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Journal Item

New mass increase beneath Askja volcano, Iceland – a precursor to renewed activity?

Hazel Rymer[a], Corinne Locke[b], Benedikt G. Ófeigsson[c], Páll Einarsson[c] and Erik Sturkell[c,d]

a. Dept Earth & Environmental Sciences, The Open University, Walton Hall, Milton Keyes, MK7 6AA, UK
b. Geology and Environmental Science, The University of Auckland, Auckland, New Zealand
c. Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland
d. Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden

Abstract

Askja is an active central volcano located on the NS trending en echelon rift zone marking the mid-Atlantic plate boundary in North Iceland. Between 2007 and 2009, we observed a gravity increase at the centre of the caldera. This contrasts with net gravity decreases recorded between 1988 and 2007 interpreted previously in terms of magma drainage. The recent gravity increase is rapid but similar in terms of lateral extent to the preceding decrease. This gravity increase corresponds to a sub-surface mass increase of 0.68 x 10^{11} kg at about 3 km depth. It is possible that the new gravity increases observed at Askja reflect accumulation of magma beneath the caldera and thus may herald a new phase in the activity at this volcano which last erupted in 1961.

Introduction

Askja caldera in the rift zone of North Iceland (Figure 1) has been in a state of unrest for decades. The latest major rifting episode in the Askja volcanic system occurred from 1874 to 1876 and included a series of dyke injections, basaltic fissure eruptions and an explosive rhyolite eruption associated with formation of the youngest nested caldera, Öskjuvatn. The largest fissure eruptions of the episode occurred in the Sveinagja fissure swarm, 40-70 km north of Askja caldera, and it has been suggested (Sigurdsson and Sparks, 1978) that lateral magma drainage from a reservoir beneath Askja caldera induced the caldera collapse. The next eruptive period took place from 1921 to 1929, and ended with a small eruption in the early 1930s. During this episode, a fissure opened to the south of the caldera and several minor effusive eruptions occurred around the 1875 caldera margin. The most recent eruption began in October 1961 and continued into early December of the same year. An E-W trending fissure opened close to the northern rim of the main caldera and lava flowed inside and outside the main caldera (Thórarinsson and Sigvaldason, 1962).

Askja has displayed a significant rate of ground deformation during the past decades (Sturkell et al., 2006a). The deformation has been recorded by various methods for the 40 years since the last eruption. Early work used precise levelling and later EDM measurements (Tryggvason 1989); more recently deformation has been monitored by GPS and InSAR (Sturkell et al., 2006b). Although there are differences in the models used to interpret the measurements, they do show a consistent general picture of the nature of the deformation. The movements are significantly greater than the error resulting from combining results from the four types of survey (<2cm vertical over whole period). The deformation field in the first decade following the 1961 eruption was characterized by rapid inflation (Tryggvason 1989). This inflation changed to slower deflation, apparently beginning around 1973. Deflation throughout the last 35 years has been at an average rate of 3-5 cm/yr at the centre of the caldera, decreasing towards the margins (Sturkell and Sigmundsson, 2000, Sturkell et al., 2006a). Our most recent data indicate that while the greatest deflation continues to be at the centre of the caldera, the average rate of deflation at the centre has decreased to approximately 2.5 ± 0.7 cm yr^{-1} relative to a point outside the caldera (Figure 2). About 80% of the observed deformation has been consistent with a pressure decrease at two sources, one located at 1.5-3 km depth and a second source approximately 16 km deep (Rymer and Tryggvason, 1993, Sturkell et al. 2006a, 2006b, Pagli et al. 2007). Whilst the validity of using the Mogi model to interpret volcano deformation is questioned by Masterlark (2007), it can precisely describe a data population, as shown by Sturkell et al. (2006a)

At Askja, a gravity network covering the caldera itself and the 1961 lava flow outside the caldera has been reoccupied in the summer months for most of the period 1985 to the present. After correction for any height changes across the network, net gravity changes reflect sub-surface mass changes.

