Geodetic data shed light on ongoing caldera subsidence at Askja, Iceland

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Geodetic data shed light on ongoing caldera subsidence at Askja, Iceland

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Abstract

Subsidence within the main caldera of Askja volcano in the North of Iceland has been in progress since 1983. Here, we present new ground and satellite based deformation data, which we interpret together with new and existing micro-gravity data, to help understand which processes may be responsible for the unrest. From 2003-2007 we observe a net micro-gravity decrease combined with subsidence and from 2007-2009 we observe a net micro-gravity increase while the subsidence continues. We infer subsidence is caused by a combination of a cooling and contracting magma chamber at a divergent plate boundary. Mass movements at active volcanoes can be caused by several processes, including water table/lake level movements, hydrothermal activity and magma movements. We suggest that here, magma movement and/or a steam cap in the geothermal system of Askja at depth, are responsible for the observed micro-gravity variations. In this respect, we rule
out the possibility of a shallow intrusion as an explanation for the observed micro-gravity increase
but suggest magma may have flowed into the residing shallow magma chamber at Askja despite
continued subsidence. In particular variable compressibility of magma residing in the magma
chamber, but also compressibility of the surrounding rock may be the reason why this additional
magma did not create any detectable surface deformation.

Keywords
volcano deformation, caldera unrest, micro-gravity, InSAR, precise levelling, Iceland

Introduction
Long term monitoring of caldera deformation is essential for hazard evaluation and
mitigation (Gottsmann et al. 2003). Deformation measurements are most often used to quantify the
caldera unrest. However, those measurements alone can not differentiate between the different
processes which may be responsible for the unrest, such as magma movements, hydrothermal
activity, cooling and contraction of a shallow source or lake level variations. It is only by the
combination of deformation and micro-gravity monitoring that insights into which process may be
responsible for the caldera unrest, as mass movements within the system, can be quantified.

The integration of micro-gravity and deformation data has been successfully applied at
several calderas worldwide. At Campi Flegrei in Italy, Battaglia et al. (Battaglia et al. 2006), found
the migration of fluids into and out of the hydrothermal system within the caldera to be responsible
for the caldera unrest between 1980 and 1995. During a period of unrest (1982-1999) at Long
Valley caldera, similar measurements have been interpreted in terms of an intrusion of silicic
magma with a significant amount of volatiles beneath the caldera's resurgent dome (Battaglia & Hill
2009). Here, we present new deformation and micro-gravity data collected between 2007 and 2010
at Askja, Iceland and we provide insights into the processes responsible for long term caldera unrest
The Askja volcanic system in northern Iceland (Fig. 1a & b) consists of a central volcano and at least 3 calderas. The oldest caldera is difficult to observe as it is almost completely filled by lavas. The main (early Holocene) Askja caldera itself has a diameter of ~10 km and is 200-300 m deep. The youngest caldera which is 4.5 km across was formed in association with a Plinian eruption in 1875 (Sturkell et al. 2006 and references therein) and continued to form afterwards for decades (Hartley & Thordarson 2011). It is now filled by lake Öskjuvatn, one of the deepest lakes in Iceland (Rist 1975). The last eruptive activity in the area occurred in 1961 when lava erupted from a fissure at the northern boundary of the Askja caldera. Most of the lava flowed towards the east out of the caldera onto the planes beyond (Sturkell & Sigmundsson 2000).

**Previous work**

The first deformation measurements at Askja took place in 1966 when a precise levelling line, with 12 benchmarks (extended to 30 in 1968), was installed in the northern part of the caldera (see Fig. 1c) (Tryggvason 1989a). Measurements show (Fig. 2) that the caldera subsided towards the centre, compared with points outside the caldera, from 1968-1970. This trend reversed to an observed inflation from 1970-1972 showing the largest deformation rate measured so far. From 1973-1983 no measurements were conducted but after 1983 the measurements show a steady subsidence of the caldera centre relative to the surroundings and the rate of subsidence is declining with time. In 1993 the first Global Positioning System (GPS) measurements were conducted at 24 benchmarks in and around the Askja caldera. The network was completely re-measured in 1998 after which selected benchmarks (see Fig. 1c) have been measured on an annual basis (Sturkell et al. 2006) during measurement campaigns lasting up to 24 hours. The GPS data confirm the ongoing subsidence. Interferometric Synthetic Aperture Radar (InSAR) images formed using ESR-1 (Pagli et al. 2006) and RADARSAT-2 (de Zeeuw-van Dalfsen et al. 2012) show the ongoing subsidence.
within the caldera very clearly. Apart from the subsidence within the caldera, InSAR also shows broader scale subsidence 20-25 km wide, along ~50 km of the rift (Pagli et al. 2006; Pedersen et al. 2009).

