Haustfundur Jarðfræðafélags Íslands 2006

Landrek og Aflögun/Crustal Deformation

Ágrip erinda

Reykjavík, 27. október 2006

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Umsjón:
Kristín S. Vogfjörð

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Dagskrá

Yfirlit um mælitækni, niðurstöður og líkön
General overview of techniques, observations and models

13:00-13:05	***Opnunarávarp*/Opening remarks** Andri Stefánsson
13:05-13:20	***Aflögun jarðskorpu Íslands; tímaskalar, ferli og mæliaðferðir*** **Deformation of the Icelandic crust; timescales, processes and measuring methods** Rikke Pedersen
13:20-13:50	***Landreks og kvikuhreyfingar í samfelldum GPS gögnum seinustu 7 ára*** **Plate spreading and magma dynamics revealed by 7 years of continuous GPS measurements in Iceland** Halldór Geirsson, Þóra Árnadóttir, Erik Sturkell
13:50-14:20	***Líkangerð af jarðskorpuhreyfingum á Íslandi*** **Modeling of crustal deformation in Iceland** Þóra Árnadóttir, Sigurjón Jónsson, Fred Pollitz, Rikke Pedersen, Loic Dubois, Kurt L. Feigl, Pete LaFemina, Marie Keiding, Sigrún Hreinsdóttir, Halldór Geirsson, Weiping Jiang, Erik Sturkell
14:20-14:40	***Kaffi***

Aflögun vegna kvikuhreyfinga í eldfjöllum
Crustal deformation due to magma movements in volcanoes

14:40-15:05	***Aflögun íslenskra eldfjalla: Yfirlit og dæmi frá Hengli, Bárðarbungu og Gjálp*** **Deformation of Icelandic volcanoes: Overview and examples from Hengill, Bárðarbunga and Gjálp** Freysteinn Sigmundsson, Rikke Pedersen, Carolina Pagli, Erik Sturkell, Páll Einarsson, Þóra Árnadóttir, Kurt L. Feigl, Virginie Pinel
15:05-15:25	***Aflögun í Grímsvötnum, Öskju og Kröflu*** **Present-day deformation at the Grímsvötn, Askja and Krafla volcanoes** Erik Sturkell, Páll Einarsson, Freysteinn Sigmundsson, Halldór Geirsson, Heidi Soosalu, Clare Knox, Halldór Ólafsson, Rikke Pedersen, Theodór Theodórsson
15:25-15:45	***Aflögun eldfjalla í suðurhluta eystra gosbeltisins; Hekla, Torfajökull, Eyjafjallajökull og Katla*** **Volcano deformation studies in the propagating rift zone; Hekla, Torfajökull, Eyjafjallajökull and Katla** Rikke Pedersen, Freysteinn Sigmundsson, Erik Sturkell, Andrew Hooper, Halldór Geirsson, Páll Einarsson and Kristján Ágústsson
15:45-16:00	***Kaffi***

Aflögun vegna jöklabreytinga og vinnslu jarðhitasvæða

Crustal deformation related to glacier dynamics and geothermal utilization

16:00-16:20	***Aflögun við Vatnajökul vegna jöklabreytinga*** **Load induced crustal deformation at the Vatnajökull ice cap, Iceland** Freysteinn Sigmundsson, Carolina Pagli, Erik Sturkell, Halldór Geirsson, Ronni Grapenthin, Virginie Pinel, Páll Einarsson, Þóra Árnadóttir, Björn Lund, Kurt Feigl, Rikke Pedersen, Helgi Björnsson, Finnur Pálsson
16:20-16:40	***Hreyfingar Skeiðarárjökuls*** **Meltwater dynamics beneath Skeiðarárjökull from continuous GPS measurements** Matthew Roberts, Eyjólfur Magnússon, Halldór Geirsson, Erik Sturkell
16:40-17:00	***Landmælingar á jarðhitasvæðum, dæmi af Reykjanesi*** **Crustal deformation in geothermal areas, examples from Reykjanes Peninsula** Ingvar Þór Magnússon
17:00-17:15	***Umræður*/Discussion**
17:15-19:00	***Veitingar***

Yfirlit um mælitækni, niðurstöður og líkön

General overview of techniques, observations and models

Deformation of the Icelandic crust; timescales, processes and measuring methods

Rikke Pedersen

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Measuring deformation of the Earths crust is an important tool in trying to obtain insight into the geological processes working at depth. The timescale of these processes vary greatly, and their resulting deformation needs to be evaluated through both geological records as well as measured directly. Plate movement occurs at one end of the timescale with relatively continuous deformation through millions of years. Isostatic processes induced by glaciation or deglaciation typically occur on intermediate timescales on the order of thousands of years, whereas deformation due to magmatic processes generally occur on timescales of years to months or days. Tectonic faulting makes up the other end of the timescale, with deformation occurring within seconds.