Net gravity decreases measured at Askja between 1988 and 2003 have been attributed previously to a combination of factors. These factors are i) cooling/contraction of magma in a shallow (~3 km) magma chamber (Rymer and Tryggvason, 1993; Sturkell and Sigmundsson, 2000); ii) void compaction of the underlying material (Rymer and Tryggvasson 1993) and iii) magma drainage from a shallow magma chamber (de Zeeuw-van Dalfsen et al., 2005). Here we present new data that suggest this trend of gravity decreases has now reversed.

Over the period that Askja has been sinking, two other regions, one to the north and the other to the south of Askja have been rising. Grímsvötn to the south of Askja erupted beneath Vatnajökull icecap in 1998 and 2004, and Krafla to the north, erupted between 1975 and 1984 (e.g. Buck et al., 2006). These large central volcanoes in Iceland are linked by a continuous plate boundary and all have broadly NS trending fissure swarms associated with them and it is possible that magma migrates underground along these fissures (Saemundsson 1978, Einarsson 2008). It has been suggested that pressure change at one of the volcanoes may influence the others, although from geochemical evidence their magma systems are not materially connected (Tryggvason 1989, Einarsson 1991, Sturkell and Sigmundsson 2000). Mechanical interactions between the eight central volcanoes immediately south of Askja have been proposed (Gudmundsson and Andrew, 2007, Andrew and Gudmundsson, 2008).

Persistent microearthquake activity has been detected in the Askja area for more than three decades (Einarsson 1991, Jakobsdóttir 2008). Seismicity in the eastern part of the Askja caldera relates to hydrothermal activity (Einarsson and Sæmundsson, 1987; Einarsson, 1991) while the source of long term seismicity to the immediate NE of Askja through Herdubreid reflects plate boundary deformation and slip along regional faults (Sturkell and Sigmundsson, 2000; Þorbjarnardóttir et al., 2007; Sousalu et al., 2009). Recent work reveals deep (10-34 km) earthquakes (Soosalu et al, 2009, Knox, 2007; Jakobsdóttir et al., 2008) in a region just immediately north of Askja, in a zone through which magma would need to travel if it were to migrate through the Askja fissure swarm.

New gravity changes at Askja

The microgravity network at Askja comprises stations which are grouped according to location: caldera centre, northern and southeastern (Figure 1c). The data are expressed with respect to a reference point just outside the caldera (near Öskjuop in Figure 1c) and the gravity changes through time are expressed relative to an arbitrary datum (the values measured in 1988). Long term stability of the reference point was monitored through links with a regional network. The caldera centre stations are located in the region of maximum deformation whereas the northern and southeastern stations are more peripheral to the deformation.

Building on the uniquely long microgravity time series for Askja volcano (Rymer and Tryggvason, 1993, de Zeeuw-van Dalfsen et al., 2005), new data presented here reveal a reversal in trend after 19 years. The microgravity time series for the 3 locations is shown in Figure 3. The raw gravity changes after correction for Earth Tides and instrumental effects (Rymer, 1989) are shown by symbols joined by solid lines. The uncertainty on these data is estimated to be ±15 μGal (Rymer and Tryggvason, 1993) where 1 μGal = 10^{-8} ms^{-2}. At the caldera centre location, the raw measurements show a modest overall increase of about 40 μGal between 1988 and 2003 (Figure 3). This increase continued through to 2007 at about the same rate. Between 2007 and 2009, raw gravity increased by about 60 μGal at a substantially greater rate than observed for the previous 19 years. Thus raw gravity has increased in the period 2007-9 by almost as much as it has throughout the previous 19 years. Over the same time period, deflation has persisted.

In order to interpret gravity data in terms of sub-surface mass changes, the effects of deformation on the gravity must first be corrected for. Corrections are usually made using the theoretical free air gradient (FAG =-308.6 μGal m^{-1}); measured FAG values at Askja are -360, -310 and -240 μGal m^{-1} in the centre, northern and southeastern locations respectively (Rymer and Trggvasson 1993). As the average of these is very close to the theoretical gradient and given the uncertainty in these measurements (LaFehr, 1991), the theorectical value was used here. Net gravity changes were calculated using the theoretical FAG and the observed deflation for 1993-2008 in the caldera centre (Sturkell et al., 2006a and Figure 2). Prior to 1992 an average deflation value of -0.04 m yr^{-1} was used, based on the Mogi model interpolation of de Zeeuw-van Dalfsen et al., (2005). Notwithstanding the limitations of the Mogi model in terms of crustal layering and heterogeneities, where there are observations, the Mogi model fits the data to within 8 mm (Sturkell et al. 2006a).