Micro-gravity data have been collected regularly since 1988 at Askja (Rymer & Tryggvason 1993; de Zeeuw-van Dalksen et al. 2005). The raw data for each location are corrected for instrumental drift, tares, earth tides and station height changes (e.g. Rymer 1989) to calculate the net micro-gravity change with respect to the base station and referred to values observed in 1988. De Zeeuw-van Dalksen et al. (2005), used a point source, to model a net micro-gravity decrease of 115 μGal (1 μGal=10⁻⁸ m/s²) between 1988 and 2003 in the centre of the caldera, in terms of a subsurface mass decrease of 1.6x10¹¹ kg. Rymer et al. (2010), observed from 1988-2007 a net micro-gravity decrease of 140 μGal in the caldera centre of Askja. They also reported a dramatic reversal in the net micro-gravity change in 2007-2008 to an increase of ~60 μGal (Rymer et al. 2010).

To be able to integrate deformation and micro-gravity data sets, two factors are very important: i) the times of data acquisition should be as close as possible (since gravity and elevation changes are clearly on-going) and ii) the reference point used for comparison. At Askja, data are most often collected from late June to early September, which is the only time the caldera is not covered in snow. The first condition is, therefore, normally met without problem. However, with respect to the base station, the analysis becomes more complicated. For the precise levelling data the cumulative height change between two chosen levelling benchmarks (406 and 429) is reported with 1968 as the start year (Sturkell et al. 2006). GPS data are referred to base station DYNG located outside the caldera and referred to 1993. Micro-gravity data are usually reported with respect to a station on the 1961 lava flow close to the caldera rim (83001, at the same location as the new GPS station VIKR, see Fig. 1c) (de Zeeuw-van Dalksen et al. 2005). To overcome these differences, the micro-gravity benchmark at the caldera rim (83001) was measured as part of the
'extended' levelling line in 2003, 2007, 2008 and 2009 and GPS has been measured yearly at VIKR since 2009.

Previous modeling and interpretation

All previous inverse modelling of geodetic data at Askja assumes one or more contracting point sources embedded in a homogeneous elastic half space, thereby implying that the entire vertical deformation signal should be attributed to processes within the magmatic plumbing system. Outcomes of such modelling of geodetic data at Askja suggests a shallow magma chamber directly below the centre of the caldera (65.05ºN 16.78ºW) at 3-3.5 km depth (Pagli et al. 2006; Rymer & Tryggvason 1993; Sturkell & Sigmundsson 2000). RADARSAT-2 InSAR analyses suggest that the concentric fringes centred in the Askja caldera can be modelled by a point source at a depth of 3.2-3.8 km with a volume decrease of 0.0012-0.0017 km³/yr from 2000-2009. The horizontal contraction detected by the GPS data 10-15 km outside the caldera was interpreted in terms of a second, deep source at ~16 km, depth (Sturkell et al. 2006).

De Zeeuw-van Dalfsen et al. (2012) show that a homogeneous elastic half-space may not be the best assumption for modelling the deformation at Askja caldera. Their two-dimensional Finite Element Models (FEM) include structural complexities in the crustal layers, such as a visco-elastic 'ridge' at the location of the Askja fissure system and a mechanically weak caldera filling. The ridge represents an area of visco-elastic material reaching to shallow (1-2.5 km) depth (immediately beneath the plate boundary) with the same visco-elastic properties as the layer representing the lower crust. This configuration is supported by the results from the deformation based study of the structure of the plate spreading segment (Pedersen et al. 2009). The weak layer is envisioned as the result of a combination of geothermal alteration and the presence of explosive eruption products. The results indicate that the tectonic setting of Askja plays a major role in the continuous, long-term high subsidence rates observed.
Models using three-dimensional FEM have been developed (Dickinson 2010) that combine magma extraction from a shallow, fluid-filled cavity with a plate spreading model that depicts rheologic partitioning to simulate a rift segment. They predict both the radially symmetric pattern of subsidence observed within the Askja caldera and the elongated pattern of subsidence tracking the rift segment, rather well, suggesting the contraction of a deeper source (~16 km) is not needed to explain the InSAR data.

The net micro-gravity decrease from 1988 to 2003, was explained by de Zeeuw-van Dalfsen et al. (2005) as a combination of cooling and contraction of magma in a shallow chamber (30%) and magma drainage from this shallow reservoir (70%). Rymer et al. (2010) suggested that the net micro-gravity increase in 2008-2009 might be caused by accumulation of magma beneath the caldera.

