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

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Response to Reviewers:	see attachment

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.

31

Keywords

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

34

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

51 there.

52 The Askja volcanic system in northern Iceland (Fig. 1a & b) consists of a central volcano
53 and at least 3 calderas. The oldest caldera is difficult to observe as it is almost completely filled by
54 lavas. The main (early Holocene) Askja caldera itself has a diameter of ~10 km and is 200-300 m
55 deep. The youngest caldera which is 4.5 km across was formed in association with a Plinian
56 eruption in 1875 (Sturkell *et al.* 2006 and references therein) and continued to form afterwards for
57 decades (Hartley & Thordarson 2011). It is now filled by lake Öskjuvatn, one of the deepest lakes in
58 Iceland (Rist 1975). The last eruptive activity in the area occurred in 1961 when lava erupted from a
59 fissure at the northern boundary of the Askja caldera. Most of the lava flowed towards the east out
60 of the caldera onto the planes beyond (Sturkell & Sigmundsson 2000).

61

62 **Previous work**

63 The first deformation measurements at Askja took place in 1966 when a precise levelling
64 line, with 12 benchmarks (extended to 30 in 1968), was installed in the northern part of the caldera
65 (see Fig. 1c) (Tryggvason 1989a). Measurements show (Fig. 2) that the caldera subsided towards
66 the centre, compared with points outside the caldera, from 1968-1970. This trend reversed to an
67 observed inflation from 1970-1972 showing the largest deformation rate measured so far. From
68 1973-1983 no measurements were conducted but after 1983 the measurements show a steady
69 subsidence of the caldera centre relative to the surroundings and the rate of subsidence is declining
70 with time. In 1993 the first Global Positioning System (GPS) measurements were conducted at 24
71 benchmarks in and around the Askja caldera. The network was completely re-measured in 1998
72 after which selected benchmarks (see Fig. 1c) have been measured on an annual basis (Sturkell *et*
73 *al.* 2006) during measurement campaigns lasting up to 24 hours. The GPS data confirm the ongoing
74 subsidence. Interferometric Synthetic Aperture Radar (InSAR) images formed using ESR-1 (Pagli
75 *et al.* 2006) and RADARSAT-2 (de Zeeuw-van Dalfsen *et al.* 2012) show the ongoing subsidence

76 within the caldera very clearly. Apart from the subsidence within the caldera, InSAR also shows
77 broader scale subsidence 20-25km wide, along ~50 km of the rift (Pagli *et al.* 2006; Pedersen *et al.*
78 2009).

79 Micro-gravity data have been collected regularly since 1988 at Askja (Rymer & Tryggvason
80 1993; de Zeeuw-van Dalfsen *et al.* 2005). The raw data for each location are corrected for
81 instrumental drift, tides, earth tides and station height changes (e.g. Rymer 1989) to calculate the net
82 micro-gravity change with respect to the base station and referred to values observed in 1988. De
83 Zeeuw-van Dalfsen *et al.* (2005), used a point source, to model a net micro-gravity decrease of 115
84 μGal ($1 \mu\text{Gal}=10^{-8} \text{ m/s}^2$) between 1988 and 2003 in the centre of the caldera, in terms of a
85 subsurface mass decrease of $1.6 \times 10^{11} \text{ kg}$. Rymer *et al.* (2010), observed from 1988-2007 a net
86 micro-gravity decrease of 140 μGal in the caldera centre of Askja. They also reported a dramatic
87 reversal in the net micro-gravity change in 2007-2008 to an increase of ~60 μGal (Rymer *et al.*
88 2010).

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

101 'extended' levelling line in 2003, 2007, 2008 and 2009 and GPS has been measured yearly at VIKR
102 since 2009.

