilled and cemented typically 0.5 to 2 m into bedrock and welded together at the top for the antenna mount. A few stations are on top of buildings or have different kind of monuments. The ISGPS and PBO monuments each have their advantages and both can be regarded as highly stable geodetic monuments when properly installed.

As the sites have been installed over more than a 10 year period, there is a wide range of instrumentation and communication types in use. The bulk of the older sites nominally collect raw data every 15 seconds as 24 hour-long files that are transmitted automatically to IMO on a daily basis. Data collected at a higher sampling rate (1 sample per second) are transmitted from many of the newer sites, depending on instrumentation and communication bandwidth. Some sites collect high-rate data that are not transferred unless investigation of seismic, volcanic, or other events require the data. Many of the sites are co-located with seismic stations, or transmit data to a nearby seismic station through radio links, to make common use of the existing infrastructure. Where the GPS equipment has been upgraded an effort has been made not to change or move the GPS antennas unless absolutely necessary, to avoid creating artificial offsets in the time series.

In addition to episodic and continuous GPS stations, there exist a number of semi-continuous sites around the country, where data are collected repeatedly over shorter continuous periods of time (weeks to a few years). These sites typically do not transmit data, although communications were established at sites around Eyjafjallajökull in 2010 for enhanced monitoring capabilities of the volcano. We do not include data from semi-continuous sites in this summary.

## 3. Data Processing and Site Velocities

To go from the raw daily data files to daily solutions for site positions, here termed data processing, and estimating and interpreting site velocities from time series of daily position solutions, is an important process that can be performed in various ways. Once the daily data files have been archived at IMO, they are automatically processed and the daily results displayed on IMO´s website (www.vedur.is). Each of the research groups that routinely analyze data from the Iceland stations processes slightly different subsets of the data set using different processing software or different processing options and external information (e.g. satellite orbits, antenna calibrations, tidal loading models) within each software package. So far, the data have been processed using the Bernese version 5.0 software (Dach et al., 2007), the GAMIT/GLOBK version 10.3 (King and Bock, 2005), and the GIPSY/OASIS II version 5 software (Zumberge et al., 1997). Geirsson et al. (2006) compared the outcomes from these three different processing packages for Icelandic CGPS data collected from 1999 to 2004, and found the results to be in a general agreement. The purpose of this summary is to focus on specific geodynamic processes observed by CGPS in Iceland. We therefore present results from the different processing approaches as fits each subject best, and leave more detailed comparison of time series obtained from the different processing approaches for separate future studies.

From the daily solutions we can build time series of the motion of the stations. The time series (Figure 2) show the temporal evolution of the station coordinates in east, north and vertical components, relative to the ITRF05 reference frame (Altamimi et al., 2007). Plate motion results in a linear trend in the horizontal components, whereas offsets in the time series are typically due to equipment changes, earthquakes or volcanic activity. One example of a co-seismic offset is seen in the time series from HVER at the time of the May 29, 2008 earthquakes (Figure 2). In general, the daily scatter of the vertical component is higher than for the horizontal components. Seasonal signals are seen at many stations in the highlands, thought to be caused by snow loading in winter and melting in summer (Geirsson et al., 2006, Grapenthin et al., 2006). The time series can be detrended to remove the steady plate motion and offsets (Figure 3), and annual and semi-annual signals can be filtered out, or estimated and removed, to display deviations from constant motion more clearly. Examples of detrended time series from stations north of Vatnajökull are shown in Figure 3. The observed station velocities presented here are estimated after the time series have been corrected for offsets due to earthquakes or equipment changes. Data from stations north of Vatnajökull, affected by the Upptyppingar intrusive episode (see below), are not used when estimating the velocities shown in Figures 1 and 4, nor are data spanning the Eyjafjallajökull episode. Figure 1 shows the average station velocities from the installation of the stations until January 2010 with respect to a stable North America plate, and Figure 4 shows the same velocities with respect to a fixed Eurasia plate. Euler rotation poles from the MORVEL model (DeMets et al., 2010) were used to do the transformations from ITRF2005 to stable North America and Eurasia (Figures 1 and 4).

## 4. Results

### 4.1. The plate boundary

The plate boundary in Iceland is composed of several rift segments and transform zones connecting the rift segments (Figure 1), as a result of interaction of the Icelandic hotspot with the mid-Atlantic plate boundary. The mid-Atlantic ridge is spreading at a full rate of a little less than 2 cm/yr in Iceland, according to plate motion models based on either geological and/or geodetic observations (e.g. DeMets et al., 1994; Kreemer et al., 2003; DeMets et al., 2010). Reconstructions of the plate spreading rates from magnetic anomalies indicate constant rates since about 6.5 to 7.5 Ma (Merkouriev and DeMets, 2008). The spreading rate is slightly higher in South Iceland than in North Iceland (Figure 1). The observed CGPS velocities generally agree reasonably well with plate motion model predictions (Figure 1) though formally many of the sites individual sites do not agree with the MORVEL model. This discrepancy is because many of the sites are located within the plate boundary deformation zone and thus are moving at intermediate rates, or the sites are affected by other processes such as glacial rebound or volcanic deformation. For example sites VMEY and RHOF are likely still slightly affected by the proximity to the plate boundary (Figure 1), and the horizontal velocity of site HOFN is affected by the glacial rebound. Site HEID, on the other hand, should be less affected by the glacial rebound and its velocity agrees well with the MORVEL model (Figure 4). The most complete study to date of the plate boundary in Iceland is published in Arnadottir et al. (2009), where they use the velocity field from the ISNET 1993 and 2004 nationwide campaigns, along with available CGPS data. Their results agree fairly well with predicted rates, except the spreading rate is somewhat higher in the Northern Volcanic Zone. While the CGPS network is still too sparse in many places to constrain the over-all spreading of the plate boundary, it does provide important constraints, especially where there are transient changes in the site velocities and/or co-seismic offsets.

The plate boundary on the Reykjanes peninsula is highly oblique, where the on-land continuation of the Reykjanes ridge connects to the Western Volcanic Zone and the South Iceland Seismic Zone (SISZ). Geodetic studies show that the plate spreading across the peninsula is accommodated by left-lateral shear (17-19 mm/yr) and a significant component of opening (7-9 mm/yr) below a locking depth of 6-9 km (Árnadóttir et al., 2006; Keiding et al., 2008). The South Iceland Seismic Zone is an E-W transform zone. The deformation in the brittle part of the crust (above 10-15 km) is taken up by many parallel N-S, right lateral strike slip faults, a fault configuration that has been called “book-shelf” faulting (Einarsson et al., 1981; Einarsson 2008). Several sequences of magnitude 6-7 earthquakes are documented in the SISZ (Stefánsson and Halldórsson, 1988), with the latest sequence starting in the year 2000, as described in section 4.2.