Deflation in the northern and southeastern areas is approximately equal and considerably less than at the centre (fitting the Mogi model closely; de Zeeuw-van Dalfsen et al., 2005). The values observed by Sturkell et al., (2006a) have been used for both of these locations.

After correction for elevation changes, net gravity for the caldera centre location decreases between 1988 and 1995 by 110±20 μGal (Figure 3). Between 1995 and 2007, the rate of net gravity decrease flattens off. For the period 2007-8 however, the net gravity decrease reverses and becomes an increase of about 50±20 μGal. No elevation data for 2009 are yet available; however the raw gravity data for 2009 confirms the marked increase since 2007.

For the southeastern caldera group, raw gravity data remain fairly stable between 1988 and 1997 and then increase by about 60±20 μGal until 2003 and subsequently decrease slightly. After correction for the observed deformation, this group oscillate about zero net gravity change. For the northern caldera group, raw gravity data reveal only minor variations of less than 40±20 μGal throughout the entire period of study. After correcting for deformation, the net gravity changes are even smaller and for this group, mainly within the ±20 μGal error.

Thus after correcting for the known sources of gravity change, there are significant net gravity changes at the caldera centre station group, but net changes at the other stations are barely significant. The long time series provides a means to identify the sub-surface processes responsible for these gravity changes and the rate of these processes. However with measurements made once a year, only integrated annual effects are resolved; no information on shorter term variations is provided.

Mass movement at Askja volcano

Given that the gravity changes are focussed at the caldera centre, a simple point source model is used to estimate the change in sub-surface mass. Assuming this mass change occurs at a similar depth to the 3km deep source located below the NW shore of Öskjuvatn lake modelled from the elevation data (Sturkell et al., 2006a), for the period 1988 to 1995, the mass change is approximately 1.6±0.3 x 10^{11} kg which gives a mass loss rate of about 0.23 x 10^{11} kg yr^{-1}. Between 1995 and 2007, the mass loss is 0.50±0.3 x 10^{11} kg which over 12 years gives a rate of 0.04 x10^{11} kg yr^{-1}, i.e. just one sixth of the earlier rate. Between 2007 and 2008, there was a mass increase of 0.68±0.3 x 10^{11} kg and so in that one year, about 30% of the mass lost since 1988 was restored.

This reversal in trend from mass loss to mass gain in the region beneath the caldera centre at Askja may be particularly significant when considered alongside recent seismicity detected just outside the Askja caldera (Jakobsdottir et al., 2008; Soosalu et al., 2009), together with new deformation detected some 20-25 km NE of Askja in the Upptyppingar region which is volcanically inactive historically (Jakobsdottir et al., 2008). There may have been sub-surface mass changes associated with the seismicity and ground deformation detected in the Upptyppingar region, but no micro-gravity network was established at the time. A micro-gravity network was installed in 2008 and so repeat measurements will be available in future. Nevertheless, it is clear that there are mass increases beneath the Askja caldera centre and the seismic activity and deformation around Upptyppingar suggest that there may have been mass changes beneath this region too.

Intriguingly, the long term deflation at Askja coincides with inflation at Krafla volcano in the period (1978-1984) leading to some suggestions that there may be a link between these systems (e.g. Rymer and Tryggvason, 1993; Rymer et al., 1998; Sturkell et al., 2008). Following prolonged eruptive activity during 1975-1984, Krafla has been deflating since 1989 with an exponential decrease in the rate of deflation (from 7 cm yr^{-1} to 1 cm yr^{-1} in 10 years; de Zeeuw-van Dalfsen et al., 2006). Microgravity data have also been collected at Krafla between 1990 and 2003 (Rymer et al., 1998; de Zeeuw-van Dalfsen et al., 2006) and we have made repeat measurements in 2008 and 2009. Regardless of station location, whether within the caldera or 20km along the Krafla rift, these data show there has been no significant net gravity change (within the error of ±10 µGal) and therefore no sub-surface changes in mass in the period 1997-2009.