**New deformation data**

We present precise levelling data up to 2011, adding 7 more years to the previously published data. The yearly difference (Fig. 2a), between levelling benchmarks 404 and 429, shows only slight variations through time. The 2009 measurement is slightly anomalous and it is unclear if its deviation is significant, but the overall cumulative vertical displacement (Fig. 2b) reflects a smooth subsidence trend since 1983. New GPS data (Fig. 1c and Fig. 3) covering the 2003-2010 period, for stations 404 and BATS, and covering the 2003-2009 period, for stations OLAF and MASK, confirm this trend. The GPS data were processed with the Bernese software, version 5.0, using double-difference based analysis with quasi-ionosphere-free (QIF) resolution strategy (Dach et al. 2007). The final network solution is a minimum constraint solution, realised by three no-net-translation conditions imposed on a set of reference coordinates of GPS stations derived by the International GNSS Service (IGS). The set of IGS stations used includes stations in North America, Iceland and Europe. The reference coordinates that are used are termed IGS05 and are a realization...
of the ITRF2005 reference frame (Altamimi et al. 2007). The scatter in the data, as for example for the vertical movement of station BATS, is due to atmospheric disturbances.

We created Interferometric images using StaMPS (Hooper 2008) following the method as described by de Zeeuw van Dalfsen et al. (2012). Three RADARSAT satellite images of three different frames were obtained during the summer of 2010. Combined with the previously acquired images (de Zeeuw-van Dalfsen et al. 2012), we formed twelve new interferograms with good coherence, all covering the Askja caldera. Here we present the descending F5 frame as this is the most complete time-series (Fig. 4). The 2000-2010 unwrapped interferogram shows ~22.3 cm line-of-sight (LOS) deformation or about ~2.2 cm LOS deformation per year. There are two specific signatures visible in the unwrapped interferograms: i) a concentric feature depicting subsidence in the main Askja caldera, ii) an oval feature elongated along the rift indicating subsidence. Profiles tracing the green EW-line in the unwrapped interferograms (Fig. 4) show the decreasing LOS subsidence with time (Fig. 5). Up to 2008 this decrease seems to be similar to the decrease suggested from precise levelling data. The 2009 and 2010 InSAR data show less LOS subsidence than observed with ground based methods. This deviation is comparable to that observed in the 2009 measurement of the precise levelling data.

New micro-gravity data

The micro-gravity benchmarks at Askja are grouped by location in the 'Centre', 'South-eastern' and 'Northern' regions of the caldera. Each group consists of two or more benchmarks which are then measured repeatedly during each survey season. During the summer of 2007, a micro-gravity survey was carried out, but due to the poor weather conditions and problems with the instrumentation, the data for the Northern and South-eastern stations are not reliable.

To evaluate the micro-gravity data in terms of mass changes we correct the data for height changes (Fig. 6). Due to the lack of real-time geodetic measurements, we are forced to use a model
(Sturkell et al. 2006) to calculate the height change at each station relative to base station 83001. It is evident that the micro-gravity data are influenced by noise. To test for the statistical significance of the net micro-gravity variations we apply a student's t-test using 95% confidence levels (Table 1) following the suggestions of Saibi et al. (Saibi et al. 2010) at Unzen volcano. The error on net micro-gravity data for location groups is less than +/- 20 μGal (Rymer et al. 2010). In Fig. 6 we show the best-fit location of the 2007 'Centre' point, which fits the trend between 1988 and 2005, but has a larger error bar than the data points of other years. The average net micro-gravity is displayed for each station group, but only when the data are significant.

The net micro-gravity variations at the 'Northern' and 'South-eastern' stations lie within the uncertainty for the data of ± 20 μGal, and thus do not show any significant change over the 1988-2010 period. The net micro-gravity at the 'Centre' was measured at 3 different benchmarks (OLAF, D-19, MASK), all located close (856 m, 926 m and 742 m) to the centre of deformation. The 'Centre' stations show the biggest net micro-gravity variations: from 1988 to 2007, a decrease of ~140 μGal, followed by an increase of ~40 μGal between 2007 and 2008. No changes occurred from 2008-2009, and finally a decrease of ~50 μGal occurred from 2009 to 2010. Overall, from 1988-2007 the net micro-gravity change at Askja shows a decrease, which reversed to an increase from 2007-2009. Our recent measurements indicate the reversal was temporary and the net micro-gravity changes since then (2009-2010) follow the previously reported decreasing trend.

In all these analyses it should be noted that there is the potential for data aliasing. Data are obtained during the summer months for logistical reasons and so variations occurring during the winter months are masked.

**Interpretation**

Focusing on the 2003-2010 period, we can divide the data into two groups. For 2003-2007 and 2009-2010, we observe a net micro-gravity decrease combined with subsidence and from 2007-
2009, we observe a net micro-gravity increase while the subsidence continues albeit at a decreased rate. The simplest model for these observations would be that the same source and the same process are responsible for all the observations. This might be appropriate if we had observed inflation in the 2007-2009 period. However all deformation data: precise levelling, GPS and InSAR confirm the ongoing, albeit decreasing, subsidence at the caldera centre to the present time.