The Eastern and Western volcanic zones have been observed to divide the plate spreading between them (LaFemina et al., 2005, Sigmundsson et al., 1995). The CGPS stations in the CHIL subnetwork can be used to constrain the interplay of the volcanic zones and the role of the Hreppar block (Figure 1). The CGPS stations indicate low spreading rates across the WVZ and we observe a small increase in velocities from west to east across the central Hreppar block (Figure 1). The observed velocities within and around the Central Iceland Volcanic Zone (Figure 1) reveal a complex pattern of deformation, that is not yet well understood. CGPS stations north-west of Vatnajökull icesheet, have a clear northward signal, indicating north-south extension. A comparable signal was observed in the 1993 – 2004 velocity field presented by Arnadottir et al (2009). Additional data and further deformation analysis are required to better understand the significance of the velocity estimates in this area.

The North Iceland CGPS network provides new data to estimate the dynamics within a 120 km-long offset of the Mid-Atlantic ridge that connects to the Northern Volcanic Zone in the South to the Kolbeinsey Ridge in the North. Two parallel fault systems accommodate the right-lateral transform motion between these two segments of the ridge, the Húsavík-Flatey fault (HFF) and the Grímsey oblique rift (GOR) (Figure 1). A third zone, the Dalvík zone, is indicated by seismicity about 30 km south of the HFF (Einarsson, 1991, 2008) where earthquakes as large as $M_s$ 7 have occurred, latest in 1963. These three zones comprise the Tjörnes Fracture Zone (TFZ). The last major earthquake rupturing the on-shore part of the HFF, where the fault runs through a town, occurred in 1872, and another major earthquake may therefore possibly be due on the fault system. It is thus important to estimate the slip rate, slip deficit and resulting moment accumulation on the two fault systems to gain further information about the seismic hazard in the region. The observed GPS velocities in north Iceland show a gradual increase in velocities as one crosses the TFZ (Figures 1 and 4). Preliminary modeling of the CGPS velocities show that the distribution of motion between HFF and GOR appears to be closer to 30/70 (Metzger and Jónsson 2010) than to the 40/60 percent estimated earlier (Geirsson et al., 2006) from a more sparse network. Despite the low slip rate of the HFF, the accumulated moment on the HFF since 1872 would still correspond to an earthquake of a magnitude just below 7 (Metzger and Jónsson 2010).

## 4.2. Earthquakes

On June 17, 2000, an earthquake sequence started in the South Iceland Seismic Zone with a magnitude 6.5 event. The event triggered earthquakes across southwest Iceland, all the way west to the Reykjanes Peninsula, with the largest triggered event being a magnitude 6.5 earthquake that occurred 81 hours later, located 17 km west of the initial mainshock (Árnadóttir et al., 2001, 2003, 2004; Geirsson et al., 2006). The CGPS network was rather sparse at the time, but provided important constraints on the co-seismic offsets. The June 2000 sequence demonstrated the need for automatic processing of the data with low latency, which was initiated at IMO shortly after the earthquakes. An earthquake doublet with a composite $M_w$=6.3 struck the western part of the South Iceland Seismic Zone on May 29, 2008. Within a few seconds of the onset of the first mainshock, the second event was triggered on a fault located 5 km further west. A clear co-seismic offset is observed in the time series at the CGPS stations in the epicentral area, with a maximum offset of about 20 cm (Figure 2).

The May 29 2008 earthquake sequence is the first event recorded by the high rate CGPS network in Iceland (Hreinsdottir et al. 2009). The two mainshocks occurred so close in space and time that the seismic waves from the second rupture were embedded in the coda from the first event, making precise location and timing of the second event difficult using conventional seismic data. Source models of the two main faults were estimated from static offsets of the CGPS stations. Based on these source models and the high-rate CGPS time series, Hreinsdottir et al. (2009) concluded that the second fault ruptured within 3 seconds of the initial mainshock. Data from the CGPS network therefore provided important constraints on location, timing, and magnitude of the earthquakes.

Post-seismic deformation was observed after both the 2000 and 2008 earthquake sequences. During the first months after the 2000 sequence, deformation was most rapid in the epicentral area and dominated by poroelastic rebound, as observed by InSAR (Jónsson et al., 2003). A slower transient was observed from annual campaign GPS measurements during the first 4-5 years following the main shocks (Árnadóttir et al., 2005). Modeling of the GPS data indicates fairly low viscosities, with 5–10 $\cdot 10^{18}$ Pa s in the lower crust and $3\cdot 10^{18}$ Pa s in the upper mantle (Árnadóttir *et al.,* 2005). Subsequent analysis of InSAR data indicate that the year-scale transient signal is more likely due to visco-elastic relaxation in the lower crust and upper mantle, rather than afterslip (Jónsson, 2008). A ~2 cm deformation transient was observed at the CGPS station (HVER) in the week following the May 2008 earthquakes (Figure 2). The post-seismic deformation following the May 2008 earthquakes appears to be less pronounced than the signals observed after the June 2000 earthquakes. This is perhaps not surprising since the June 2000 earthquakes were significantly larger events.

The main shocks in the June 2000 and May 2008 sequences released about half of the moment accumulated by plate motion since the previous earthquake sequence in 1896–1912 (Decriem et al., 2010). Continued earthquake activity with moderate size events rupturing N–S faults in the SISZ can thus be expected in the coming decades. It is therefore important to continue the deformation studies in southwest Iceland and further densify the CGPS network in the South Iceland Seismic Zone as well as further west on the Reykjanes Peninsula.

## 4.3. Volcanoes and magma movements

The CGPS network has proven very useful for monitoring and improving understanding of the volcanoes in Iceland. In the following sections we review the deformation episodes observed. Importantly, the network also indicates whether or not volcanoes are showing signs of magma movement. This is the case with the Heimaey island in the Vestmann islands, which erupted last in 1973. There, the site VMEY (Figure 1) has not shown signs of volcanic deformation since the station was installed in 2000.