103

104 **Previous modeling and interpretation**

105 All previous inverse modelling of geodetic data at Askja assumes one or more contracting
106 point sources embedded in a homogeneous elastic half space, thereby implying that the entire
107 vertical deformation signal should be attributed to processes within the magmatic plumbing system.
108 Outcomes of such modelling of geodetic data at Askja suggests a shallow magma chamber directly
109 below the centre of the caldera (65.05°N 16.78°W) at 3-3.5 km depth (Pagli *et al.* 2006; Rymer &
110 Tryggvason 1993; Sturkell & Sigmundsson 2000). RADARSAT-2 InSAR analyses suggest that the
111 concentric fringes centred in the Askja caldera can be modelled by a point source at a depth of 3.2-
112 3.8 km with a volume decrease of 0.0012-0.0017 km³/yr from 2000-2009. The horizontal
113 contraction detected by the GPS data 10-15 km outside the caldera was interpreted in terms of a
114 second, deep source at ~16 km, depth (Sturkell *et al.* 2006).

115 De Zeeuw-van Dalssen *et al.* (2012) show that a homogeneous elastic half-space may not be
116 the best assumption for modelling the deformation at Askja caldera. Their two-dimensional Finite
117 Element Models (FEM) include structural complexities in the crustal layers, such as a visco-elastic
118 'ridge' at the location of the Askja fissure system and a mechanically weak caldera filling. The ridge
119 represents an area of visco-elastic material reaching to shallow (1-2.5 km) depth (immediately
120 beneath the plate boundary) with the same visco-elastic properties as the layer representing the
121 lower crust. This configuration is supported by the results from the deformation based study of the
122 structure of the plate spreading segment (Pedersen *et al.* 2009). The weak layer is envisioned as the
123 result of a combination of geothermal alteration and the presence of explosive eruption products.
124 The results indicate that the tectonic setting of Askja plays a major role in the continuous, long-term
125 high subsidence rates observed.

126 Models using three-dimensional FEM have been developed (Dickinson 2010) that combine
127 magma extraction from a shallow, fluid-filled cavity with a plate spreading model that depicts
128 rheologic partitioning to simulate a rift segment. They predict both the radially symmetric pattern of
129 subsidence observed within the Askja caldera and the elongated pattern of subsidence tracking the
130 rift segment, rather well, suggesting the contraction of a deeper source (~16 km) is not needed to
131 explain the InSAR data.

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

137

138 **New deformation data**

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

151 of the ITRF2005 reference frame (Altamimi *et al.* 2007). The scatter in the data, as for example for
152 the vertical movement of station BATS, is due to atmospheric disturbances.

153 We created Interferometric images using StaMPS (Hooper 2008) following the method as
154 described by de Zeeuw van Dalfsen *et al.* (2012). Three RADARSAT satellite images of three
155 different frames were obtained during the summer of 2010. Combined with the previously acquired
156 images (de Zeeuw-van Dalfsen *et al.* 2012), we formed twelve new interferograms with good
157 coherence, all covering the Askja caldera. Here we present the descending F5 frame as this is the
158 most complete time-series (Fig. 4). The 2000-2010 unwrapped interferogram shows ~22.3 cm line-
159 of-sight (LOS) deformation or about ~2.2 cm LOS deformation per year. There are two specific
160 signatures visible in the unwrapped interferograms: i) a concentric feature depicting subsidence in
161 the main Askja caldera, ii) an oval feature elongated along the rift indicating subsidence. Profiles
162 tracing the green EW-line in the unwrapped interferograms (Fig.4) show the decreasing LOS
163 subsidence with time (Fig. 5). Up to 2008 this decrease seems to be similar to the decrease
164 suggested from precise levelling data. The 2009 and 2010 InSAR data show less LOS subsidence
165 than observed with ground based methods. This deviation is comparable to that observed in the
166 2009 measurement of the precise levelling data.

