Deflation of the Askja volcanic system: Constraints on the deformation source from combined inversion of satellite radar interferograms and GPS measurements

Carolina Pagli a,*, Freysteinn Sigmundsson a, Thóra Árnadóttir a, Páll Einarsson b, Erik Sturkell c,1

a Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland
b Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland
c Icelandic Meteorological Office, Reykjavík, Iceland

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Abstract

The Askja central volcano in northern Iceland has been continuously subsiding at least since 1983. GPS and optical leveling tilt measurements show subsidence of at least 75 cm from 1983 to 1998 in the center of the Askja caldera, without any eruptive activity. We have performed an interferometric analysis of Synthetic Aperture Radar images (InSAR) of the area, utilizing data from the ERS satellites. We observe subsidence of the Askja caldera and its fissure swarm, up to a distance of 25 km from the volcano. We evaluate the geometry of the magma chamber at Askja, from a combined inversion of satellite radar interferograms and GPS measurements. Several models were tested, including a Mogi point source as well as an ellipsoidal source. The use of an ellipsoidal source instead of a Mogi source gives an estimate of the dimensions of the magma chamber and its deflating pressure, whereas these parameters are not independently resolved if a Mogi source is used. Two-source models were also considered in order to explain the additional subsidence observed along the Askja fissure swarm. We tested a model using two Mogi sources at different depths, a shallow ellipsoidal cavity with a deeper Mogi source, and then a shallow Mogi source with a deeper elongated ellipsoid, oriented along the fissure swarm. Results indicate that an ellipsoidal source at about 3 km depth can accommodate most of the deflation occurring in the caldera. Residual subsidence occurs along the Askja fissure swarm suggesting the existence of a deeper source of contraction. We interpret this signal in terms of subsidence of the plate boundary.

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Keywords: magma chamber; Askja volcano; deflation; ellipsoidal source; Mogi source

1. Introduction

1.1. Geology and tectonics

The Askja central volcano is located on a divergent plate boundary in the Northern Volcanic Zone (NVZ), in Iceland (Fig. 1). The plate boundary at Askja is oriented N16°E and the full spreading rate of Eurasia relative to North America, is ~2 cm/yr in the direction...
N106°E (DeMets et al., 1994). The Askja volcanic system consists of three different caldera structures, an active geothermal system and fissure swarms. The term fissure swarm is commonly used in Iceland to describe a zone of extensive fissuring and normal faulting. The largest caldera has a diameter of 8 km and formed in the early Holocene (Sigvaldason, 1979). The smallest one is located to the north of the main caldera and is today completely filled with eruptive products. The youngest caldera has a diameter of 4.5 km and is filled by Lake Óskjuvatn.

Seismic activity tends to cluster in three main areas near the Askja central volcano as described by Einarssson (1991). One cluster of earthquakes is located beneath the southeastern part of the volcano and seems to be related to the geothermal activity. The second cluster is located NE of Askja. Epicenters there mark a NE–SW oriented zone that does not resemble any geological structure at the surface. The third cluster is northwest of Askja and, as well as the previous cluster, does not have any surface expression.

As Askja is located in a rift, the volcanic activity is characterized by basaltic dike injections and fissure eruptions, but rhyolitic explosive activity has also occurred. The last rifting episode occurred in Askja in 1874–1876. The volcanic activity was focused on the northern part of the fissure swarm and in the center of Askja, where an explosive eruption occurred. The youngest caldera at Askja was formed during this rifting episode. Another period of eruptions occurred in 1921–1929 (Sigvaldason, 1979). The most recent eruption in Askja was in 1961 (Thórarinsson and Sigvaldason, 1962), and earthquake activity followed it in 1962, apparently related to an intrusion (Brandsdóttir, 1992). Recent volcanic activity in nearby volcanoes includes the Gjálp eruption beneath the Vatnajökull ice cap in 1996. At that time, a 7-km-long eruptive fissure opened midway between Bárðarbunga and Grimsvötn volcanoes, 60 km south of Askja (Einarsson et al., 1997; Gudmundsson et al., 1997). A major rifting episode occurred in the NVZ from 1975 to 1984, with intense volcanic activity being confined to the Krafla volcanic system (Einarsson, 1991). During this episode, the Krafla magma chamber inflated due to inflow of magma from depth. The inflation was interrupted at least 20 times by periods of deflation due to eruptions and dike injections.