Mass movements at active volcanoes can be caused by several processes such as water table/lake level movements, hydrothermal activity and magma movements. It is important to evaluate the possible effects of each of these processes and to monitor parameters that may assist in their quantification. From this perspective it is unfortunate that no continuous record exists of the lake level height of lake Öskjuvatn. The controlling factors for the Öskjuvatn water level are the amount of snow, its melting rate and permeability of the surrounding rock. The Mt Dyngjufjöll massif, hosting the Öskjuvatn lake, is build up by huge amounts of hyloclastite which is permeable.

It has been observed that the lake level is highest towards the end of summer when most of the snow has melted (Tryggvason 1989b). Seasonal variation of the lake level is on the order of 1-2 m, while during summer, the variation can be ~0.5 m depending on the presence of snow. The lake is drained through ground water motion. From 1950 to 1968 sporadic relative measurements were noted by Sigurjón Rist (Tryggvason 1989b). In 1968, 20 benchmarks were installed around the lake to monitor its level. Several of these became submerged or lost over the years. (Tryggvason 1989a; Tryggvason 1989b). Overall, up to 1961, the lake level was more or less stable. After the 1961 eruption, the lake level decreased a total of 6 m due to the reactivation of old cracks and possibly the opening of new cracks, increasing the drainage. In 1968, this trend was reversed to a gradual increase in lake level (Tryggvason 1989b) as drainage passages presumably became clogged. It is believed that this slow increase continues up to the present. The lake level data do not correlate with the observed deformation nor does it follow the opposite trend, suggesting no direct influence.

Tryggvason (1989b) also observed 'tilting' in 1968 of the 'highest' lake shore data, with a difference
of 5 m between the North and South shore. He interpreted this 'tilting' as caused by inflation to the
north of the caldera related to the 1961 eruption and that this inflation must have been rather large
compared to the extruded material.

To estimate the expected gravity change ($\Delta g_{\text{wt}}$), resulting from water table and lake level
movements ($\delta z$), we approximate an unconfined aquifer with density ($\rho_w$) and effective porosity
($\phi_e$) as an infinite slab such that:

$$\Delta g_{\text{wt}} = \frac{2\pi G \phi_e \rho_w \delta z}{\text{eq. 1}}$$

This is an oversimplification as it assumes the lake level reflects the water table level within the
caldera. It therefore under-estimates the necessary water table rise/fall required to produce the
observed gravity changes. To explain the totality of the net gravity increase of 50 $\mu$Gal, assuming an
effective porosity of 17% (Franzson et al. 2001), a water table rise of ~7 m needs to take place.

Although only limited observations of the lake level have been carried out, such a large change is
highly implausible. Furthermore if a rise in water table/lake level was responsible for the net micro-
gravity increase, the same increase should have been observed at the South-eastern stations, which
are just as close to the level of the lake, and this is not the case.

Geothermal activity at Askja is focused along the boundaries of the newest caldera collapse;
Along the shore of lake Öskjuvatn. It includes the explosion crater Víti, which is filled with
lukewarm water. One geothermal vent is known on the lake bottom (Fig. 1c), offshore, at the West
side of the lake, next to Myvatningahraun (Olafsson 1980). In winter, some years, thermal activity
is sufficient to maintain an opening in the ice cover of the lake (Sigvaldason 1964 and later
observations). This has also been observed in recent (April 2012, June 2011, June 2010, May 2009
for example) ASTER satellite images (http://igg01.gsj.jp/vsidb/image/proto_header.html). The
distance from Myvatningahraun to the 'Centre' stations is ~ 1.5 km, short enough to influence
micro-gravity observations there. In 2012, the whole Öskjuvatn lake became ice free unusually
eyearly in the year, after fast progressive enlarging in the lake opening above the geothermal vent.
This may have been a response to increased heat flow from below, although other possibilities can not be ruled out, such as convection of the lake bringing heat from the water body, contributing to the ice melt.

Unrest at other calderas has been (partly) attributed to hydrothermal activity (e.g. Campi Flegrei (Gottsmann et al. 2006), Yellowstone (Battaglia et al. 2003)). A steam cap in the geothermal system of Askja at depth, of variable size and with a link to the surface of variable efficiency may induce micro-gravity variations. Such a steam cap could develop above the centre of the magmatic source - literally under the 'Centre' group of micro-gravity stations, causing variations in micro-gravity measurements there. Reduction of the steam cap (replacing steam with water) in 2007-2009 could possibly explain the micro-gravity increase. Increase in the steam cap would then cause a reduced density after 2009 resulting in a micro-gravity decrease. If part of the geothermal system is close to critical conditions then steam can change to liquid water (or visa-versa) without much pressure changes. This process would cause little to no detectable deformation at the surface but large micro-gravity changes and is considered more plausible than the vertical migration of the water table as the cause of the observed gravity changes. At the resolution of this survey, the gravitational effect observed at the surface of an infinite slab and a vertical cylinder with a radius of >2.5 km is the same. Therefore although we cannot pinpoint the lateral extent of the steam cap exactly, its radius certainly cannot be larger than 5 km, as it would then also have influenced the Northern and South-eastern stations. A steam cap with a much smaller radius would require an unrealistically large vertical movement and is therefore not considered. In our case the steam cap can, as a first approximation, be represented by the same infinite slab model. Thus of the order of 7 m of increased/decreased depth of the steam layer would be required to account for the magnitude of the gravity changes.