The Icelandic crust deforms continuously due to a variety of processes. Changes in the location of the plate spreading zone (rift jumps) occurring at intervals of a few million years have been documented through geological mapping and paleomagnetic studies. Following the last glaciation, rapid uplift resulted from unloading of the crust, inferred from studies of uplifted old shorelines. The focus of this meeting however, is measurement and modeling of current crustal deformation, e.g. deformation measured over the past four decades, which includes processes such as plate spreading, subsurface magma movements, co-seismic faulting, aseismic faulting, poro-elastic rebound, co-eruptive displacements, glacial rebound due to glacial thinning, glacial ice deformation and pressure changes in subsurface water reservoirs due to geothermal utilization.

A range of measuring techniques has been applied in Iceland in the past decades. Significant technical development of measuring techniques in recent years enables increasingly sophisticated Earth deforming models to be applied. Focus will here be on the main techniques applied presently, hence dry tilt leveling, volumetric strain measurements, GPS and InSAR.

Dry tilt leveling is carried out by repeated measurements of a permanently installed benchmark array, typically in an L-shaped configuration. A leveling instrument is used to scan measuring rods, placed in a vertical position on the benchmarks. The resulting data is given as the relative difference in height between benchmarks. Crustal deformation will cause changes in the relative height difference of subsequent measuring campaigns. The detection limit of the technique is on the order of 1 µrad, hence it is possible to measure a 1 cm uplift occurring over a distance of 10 km. The technique has been applied in Iceland since the early 1960ies.

Volumetric strain is continuously measured at 6 stations in Iceland, all installed in 1979. Borehole strainmeters measure strain changes caused by crustal deformation by very accurately sensing a change in the shape of the instrument, which is firmly cemented into the rock. Because the width of the instrument is only about 10 cm, very precise measurements are required. A typical signal is 10 nanostrain. In order to avoid noise introduced by thermal effects, wind, and cultural activity, borehole strainmeters are usually installed several hundred meters below the ground surface. Even at these depths, the instruments are subject to many effects which cause the signal to drift. Therefore a borehole strainmeter achieves the highest precision for periods shorter than a few weeks. Volumetric strain measurements in Iceland have provided essential information on magmatic processes in connection with the ascent of magma a few hours prior to recent Hekla eruptions.

Since the mid-1980ies space geodetic methods have been increasingly utilized in Iceland. One method is GPS, which is the acronym for Global Positioning System. It is based on satellite ranging, i.e. distance from a fixed point on the ground to a number of satellites orbiting the earth. Simultaneous measurements from at least 4 satellites are necessary to obtain a position in space. Currently there are more than 20 GPS satellites in orbit around the Earth. GPS measurements for crustal deformation monitoring are done by repeated measurements on a network of benchmarks permanently installed in stable surface layers. Repeated measurements of the same point on the ground enable calculation of a 3-dimensional displacement vector representing the resultant deformation within the period spanned by the measurements. The accuracy of the GPS measurement depends on the length of the observation time, but for campaign measurements it is typically on the level of sub-centimetre, and often as good as on the millimetre scale. In 1999 a network of continuous GPS stations were initialized by installation of four antennas in the Hengill area. The network has been expanding ever since, and it now covers the entire country, though relatively sparsely.

Satellite radar interferometry (InSAR) is another space geodetic method used for measuring ground deformation. The basic principle behind InSAR is to take two radar scenes acquired over the same area (typically about 100 by 100 km) from about the same orbital position in space but at different times, and subtract one from the other. After topographic correction has been applied, due to the two slightly different look angles, a phase image of the difference will (under favorable conditions) show, if surface movements have occurred in the time interval between acquisitions. The measurement is one-dimensional, performed in the “line-of-sight” direction (LOS), with a detection threshold on the sub-centimeter level. The sensibility to surface deformation varies in accordance with the LOS, being most sensitive to vertical changes, less sensitive to east-west movements, and least sensitive to north-south movements. Pixel sizes vary according to the chosen processing procedure, as over-sampling is often required in the signal processing. The standard conventional InSAR processing carried out at the Nordic Volcanological Office has a pixel size of 100 by 100 meters.