1.2. Previous geodetic measurements in the area

Askja has been continuously deforming since crustal deformation studies started in the area in 1966. A recent overview is given by Sturkell and Sigmundsson (2000). Their data set consists of both leveling data from 1983 to 1998 and GPS measurements from 1993 to 1998 showing continuous deflation of the Askja volcano from 1983 to 1998, by at least 75 cm. The data were fitted with a Mogi source centered in the main Askja caldera at 2.8 km depth. The subsidence at Askja has been interpreted as mostly a result of magma solidification at depth. Part of the subsidence may be attributed to the location of Askja on the divergent plate boundary and drainage of magma into the Askja fissure swarm.
(Sturkell and Sigmundsson, 2000). Leveling data from Askja show that there is a gradual decay in the subsidence rate. The temporal decay of subsidence scales with $e^{-t/\tau}$, where $\tau$ is 39 yr (Sturkell et al., in press). Recent results from micro-gravity data show a net decrease of 115 $\mu$Gal from 1988 to 2003 in the center of the Askja caldera (de Zeeuw-van Dalfsen et al., 2005). This value corresponds to a minimum sub-surface mass decrease of $1.6 \times 10^{11}$ kg or a change in magma volume of 0.06 km$^3$, assuming a density of the magma of 2700 kg/m$^3$. The authors suggest that this volume is drained from the shallow magma chamber to deeper levels and conclude that the surface deformation at Askja results from a combination of cooling as well as drainage of magma. Reanalysis of GPS data from 1993 to 1998 shows that the horizontal GPS data can be better fitted with a model invoking two Mogi sources located at 3 and 16 km depth. The cause of the Askja subsidence is interpreted as cooling of magma and/or pressure reduction along the plate boundary due to spreading process. The subsidence at Askja can be caused by magma flowing out of the magma chambers to accommodate the plate spreading across Askja (Sturkell et al., in press).

2. Data

2.1. Interferograms

Interferograms were formed using images from the ERS satellites in descending passes, and were calculated using the PRISME/DIAPASON software with the standard two-pass method (Massonet and Feigl, 1998). An interferogram can be described as a deformation map, where one fringe (one full cycle of colors) represents a displacement of 28 mm along the line of sight from the satellite to the ground. All the images are acquired with a mean incidence angle of $23^\circ$ from the vertical. The resulting interferograms are most sensitive to vertical deformation. The interferograms cover all the Askja area and span different time periods in 1992–2000 (Table 1 and Fig. 2). The images were acquired in the summer and with high altitude of ambiguity, resulting in a low level of noise in all the interferograms (Table 1). The limiting factor is snow that covers the Askja volcano most of the year. For subsequent modeling, we used uncertainties of 10 mm for all the interferograms. This value is commonly considered the precision of an interferogram (Massonet and Feigl, 1998; Pedersen et al., 2003).