167

168 **New micro-gravity data**

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

174 To evaluate the micro-gravity data in terms of mass changes we correct the data for height
175 changes (Fig. 6). Due to the lack of real-time geodetic measurements, we are forced to use a model

176 (Sturkell *et al.* 2006) to calculate the height change at each station relative to base station 83001. It
177 is evident that the micro-gravity data are influenced by noise. To test for the statistical significance
178 of the net micro-gravity variations we apply a student's t-test using 95% confidence levels (Table 1)
179 following the suggestions of Saibi *et al.* (Saibi *et al.* 2010) at Unzen volcano. The error on net
180 micro-gravity data for location groups is less than $\pm 20 \mu\text{Gal}$ (Rymer *et al.* 2010). In Fig. 6 we
181 show the best-fit location of the 2007 'Centre' point, which fits the trend between 1988 and 2005,
182 but has a larger error bar than the data points of other years. The average net micro-gravity is
183 displayed for each station group, but only when the data are significant.

184 The net micro-gravity variations at the 'Northern' and 'South-eastern' stations lie within the
185 uncertainty for the data of $\pm 20 \mu\text{Gal}$, and thus do not show any significant change over the 1988-
186 2010 period. The net micro-gravity at the 'Centre' was measured at 3 different benchmarks (OLAF,
187 D-19, MASK), all located close (856 m, 926 m and 742 m) to the centre of deformation. The
188 'Centre' stations show the biggest net micro-gravity variations: from 1988 to 2007, a decrease of
189 $\sim 140 \mu\text{Gal}$, followed by an increase of $\sim 40 \mu\text{Gal}$ between 2007 and 2008. No changes occurred
190 from 2008-2009, and finally a decrease of $\sim 50 \mu\text{Gal}$ occurred from 2009 to 2010. Overall, from
191 1988-2007 the net micro-gravity change at Askja shows a decrease, which reversed to an increase
192 from 2007-2009. Our recent measurements indicate the reversal was temporary and the net micro-
193 gravity changes since then (2009-2010) follow the previously reported decreasing trend.

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

197

198 **Interpretation**

199 Focusing on the 2003-2010 period, we can divide the data into two groups. For 2003-2007
200 and 2009-2010, we observe a net micro-gravity decrease combined with subsidence and from 2007-

201 2009, we observe a net micro-gravity increase while the subsidence continues albeit at a decreased
202 rate. The simplest model for these observations would be that the same source and the same process
203 are responsible for all the observations. This might be appropriate if we had observed inflation in
204 the 2007-2009 period. However all deformation data: precise levelling, GPS and InSAR confirm the
205 ongoing, albeit decreasing, subsidence at the caldera centre to the present time.

206 Mass movements at active volcanoes can be caused by several processes such as water
207 table/lake level movements, hydrothermal activity and magma movements. It is important to
208 evaluate the possible effects of each of these processes and to monitor parameters that may assist in
209 their quantification. From this perspective it is unfortunate that no continuous record exists of the
210 lake level height of lake Öskjuvatn. The controlling factors for the Öskjuvatn water level are the
211 amount of snow, its melting rate and permeability of the surrounding rock. The Mt Dyngjufjöll
212 massif, hosting the Öskjuvatn lake, is build up by huge amounts of hyloclastite which is permeable.
213 It has been observed that the lake level is highest towards the end of summer when most of the
214 snow has melted (Tryggvason 1989b). Seasonal variation of the lake level is on the order of 1-2 m,
215 while during summer, the variation can be ~0.5 m depending on the presence of snow. The lake is
216 drained through ground water motion. From 1950 to 1968 sporadic relative measurements were
217 noted by Sigurjón Rist (Tryggvason 1989b). In 1968, 20 benchmarks were installed around the lake
218 to monitor its level. Several of these became submerged or lost over the years. (Tryggvason 1989a;
219 Tryggvason 1989b). Overall, up to 1961, the lake level was more or less stable. After the 1961
220 eruption, the lake level decreased a total of 6 m due to the reactivation of old cracks and possibly
221 the opening of new cracks, increasing the drainage. In 1968, this trend was reversed to a gradual
222 increase in lake level (Tryggvason 1989b) as drainage passages presumably became clogged. It is
223 believed that this slow increase continues up to the present. The lake level data do not correlate with
224 the observed deformation nor does it follow the opposite trend, suggesting no direct influence.
225 Tryggvason (1989b) also observed 'tilting' in 1968 of the 'highest' lake shore data, with a difference

226 of 5 m between the North and South shore. He interpreted this 'tilting' as caused by inflation to the
227 north of the caldera related to the 1961 eruption and that this inflation must have been rather large
228 compared to the extruded material.