### 4.3.1. Hekla 2000 eruption and inter-eruptive deformation

Hekla is one of Icelands most active volcanoes with 18 documented eruptions for the past 1100 years (Thordason and Larsen, 2007). Hekla erupted in 1970, 1980, 1991 and 2000, and recent dry-tilt measurements indicate that an eruption could take place any time (Sturkell et al., 2006). When the Hekla eruption occurred in February to March 2000, the closest CGPS station (SOHO) was 50 km away from Hekla, however, as of 2006 a dense CGPS network has been operating at the volcano. Geirsson et al. (2006) report up to 5 mm co-eruptive horizontal displacements of site SOHO for the year 2000 eruption. Co-eruptive borehole strain, tilt and episodic GPS measurements indicate that the dike formed in the eruption was probably mostly within the volcanic edifice, fed by a small conduit from the magma chamber residing at 11 km depth (Sturkell et al., 2005). Ofeigsson et al., (in press) place the magma chamber at 16 km depth, using InSAR observations. These models predict a co-eruptive horizontal signal on the order of 2-5 mm, in general agreement with the observed displacements at SOHO in 2000.

Between eruptions, a somewhat complicated deformation pattern is observed at Hekla from InSAR, with maximum uplift of less than 3 mm/yr occurring at a distance of about 10 km surrounding Hekla and subsidence in the center relative to the maximum uplift (Ofeigsson et al., in press). This signal is interpreted as being a broad inflation signal from a deep magma source with subsidence due to the load of Hekla volcano itself superimposed (Ofeigsson et al., in press; Grapenthin et al., 2010). Despite a short time series of the CGPS stations at Hekla, we can conclude that the deformation is steady in time. Crustal widening is observed across Hekla (Figure 5), which could be caused by magma recharge and/or plate spreading because Hekla is at essentially within the Eastern Volcanic Zone. The CGPS station closest to the volcano edifice subsides slightly relative to sites away from Hekla, which is in a general agreement with the InSAR observations.

### 4.3.2. Eyjafjallajökull and Katla

The 2010 eruption at Eyjafjallajökull caught widespread media attention because of the severe effects of the ash-plume on air travel. The eruption is but a part of a long chain of events leading up to the eruption. The most recent eruption of Eyjafjallajökull before 2010 occurred in 1821-1823, and the volcano experienced two inflation episodes in 1994 and 1999 (Pedersen and Sigmundsson, 2004, 2006; Sturkell et al., 2010). The CGPS site THEY, south of Eyjafjallajökull, was originally installed to monitor the 1999 intrusion, but the episode ceased before the site was installed in May 2000.

In July 1999 a jökulhlaup emerged from the southern part of the neighboring Mýrdalsjökull ice cap, that covers the Katla volcano. Katla erupted last in 1918, and is historically known for more frequent and more violent eruptions than Eyjafjallajökull. Following the 1999 jökulhlaup, cauldrons at a few places under the icecap were observed to deepen, indicating increased heat flow from the volcano (Gudmundsson et al., 2007). Episodic GPS measurements at nunataks showed steady inflation of Katla between 1999 and 2004, and were explained by inflation of a magma chamber at depths of 2-5 km (Sturkell et al., 2008). From 2004 onwards seismic activity has been at lower levels. The station SOHO south of Katla moves outward from the caldera at a rate of ~6 mm/yr in excess of plate movements (Figure 1). This rate did decrease slightly at the 2004 transition (Sturkell et al., 2010), but the site continues to move outward from the Katla caldera.

In May 2009 intrusive activity continued under Eyjafjallajökull, which had remained quiet since the 1999 intrusive episode. Seismic activity increased and subtle surface deformation was observed at the CGPS station THEY (Figure 6). The activity continued until mid-august 2009, when both deformation and seismicity halted. During this intrusive episode, THEY moved southwards by about 15 mm, which is about 10 times less than displacements of a nearby episodic GPS site during the 1999 intrusion (Sturkell et al., 2003a). Towards the end of the 2009 episode, two new semi-continuous stations were set up in the area, and four more were installed in the spring of 2010. This data, along with other geodetic, seismic and geochemical observations, have already been used for further interpretation of the chain of events (Sigmundsson et al., 2010).

In December 2009 seismic activity and deformation resumed, in a more intense manner compared to the summer's activity. In March 2010 a change in the surface deformation and seismic activity indicated the formation of an ESE-striking dike (Sigmundsson et al., in press). A few days after that, the magma broke its way to the surface at the eastern flank of the volcano, mid-way between the Eyjafjallajökull and Katla volcanoes. The flank eruption was hawaiian style and confined to a small area. The eruption did not seem to relieve much of the pressure previously built up by the intrusions, as the observed co-eruptive deformation was subtle (Figure 6). On April 12$^{th}$ , the flank eruption ceased. On April 14$^{th}$ 2010 a new phase of the activity started with the summit eruption. This phase was much more explosive, and the co-eruptive deformation rates were larger than during the flank eruption (Figure 6), indicating that magma pressure was released more efficiently than during the summit eruption.

#### 4.3.3. Grímsvötn eruption 2004 and subsequent inflation

Grímsvötn is Iceland's most frequently erupting volcano in recent times (Thordason and Larsen, 2007). It erupted last in 2004 and before that in 1998. It is of great interest to try to cast light on the magma movements of the volcano and try to forecast when the next eruption could occur. The Grímsvötn caldera is in the interior of the Vatnajökull ice-cap and is mostly covered by ice with only one nunatak suitable for a GPS site, located on the SE-rim of the caldera. Episodic GPS measurements were occasionally made at the nunatak, capturing the deformation associated with the 1998 eruption (Sturkell et al., 2003b) and subsequent inflation (Sturkell et al., 2006).

By 2004, episodic GPS measurements and seismic observations indicated that the volcano had reached its pre-1998 eruption state. In June 2004, a CGPS station was installed on the nunatak on a temporary monument 500 meters from the episodic site. Due to the intense atmospheric icing conditions on the nunatak, a special monument was designed by IMO technical staff for the site in 2006, installed on the same foundation as the original monument. The monument consists of a 2 m high metal pier anchored to the bedrock. The pier receives heat from a geothermal well close to the monument, and is covered by a high-gloss black plastic tube to prevent ice from collecting on the monument. Despite these preventive actions, there still are periods of intense icing causing apparent changes in the position (Figure 7).

A few days before the November 1st 2004 Grímsvötn eruption the GPS receiver unfortunately stopped logging data due to a power failure. Power was restored on November 20, 2004, and the resulting deformation showed a co-eruptive movement of about 0.2 m inwards to the caldera, and 0.2 m of subsidence (Figure 7). There is uncertainty whether the periods shortly before and after the eruption are affected by ice accumulation on the antenna radome since the monument was not heated at the time. After the eruption the magma chamber started inflating again, rapidly for the first few months after the eruption and then slowing to a constant rate. This behavior is comparable to what was observed for the 1998 eruption and subsequent inflation (Sturkell et al. 2003b, 2006).