Plate spreading and magma dynamics revealed from 7 years of continuous GPS measurements in Iceland

Halldór Geirsson[1], Þóra Árnadóttir[2], Erik Sturkell[2] (and many more)

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The continuous GPS (CGPS) network in Iceland currently consists of 23 active stations. A significant expansion of the network is now underway, where 25-30 new sites will be installed with a sampling rate of 1 second or higher in selected areas in Iceland. This high sampling rate will allow us to study dynamic processes related to volcanic and seismic activity. The data are automatically downloaded and then processed using the Bernese V4.2 software. We have also processed a large portion of the data using the GAMIT/GLOBK and GIPSY/OASIS II software. We observe large-scale crustal deformation due to plate spreading across Iceland. The observed plate divergence between the North-American and the Eurasian plates is in general agreement with existing models of plate motion and the spreading - about 2 cm/yr - is taken up within a 100-150 km wide plate boundary zone that runs through the island. Of the 2 parallel branches of the plate boundary in south Iceland, the Eastern volcanic zone is currently taking up a majority of the spreading and little is left for the Western volcanic zone. The plate boundary deformation field has been spatially and temporarily affected in by two Mw=6.5 earthquakes in June 2000, inflation at Katla volcano during 2000 to 2005, an eruption of Hekla volcano in February 2000. Local deformation was also observed for the 2004 Grímsvötn eruption. The CGPS and campaign GPS agree that there is a broad-scale uplift signal in the center of Iceland with the highest velocities exceeding 2 cm/yr.

Models of crustal deformation in Iceland

Þóra Árnadóttir[1], Sigurjón Jónsson[2], Fred Pollitz[3], Rikke Pedersen[1], Loic Dubois[4], Kurt L. Feigl[5], Pete LaFemina[6], Carolina Pagli[1,7], Marie Keiding[1], Sigrún Hreinsdóttir[8], Halldór Geirsson[9], Weiping Jiang[1,10], Erik Sturkell[1]

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The talk will give an overview of results from crustal deformation studies, focusing on earthquakes and plate boundary deformation models in central and southwest Iceland.

The June 2000 earthquake sequence is the best-documented series of earthquakes in Iceland to date. Signals from the earthquakes were detected by the SIL digital seismic network, strong motion accelerometers, volumetric strain meters, GPS, satellite radar interferometry (InSAR) and pressure changes in geothermal reservoirs.

The sequence caused significant crustal deformation over a large area, extending from the epicentral area of the two Mw=6.5 main shocks in the south Iceland seismic zone (SISZ) to the central part of the Reykjanes Peninsula, where three M~5-5.5 earthquakes were triggered. The co-seismic crustal deformation signals observed in the SISZ and on the Reykjanes Peninsula have been modeled in several studies [*Pedersen et al.,* 2001*; Árnadóttir et al.,* 2001*; Pagli et al.,* 2003*; Pedersen et al.,* 2003*; Árnadóttir et al.,* 2004*; Dubois et al., submitted* 2006]. The main results from modeling of the co-seismic deformation are that the June 17 and June 21 main shocks ruptured two 12-15 km long, sub-parallel N-S oriented faults, with right-lateral strike slip, extending from the surface to about 8 km depth. The details of the optimal models obtained from inversion of geodetic data depend on the Earth model assumed (homogeneous elastic half-space or layered models), and the slip distribution (uniform slip vs. variable slip). In general, the homogeneous half-space models suggest that most of the slip occurred above 6 km depth, whereas layered models predict deeper slip. In particular *Dubois et al.* [2006] find significant slip (~1 m) at 5-10 km depth on the June 21 fault.

Dynamic and static stress change calculations have been used to examine the triggering of earthquakes in the sequence [*Antonioli et al.,* 2006; *Árnadóttir et al., 2003].* Static Coulomb stress changes calculated using the slip models obtained from geodetic data for the main shocks [*Pedersen et al., 2003*] suggest that the June 17 main shock brought the June 21 fault closer to failure [*Árnadóttir et al., 2003*]. The dynamic stress triggering study concluded that the M~5-5.5 events occurring within the first 30 sec of the main shock can be explained by short-term fault interaction and instantaneous triggering for low values of the initial effective normal stress [*Antonioli et al.,* 2006]. Neither the dynamic nor the static stress changes can, however, explain the 81-hour delay time between the June 17 and 21 main shocks.