A total of 29 satellite radar interferograms from three different ERS satellite tracks, frame 2295, were constructed. Ten of these interferograms show good coherence on Askja and appear in this paper (Fig. 2). All of them show deflation of the Askja volcano at a mean subsidence rate of about 5 cm/yr. Four interferograms are from track 238, covering the entire Askja volcano and the northern part of the fissure swarm up to a distance of 25 km (Fig. 2a–d). In these interferograms, the shape of the deformation field is most evident. The main part of the signal consists of the subsidence centered at the main Askja caldera but some fringes are also located along the northern and southern part of the fissure swarm. The subsidence signal vanishes at a distance of approximately 25 km north of Askja. Four interferograms are from track 9, covering the entire Askja volcano and the northern part of the fissure swarm up to a distance of 15 km (Fig. 2e–h). Interferograms 2f, 2g and 2h show a clear concentric subsidence signal centered at the main Askja caldera but they are noisy along the fissure swarm. However, interferogram 2c and 2a, spanning the same time period, show a consistent subsidence signal in the main Askja caldera and along its fissure swarm, indicating that both signals are real. Interferograms 2a and 2e are from two different tracks and have been acquired under different atmospheric conditions, excluding the possibility of having the same atmospheric noise in both interferograms. The other two interferograms (Fig. 2i and l) are from track 281, covering all the main Askja caldera but not the northern part of the Askja fissure swarm. In this track, the shape of the deformation signal at the northern edge of the volcano cannot be observed. The last two interferograms (Fig. 2i and l) span the 1992–1998 and 1998–2000 periods and show a concentric fringe pattern centered at the Askja caldera indicating subsidence of the volcano. Up to nine fringes are seen in the interferogram spanning 6 yr and three fringes are evident in the 2-yr interferogram. The deformation is time-

### Table 1

<table>
<thead>
<tr>
<th>Orbits</th>
<th>Track</th>
<th>Time span</th>
<th>$h_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2096–27647</td>
<td>238</td>
<td>1995–2000</td>
</tr>
<tr>
<td>b</td>
<td>2096–12617</td>
<td>238</td>
<td>1995–1997</td>
</tr>
<tr>
<td>c</td>
<td>17627–23138</td>
<td>238</td>
<td>1998–1999</td>
</tr>
<tr>
<td>d</td>
<td>17126–23138</td>
<td>238</td>
<td>1998–1999</td>
</tr>
<tr>
<td>e</td>
<td>1867–27919</td>
<td>009</td>
<td>1995–2000</td>
</tr>
<tr>
<td>g</td>
<td>11887–27919</td>
<td>009</td>
<td>1997–2000</td>
</tr>
<tr>
<td>h</td>
<td>10174–17398</td>
<td>009</td>
<td>1993–1998</td>
</tr>
<tr>
<td>i</td>
<td>5436–17169</td>
<td>281</td>
<td>1992–1998</td>
</tr>
</tbody>
</table>

Interferometric pairs by the ERS satellites, frame 2295. $h_a$ is the altitude of ambiguity, the difference in topographic elevation that produces one (artefactual) fringe in an interferogram.
progressive and thus more evident in the interferograms covering longer periods.

2.2. GPS

The GPS surface displacement solutions used in this paper are from Sturkell and Sigmundsson (2000) and cover the 1993–1998 period. We used data from 22 points (Fig 2a and m), each measured for at least three consecutive 8-h-long sessions. Data were collected every 15 s. Both in 1993 and in 1998, the reference station was DYNG which was occupied for the whole duration of the campaigns. The 1993 data were processed with the Bernese GPS software version 3.3, using broadcast orbits, while the 1998 data were processed with the version 4.0 of the same software, using precise orbits from the Center for Orbit Determination in Europe (CODE). Using broadcast orbits
instead of precise orbits did not significantly affect the uncertainty of the results, because of short distances between the reference station and the other GPS stations (≤ 18 km) (Sturkell and Sigmundsson, 2000). The horizontal displacements show contraction towards the caldera. The vertical deformation field not only shows a circular deflating pattern but it is also affected by an unexplained regional component with subsidence on the west side of Askja relative to its east side.

3. Modeling

We model the deformation signal assuming a uniform elastic isotropic half-space with a Poisson’s ratio, $\nu$, of 0.25 and a rigidity, $\mu$, of 30 GPa. We used an inversion procedure employing a simulated annealing algorithm followed by a derivative-based method, as described by Cervelli et al. (2001).