If we assume that the station GFUM is located on the Eurasian plate, we can estimate when the station displacements surpasses its previous pre-eruptive stage, as an indicator of how imminent the next eruption is. Depending on which component is used (east, north or up), the station reaches its pre-eruptive stage anywhere between late 2007 and 2011 (Figure 7) after the 2004 eruption. If the station is within the plate boundary, as suggested by Sturkell et al. (2003b), the east component has surpassed its pre-2004 eruption levels even earlier, but the north component is less biased by plate motion. In order to account for crustal rebound due to the melting of the glacier range, an ad-hoc rate of 22 mm/yr was subtracted from the vertical component. Judging from the discrepancy between the components of the time series for GFUM, it can be inferred that the deformation sources for the

2004 eruption and subsequent inflation are not the same, but we leave the details of that research to further studies.

#### 4.3.5. Upptyppingar-Álftadalsdyngja intrusion between 2007 and 2008

During 2007 to 2008, an intense earthquake swarm associated with surface deformation occurred north of Vatnajökull ice-cap, east of the plate boundary (Figure 1). A network of CGPS and seismic stations was installed not far from the activity in 2004-2005 to monitor possible deformation and seismic activity at a water reservoir being formed for a hydro-electric power plant. The seismicity was unusually deep, 11-22 km, and showed patterns that could be related to a magma intrusion (Jakobsdóttir et al., 2008; White et al., 2009).

Two CGPS stations (SAUD and BRUJ) showed clear signs of the intrusion (Figure 3). The lack of vertical motion detected at the stations, relative to the horizontal velocity change of about 30 mm/yr, supported the idea that a dipping dike of a volume of 0.05 km^3 was intruding into the crust (Jakobsdóttir et al., 2008). This interpretation was further supported by episodic GPS measurements and modeling of InSAR observations (Hooper et al., 2009). The deformation ceased in April 2008 following a culmination and a change in character of the seismic activity (Geirsson et al., 2009).

The episode has been interpreted as a magma intrusion into the lower parts of the crust (20-12 km depth), and the earthquakes are thought to be caused by brittle fracturing of the host rock where magma is intruding. This episode provided the first real test of the ability of using data from the CGPS network to follow a magma intrusion. The CGPS network proved very valuable for assessing the state of the intrusive episode along with seismic and other deformation data.

### 4.4. Load induced deformation

#### 4.4.1. Glacier retreat

Warming climate is causing the glaciers in Iceland to melt, causing thinning of the ice caps and retreat of the edges (Björnsson and Pálsson, 2008). The melting reduces the load on the earth´s crust, resulting in crustal uplift around and under the glaciers. This uplift has been captured by the CGPS network (Figure 4), and importantly also by two GPS campaigns in 1993 and 2004 that covered the whole of Iceland (Árnadóttir et al., 2009). The observations show that a broad area in central Iceland is being uplifted by more than 1-2 cm/yr. This result, along with models of the history of the ice load deduced from glaciological observations, has been used to infer crustal structure and viscoelastic properties of the crust (Árnadóttir et al 2009). Interestingly, the present uplift rates observed by the CGPS network deviate somewhat from the 1993 to 2004 episodic campaigns, with higher present rates of uplift, which may reflect increased melting rates of the ice-caps since mid-1990. In addition to the high uplift rates, annual cyclic variations in the CGPS site elevation are also observed (Geirsson et al. 2006), coinciding with annual snow accumulation and melting of the ice caps (Grapenthin et al. 2006). Grapenthin et al. (2006) used these observations to infer the elastic properties of the crust, since viscoelastic response can be ignored for annual frequencies.

#### 4.4.2. The Hálslón water reservoir

In September 2006, a new 25 km long and 2 km wide lake, with a maximum depth of nearly 200 meters, was formed north of the Vatnajökull ice-cap for a hydro-electric power plant. The National Power Company had a network of seismic stations and three CGPS stations installed by IMO in the area to follow possible deformation and seismicity caused by the formation of the lake. The CGPS deformation monitoring was augmented by episodic GPS measurements in the area (Ófeigsson, 2007). Three of the episodic sites were upgraded to continuous sites, coming into full operation in 2008. The CGPS sites show a maximum of 15 mm observed subsidence due to the initial filling of the lake. The observed deformation during the initial filling of the reservoir seems to rather indicate outward movement (Ófeigsson, 2008). The reservoir is subject to large annual variations in lake level, around 50 m in a normal year, with a high-stand in September. Seasonal variations are observed in the CGPS time series, but they are subtle.

### 4.5 Other transient deformation

#### 4.5.1. Krísuvík uplift-subsidence episode

A rapid increase in seismic activity accompanied with a significant surface uplift in the Krísuvík region (Figure 1) was detected in 2009. This is the first time such activity has been documented on the Reykjanes Peninsula. Continuous GPS measurements started in Krísuvík in February 2007 when the station KRIV was installed. A velocity anomaly is apparent in the time series from KRIV since late 2008 or early 2009 (Figure 8). The station has experienced both increased southward motion and uplift  followed by a period of reversed motion. During the period of uplift, seismic activity in the region increased substantially. Preliminary analysis of InSAR and campaign GPS data show uplift with a maximum of 2-3 cm/yr during 2007-2009, centered southwest of Lake Kleifarvatn and north of the CGPS station KRIV. The station showed subsidence at similar rates between September 2009 and April 2010 when uplift started again. The activity suggests pressure changes related to a magma source at shallow depth and/or a natural pressure increase in the high-temperature geothermal system in Krísuvík followed by a pressure release.

#### 4.5.2. Hengill transient deformation

The 1994 to 1998 Hengill intrusion and seismic activity (Feigl et al. 2000) had an important impact on starting the network of CGPS measurements for hazards monitoring in Iceland. The stations closest to the 1994-1998 magma intrusion, HVER and OLKE, were installed in April and May 1999.

By then the activity had already ceased, and the sites show no significant signals of the 1994 to 1998 intrusion. However, the sites in the area have shown significant temporal variation in site velocities (Figure 8) with gradually increasing velocities towards north and west and subsidence at increasing rates. In particular, OLKE subsided and moved more rapidly towards west during 2006-2010 than before. A new geothermal power plant started operating in the Hengill area in 2006, and the production capabilities of an older geothermal power plant drawing fluids from the northern part of the area was increased substantially in 2008. It is tempting to suggest that the increase in geothermal fluid withdrawal is causing the changes in the site motions in the Hengill area, however, more detailed research is required because a wealth of other geodetic data better suited for spatial constraints of the deformation source exists for the area.