Post-seismic deformation following the June 2000 earthquakes was observed on two spatio-temporal scales [*Árnadóttir et al.,* 2005; *Jónsson et al.*, 2003]. A deformation transient lasting no more than 2 months observed by InSAR, has been explained by poro-elastic rebound due to pore-fluid flow in response to the main shock induced pore-pressure changes [*Jónsson et al.*, 2003]. In contrast, the year-scale deformation observed by GPS can be explained by either afterslip at 8-14 km depth or visco-elastic relaxation of the lower crust and upper mantle in response to the coseismic stress changes. Models with lower crustal viscosities of ~10^{19} Pa s and upper mantle viscosity less than ~3 x 10^{18} Pa s yield the best fit to the combined horizontal and vertical post-seismic velocity field [*Árnadóttir et al.,* 2005]. These viscosity estimates fall within the range of values estimated from glacial rebound studies around Vatnajökull (0.1-1 x 10^{19} Pa s) [*Sigmundsson and Einarsson*, 1992; *Pagli et al.,* submitted 2006] and models of post-rifting deformation following the Krafla fires in 1975-1984 (0.1- 3 x 10^{19} Pa s) [*Hofton and Foulger*, 1996; *Pollitz and Sacks*, 1996]. Coulomb stress change calculations based on the postseismic SISZ deformation models suggest that N-S faults in the area of large coseismic stress increase east of the June 17 fault and west of the June 21 fault continue to be loaded by the postseismic deformation [*Árnadóttir et al.,* 2005; *Dubois et al., submitted* 2006]. The June 2000 earthquake sequence and postseismic deformation is estimated to have released less than half of the moment built up due to plate spreading in the 88 yrs since the Ms=7.0 earthquake in the SISZ in 1912 [*Pedersen et al.,* 2003; *Árnadóttir et al.,* 2005]. There is still a significant amount of moment stored in the brittle crust in the SISZ, suggesting that we may expect large earthquakes there in the near future.

Several studies have documented the plate boundary deformation across the active rift zones in central and southwestern Iceland. Two parallel rift zones, the Eastern and the Western volcanic zones accommodate the spreading across central Iceland. In study re-measuring an EDM network across the EVZ by a GPS campaign in 1994, *Jónsson et al.,* [1997] estimated a 12 mm/yr rate of extension across the zone. The GPS measurements were repeated in 2003, extending the profile across both the Western and Eastern rift zones [*LaFemina et al.,* 2005]. This study indicated that the spreading rates along the rift zones vary along strike of the zone, with rates across the EVZ decreasing from ~19 mm/yr to ~11 mm/yr from north to south, while the rate of opening across the WVZ increases from ~3 mm/yr near Langjökull, to ~7 mm/yr in the Þingvellir area. This is in agreement with a simple propagating ridge model where the WVZ is deactivating in the direction of EVZ southwestward propagation. *LaFemina et al.* [2005] also note that the maximum velocity gradient in the EVZ is across the Bárðarbunga-Veiðivötn fissure swarm, possibly signifying magma accumulation in the system.

Crustal deformation at the oblique plate boundary along the Reykjanes Peninsula, has been documented in several studies. *Hreinsdóttir et al.,* [2001] modeled the surface deformation observed with campaign GPS from 1993 to 1998, using a simple 2D screw dislocation, approximating a left-lateral shear zone at depth. They found that the data could be explained by assigning a deep slip rate of ~16.5 mm/yr below ~6.5 km depth, but conclude that no rift normal motion is needed to explain the data. Based on this interpretation they suggested alternating cycles of volcanic and seismic activity to explain the oblique spreading across the peninsula. The plate spreading across SW Iceland observed by the continuous GPS network since 2000 is, however, consistent with plate motion models, indicating that the motion observed on a regional scale over a few years is comparable to the motion estimated on a geologic time scale (thousands of years) [*Geirsson et al.,* 2006]. A study by *Árnadóttir et al.* [2006] applied a complex model to the velocity field observed by campaign GPS measurements from 1992 to 2000 in SW Iceland. Their kinematic model approximated the plate boundary in SW Iceland with vertical dislocations, in addition to point sources to account for local deformation in at Hengill and in the Svartsengi geothermal area. The best-fit models indicated a locking depth of ~8 km in the central and eastern part of the Reykjanes Peninsula, with a deep slip rate of ~17 mm/yr, in agreement with *Hreinsdóttir et al.,* [2001], but with a rate of opening of ~9 mm/yr. The spatial and temporal GPS velocity variations on the Reykjanes Peninsula and the SISZ are enhanced in maps of areal and shear strain rates calculated for the time interval before and after June 2000. The strain rate signals are for the most part associated with geothermal exploration, postseismic deformation and the inflation episode in the Hengill area.