Another possible explanation for the net micro-gravity increase is magma movement. We can envisage such magma movement as a shallow magma intrusion into the crust or as an intrusion...
of magma into the residing magma chamber. A shallow intrusion would be expected to produce additional signatures at the surface, such as increased heat flow and localized deformation. However, a deeper intrusion, focused within the existing magma chamber, is a plausible explanation of the data presented. The geodetic data are consistent with contributions from both processes: a magma intrusion into the magma chamber and fluctuations in a steam cap underneath the centre of the caldera. It is not possible to determine the relative contributions from either process using the current data. In the following section we will discuss in more detail how magma intrusion can explain the micro-gravity increase without large surface deformation.

Discussion and implications

Askja caldera has been continuously subsiding at least since 1983 but quite likely since 1973. The rate of subsidence has decayed exponentially from 1983-2003 (Sturkell et al. 2006) and this continues up to 2010 (see Fig. 2). At Krafla caldera, 70 km North of Askja, (Fig. 1a), subsidence decayed much more rapidly after its last rifting episode (1975-1984) and the decay was attributed to relaxation of the crust (Sturkell et al. 2008). The most recent activity at Askja consisted of relatively gentle magma extrusion compared with Krafla's rifting episode. Furthermore, simple 2D FEM models show that rheological complexities, arising from the tectonic setting of the Askja caldera at a divergent plate boundary, may have large effects on the surface deformation (de Zeeuw-van Dalfsen et al. 2012; Pedersen et al. 2009). These rheological complexities can be envisaged as a visco-elastic 'ridge' at the location of the Askja fissure system and a 'weak' layer filling the caldera. The 'ridge' represents an area of visco-elastic material reaching to shallow depth (immediately beneath the plate boundary) with the same visco-elastic properties as the layer representing the lower crust. As Askja is located closer to the inferred centre of up-welling in Iceland than Krafla, a 'ridge' underneath Askja may be able to intrude to relatively shallow levels hence enhancing the effect of such a rheological complexity. Inversion of our data with 2D models, as suggested by de
Zeeuw-van Dalffen et al. (2012), are beyond the scope of this work because the resolution of the gravity data do not support this level of detail. However, based on the results from that paper, we suggest the subsidence at Askja is caused by a combination of the plate spreading and cooling/contraction of the shallow magma chamber. The plate spreading at Askja, during the current inter-rifting phase, is a steady process (e.g. Camitz et al. 1995), hence the decay may be attributed to the cooling/contraction of the shallow magma chamber.

During the 2000-2010 period several episodes of unrest occurred within a 100 km radius of Askja. The Grimsvötn volcano, located 70 km to the SW of Askja beneath the Vatnajökull icecap, erupted in November 2004 (Sigmundsson & Gudmundsson 2005). An ~0.05 km$^3$ magma dike intruded in 2007-2008 at ~15 km depth in the Upptyppingar area, just 20-25 km to the E of Askja (Fig. 1b) (Hooper et al. 2011; Jakobsdóttir et al. 2008). In 2006, for the first time, very deep (>20 km) micro-earthquakes were detected in the Askja area using a temporary dense network of seismometers. These earthquakes are located at the NE edge of the Askja caldera, in a NE-SW trending belt ~10 km long, as well as in two zones >40 km away (Soosalu et al. 2010). Each of these three zones are interpreted as foci of melt supply from where magma feeds the volcanic rift zone (Key et al. 2011).

It is not unfeasible that a small pocket of magma intruded into shallower levels rather than flowing into the diverging rift zone at depth. Such an intrusion, outside the previously existing magma chamber, would likely cause an earthquake swarm and ground deformation. To explain the net micro-gravity increase of ~50 μGal, just ~0.01 km$^3$ magma would need to pond 2 km below the surface, assuming a point source, or ~0.02 km$^3$, assuming a penny shaped crack. This is only 17-34% of the volume extruded during the most recent eruption in 1961. However, forward calculations of the surface deformation potentially caused by such an intrusion predict inflation on the order of 10-50 cm which we have not observed in any of the deformation data. Furthermore, the time lag between the earthquake activity at depth and the possible magma intrusion into shallower levels
seems too large. Hence an intrusion of this kind is an unlikely explanation for our observations.