## 5. Discussion

Since the first CGPS station was installed in Reykjavik in 1995, the signals captured by the growing CGPS network have been of a great importance to the scientific community and civil defense in Iceland. Data from the network have also been used as a reference for numerous precision mapping projects. The processes causing surface deformation in Iceland are diverse, covering plate motion, the earthquake cycle, eruptions, magma movements, glacial rebound, and geothermal system pressure changes. CGPS is one of the available tools to study these processes. The integration of CGPS data with other geodetic (episodic GPS, InSAR, tilt, leveling), seismic, and other data of relevance has proven well, emphasizing the importance of interdisciplinary cooperation.

We have yet to capture a plate boundary rifting event by the CGPS network, which seem to occur every few hundred years on the plate boundary. The last rifting episode in Iceland occurred in the Krafla volcanic system in 1975-1984 (e.g. Björnsson, 1985). The last major rifting episode in the Eastern Volcanic Zone occurred in 1783-85, when the Lakagigar crater row formed and around 27 $km^3$ were erupted (Thordason and Larsen, 2007). Although much can be learned from the ongoing Afar rifting episode (Ebinger et al., 2010), there are questions specific to Iceland that need to be addressed by direct observations, such as improved understanding of the magma plumbing systems, the propagating EVZ (LaFemina et al., 2005) and precursors of rifting episodes.

The south Iceland seismic crisis in 2000 and 2008 demonstrated the importance of the CGPS network and applications of high-rate data sampling. Since only a part of the accumulated energy has been released in the south Iceland seismic zone, continuation of the sequence might be expected. The Húsavík-Flatey fault in Northern Iceland had its last large earthquake in 1872 and may be due for another event, although results from the CGPS network indicate that the Grímsey lineament is presently taking up a majority of the deformation in the Tjörnes fracture zone.

Some of the most active volcanoes in Iceland are now being monitored with continuous GPS measurements. However, most of the EVZ, where the volcanic production in Iceland is greatest, is poorly instrumented. The same holds true for many recently active volcanoes such as Krafla, Askja, and Öræfajökull. The ability of the CGPS technique to track subsurface magma movements with time, as best demonstrated by the 2009-2010 Eyjafjallajökull intrusive and eruptive episodes, has the potential of being pushed further towards real-time.

There is a global concern for ongoing climate changes and the retreat of the icecaps causing the observed rapid uplift of the highlands. The CGPS data have been used to constrain structural parameters of the Icelandic crust, but they could as well be used as an indirect measure of how fast the ice-caps are melting and temporal mass-balance of the ice-caps. In addition, the retreat of the glaciers has a notable effect on the volcanic activity through increased partial melting of the mantle and stress changes around the ice-caps (Pagli et al., 2007, 2008).

## 6. Acknowledgements

We acknowledge grants from the Icelandic Research Council (Grant of Excellence, and several project and equipment grants), NSF (EAR grant numbers 0711446 and 0711456), ETH Zurich research grant, and the EU funded project VOLUME. Additional funding was provided by University of Arizona, Pennsylvania State University, and the Icelandic Meteorological Office. We wish to thank deeply all the numerous people involved in installing and running the CGPS network in Iceland. We thank reviewers Mangús Tumi Guðmundsson and Bradford Hager for their constructive comments. The figures were produced using the GMT public domain software (Wessel and Smith, 1998).

**References**

Altamimi, Z., X. Collilieux, J. Legrand, B. Garayt and C. Boucher 2007. ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters. *J. Geophys. Res*., 112, B09401, doi:10.1029/2007JB004949.

Árnadóttir, Th., S. Hreinsdóttir, G. Gudmunsson, P. Einarsson, M. Heinert and C. Völksen 2001. Crustal deformation measured by GPS in the South Iceland Seismic Zone due to two large earthquakes in June 2000. *Geophys. Res. Lett*., 28(21), 4031-4033.

Árnadóttir, Th., S. Jónsson, R. Pedersen and G. Gudmundsson 2003. Coulomb stress changes in the South Iceland Seismic Zone due to two large earthquakes in June 2000. *Geophys. Res. Lett.*, 30(5), doi:10.1029/2002GL016495.

Árnadóttir, Th., H. Geirsson and P. Einarsson 2004. Coseismic stress changes and crustal deformation on the Reykjanes Peninsula due to triggered earthquakes on 17 June 2000. *J. Geophys. Res*., 109, B09307, doi:10.1029/2004JB003130.

Árnadóttir, Th., S. Jónsson, F.F. Pollitz, W. Jiang and K.L. Feigl 2005. Postseismic deformation following the June 2000 earthquake sequence in the south Iceland seismic zone. *J. Geophys. Res.,* 110, B12308, doi:10.1029/2005JB003701.

Árnadóttir, T., W. Jiang, K. L. Feigl, H. Geirsson and E. Sturkell 2006. Kinematic models of plate boundary deformation in southwest Iceland derived from GPS observations. *J. Geophys. Res.* 111, B07402, doi: 10.1029/2005JB003907.

Árnadóttir, Th., B. Lund, W. Jiang, H. Geirsson, H. Björnsson, P. Einarsson and Th. Sigurdsson 2009. Glacial rebound and plate spreading: Results from the first countrywide GPS observations in Iceland. *Geophys. J. Int.*, 177(2), 691–716, doi: 10.1111/j.1365-246X.2008.04059.x

Björnsson, A. 1985. Dynamics of Crustal Rifting in NE Iceland. *J. Geophys. Res*., 90(B12), 10,151–10,162, doi:10.1029/JB090iB12p10151.

Björnsson, H. and F. Pálsson 2008. Icelandic glaciers. Jökull, 58, 365-386.

Dach, R., U. Hugentobler, P. Fridez and M. Meindl 2007. Bernese GPS Software Version 5.0. Astronomical Institute, University of Bern, Switzerland

Decriem, J., Th. Árnadóttir, A. Hooper, H. Geirsson, F. Sigmundsson, M. Keiding, B. G. Ófeigsson, S. Hreinsdóttir, P. Einarsson, P. LaFemina and R. A. Bennett 2010. The 29 May 2008 earthquake doublet in SW Iceland. *Geophys. J. Int.*, 181(2), 1128-1146, doi: 10.1111/j.1365-246X.2010.04565.x.