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Aflögun vegna kvikuhreyfinga í eldfjöllum

Crustal deformation due to magma movements in volcanoes

Deformation of Icelandic volcanoes: Overview and examples from Hengill, Bárðarbunga and Gjálp

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The flow of magma through the lower crust in Iceland towards shallow levels is highly episodic. It results in episodic inflation periods and measurable ground deformation on the surface of the Earth. Recorded inflation episodes range in time from several months up to 15 years, with cumulative magma volumes ranging from 0.001-1 km^3. Only few of these episodes result in eruptions; often magma is emplaced at depth in the crust without an eruption at the surface.

Between the relatively short periods of inflation, Icelandic volcanoes subside or show no signs of deformation. In the absence of renewed magma inflow, the rate of volcano deflation generally decreases with time from the last eruption. The processes responsible for deflation include: magma cooling and solidification, pressure reduction, and outflow of magma. Extensional plate movements across volcanic systems may also effectively reduce pressure in deeper parts of magmatic systems by ductile accommodation of plate spreading (below the brittle-ductile transition). A fluid connection between the deeper parts of a magmatic system and a shallow reservoir will then cause the shallow reservoir to respond as a “pressure gauge” for reduction of pressure in its deeper parts.

The channels feeding the shallow magma bodies in the crust are narrow (on the order of meters) and are only active for relatively short periods, separated by periods of no magma transport. The channels solidify unless reactivated by new magma batches. The rate of solidification will depend on heat transfer away from these channels, influenced by the ambient temperature. A shallow magma chamber will be sustained only if the rate of inflow of magma is sufficiently high. Because of limited magma inflow, shallow crustal magma chambers at 3-7 km depth may be limited to only the most active volcanoes in Iceland. The seismic and geodetic evidence suggest shallow magma chambers at least at Krafla, Askja, Grímsvötn, Katla, and Torfajökull volcanoes. Magma chambers under Hekla and Bárðarbunga appear to reside at a significantly deeper level than at the other volcanoes.

In many cases, intrusions are the heat source for geothermal systems. For example, the volume of magma intruded into the Hengill area 1993-1998 is inferred to have been 0.02 km^3. Solidification and cooling of intrusions can provide extensive heat sources for geothermal areas.

A satellite radar interferometry study has revealed crustal deformation associated with the 1996 Gjálp subglacial eruption, in affected areas next to the Vatnajökull ice cap. A M5.6 earthquake occurred at the Bárðarbunga volcano and on September 30 seismicity propagated 20 km southwards where the Gjálp eruption occurred. Analysis of interferograms spanning 1992-2000 allow us to separate two different co-eruptive deformation periods in areas outside the ice cap. Diking at the Bárðarbunga caldera rim appears to be responsible for deformation during the first week of the eruption while significant deflation occurred at Bárðarbunga after October 6. Furthermore, fault slip was triggered by deflation in distant areas.

Present-day deformation at the Grímsvötn, Askja and Krafla volcanoes

Erik Sturkell[a], Páll Einarsson[b], Freysteinn Sigmundsson[a], Halldór Geirsson[c], Heidi Soosalu[d], Clare Knox[d], Halldór Ólafsson[a], Rikke Pedersen[a], Theodór Theodórsson[e]

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We review the geodynamic signals detected by volcano geodesy during the recent years at Grímsvötn, Askja and Krafla volcanoes. The magma chamber of Grímsvötn is re-charging from its most recent eruption and exhibits inflation at a rate of centimetres per year. Subsidence is occurring presently at Askja and Krafla. Extensive measurements of crustal deformation have been conducted using a variety of geodetic techniques. They include leveling, campaign and continuous Global Positioning System (GPS) geodesy, and interferometric analysis of synthetic aperture radar images (InSAR).

At Grímsvötn, long-term and short-term warnings from crustal deformation studies and seismicity did prove successful prior to the eruption in November 2004. Crustal deformation studies by GPS have been performed at a benchmark located at the caldera rim since 1992. This point was re-measured in 1997, one and a half year before the eruption in December 1998. Since 1999 the benchmark has been measured annually, and at times more often. When the amount of uplift in 2003 surpassed the uplift in 1997, it was taken as a sign that the volcano was close (within 1-2 years) to the next eruption. The measurements before both the 1998 and the 2004 eruptions showed that magma accumulated prior to the eruptions. The vertical displacement shows uplift before an eruption followed by a sharp drop after its onset. However, the vertical signal is contaminated by a signal generated by fluctuations of ice load. Both the station at Grímsvötn and the reference station Jökulheimar (JOKU) at the glacier edge are affected. Special attention is needed in interpretation, because of contribution to deformation from ongoing glacio-isostasy. The horizontal displacements do, however, show a much clearer signal due to magma movements. The GPS vector at Grímsvötn has only minor amounts of east-west plate-spreading signal when referenced to the JOKU reference site. During inflation time the horizontal displacements show an outward vector, signifying magma accumulation in a shallow magma chamber, and contraction during eruptions as material is extruded. Since the eruption in November 2004 the volcano is inflating, with a vertical rate of 6 cm/year.