There are slight deviations from the average subsidence rate observed in the precise levelling (2009 data) and InSAR images and profiles (2009 and 2010 data). They may show the beginning of what could have been a reversal of deformation data had the magma intrusion persisted. We postulate that the mass increase was too small, and the overprint of the larger subsidence signal related to the divergent plate boundary too large to result in detectable net inflation at the surface. To test this hypothesis and to observe if there is any hidden 'signal' in the InSAR data, we calculate the residual surface deformation (Fig. 7). The average LOS – velocity field estimated from all interferograms before 2009, multiplied by the time span, gives the 'secular' deformation for the 2000-2009 period. We subtract this deformation from the original 2000-2009 interferogram to get the residual. For the 2000-2009 period the residual shows a variation of ~2 cm, within the atmospheric noise expected. Similarly the residual for 2008 and for 2010 were calculated (Fig. 8). For 2010, the residual shows a variation of ~1.5-2 cm, within the expected atmospheric noise, however, the residual of 2008 shows a variation of 5 cm, suggesting there was extra uplift at this time. We invert this uplift signal using a spherical chamber in a homogeneous elastic half-space, represented by a point pressure source (Mogi, 1958), and a penny shaped crack in a homogeneous, elastic half-space (Fialko et al. 2001). We find reasonable fits for both, but neither of the best-fit models can explain more than 20% of the observed micro-gravity increase. This implies that the observed micro-gravity change was not associated with detectable surface deformation and that an intrusion into shallower levels can not explain the observed micro-gravity data.

The tectonic setting of Askja plays an important role in the continuous, long-term high subsidence rates observed there (de Zeeuw-van Dalfsen et al. 2012). If indeed part of the observed subsidence at the Askja caldera is caused by the ongoing divergence of the plate boundary, then the amount of subsidence related to the shallow source may be smaller than previously suggested.

Continuing this reasoning, we postulate that the use of a more realistic rheological model of the
area, would suggest a shallower source depth. This has direct consequences for the calculated mass changes needed to explain the observed net gravity changes. All observations could be explained with smaller mass changes when the assumed source depth is shallower. For example: to explain a net micro-gravity increase of \(~50 \mu\text{Gal}\), using a source at 3 km depth, \(~0.7 \times 10^{11}\ \text{kg}\) mass inflow is needed. When the source is at 2 km depth, only \(~0.3 \times 10^{11}\ \text{kg}\) mass inflow is needed to explain the same net micro-gravity change.

Is it possible that magma flows into the shallow chamber without any detectable effects in the deformation observations? If there is a well-developed conduit or pocket for magma, then it is possible to generate measurable gravity changes without any deformation signals. Such a change was for example observed at Izu-Oshima, Japan, after the 1986 eruption (Watanabe et al. 1998). However, the processes at this open conduit volcano, displaying effusive activity, are very different from unrest at a caldera. Maybe magma flowing into the residing shallow magma chamber at Askja is accommodated by the compressibility of the magma already in the chamber and elastic compressibility of the surrounding rock, hence not inducing any detectable surface deformation. This would represent the other side of the spectrum of the model proposed to explain the bigger volume of dike intrusions compared to deflating source volumes at Kilauea (Rivalta & Segall 2008). The mass input, \(\Delta M\), associated with an increase of magma chamber volume, \(\Delta V\), is not simply: \(\Delta M = \rho_0 \Delta V\) (where \(\rho_0\) is the density of magma before the intrusion). In fact mass input into an existing magma chamber compresses both the surrounding rock (creating more space for the chamber) and the resident magma (causing a density change, \(\Delta \rho\), of magma residing in the chamber). Differentiation and substitution of equations (see Johnson et al. 2000; Segall et al. 2001; Rivalta 2010; Anderson & Segall 2011) suggests that for a spherical magma chamber:

\[
\Delta M = r_v \rho_0 \Delta V \quad \text{(eq. 2)}
\]

with \(r_v = 1 + \beta_m/\beta_c\) and \(\beta_m\) is magma compressibility and \(\beta_c\) is the elastic compressibility of a magma chamber.
This equation states that a mass of magma bigger than $\rho_0 \Delta V$ can be squeezed into a magma chamber and still result in an apparent volume change $\Delta V$, while its 'true' volume (before injection, or once erupted) is actually $r_V$ times larger. For gas-poor magmas and spherical or cigar-shaped chambers, $r_V$ may be in the range of 1–5, for gas-rich magmas this could be even larger (Mastin et al. 2008).