Before running the inversion the data are first unwrapped, masked and quadtree partitioned (Fig. 3).
The unwrapping transforms the interferometric deformation signal, that is expressed as a series of fringes, into a continuous scale (Gudmundsson et al., 2002). The masking removes from the data set all the incoherent areas and the quadtree partitioning reduces the data size, using a two-dimensional quantization algorithm (e.g., Jónsson et al., 2002). The resultant data represent the statistically significant part of the deformation signals. Our quadtree interferograms have a number of data points that vary between 200 and 400. These data are used as input into the inversion.

We can express the relationship between surface deformation and source parameters by: $d = G(m) + e$, where $d$ are the surface displacement data, $e$ is the observation error, $m$ are the source parameters (e.g., the location, and volume change for a Mogi source), and $G$ is the Green’s function that connects $d$ to $m$. We seek the optimal model ($m$) that will minimize the difference between the observations and model predictions using a nonlinear optimization method. To find this absolute minimum, we use a procedure that involves both a random search and a derivative-based method. The derivative-based method will make the solution approach the minimum and the random search permits it to escape local minima, to find the absolute minimum value.

We consider different source types in the modeling, a Mogi source and a rotational ellipsoid. First, we inverted the InSAR data alone, then we performed a joint inversion of InSAR and GPS data, using a Mogi source, a rotational ellipsoid, and a combination of both. We used two Mogi sources at different depths, a shallow ellipsoid along with a deeper Mogi source, and a shallow Mogi source along with a deeper elongated ellipsoid.

### 3.1. Mogi model

Initially, we modeled the subsidence at Askja with a Mogi source. We estimate four model parameters (latitude, longitude, depth and volume change of the source) and an offset to correct the uncertainty in identifying the fringe corresponding to zero displacement. For inversion of the InSAR data only, we left all the parameter bounds fairly loose at the beginning of the inversion. We modeled independently 10 different interferograms. Modeling results showed that the source location was varying within few hundred meters. We subsequently fixed the source location, to mimic better the behavior of a magma chamber that does not move with time. We modeled again all the interferograms fixing the location of the source. We use the modeling result from an interferogram spanning 6 yr and with low noise (Fig. 2i) to fix the source location (65.046°N, 16.763°W). This value does not differ much from the average source location (65.046°N, 16.761°W). Results are summarized in Table 2. We show the best-fit fault parameters, their RMS and reduced $\chi^2$, $r^2\Sigma^{-1}r/(n - m)$, where $r$ is the residual, $\Sigma$ is the data covariance matrix, $n$ is the number of data points and $m$ is number of model parameters. The reduced $\chi^2$ is expected to be 1 if optimal solutions are found and our assessments of the data errors are correct. However, in Table 2 some of these values are much lower than 1, indicating that an uncertainty of 10 mm is too high for some interferograms. However, we did not decrease the uncertainties on the interferograms (it would not change the resulting model). The source is located at a mean depth of 3.5 km, and has a mean volume change of 0.0021 km³/yr (Table 2). Sturkell and Sigmundsson (2000) located the Mogi source at 65.046°N, 16.767°W at a depth of 2.8 km with a volume change of 0.0025 km³/yr from 1993 to 1998. Our results indicate that the source is somewhat deeper. Despite the good fit, systematic residual signals can be identified. A concentric fringe pattern of approximately 8 mm/yr of residual subsidence is located near the W shore of Lake Óskjuvatn. This unmodeled subsidence is related to the use of a Mogi source that cannot completely account for the deformation in the area of the caldera. Additional residual subsidence of approximately 6 mm/yr takes place along the northern part of the Askja fissure swarm, all the way from the Askja center to the edge of the interferogram, up to 25 km from the volcano. This residual signal suggests a contracting source along the fissure swarm. The only residual uplift is located near the NE shore of lake Óskjuvatn. The signal is a small concentric fringe pattern of approxi-
The GPS measurements from 1993 to 1998 have formal uncertainties on the horizontal displacements between 1 and 2.5 mm, and between 8 and 10 mm on the vertical. Initially, the GPS displacements were calculated relative to the reference station DYNG. However, the reference station is located well within the deformation field and all the other stations have to be corrected for its displacement. We included this correction in our modeling. During each model run, the inversion procedure calculates the movement of DYNG and systematically adds it to all the other stations. The corrected horizontal displacements show contraction towards the center of the caldera (Fig. 2a and m).