The Krafla rifting episode in 1975–1984, was followed by inflation of a shallow magma chamber until 1989. At that time, gradual subsidence began above the magma chamber and has continued to date, at a diminishing rate. Pressure decrease in a shallow magma chamber is not the only source of deformation at Krafla, as other deformation processes occur at two geothermal fields, together with plate spreading. In addition, deep-seated magma accumulation appears to take place, with its centre about 15 km north of the location of the shallow magma chamber. The relative strength of these sources has varied with time. New results from a leveling survey and GPS measurements in 2005 allow an updated view on the deformation field. Deformation rates spanning 2000–2005 are the lowest recorded in the 30-year history of geodetic studies of the shallow magma chamber. The inferred rate of subsidence 2000–2005 related to processes in the shallow magma chamber is less than 0.3 cm/yr, whereas it was about 5 cm/yr in 1989–1992. The decay fits an exponential function of the form $e^{-t/\tau}$ where $\tau = 4.4$ is a decay constant expressed in years. Currently, the highest rate of subsidence takes place in the Leirbotnar area and appears to be a result of geothermal exploitation.

One of the longest geodetic time series in Iceland is the Askja leveling profile, installed in 1966 by Eysteinn Tryggvason. The line consists of 30 benchmarks located on a pahoehoe lava formed in the 1961 eruption. This profile has been measured annually since 1983. Deformation data from the Askja volcano show that its caldera has been deflating continuously for over 20 years, and confirm that the rate of subsidence is slowing down. The decay in subsidence rate can be fitted with a function of the form $e^{-t/\tau}$ where τ is 39 years. The measurements in 2006 indicate a current subsidence rate of 4.7 cm/yr, compared to the rate of 10.3 cm/yr in 1984. Re-analysis of GPS data from 1993–1998 show that these data can be fitted with a model calling for two Mogi point sources, one shallow, and another one much deeper (16.2 km depth). Pressure decrease occurs in both sources. The deeper source is responsible for observed horizontal contraction towards Askja at distances that cannot be addressed to the shallower source. The deflation of the shallow-level magma chamber has not yet led to increased seismic activity. Earthquakes in the region mainly occur E and NE of Askja, clustered near Herðubreið and Herðubreiðartögl mountains. Studies in 2005 and 2006 of this activity by portable seismograph networks show that the hypocenters are mainly at depths of 2-8 km. We speculate that the seismicity is caused by stress field changes related to spreading of the plate boundary, possibly combined with the local sinking of Askja and regional uplift of central Iceland.

Volcano deformation studies in the propagating rift zone; Hekla, Torfajökull, Eyjafjallajökull and Katla

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Deformation measurements within the propagating rift zone have been applied successfully, detecting deformation originating from a number of sources. We here present the main results from deformation due to magmatic activity spanning at least a decade.

Hekla: The Hekla Volcano is one of the most active volcanic centers in Iceland, and appears to be continuously deforming. It has for that reason been studied with a great variety of geodetic techniques. The geodetic network has evolved considerably through the past four decades, while measuring several cycles of pre- post- and co-eruptive periods. The main techniques currently in use at Hekla are: dry-tilt leveling, volumetric strain, campaign GPS and InSAR. A network of 6 dry tilt stations has been measured at variable intervals since 1968. Volumetric strain is continuously measured at 6 stations, all installed in 1979. Campaign GPS measurements started in 1986, and the network now includes more than 20 benchmarks distributed around the volcano. The InSAR time series starts in 1992 and provides data for summer months through 2000. Furthermore, currently a network of 5 continuous GPS stations is being installed in the Hekla region.

Interdisciplinary geodetic studies of Hekla and the immediate surroundings display a composite deformation pattern. During inter-eruptive periods an area approximately 20 km in diameter (centered at the summit) subsides. The subsidence peaks on the most recent lava flows, due to cooling and compaction of the erupted material. The subsidence is however not confined within the areas covered by lava flows, but extends over a broader region. A subtle uplift signal (<1cm/yr) is seen circumscribing the subsidence. The uplift has a diameter of approximately 40 km, inverting to subsidence at about 10 km distance from the summit. This composite deformation pattern can be interpreted in two ways: a) gradual inflation of a deep seated magma storage area or b) ongoing visco-elastic lithospheric flexure, caused by gravitational loading. Co-eruptive periods are characterized by large displacements in the summit area due to the ascent of a shallow dike to the surface, and subtle subsidence in a large area interpreted as being due to magma chamber pressure decrease. The temporal resolution of volumetric strain data enables modeling of magma ascent from depth immediately prior to an eruption.