Conclusions

Deformation data show that Askja caldera continues to subside up to 2010. The subsidence is smooth but slowly decaying and is strongest in the centre of the main Askja caldera. This subsidence is caused by a combination of the cooling and contracting magma chamber at a divergent plate boundary. The net micro-gravity decrease observed with this trend indicates a mass decrease, e.g. mass moving away from the centre of subsidence for example into the diverging rift. Statistical tests show the net micro-gravity increase observed in 2007-2009 is significant. This mass increase was not accompanied by detectable net inflation at the surface nor can it be explained by an intrusion at shallow depth. We suggest two plausible explanations: i) the observed mass increase was caused by magma flow into the existing magma chamber at Askja. In particular compressibility of magma residing in the chamber, but also compressibility of the surrounding rock may explain why this intrusion remained undetectable through surface deformation. ii) Alternatively, variations within a steam cap in the geothermal system of Askja at depth, may be responsible for the observed micro-gravity variations. We suggest that 2D modelling or detailed 3D FEM modelling, taking into account the rheological complexities of the area, may help to estimate the relative contribution that each process makes to the ongoing unrest at Askja caldera.

Acknowledgements

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Fig. 1

a) Volcanic systems in Iceland depicting the fissure swarms in grey, with their associated central volcanoes and calderas (after Einarsson & Saemundsson 1987). The black box shows the coverage of RADARSAT images in the F5 frame, with the dotted line displaying the area shown in Fig. 4. The following volcanoes are annotated: Askja (A), Krafla (K), Bárðarbunga (B), Grimsvötn (G) and Tungnafjellsjökull (T). Modified after de Zeeuw-van Dalfsen et al., 2012.

b) Digital elevation model of the study area depicting the fissure swarm in yellow. Lake Öskjuvatn is a nested caldera, located within the main Askja caldera (both indicated by depression contours). Mt. Upptyppingar is located 20-25 km to the east of Askja. Two purple stars show the locations of the geothermal areas, Viti in the NE and Myvetningahraun in the SW. The geodetic network is depicted but is better visible and described in Fig. 1c. Modified after de Zeeuw-van Dalfsen et al., 2012.

c) Close up of survey area showing the micro-gravity benchmarks: the base station with an open black square, the 'Northern' stations with open red circles, the 'South-eastern' stations with yellow squares and the 'Centre' stations with open blue squares. The precise levelling line is shown with
small black squares and levelling stations 406 and 429 are pointed out. GPS stations are marked
with open black circles and the geothermal areas, Viti and Myvatnignahraun, are depicted.

**Fig. 2**

Precise levelling data from 1968 to 2010. Upper figure shows the absolute yearly height difference
in m between two of the precise levelling benchmarks (429 and 406, respectively see Fig. 1c). The
lower figure shows the cumulative vertical displacement in m between those benchmarks. Data
were fitted with an exponential function (Sturkell et al. 2006). Note the systematic decay of the
subsidence rate which has not changed considerably in the last decades.

**Fig. 3**

Time series of horizontal and vertical displacement (in mm), at Ólafsgígar (OLAF), Miðaskja
(MASK), A404 and Bátshraun (BATS) GPS stations, relative to the ITRF2005 reference frame.
Error bars show the uncertainties of each measurement. The vertical measurements (bottom panel)
show increased subsidence rates toward the centre of the caldera. OLAF and MASK are located
close to the centre while A404 and BATS are at the caldera rim (see Fig. 1c).

**Fig. 4**

Unwrapped small baseline interferograms of the F5 frame, covering the 2000 to 2010 period. See
text for description of visible features. Thin lines show the outlines of the Askja fissure swarm and
central volcano, as well as the Askja caldera and lake Öskjuvatn. Interferograms have been
corrected for orbital fringes by removal of a ramp and unwrapped. Incoherent areas, such as lake
Öskjuvatn, do not have any pixels and are hence white. Time indication refers to the master and
slave date, respectively. The green line projects the profile of Fig. 5.
Fig. 5
EW profile though the unwrapped interferograms displayed in Fig. 4, showing the decreasing rate of subsidence with time.

Fig. 6
Net micro-gravity data, corrected for height changes within the caldera, using benchmark 83001 (same location as GPS station VIKR) as a base and 1988 as a reference year, for each area within the Askja caldera. As uncertainty for the 2007 point is high dashed lines are used for the 'Centre' stations around this point. See text for discussion.

Fig. 7
Residual surface deformation for 2009 (c and d), calculated by subtracting the secular deformation (b), found by multiplying the velocity for the correct number of years, from the original interferogram (a). Small black dots approximate the outline of lake Öskjuvatn. Open squares represent the location of the micro-gravity stations: 'Centre' in blue, 'South-eastern' in yellow and 'Northern' in red. Open black square shows the location of the micro-gravity reference station on the 1961 lava flow.

Fig. 8
Residual surface deformation for 2008 (a) and 2010 (b) calculated in the same way as for Fig. 7. Annotations as for Fig. 7.

Table I
Results of the students' t-test applied to the net micro-gravity data using a set standard deviation of 25 μGal for each measurement and a confidence level of 95%. A value of '1' indicates significant
change, '0' indicates insignificant change and '-' indicates no data, at the station.