229 To estimate the expected gravity change (Δg_{wt}), resulting from water table and lake level
230 movements (δz), we approximate an unconfined aquifer with density (ρ_w) and effective porosity
231 (ϕ_e) as an infinite slab such that:

232
$$\Delta g_{wt} = 2\pi G \phi_e \rho_w \delta z \quad \text{(eq. 1)}$$

233 This is an oversimplification as it assumes the lake level reflects the water table level within the
234 caldera. It therefore under-estimates the necessary water table rise/fall required to produce the
235 observed gravity changes. To explain the totality of the net gravity increase of 50 μGal , assuming an
236 effective porosity of 17 % (Franzson *et al.* 2001), a water table rise of ~ 7 m needs to take place.
237 Although only limited observations of the lake level have been carried out, such a large change is
238 highly implausible. Furthermore if a rise in water table/lake level was responsible for the net micro-
239 gravity increase, the same increase should have been observed at the South-eastern stations, which
240 are just as close to the level of the lake, and this is not the case.

241 Geothermal activity at Askja is focused along the boundaries of the newest caldera collapse;
242 Along the shore of lake Öskjuvatn. It includes the explosion crater Víti, which is filled with
243 lukewarm water. One geothermal vent is known on the lake bottom (Fig. 1c), offshore, at the West
244 side of the lake, next to Myvetningahraun (Olafsson 1980). In winter, some years, thermal activity
245 is sufficient to maintain an opening in the ice cover of the lake (Sigvaldason 1964 and later
246 observations). This has also been observed in recent (April 2012, June 2011, June 2010, May 2009
247 for example) ASTER satellite images (http://igg01.gsj.jp/vsldb/image/proto_header.html). The
248 distance from Myvetningahraun to the 'Centre' stations is ~ 1.5 km, short enough to influence
249 micro-gravity observations there. In 2012, the whole Öskjuvatn lake became ice free unusually
250 early in the year, after fast progressive enlarging in the lake opening above the geothermal vent.

251 This may have been a response to increased heat flow from below, although other possibilities can
252 not be ruled out, such as convection of the lake bringing heat from the water body, contributing to
253 the ice melt.

254 Unrest at other calderas has been (partly) attributed to hydrothermal activity (e.g. Campi
255 Flegrei (Gottsmann *et al.* 2006), Yellowstone (Battaglia *et al.* 2003)). A steam cap in the geothermal
256 system of Askja at depth, of variable size and with a link to the surface of variable efficiency may
257 induce micro-gravity variations. Such a steam cap could develop above the centre of the magmatic
258 source - literally under the 'Centre' group of micro-gravity stations, causing variations in micro-
259 gravity measurements there. Reduction of the steam cap (replacing steam with water) in 2007-2009
260 could possibly explain the micro-gravity increase. Increase in the steam cap would then cause a
261 reduced density after 2009 resulting in a micro-gravity decrease. If part of the geothermal system is
262 close to critical conditions then steam can change to liquid water (or visa-versa) without much
263 pressure changes. This process would cause little to no detectable deformation at the surface but
264 large micro-gravity changes and is considered more plausible than the vertical migration of the
265 water table as the cause of the observed gravity changes. At the resolution of this survey, the
266 gravitational effect observed at the surface of an infinite slab and a vertical cylinder with a radius of
267 >2.5 km is the same. Therefore although we cannot pinpoint the lateral extent of the steam cap
268 exactly, its radius certainly cannot be larger than 5 km, as it would then also have influenced the
269 Northern and South-eastern stations. A steam cap with a much smaller radius would require an
270 unrealistically large vertical movement and is therefore not considered. In our case the steam cap
271 can, as a first approximation, be represented by the same infinite slab model. Thus of the order of 7
272 m of increased/decreased depth of the steam layer would be required to account for the magnitude
273 of the gravity changes.