DeMets, C., R. G. Gordon, D. F. Argus and S. Stein 1994. Effect of recent revisions to the geomagnetic reversal timescale on estimates of current plate motions. *Geophys. Res. Lett.*, 21,2191-2194.

DeMets, C., R. G. Gordon and D. F. Argus 2010. Geologically current plate motions. *Geophys. J. Int.*, 181, 1–80. doi: 10.1111/j.1365-246X.2009.04491.x.

Ebinger, C., A. Ayele, D. Keir, J.V. Rowland, G. Yirgu, T. Wright, M. Belachew and I. Hamling 2010. Length and timescales of rift faulting and magma intrusion: the Afar rifting Cycle from 2005 to Present. *Ann. Revs. Earth Planet Sci.*, 38, 439-466, doi:10.1146/annrev-earth-040809-152333.

Einarsson, P., S. Björnsson, G. Fougler, R. Stefánsson and Th. Skaftadóttir 1981. Seismicity pattern in the South Iceland Seismic Zone. I*n: Earthquake Prediciton- An International Review,* eds. D. Simpson and P.G. Richards. American Geophys. Union, Maurice Ewing Series 4: pp.141-151.

Einarsson, P. 1991. Earthquakes and present-day tectonism in Iceland. *Tectonophysics* 189, 261–279.

Einarsson, P., F. Sigmundsson, E. Sturkell, Th. Árnadóttir, R. Pedersen, C. Pagli and H. Geirsson. 2006. Geodynamic signals detected by geodetic methods in Iceland. *In: Festschrift for Prof. G. Seeber*, ed. C. Hirt, Wissenschaftliche Arbeiten der Fachrichtung Geodäsie und Geoinformatik der Universität Hannover Nr. 258, 39-57.

Einarsson, P. 2008. Plate boundaries, rifts and transforms in Iceland. *Jökull*, 58, 35-58.

Feigl, K. L., J. Gasperi, F. Sigmundsson and A. Rigo 2000. Crustal deformation near Hengill volcano, Iceland 1993–1998: Coupling between magmatic activity and faulting inferred from elastic modeling of satellite radar interferograms. *J. Geophys. Res.*, 105(B11), 25,655–25,670, doi:10.1029/2000JB900209.

Foulger, G., G. Beutler, R. Bilham, P. Einarsson, S. Fankhauser, W. Gurtner, U. Hugentobler, W. J. Morgan, M. Rothacher, G. Thorbergsson and U. Wild 1993. The Iceland 1986 GPS geodetic survey: Tectonic goals and data processing results. *Bull. Geodetica*, 67, 148-172, 1993.

Geirsson, H., Th. Árnadóttir, C. Völksen, W. Jiang, E. Sturkell, T. Villemin, P. Einarsson, F. Sigmundsson and R. Stefánsson 2006. Current plate movements across the Mid-Atlantic Ridge determined from 5 years of continuous GPS measurements in Iceland. *J. Geophys. Res.*, 111, B09407.

Geirsson, H., S.S. Jakobsdóttir, G.B. Guðmundsson, M.J., Roberts and J. Decriem 2009. A deep seated magmatic intrusion at Upptyppingar, Iceland, during 2007 and 2008. *In: The VOLUME Project, VOLcanoes: Understaning subsurface mass moveMEnt*, ed. C.J. Bean, A.K. Braiden, I. Lokmer, F. Martini, G.S. O'Brien. School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland.

Grapenthin, R., F. Sigmundsson, H. Geirsson, T. Arnadottir and V. Pinel 2006. Icelandic rhythmics: Annual modulation of land elevation and plate spreading by snow load. *Geophys. Res. Lett.*, 33, L24305, doi:10.1029/2006GL028081.

Grapenthin, R., B. G. Ófeigsson, F. Sigmundsson, E. Sturkell and A. Hooper 2010. Pressure sources versus surface loads: Analyzing volcano deformation signal composition with an application to Hekla volcano, Iceland. *Geophys. Res. Lett.*, 37, L20310, doi:10.1029/2010GL044590.

Gripp, A.E. and R.G. Gordon 2002. Young tracks of hotspots and current plate velocities. *Geophys. J. Int.,* 150, 321-364.

Gudmundsson, M.T., Th. Högnadóttir, A.B. Kristinsson and S. Guðbjörnsson 2007. Geothermal activity in the subglacial Katla caldera, Iceland, 1999-2005, studied with radar altimetry. *Annals of Glaciology*, 45, 66-72.

Hooper, A., B.G. Ofeigsson, F. Sigmundsson and H. Geirsson 2008. Recent Deep-Seated Magmatic Activity and the 2008 M6.3 Earthquake: Applicability of ALOS/PALSAR in Iceland. *Proceedings ALOS Workshop*, Rhodes.

Hreinsdóttir, S., T. Árnadóttir, J. Decriem, H. Geirsson, A. Tryggvason, R. A. Bennett and P. LaFemina 2009. A complex earthquake sequence captured by the continuous GPS network in SW Iceland. *Geophys. Res. Lett.*, 36, L12309, doi:10.1029/2009GL038391.

Jakobsdóttir, S.J., M.J. Roberts, G.B. Guðmundsson, H. Geirsson and R. Slunga 2008. Earthquake swarms at Upptyppingar, north-east Iceland: a sign of magma intrusion? *Stud. Geophys. Geod*., 52, 513-528.

Jónsson, S., P. Segall, R. Pedersen and G. Björnsson 2003. Post-earthquake ground movements correlated to pore-pressure transients. *Nature*, 424, 179-183, doi:10.1038/nature01776.

Jónsson S. 2008. Importance of post-seismic viscous relaxation in southern Iceland. *Nature Geoscience*, 1, doi:10.1038/ngeo105.

Keiding, M., T. Árnadóttir, E. Sturkell, H. Geirsson and B. Lund 2008. Strain accumulation along an oblique plate boundary: The Reykjanes Peninsula, southwest Iceland. *Geophys. J. Int.* 172, 1, 861–872, doi:10.1111/j.1365–246X.2007.03655.x.

King, R.W. and Y. Bock 2005. Documentation for the GAMIT GPS Analysis Software. Release 10.2, Mass. Institute of Technology and Scripps Institution of Oceanography.

Kreemer, C., W.E. Holt and A.J. Haines 2003. An integrated global model of present-day plate motions and plate boundary deformation. *Geophys. J. Int.*, 154, 1, 8–34, doi:10.1046/j.1365-246X.2003.01917.x.