The GPS measurements span the time from 1993 to 1998, while the interferograms span various time periods between 1992 and 2000. However, the subsidence rate at Askja between 1992 and 2000 was practically constant, since it appears to decay over a much longer time period, with a decay constant of 39 yr (Sturkell et al., in press). This allowed us to consider the GPS data and the whole InSAR data set together in the inversion. The 1993–1998 GPS displacements were multiplied by a time scaling factor, in order to obtain the displacements relative to the time spanned by the different interferograms. As for modeling of the InSAR data alone, we estimate the source location after some preliminary modeling of the 10 different interferograms and our estimate of the co-temporal GPS displacements. We use the modeling result from an interferogram spanning 6 yr and with low noise (Fig. 2i) to fix the source location. We model again all the data fixing the location of the source at 65.044°N, 16.769°W. Modeling results indicate that the source is located at a mean depth of 3.5 km, and has a mean volume change of 0.0021 km³/yr (Table 3). The residual GPS horizontal displacements show an unmodeled contraction towards the center of the caldera, suggesting that a second deeper source of deformation is present or that a different source shape should be considered.

### 3.2. Ellipsoidal source model

We consider an ellipsoidal source in order to minimize the residual subsidence in the main Askja caldera. In addition, ellipsoidal models can provide a direct estimate of the pressure decrease in a magma source and its dimensions. These parameters are of great interest and have not been resolved before at Askja. Residual subsidence along the Askja fissure swarm is not explained by this source.

Ellipsoidal sources have been used elsewhere to fit geophysical data, e.g., by Battaglia et al. (2003). They modeled GPS, leveling and two-color EDM data in the Long Valley area from 1975 to 1999, using both a Mogi and a rotational ellipsoidal source. They found that the ellipsoidal source fits both the vertical and the horizontal data, while the Mogi model cannot. In Iceland, ellipsoidal models have been tested by Ewart et al. (1991). They modeled leveling data collected between 1976 and 1985 in the Krafal area, using spherical sources and a triaxial ellipsoid. They conclude that

<table>
<thead>
<tr>
<th>Fig. 2</th>
<th>Reduced $\chi^2$</th>
<th>RMS (mm)</th>
<th>Depth (km)</th>
<th>$\Delta V^a$ (km³)</th>
<th>$\Delta V^a$ per yr (km³/yr)</th>
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<tr>
<td>d</td>
<td>0.39</td>
<td>5</td>
<td>3.6</td>
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<tr>
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<td>5</td>
<td>3.7</td>
<td>0.0041</td>
<td>0.0020</td>
</tr>
</tbody>
</table>

$^a$ $\Delta V$ is the volume decrease of the source.
the ellipsoidal source provided a good fit but they obtained a shallow depth of magma storage that made this model less plausible.

For our ellipsoidal source model, we used the analytic expressions derived by Yang et al. (1988). The resulting displacement field is a function of the pressure change, $\Delta P$, the ellipsoidal geometry and its orientation (semi-major and semi-minor axes, depth, dip angle, azimuth angle of the major axis and location). In total, there are eight model parameters. The volume change, $\Delta V$, caused by a pressure change in the ellipsoidal cavity, is (Tiampo et al., 2000):