274 Another possible explanation for the net micro-gravity increase is magma movement. We
275 can envisage such magma movement as a shallow magma intrusion into the crust or as an intrusion

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

284

285 **Discussion and implications**

286 Askja caldera has been continuously subsiding at least since 1983 but quite likely since
287 1973. The rate of subsidence has decayed exponentially from 1983-2003 (Sturkell *et al.* 2006) and
288 this continues up to 2010 (see Fig. 2). At Krafla caldera, 70 km North of Askja, (Fig. 1a),
289 subsidence decayed much more rapidly after its last rifting episode (1975-1984) and the decay was
290 attributed to relaxation of the crust (Sturkell *et al.* 2008). The most recent activity at Askja consisted
291 of relatively gentle magma extrusion compared with Krafla's rifting episode. Furthermore, simple
292 2D FEM models show that rheological complexities, arising from the tectonic setting of the Askja
293 caldera at a divergent plate boundary, may have large effects on the surface deformation (de Zeeuw-
294 van Dalfsen *et al.* 2012; Pedersen *et al.* 2009). These rheological complexities can be envisaged as a
295 visco-elastic 'ridge' at the location of the Askja fissure system and a 'weak' layer filling the caldera.
296 The 'ridge' represents an area of visco-elastic material reaching to shallow depth (immediately
297 beneath the plate boundary) with the same visco-elastic properties as the layer representing the
298 lower crust. As Askja is located closer to the inferred centre of up-welling in Iceland than Krafla, a
299 'ridge' underneath Askja may be able to intrude to relatively shallow levels hence enhancing the
300 effect of such a rheological complexity. Inversion of our data with 2D models, as suggested by de

301 Zeeuw-van Dalfsen *et al.* (2012), are beyond the scope of this work because the resolution of the
302 gravity data do not support this level of detail. However, based on the results from that paper, we
303 suggest the subsidence at Askja is caused by a combination of the plate spreading and
304 cooling/contraction of the shallow magma chamber. The plate spreading at Askja, during the current
305 inter-rifting phase, is a steady process (e.g. Camitz *et al.* 1995), hence the decay may be attributed
306 to the cooling/contraction of the shallow magma chamber.

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

317 It is not unfeasible that a small pocket of magma intruded into shallower levels rather than
318 flowing into the diverging rift zone at depth. Such an intrusion, outside the previously existing
319 magma chamber, would likely cause an earthquake swarm and ground deformation. To explain the
320 net micro-gravity increase of $\sim 50 \text{ } \mu\text{Gal}$, just $\sim 0.01 \text{ km}^3$ magma would need to pond 2 km below the
321 surface, assuming a point source, or $\sim 0.02 \text{ km}^3$, assuming a penny shaped crack. This is only 17-34
322 % of the volume extruded during the most recent eruption in 1961. However, forward calculations
323 of the surface deformation potentially caused by such an intrusion predict inflation on the order of
324 10-50 cm which we have not observed in any of the deformation data. Furthermore, the time lag
325 between the earthquake activity at depth and the possible magma intrusion into shallower levels

326 seems too large. Hence an intrusion of this kind is an unlikely explanation for our observations.