La Femina, P.C., T.H. Dixon, R. Malservisi, T. Arnadottir, E. Sturkell, F. Sigmundsson and P. Einarsson 2005. Strain partitioning and accumulation in a propagating ridge system: Geodetic GPS measurements in south Iceland. *J. Geophys. Res*., 110, B11405, doi:10.1029/2005JB003675.

Merkouriev, S. and C. DeMets 2008. A high-resolution model for Eurasia–North America plate kinematics since 20 Ma. *Geophys. J. Int.*, 173, 1064–1083, doi: 10.1111/j.1365-246X.2008.03761.x.

Metzger, S. and S. Jónsson 2010. Slip rate of the Húsavík-Flatey Fault, North Iceland, derived from GPS and InSAR Time Series. *Eos Trans. AGU*, 91(52), Fall Meet. Suppl., abstract T44A-07.

Ófeigsson, B.G. 2008. Crustal movements 2005-2007 in the Kárahnjúkar area, NE-Iceland, in relation to formation of the Hálslón water reservoir. Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Report 0801, 75 pp.

Ofeigsson, B.G., F. Sigmundsson, A. Hooper and E. Sturkell 2010. InSAR time series analysis at Hekla volcano, Iceland: Inflation periods and crustal deformation associated with the 2000 eruption. *J. Geophys. Res*., in press, doi:10.1029/2010JB007576.

Pagli, C., F. Sigmundsson, B. Lund, E. Sturkell, H. Geirsson, P. Einarsson, T. Arnadottir and S. Hreinsdottir 2007. Glacio-isostatic deformation around the Vatnajökull ice cap, Iceland, induced by recent climate warming: GPS observations and finite element modeling. *J. Geophys. Res*., 112, B08405, doi:10.1029/2006JB004421.

Pagli, C. and F. Sigmundsson 2008. Will present day glacier retreat increase volcanic activity? Stress induced by recent glacier retreat and its effect on magmatism at the Vatnajokull ice cap, Iceland, *Geophys. Res. Lett*., 35, doi:10.1029/2008GL033510

Pedersen, R. and F. Sigmundsson 2004. InSAR based sill model links spatially offset areas of deformation and seismicity for the 1994 unrest episode at Eyjafjallajökull volcano, Iceland. *Geophys. Res. Lett.*, 31, L14610, doi:10.1029/2004GL020368.

Pedersen, R. and F. Sigmundsson 2006. Temporal development of the 1999 intrusive episode in the Eyjafjallajökull volcano, Iceland, derived from InSAR images. *Bull. Volcanol.,* 68, 377-393, doi: 10.1007/s00445-005-0020-y.

Rülke, A., R. Dietrich, M. Fritsche, M. Rothacher, P. Steigenberger 2008. Realization of the Terrestrial Reference System by a reprocessed global GPS network. *J. Geophys. Res*., 113, B08403, doi:10.1029/2007JB005231.

Sigmundsson, F., P. Einarsson, R. Bilham and E. Sturkell 1995. Rift-transform kinematics in south Iceland: Deformation from Global Positioning System measurements, 1986-1992. *J. Geophys. Res.*, 100, 6235-6248, doi:10.1029/95JB00155.

Sigmundsson, F., S. Hreinsdóttir, A. Hooper, T. Árnadóttir, R. Pedersen, M.J. Roberts, N. Óskarsson, A. Auriac, J. Decriem, P. Einarsson, H. Geirsson, M. Hensch, B.G. Ófeigsson, E. Sturkell, H. Sveinbjörnsson and K.L. Feigl 2010. Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption. *Nature*, in press.

Stefánsson, R. and P. Halldórsson 1988. Strain build-up and strain release in the South Iceland seismic zone.

*Tectonophysics*, 152, 267-276, doi:10.1016/0040-1951(88)90052-2.

Sturkell, E., F. Sigmundsson and P. Einarsson 2003a. Recent unrest and magma movements at Eyjafjallajokull and Katla volcanoes, Iceland. *J. Geophys. Res*., 108(B8), 2369, doi: 10.1029/2001JB000917.

Sturkell, E., P. Einarsson, F. Sigmundsson, S. Hreinsdóttir and H. Geirsson 2003b. Deformation of Grımsvotn volcano, Iceland: 1998 eruption and subsequent inflation. *Geophys. Res. Lett*., 30(4), 1182, doi:10.1029/2002GL016460.

Sturkell, E., K. Agustsson, A.T Linde, S.I. Sacks, P. Einarsson, F. Sigmundsson, H. Geirsson, R. Pedersen and P. LaFemina 2005. Geodetic constraints on the magma chamber of the Hekla volcano, Iceland, *Eos Trans. AGU*, 86(52), Fall Meet. Suppl., abstract V21D-0636.

Sturkell, E., P. Einarsson, F. Sigmundsson, H. Geirsson, H. Olafsson, R. Pedersen, E. de Zeeuw-van Dalfsen, A. L. Linde, I. S. Sacks and R. Stefansson 2006. Volcano geodesy and magma dynamics in Iceland, *J. Volc. Geotherm. Res*., 150, 14-34, doi:10.1016/j.jvolgeores.2005.07.010.

Sturkell, E., P. Einarsson, M.J. Roberts, H. Geirsson, M.T. Gudmundsson, F. Sigmundsson, V. Pinel, V., G.B. Guðmundsson, H. Ólafsson and R. Stefánsson 2008. Seismic and geodetic insights into magma accumulation at Katla subglacial volcano, Iceland: 1999 to 2005. *J. Geophys. Res*., 113, B03212, doi:10.1029/2006JB004851.

Sturkell, E., P. Einarsson, F. Sigmundsson, A. Hooper, B.G. Ofeigsson, H. Geirsson and H. Olafsson 2010. Katla and Eyjafjallajokull Volcanoes. In: *Developments in Quaternary Science*, eds. A. Schomacker, J. Kruger and K.H. Kjaer, Elsevier, Volume 13, The Myrdalsjokull Ice Cap, Iceland. Glacial processes, sediments and landforms on an active volcano, 5-21, doi:10.1016/S1571-0866(09)01302-5.

Thordarson, T., and G. Larsen 2007. Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history. *Journal of Geodynamics*, 43, p. 118-152, doi:10.1016/j.jog.2006.09.005.

Völksen, C., Th. Arnadottir, H. Geirsson and G. Valsson 2009. Present day geodynamics in Iceland monitored by a permanent network of continuous GPS stations. *J. of Geodynamics*, 48(3-5), New Challenges in Earth's Dynamics - Proceedings of the 16th International Symposium on Earth Tides, December 2009, 279-283, doi:10.1016/j.jog.2009.09.033.