$$\Delta V = \frac{\Delta P}{\mu} \pi ab^2$$

where $a$ is the semi-major axis and $b$ is the semi-minor axis of the ellipse. First, we modeled the InSAR data only (Table 4) and then we proceeded with a combined inversion of InSAR and GPS (Table 5). Four interferograms were selected for the modeling. We chose interferograms a, e, i and l (Fig. 2), because they have high coherence in the area of the caldera. For the inversion, we started by leaving all the bounds loose. The source could assume any orientation in the half-space, and its pressure could vary between 0 and 90 MPa. The upper limit on pressure was set to be in the range corresponding to the limit likely to cause failure of the host rock. According to the Anderson theory of faulting, under compressive forces, the deviatoric stress required to cause a thrust fault at 3 km depth is ~100 MPa, assuming a coefficient of friction of 0.85 and a rock density of 2900 kg/m$^3$ (Turcotte and Schubert, 2002, p. 345). The resulting models showed a good fit but in many cases the pressure threshold was exceeded and the models had a pressure decrease on the order of a GPa. These models were rejected as such a high pressure would cause faulting in the host rock of the magma chamber, while no significant increase in earthquakes have been recorded in the Askja caldera.

To avoid too high pressure changes, we increased the size of the ellipsoidal cavity. The source location was fixed, using modeling results from interferogram 2i, as in previous cases. Modeling results of InSAR data are shown in Table 4. The mean source depth and volume change are the same as for a Mogi model. The associated pressure change is about 1 MPa/yr. The fit of the ellipsoidal model to the data is much better than for the Mogi model. The RMS values and the reduced $\chi^2$ are in all cases lower. This indicates an increased fit of the model, given that the uncertainties are the same and that the number of model parameters (eight) is still low compared to the total number of data points. However, residual subsidence signal is still present near the W shore of Lake Óskjuvatn. Residual subsidence along

### Table 4

<table>
<thead>
<tr>
<th>Fig. 2</th>
<th>Reduced $\chi^2$</th>
<th>RMS (mm)</th>
<th>Depth (km)</th>
<th>Semi major axis (km)</th>
<th>Semi minor axis (km)</th>
<th>Azimuth (N’E)</th>
<th>Dip$^a$ (°)</th>
<th>$\Delta P^b$ (MPa)</th>
<th>$\Delta V^c$ (km$^3$)</th>
<th>$\Delta V^c$ per yr (km$^3$/yr)</th>
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</thead>
<tbody>
<tr>
<td>a</td>
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<td>2.6$^d$</td>
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<td>2.6$^d$</td>
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<td>1.4</td>
<td>0.0027</td>
<td>0.0014</td>
</tr>
</tbody>
</table>

$^a$ Dip is the angle down from the horizontal.  
$^b$ $\Delta P$ is pressure decrease.  
$^c$ $\Delta V$ is the volume decrease of the source.  
$^d$ Parameter held fixed in the modeling.
the fissure swarm is also present, but a better fit in this area is not expected from use of one shallow source only.

The ellipsoidal source was also used in the combined inversion of InSAR and GPS data. All the bounds on the model parameters were set like in our preceding modeling of the InSAR data alone. The optimal model parameters from the combined inversion are similar to those found by inversion of the InSAR data only (Table 5), and the fit of the ellipsoidal model to the joint data set is better than for the Mogi model.

We conclude that both the InSAR and the GPS data are better explained with a shallow ellipsoidal source than with a Mogi source.

3.3. Two sources models

Models with two sources were used in a joint inversion of InSAR and GPS data, in order to test contribution from deeper sources on the deformation field. Another volcano in Iceland where such a deep source has been invoked is the Krafla volcanic system in North Iceland (de Zeeuw-van Dalfsen et al., 2004). InSAR images of the Krafla area have been interpreted as magma accumulation at about 21 km depth, near the crust–mantle boundary. As Krafla and Askja are in a similar tectonic setting, a similar behavior of these volcanoes could be expected.