Torfajökull: Measurements of deformation within the Torfajökull caldera is carried out through dry-tilt leveling, campaign GPS and InSAR images. The caldera floor has been mostly subsiding at a low, but relatively steady rate through the past decade, except for the 2002-2003 period. The subsidence is interpreted to be related to cooling of a magma chamber. The distribution of low magnitude, high frequency earthquakes appears to support the existence of a cooling magma chamber within the caldera.

Eyjafjallajökull: Two seismic unrest episodes related to magmatic intrusions occurred in 1994 and 1999. Associated crustal deformation was recorded by dry-tilt, GPS and InSAR. A study based on forward modeling of GPS and tilt data suggests similar models for the two events with a Mogi point-source at 3.5 km depth, 4 km south of the summit crater. However, InSAR images have subsequently provided significant improvement in the spatial resolution of the deformation field, and two distinct episodes of

sill intrusion is the currently preferred deformation source model.
The temporal evolution of ground deformation in 1999 can be constructed through our large InSAR data set. From our modeling an average flux rate of 4-6 m^3/s can be deduced for the initial phase of the intrusion, declining over a few weeks. By extrapolation of the modeled volume vs. time curves, we obtain a rough estimate of the onset time of the intrusion. This is deduced to be in the second half of July, coinciding with the time of a burst of seismic tremor in the Katla volcanic system. The coinciding occurrence of sub-surface magma movements reinforces the suspicion of an existing connection between the two neighboring volcanic systems. Local stress perturbations created by magma migration in one system may disturb the other and thereby initiate synchronic magma movement. No evidence exists however for a common source of magma, as the two systems have distinct geo-chemical signatures.

The 1994 and 1999 sill models, both based on inversion of deformation data, have been compared against the locations of seismic events, and a possible explanation for the offset locations of main seismicity and main deformation have been put forward, describing a feeder channel situated beneath the northern slopes of the volcano.

Katla: The Katla volcano has shown persistent seismic activity, with a distinct seasonal variation, for more than four decades. However, since 2001 the activity has been accelerating, causing concern that the volcano is preparing for an eruption in the near future. Deformation measurements around the Myrdalsjökull ice cap have been carried out using dry-tilt leveling and campaign GPS measurements, as well as two continuous GPS stations installed on the southern slopes in 1999. A magma chamber at shallow depth has previously been inferred from seismic undershooting, and as crustal deformation due to a shallow source will only affect a spatially limited area, it is important to perform deformation measurements as close to the potential source as possible. Therefore, GPS measurements on nunataks in the ice cap were initiated in 1993. The repeat survey, in 2000, showed uplift and outward displacement relative to the center of the caldera, indicating magma chamber inflation. Results from the continuous GPS stations support the interpretation of ongoing inflation of a shallow magma chamber. Annual fluctuations in the CGPS have been related to snow/ice load variations.

InSAR images have contributed only little to the present knowledge of ground displacements around the Katla volcano, as the icecap renders near field InSAR measurements impossible. Furthermore, the SAR database suffers from lack of data in the main deformation period (2001-2004) due to partial satellite failure. A new processing approach is however currently being applied to the existing SAR data, in an attempt to average out atmospheric noise and gain signal quality under surface conditions problematic to conventional InSAR.

Aflögun vegna jöklabreytinga og vinnslu jarðhitasvæða

Crustal deformation related to glacier dynamics and geothermal utilization

Load induced crustal deformation at the Vatnajökull ice cap, Iceland

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Evolving ice caps in Iceland provide varying load on the surface of the Earth on three different temporal and spatial scales: (i) load decrease when warmer climate reduces ice, (ii) shift in location of large ice masses in case of surging outlet glaciers, and (iii) an annual cycle ice load associated with annual mass balance of the ice caps. Glaciers in Iceland are generally decreasing because of warmer climate, resulting in uplift over large areas next to the ice caps. At Vatnajökull, GPS stations at the southern edge of the ice cap show vertical velocities in the range of 6-25 mm/yr. These uplift rates can be attributed to ongoing glacio-isostatic adjustment due to thinning of Vatnajökull since 1890. Since then, the ice cap has lost over 400 km^3 of ice. Observations conform to the response of an Earth model with an elastic plate over a uniform viscoelastic medium. The observations are consistent with an elastic thickness of 10-20 km and favor a viscosity below it in the range 4-10 x 10^{18} Pa s. This estimate of rheological parameters allows an estimate of future uplift around Vatnajökull. In the period 2000-2100, an uplift of more than 2.5 meters next to the ice cap is anticipated.