Wessel, P. and W.H.F. Smith 1998. New, improved version of the Generic Mapping Tools released, *EOS Trans. AGU*, 79, 579.

White, R.S., J. Drew, H. Soosalu, J. Key and S. Jakobsdóttir 2009. Anatomy and melt intrusion at 15-18 depth beneath Upptyppingar, Iceland. *JSR international conference on earthquakes and pre-earthquake processes*, Abstract volume, Oct. 30, Reykjavik, Iceland.

Zumberge, J., M. Heflin, D. Jefferson, M. Watkins and F. Webb 1997. Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks. *J. Geophys. Res*. 102, 5005–5017.

## FIGURE CAPTIONS

Figure 1.

A map of Iceland showing CGPS station locations, observed horizontal velocities relative to stable North America, and main tectonic and volcanic features in Iceland. The stations are broken into sub-networks by different symbols and colors. The velocity field is calculated from daily station observations from when the station was installed until the end of 2009, using the GAMIT/GLOBK software as described by Hreinsdottir et al. (2009). Black arrows show predicted site velocities from the MORVEL plate motion model (DeMets et al., 2010). Error ellipses note 2-sigma uncertainties. The yellow areas show individual fissure swarms associated with central volcanoes (black circles). Blue N-S striking lines in the SISZ show locations of the 2000 and 2008 earthquake sequence main faults (right two lines and left two lines, respectively). Site ISAF has too short time series to allow meaningful estimates of the velocities, and GFUM is much affected by the recent eruption and ongoing inflation. Sections of the plate boundary are abbreviated in gray: RP: Reykjanes Peninsula; WVZ, EVZ, and NVZ: Western, Eastern, and Northern Volcanic Zones, respectively; SISZ: South Iceland Seismic Zone; Hb: Hreppar block; CIVZ: Central Icelandic Volcanic Zone; GOR: Grímsey Oblique Rift; HFF: Húsavík-Flatey Fault; DZ: Dalvík Zone. White areas note ice-caps, selected volcanic systems are abbreviated by: Kr: Krísuvík; He: Hengill; H: Hekla; E: Eyjafjallajökull; Ka: Katla; G: Grímsvötn; A: Askja; U/A: Upptyppingar – Álftadalsdyngja.

Figure 2

Time series of motion of selected CGPS stations in the IGS05 reference frame. Each point in east, north, and up represents a daily solution estimated from 24 hours of data using the GIPSY/OASIS II software in single-site position mode with reprocessed final orbits and clock products from the Jet Propulsion Laboratory. The vertical lines in 2000 and 2008 denote the time of the earthquake sequences in the South Iceland Seismic Zone. Offsets due to the earthquakes are observed most notably at VOGS and HVER, and a post-seismic decaying signal is evident in the north component of HVER in 2008. The north component at SAUD during 2007 to 2008 is affected by the Upptyppingar-Álftadalsdyngja intrusion. Sites moving towards west (negative slope in the east component) are moving with the North-American plate. Stations in the highlands (SKRO, SAUD, and FJOC) are moving rapidly upwards with respect to the coastal sites. Uncertainties are not shown for clarity, but points with uncertainties larger than five times the median uncertainty have been removed.

Figure 3

Time series of detrended motion for a selected set of CGPS stations north of Vatnajökull. The mean velocity of each site has been removed from the time series to emphasize time-varying motion of the sites. The original time series were processed using Bernese 5.0. Data before 2007 was processed with reprocessed products (orbits, earth-orientation parameters) from the Potsdam-Dresden Reprocessing. After 2007, final products from IGS were used for the processing. The coordinates and velocities of 11 IGS sites surrounding the North Atlantic were also constrained in the PDR05 (Rülke et al., 2008) using a minimum constraint condition, see Völksen et al. (2009) for details. All sites but MYVA are affected by the filling and seasonal level changes of the Hálslón reservoir, the Upptyppingar-Álftadalsdyngja intrusion, and seasonal load variations from Vatnajökull glacier.

Figure 4

Observed horizontal (green arrows) and vertical (white bars) site velocities. The velocity field is derived as in Figure 1, but here it is shown with respect to a fixed Eurasian plate. Black arrows show for comparison velocity predictions from the MORVEL plate motion model (DeMets et al., 2010).

Figure 5

Observed horizontal (green arrows) and vertical (white bars) site velocities at Hekla volcano relative to a stable North America plate, showing a gradual velocity increase over Hekla. The velocity field is derived as in Figure 1, and site labels are as in Figure 1.

Figure 6

Time series of the motion of site THEY, south of Eyjafjallajökull covering the 2009-2010 intrusive and eruptive episodes. The time series are plotted relative to REYK (hence the overall eastward drift), and are from IMO's automatic data processing using Bernese V 5.0 with predicted orbits from Center of Orbit Determination in Europe (CODE). The gray areas note periods of intrusion into the volcano, and the red lines note the times of the start of the flank eruption (F), and summit eruption (S). The gray period “1” marks the May to August 2009 intrusion, period “2” starts at the onset of the inflation in December 2009 and ends at period “3”, when the station started moving towards west because material was being intruded east of the station (Sigmundsson et al., in press).

Figure 7

Time series of the motion of site GFUM at Grímsvötn relative to fixed Eurasia. A constant rate of 22 mm/yr has been subtracted from the vertical component to account for glacial rebound. The time series are produced using Bernese V 5.0, as described by Decriem et al. (2010). The vertical line notes the onset of the 2004 eruption. The dashed horizontal line at -100 in the north component is set to the position of the station just before the 2004 eruption. A corresponding line for the east and vertical components coincides with zero.

Figure 8

Time series of detrended motion CGPS stations in SW Iceland. Map on lower right shows station locations. Here the mean velocity and offsets have been removed from the time series. Vertical lines note times of the 2000 and 2008 earthquakes. The original time series were processed using Bernese 5.0 and 4.2. Data before 2007 was processed with Bernese 4.2 with final orbits from CODE, relative to REYK as described by Geirsson et al. (2006). Data after 2007 was processed with Bernese 5.0 using predicted orbits from CODE tied to the ITRF2000 using fiducial stations in Europe and North Amercia. Data points with five times the median uncertainty have been rejected. Post-2007 data are shown relative to REYK for compliance. The sites are mostly affected by post-seismic deformation after the 2008 earthquake and a gradual change in velocities at some sites (e.g. HLID and OLKE). Site KRIV shows signals in the north component from a nearby inflation/deflation episode.