In order to search for an eventual deep source under Askja, interferograms that cover both the Askja caldera and the fissure swarm were used in the inversion. We selected two interferograms, a and e (Fig. 2a and e), because they show a consistent signal in the Askja caldera and also along the fissure swarm. They have minor atmospheric noise.

First, we inverted the data assuming two Mogi sources. The location of the shallow Mogi source was fixed to 65.044°N, 16.769°W, as suggested from our previous modeling. Results are shown in Table 6. The depth of the shallow Mogi source decreases to 3 km, and its associated volume change decreases too, with respect to results from using only one Mogi source. The deeper source is located 4 km horizontally away from the shallow source at a depth of about 20 km. The fit of the two Mogi sources model (Table 6) is better than one Mogi source (Table 3) but similar to the shallow ellipsoidal (Table 5). A model with two Mogi sources as well as a model with one ellipsoidal source involves estimation of eight model parameters. However, the model with one ellipsoid is favored, because it is a simpler model for the magmatic system.

We also inverted the data assuming a shallow ellipsoidal source and a deep Mogi source. Only the location of the shallow ellipsoidal source was fixed, at 65.045°N, 16.771°W, as suggested from our previous modeling. Results are shown in Table 7 and Fig. 4. The RMS of this model is better than for any other model for interferogram 2a but it is similar as for two Mogi sources (Table 6) for interferogram 2e. The model fits about 88% of the total deformation. The shallow ellipsoid is oriented about N 135°E and dipping ~23°E, consistently with previous results from joint inversion (Table 5). The deep Mogi source is located 3 km west of the center of the ellipsoidal source. In Table 6, the deep source is located at the same depth (about 20 km) both in interferogram 2a and 2e, while in Table 7 the source depth is at 21 km depth in interferogram 2e but it is only 11 km depth in interferogram 2a. A depth of the source of about 20 km is considered most likely, as it would fit with the two Mogi sources model.

**Table 6** Best-fit InSAR and GPS inversion results for two Mogi sources

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<thead>
<tr>
<th>Fig. 2</th>
<th>Reduced χ²</th>
<th>RMS (mm)</th>
<th>Depth (km)</th>
<th>Depth (km)</th>
<th>ΔV/a shallow source (km³)</th>
<th>ΔV/a per year (km³)</th>
<th>ΔV/a deep source (km³)</th>
<th>ΔV/a per year (km³/yr)</th>
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<td>14</td>
<td>3</td>
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<td>0.0074</td>
<td>0.0015</td>
<td>0.0772</td>
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<tr>
<td>e</td>
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<td>11</td>
<td>2.9</td>
<td>21</td>
<td>0.0067</td>
<td>0.0013</td>
<td>0.0842</td>
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</tbody>
</table>

*a ΔV is the volume decrease of the source.

**Table 7** Best-fit InSAR and GPS inversion results for one shallow ellipsoid fixed at 65.045°N, 16.771°W and a deep Mogi source. The ellipsoid is oriented ∼N135°E and dipping ∼23°E.

<table>
<thead>
<tr>
<th>Fig. 2</th>
<th>Reduced χ²</th>
<th>RMS (mm)</th>
<th>Depth (km)</th>
<th>Depth (km)</th>
<th>ΔV/a shallow source (km³)</th>
<th>ΔV/a per year (km³)</th>
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<th>ΔV/a per year (km³/yr)</th>
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<td>0.0069</td>
<td>0.0014</td>
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<td>0.0185</td>
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</tbody>
</table>

*a ΔV is the volume decrease of the source.
However, a small residual subsidence signal is still present near the W shore of Lake Óskjuvatn. Additional residual subsidence along the fissure swarm is also present, indicating that the deep Mogi source cannot explain most of the deformation along the Askja fissure swarm (Fig. 4c).