Conclusions and implications

A 20-year gravity time series at Askja caldera shows a sharp contrast in behaviour at the caldera centre compared with the margins. After correction for the deformation at Askja, which itself varies across the caldera and with time, there have been significant net gravity changes at the caldera centre but not in the north or southeastern parts of the caldera. The rate of net mass decrease between 1988 and 1995 was about 6 times greater than the rate observed between 1995 and 2007. The subsequent net gravity increase in 2008 equates to a mass increase, about 30% of the total mass loss since 1988.

Magma-host rock interactions at calderas in a state of unrest have been modelled from gravity-height change data (Berrino et al., 1984; Berrino et al., 1992; Battaglia and Segall, 2004; Bonafede and Ferrari, 2009). The gravity-height change gradient (defined by Rymer and Williams-Jones, 2000) has varied substantially throughout the period of study and certainly more than has been observed elsewhere. This is in part because this is the longest data set of its kind and we suggest also because we have captured a change in sub-surface processes since 2007. The gravity-height change gradient for the caldera centre at Askja has had 3 distinct values over time; + 53 μGal m^{-1} for the period 1988-1995, -228 μGal m^{-1} for the period 1995-2007 and -1360 μGal m^{-1} for^{-} the period 2007-2008. For material moving beneath the Askja caldera, the densitities of 2.0-3.0 Mg m^{-3} would be expected to produce a gravity-height gradient of -252 to -224 μGal m^{-1} (Gottsmann and Rymer, 2002). For the period 1995-2007, the observed gravity-height change gradient falls within this range. Possible interpretations range from magma drainage, creation of voids or magma vesiculation. Magma drainage and void creation are effectively the same process and magma vesiculation is unlikely to be relevant during a period of prolonged and substantial ground deflation without any surface manifestation of increased activity. For the earlier period of 1988-1995, the gradient is flatter which implies a sub-surface mass and density decrease perhaps leaving a sub-surface plexus of void space.

The most recent period in constrast however, has a steeper gradient implying sub-surface mass and density increase.

Magma intrusion is our favoured interpretation of the 2007-8 data because it is consistent with the small magnitude earthquakes in the middle crust to the north of Askja in July-August 2006. The seismicity continued through 2007 and 2008. Magma devesiculation seems unlikely as a process that would suddenly begin after at least 20 years of drainage. We can exclude water table rise as the process causing the observed mass increase because the effect is observed at the caldera centre only and any changes in water table would be expected to manifest across the caldera and to affect the northern and south-eastern locations also.

Magma pathways between central volcanoes in Iceland have been proposed previously (Rymer and Tryggvason, 1993; Rymer et al., 1998; Sturkell et al., 2006b, Gudmundsson and Andrew, 2007, Andrew and Gudmundsson, 2008). Recent seismic activity and deformation to the NE of Askja caldera at Upptyppingar may result from magma movement (Jakobsdottir et al., 2008; Soosalu et al., 2009) and the coincidence of this activity with mass increases at Askja raises the possibility that magma maybe migrating southwest towards the centre of the caldera from this area. The stability of gravity at Krafla volcano, however, shows that the 2007-2008 magma movements at Askja were independent of the Krafla volcanic system.

Whilst there is evidence that magma is accumulating beneath the caldera centre at Askja, long term deflation has persisted in the caldera. This suggests that after an extended period of magma drainage, new magma may be able to be accommodated in the crust without surface deformation by filling pre-existing voids. However, if magma accumulation continues it could be expected that the deflation rate would decrease and eventually it would be expected that inflation be observed. The reversal from long term magma drainage to magma accumulation below the caldera centre identified by these new gravity data may be the first sign heralding the next phase of activity at Askja.

Figures:

1. Location maps showing (a) the active rift systems in Iceland (dark grey) together with permanent icecaps (light grey). Arrows show direction of extension. From Einarsson and Saemundsson (1987).; b) location of Askja and Krafla volcanoes on the rift systems. Dashed outline shows location of part c) of figure 1; c) location map of Askja caldera showing centre, northern and southeastern gravity locations (gravity stations shown as dots).