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24
New questions and comments:

a) Lines 266-267

For estimating the change in steam layer thickness, you assumed an infinite slab model again as the water table case. But this simple slab model has the same difficulty as the infinite slab of water. It does not explain the observation that the decreasing trend of micro-gravity is observed only at Central stations. In order to explain this observation, the horizontal extent of the steam cap would have to be limited so that the cap affects Central stations only. Show whether the horizontal extent of the steam cap affect significantly the thickness estimation or not. If your answer is yes, show also that the newly estimated thickness of the steam cap is not unrealistic.

→ We have added the following text (265): "At the resolution of this survey, the gravitational effect observed at the surface of an infinite slab and a vertical cylinder with a radius of >2.5 km is the same. Therefore although we cannot pinpoint the lateral extent of the steam cap exactly, its radius certainly cannot be larger than 5 km, as it would then also have influenced the Northern and South-eastern stations.

A steam cap with a much smaller radius would require an unrealistically large vertical movement and is therefore not considered. In our case the steam cap can, as a first approximation, be represented by the same infinite slab model. Thus of the order of 7 m of increased/decreased depth of the steam layer would be required to account for the magnitude of the gravity changes."

b) Line 276

In order to make clear the relation between the last paragraph of the "Interpretation" (line 282), and the "Discussion and implication", how about inserting a following sentence?

"In the following section, we will discuss in more detail how magma intrusion can explain the micro-gravity increase without large surface deformation."

→ Inserted following sentence (276):

"In the following section we will discuss in more detail how magma intrusion can explain the micro-gravity increase without large surface deformation."

c) Line 293-295

In order to make much clearer your opinion about the tectonic setting of Askja, I would suggest changing line 293-294; "Although we did not combine our data directly with the 2D models, based on the work done by de Zeeuw-van Dalsen et al., 2012 and on the additional data presented in this paper, we suggest that the subsidence at Askja is caused by a combination of the plate spreading....".

→ Changed sentence to (300): "Inversion of our data with 2D models as suggested by de Zeeuw-van Dalsen et al. (2012), are beyond the scope of this work because the resolution of the gravity data do not support this level of detail. However, based on the results from that paper, we suggest the subsidence at Askja is caused by a combination of the plate spreading and cooling/contraction of the shallow magma chamber."
d) Line 307  Start a new paragraph.
   → Started new paragraph line (309)

e) Line 315

It is not clear for me what is "an intrusion of this kind". Do you mean "an intrusion in which magma intrude into a certain position where no chamber pre-exists and thus the intrusion causes clear earthquake swarm and large ground deformation."?

   → Added the following sentence (310)

   “Such an intrusion, outside the previously existing magma chamber, would likely cause an earthquake swarm and ground deformation.”

Minor comments:

(1) Line 72, Fig 1c -> Fig. 1c
   → changed

(2) Inconsistent usage of area names: "South-East", "South-eastern", and "Southeastern".

   Line 169 : "South-East", Line 173, 184 : "South-eastern",
   Line 239, 412, 453, Table1 : "Southeastern"

   → changed all to "South-eastern"

(3) Line 243, Fig.1 -> Fig.1c
   → changed

(4) Line 407-416 : Captions for Fig.1b, and 1c there are some mistakes.

In Fig.1b and Fig.1c, GPS stations are indicated by red/black circles, while captions for Fig.1c say GPS stations are marked with open black triangles.

Two geothermal locations, Viti and Myvetningahraun, are shown by purple starts in Fig.1b but not in Fig.1c
b) Digital elevation model of the study area depicting the fissure swarm in yellow. Lake Öskjuvatn is a nested caldera, located within the main Askja caldera (both indicated by depression contours). Mt. Upptyppingar is located 20-25 km to the east of Askja. Two purple starts show the locations of the geothermal areas, Viti in the NE and Myvetningahraun in the SW. The geodetic network is depicted but is better visible and described in Fig. 1c. Modified after de Zeeuw-van Dalfsen et al., 2012.

c) Close up of survey area showing the micro-gravity benchmarks: the base station with an open black square, the 'Northern' stations with open red circles, the 'South-eastern' stations with yellow squares and the 'Centre' stations with open blue squares. The precise levelling line is shown with small black squares and levelling stations 406 and 429 are pointed out. GPS stations are marked with open black circles and the geothermal areas, Viti and Myvetningahraun, are depicted.”

(5) Line 419-422 : Fig.2 No explanation for fitting curves.

→ added sentence (424):

“Data were fitted with an exponential function (Sturkell et al. 2006).”

(6) Line 466-

Your reference format does not follow the BV standard. For example, a publication year should be between parentheses, year, title, journal-title are separated not by comma but by space. etc. etc.

→ Changed format following guidelines

(7) Line 490-493 : This reference is not cited in the text.

→ Deleted reference
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