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

346 The tectonic setting of Askja plays an important role in the continuous, long-term high
347 subsidence rates observed there (de Zeeuw-van Dalfsen *et al.* 2012). If indeed part of the observed
348 subsidence at the Askja caldera is caused by the ongoing divergence of the plate boundary, then the
349 amount of subsidence related to the shallow source may be smaller than previously suggested.
350 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 $\sim 50 \mu\text{Gal}$, using a source at 3 km depth, $\sim 0.7 \times 10^{11}$ kg mass inflow is needed. When the source is at 2 km depth, only $\sim 0.3 \times 10^{11}$ kg mas 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, ΔM , associated with an increase of magma chamber volume, ΔV , is not simply: $\Delta M = \rho_0 \Delta V$ (where ρ_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 β_m is magma compressibility and β_c is the elastic compressibility of a magma chamber .

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

381

382 **Conclusions**

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

398

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407 Icelandic Geodetic Survey. GMT public domain software was used to prepare Fig. 1a and 1b. We
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409 comments.

410

411 **Fig. 1**

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

417 b) Digital elevation model of the study area depicting the fissure swarm in yellow. Lake Öskjuvatn
418 is a nested caldera, located within the main Askja caldera (both indicated by depression contours).
419 Mt. Upptyppingar is located 20-25 km to the east of Askja. Two purple stars show the locations of
420 the geothermal areas, Viti in the NE and Myvatningahraun in the SW. The geodetic network is
421 depicted but is better visible and described in Fig. 1c. Modified after de Zeeuw-van Dalssen *et al.*,
422 2012.

423 c) Close up of survey area showing the micro-gravity benchmarks: the base station with an open
424 black square, the 'Northern' stations with open red circles, the 'South-eastern' stations with yellow
425 squares and the 'Centre' stations with open blue squares. The precise levelling line is shown with

426 small black squares and levelling stations 406 and 429 are pointed out. GPS stations are marked
427 with open black circles and the geothermal areas, Viti and Myvetningahraun, are depicted.

428

429 **Fig. 2**

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

435

436 **Fig. 3**

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

442

443 **Fig. 4**

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

450

451 **Fig. 5**

452 EW profile through the unwrapped interferograms displayed in Fig.4, showing the decreasing rate of
453 subsidence with time.

454

455 **Fig. 6**

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

460

461 **Fig. 7**

462 Residual surface deformation for 2009 (c and d), calculated by subtracting the secular deformation
463 (b), found by multiplying the velocity for the correct number of years, from the original
464 interferogram (a). Small black dots approximate the outline of lake Öskjuvatn. Open squares
465 represent the location of the micro-gravity stations: 'Centre' in blue, 'South-eastern' in yellow and
466 'Northern' in red. Open black square shows the location of the micro-gravity reference station on the
467 1961 lava flow.

468

469 **Fig. 8**

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

472

473 **Table I**

474 Results of the students' t-test applied to the net micro-gravity data using a set standard deviation of
475 25 μGal for each measurement and a confidence level of 95%. A value of '1' indicates significant

476 change, '0' indicates insignificant change and '-' indicates no data, at the station.

477

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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 great detail the magma intrusion that 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 Dalssen 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 Dalssen 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 stars in Fig.1b but not in Fig.1c

→ *changed captions to read:*

“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 Dalen 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*

Fig.1a

Figure1b

Fig.1c

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Figure3

Figure4

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Figure5

Figure6

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Figure7

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Table

		'88 to '89	'89 to '90	'90 to '91	'91 to '92	'92 to '94	'94 to '95	'95 to '97	'97 to '02	'02 to '03	'03 to '07	'07 to '08	'08 to '09	'09 to '10
BM														
Centre	005	1	1	1	1	1	1	1	1	1	1	1	1	1
	D-19	1	1	0	0	1	1	1	0	1	1	1	1	1
South-eastern	D-18	1	1	1	1	1	1	1	1	0	1	1	0	0
	IV16	1	1	0	1	-	-	1	1	1	-	-	-	-
	Von Knebel	0	0	0	1	0	1	0	1	1	1	1	1	1
Northern	405	1	0	0	0	1	1	0	1	1	-	-	1	0
	412	1	0	1	1	0	0	1	1	1	-	-	1	1