2. GPS ground deformation data for the period 2003-2008 at a station located in the centre of the Askja caldera relative to a station outside the caldera.

3. Raw and height corrected gravity data for Askja for the period 1998-2008. The raw gravity data are shown by solid lines (red: caldera centre, green: southeast and blue: north). The net gravity changes, calculated using the theoretical FAG value for each location are shown as broken lines.

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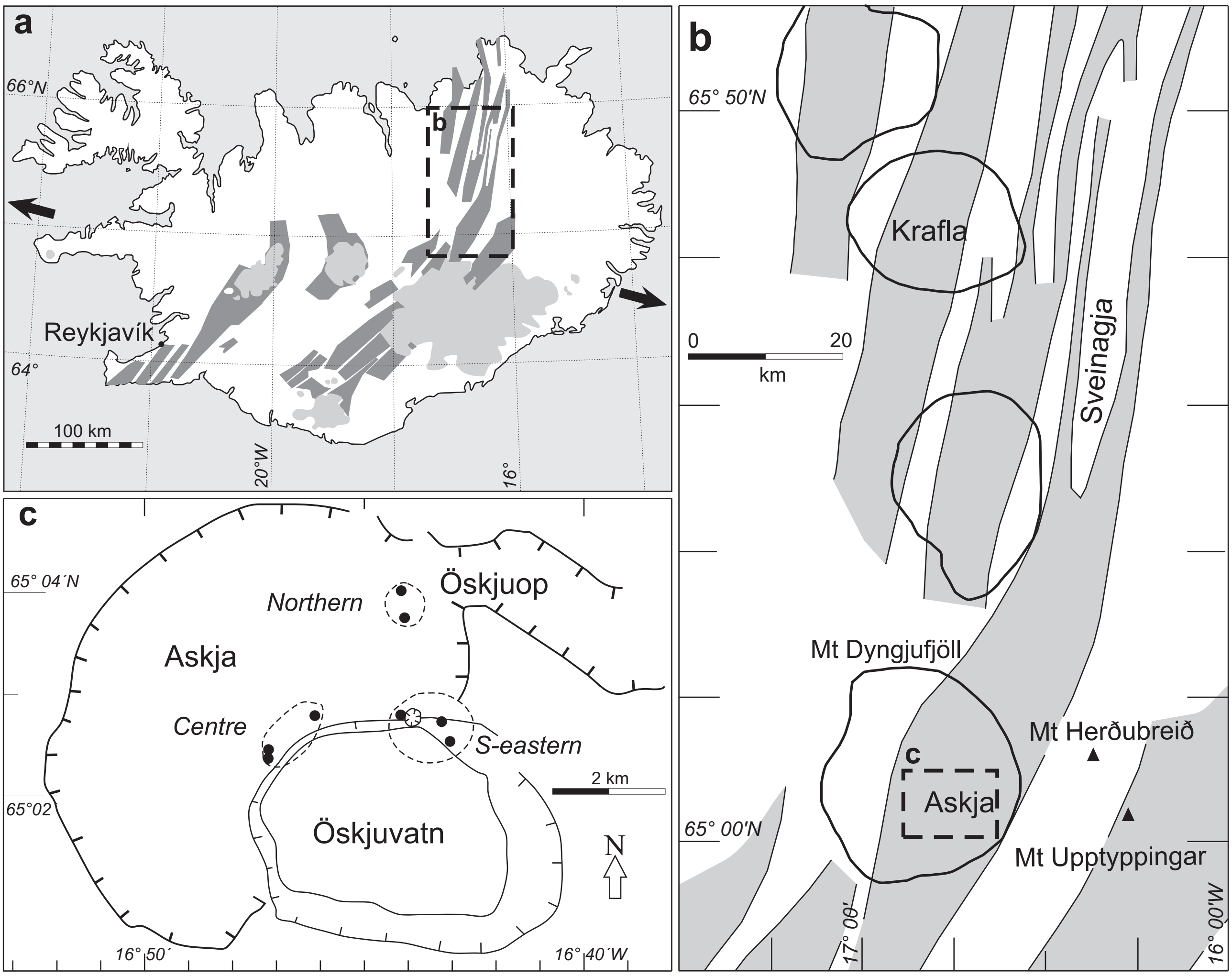
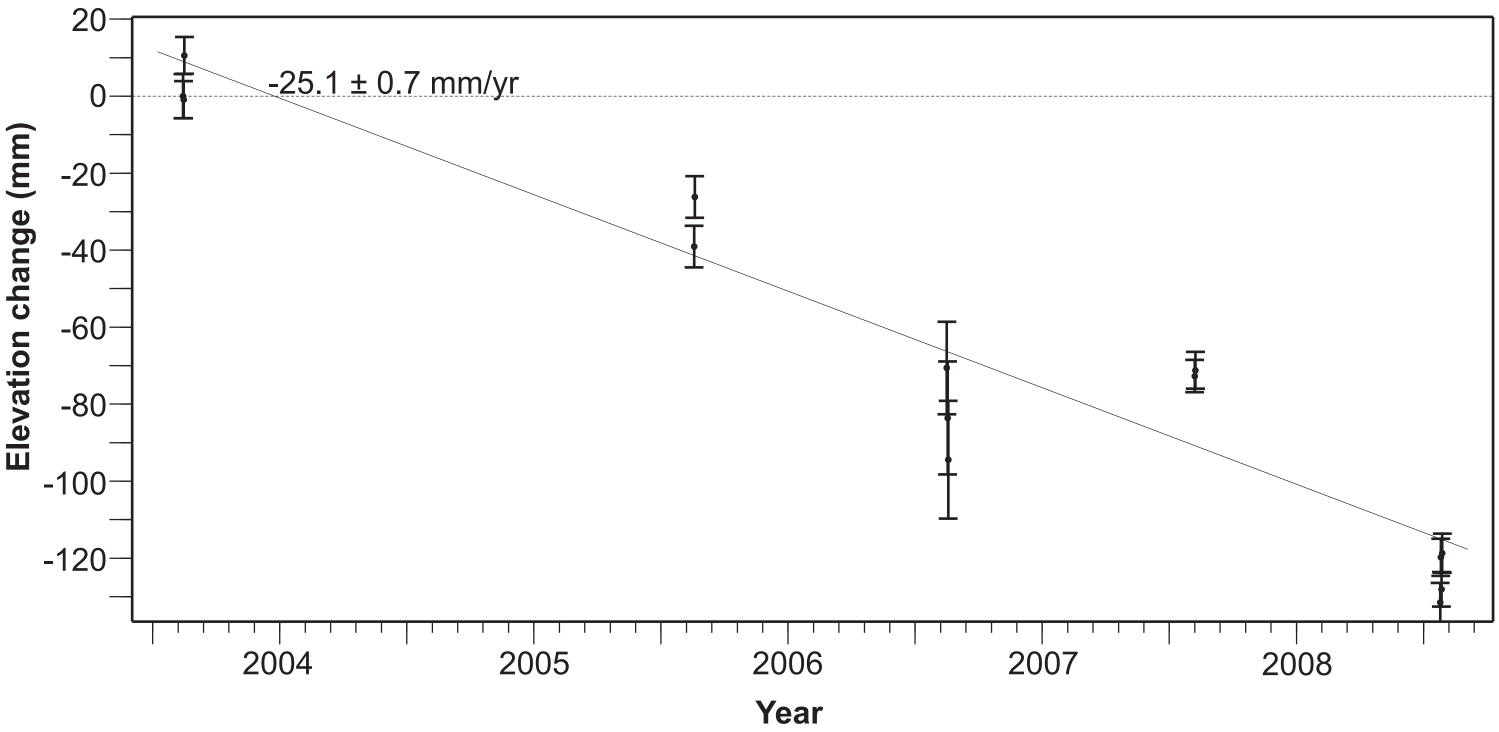
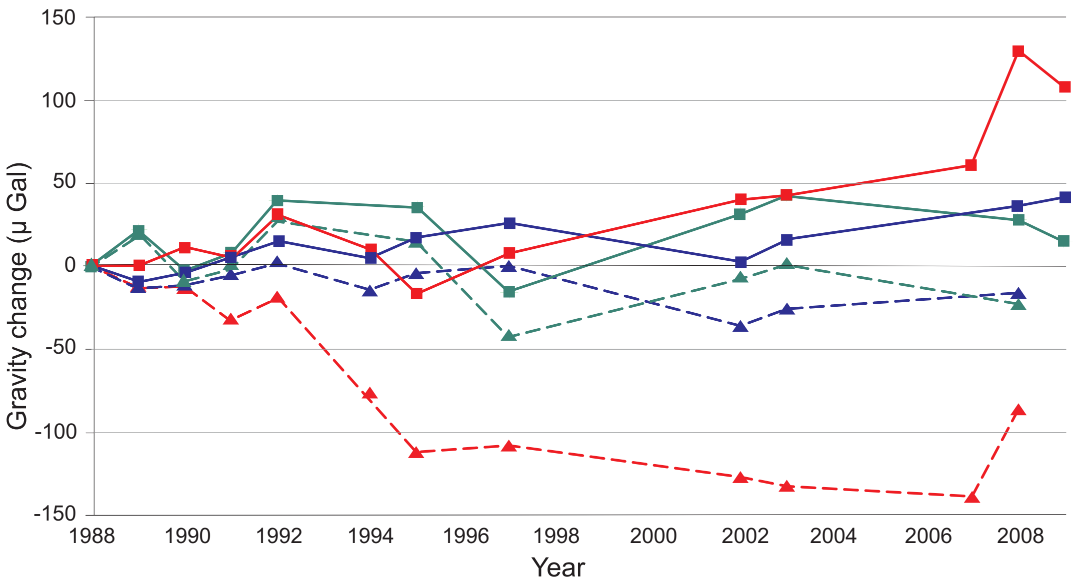