The general uplift around Vatnajökull may be interrupted by sudden subsidence. Instability in ice flow at outlet glaciers can cause sudden glacial surges, when large volumes of ice flow from accumulation areas on the ice caps towards their edges. InSAR observations have revealed subsidence associated with such glacial surges. The most pronounced of these is deformation associated with a glacial surge at the Síðujökull outlet glacier, SW Iceland. A glacial surge in 1994 was associated with transfer of 20 cubic km of ice from the accumulation area, towards the outlet areas, with a thickening of the ice front of over 50 m along a more than 20 km long circular edge of this outlet glacier. Subsidence of up to several centimeters is observed in about 20 km wide area next the ice edge. The observed deformation is evaluated against an elastic deformation model. A map of inferred mass redistribution during the glacial surge is convolved with a Green's function, giving vertical displacement due to a unit point mass applied on an elastic half-space. The resulting displacement scales inversely with E, the Young's modulus of the underlying crust. Comparison of observations and model predictions suggests the effective Young's modulus is 50-70 GPa, significantly lower than the dynamic value of E inferred from seismic studies.

A third type of deformation signal related to ice mass changes appears to be seasonal variation in continuous GPS time series. A strong correlation is found between them and the annual snow load at ice caps. A similar Green's function approach as for the glacial surges, and a simple sinusoidal load history on Iceland's four largest ice caps constrains the effective E to be in the range 30-60 GPa. Predicted annual peak-to-peak land oscillations amount to 37 mm, with largest observed signal outside the ice cap about 16 mm per year. East and north of Vatnajökull, maximum annual horizontal displacement is about 6 mm due to this process, resulting in apparent modulation of the plate spreading rate in this area.

Meltwater dynamics beneath Skeiðarárjökull from continuous GPS measurements

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Glacier and ice-sheet motion is influenced strongly by the amount of meltwater within subglacial drainage. Velocity estimates from remotely-sensed data illustrate the variability of glacier flow in response to factors ranging from intense rainfall to glacial surges. Such time-dependent data illuminate the subglacial extent of pressurised water, but the exact timing, duration, and strength of the forcing is often unknown. Here we present results from ongoing measurements of surface movement in the lower ablation zone of Skeiðarárjökull (1,380 km^2): the largest piedmont glacier of the Vatnajökull ice-cap, Iceland. In April 2006, motivated by frequent floods and regional-scale seismicity from the glacier, we deployed three continuous, high-precision global positioning system (GPS) receivers on Skeiðarárjökull. The array had an initial station-to-station distance of 3 km, with the uppermost GPS station located 8 km from the glacier terminus - in a region where ice thickness exceeds 400 m and icequakes are common. Data, sampled at 15-s intervals, were processed alongside permanent stations in Iceland's national GPS network. To enable long-term observations, we devised a broad, low antenna platform, which comprised four aluminium supports designed to be embedded partly into the glacier surface. Each GPS receiver was powered by a 12 V battery connected to a 50 W solar panel. Within the study period, horizontal velocities varied from 0.3 to 1 m d^{-1}, with periods of temporary ice-surface uplift and glacier seismicity accompanying the highest displacement rates. In addition, a GPS record of ice-surface velocities exists for a glacial flood that took place in August 2006. In combination with meteorological data from nearby sites, our observations show that Skeiðarárjökull is remarkably sensitive to variations in meltwater input to the glacier bed. Seemingly, transient changes in sliding rate – forced by hydraulic jacking of the glacier base – can take place over large areas of the glacier bed during intense rainfall and glacial flooding.

Landmælingar á jarðhitasvæðum - Dæmi af Reykjanesi

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Greint er frá landmælingum, sem Íslenskar orkurannsóknir (áður Orkustofnun) gera á jarðhitasvæðum. Tilgangur mælinganna er að fylgjast með landbreytingum, hvort sem þær stafa af náttúrulegum ástæðum eða vegna virkjunar jarðhitans. Helstu aðferðir, sem beitt er, eru: Fallmælingar, GPS-mælingar, þyngdarmælingar og lengdarmælingar yfir sprungur. Lauslega er rakin saga landmælinga á utanverðum Reykjanesskaga og niðurstöður þeirra tengdar við vinnslu jarðhitans í Svartsengi.