	Centre N65°02'32.6'' W16°46'58.1'' N65°02'30.3'' W16°46'58.0''		**Northern** N65°03'48.6'' W16°44'06.1'' N65°03'35.6'' W16°43'55.8''		**South Eastern** N65°02'49.4'' W16°43'10.9'' N65°02'36.9'' W16°43'08.8''	
Year	**Δg (μGal)**	**Δh (m)**	**Δg (μGal)**	**Δh (m)**	**Δg (μGal)**	**Δh (m)**
1988	0	0	0	0	0	0
1989	0	-0.04	-10	-0.009	21.5	-0.009
1990	11	-0.08	-5	-0.02	-3	-0.02
1991	5	-0.12	4	-0.0285	8	-0.0285
1992	30.5	-0.16	14.5	-0.038	39.5	-0.038
1994	10	-0.28	4.5	-0.062		-0.062
1995	-16.5	-0.31	17	-0.069	35.5	-0.069
1997	7.5	-0.37	26	-0.084	-16	-0.084
2002	39.5	-0.52	2.5	-0.124	31.5	-0.124
2003	42	-0.545	15	-0.1315	42	-0.1315
2007	60	-0.625				
2008	128	-0.675	35.5	-0.1665	28	-0.1665
2009	107.5		40.5		14.5	

Table 1 Cumulative gravity and height change data for the Central, Northern and South-eastern groups of stations. Height changes are from Sturkell et al., 2006a and Figure 2, prior to 1992, height changes for the Centre group are based on the Mogi model interpolation of de Zeeuw-van Dalfsen et al. (2005).


a
66°N
b
Reykjavík
64°
100 km
20°W
16°
b
65° 50'N
Krafla
0
20
km
Sveinagja
Mt Dyngjufjöll
c
Askja
Mt Herðubreið
65° 00'N
Mt Upptyppingar
17° 00'
16° 00'W
c
65° 04´N
Northern
Öskjuop
Askja
Centre
S-eastern
2 km
65°02
Öskjuvatn
N
16° 50´
16° 40´W



-25.1 ± 0.7 mm/yr
Elevation change (mm)
20
0
-20
-40
-60
-80
-100
-120
2004
2005
2006
2007
2008
Year


Gravity change (μ Gal)
150
100
50
0
-50
-100
-150
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year