The additional subsidence along the fissure swarm may be caused by subsidence of the plate boundary as the Askja volcano is located on an active rift. For comparison, subsidence of 6.5 mm/yr along the plate boundary at the Reykjanes Peninsula, SW-Iceland has been observed (e.g., Vadon and Sigmundsson, 1997). It has been suggested that the subsidence is due to lack of magma inflow to compensate for the rifting. As a last model, we conduct a joint inversion of InSAR and GPS data for subsidence caused by a shallow Mogi source and subsidence along the fissure swarm caused by an elongated ellipsoid of pressure decrease. The first source should model most of the deformation at the caldera, while the elongated ellipsoid should model the additional subsidence along the fissure swarm. We try this model on only one interferogram (2a) as it covers the largest area around Askja. The location of the Mogi source was fixed at 65.044°N, 16.769°E, as indicated by previous modeling. The ellipsoid was fixed at an azimuth of N16°E (oriented along the fissure swarm), and assumed to be horizontal. A best-fit model consists of a 3-km-deep Mogi source, located in the center of the Askja caldera and a 27-km-deep ellipsoid. The model has a reduced $\chi^2$ of 3.94 and an RMS of 14 mm. The fit of this model is not as good as any of the other two source models.

4. Discussion

Subsidence at the Askja volcano has been measured since 1983, without any eruptive activity. Similar subsidence patterns have been observed at other calderas worldwide. Episodes of inflation followed by deflation have been observed, e.g., at the Campi Flegrei caldera, Italy since 1969, without any eruptions. Lundgren et al. (2001) observed continuous subsidence of the Campi Flegrei caldera with InSAR from 1993 to 1998. They model the deformation with a subhorizontal rectangular contracting tensile dislocation at about 3 km depth. Their interpretation favors a model with a zone of deflation due to hydrothermal diffusion. Pressurization of fluids above the magma chamber caused by inflow of magma into the chamber could explain uplift while hydrothermal diffusion of the pressurized fluid could explain the following subsidence. This process is unlikely at the Askja caldera because gravity study indicates a subsurface mass decrease (de Zeeuw-van Dalmen, et al., 2005).

Results from joint inversion of InSAR and GPS measurements indicate that a shallow deflating ellipsoidal source can explain most of the deformation in the Askja caldera. Two sources modeling reveals that the fit is somewhat better if a Mogi source at about 21 km depth is included but residual subsidence is still observed along the Askja fissure swarm, suggesting that a deep elongated source of contraction might better explain the deformation than a deep Mogi source. However, our model using a deep elongated ellipsoid cannot improve the fit found by using other two source mod-
This may suggest that the elastic half-space is not a valid approximation for deep processes. The deep elongated ellipsoid is located at 27 km depth, where ductile processes are dominant. Our interpretation of the subsidence along the Askja fissure swarm is that it represents subsidence of the plate boundary, as observed, e.g., on the Reykjanes Peninsula. This hypothesis can be tested with more advanced modeling, using an elastic layer over a ductile one.

The surface deformation at the Askja caldera has been interpreted as due to a combination of cooling as well as drainage of magma (de Zeeuw-van Dal~sen et al., 2005). According to their calculations, a magma volume of 0.06 km$^3$ was drained from the shallow magma chamber to deeper levels from 1988 to 2003. Our modeling results show that upon removal of the subsidence signal of the Askja caldera, no large residual uplift is evident. The only observed uplift is a small signal of 6 mm/yr in a restricted area, NE of lake Öskjuvatn. Therefore, if magma drainage is taking place we must assume that the magma is flowing to a deep source that would not give any detectable uplift in our longest interferogram (6 yr). We use the formula given by Johnson et al. (2000) to obtain the deflation volume related to a volume of magma of 0.06 km$^3$, flowing into a deeper magma chamber. We assume a Poisson’s ratio, $\nu$=0.25, host rock shear modulus, $\mu$=30 GPa, and an effective magma bulk modulus $k$=17 GPa. We estimate that if the magma from the shallow Askja chamber flows to another single source, its depth must be at least 15 km in order to be “invisible” in a 6-yr interferograms (causing less than 6 mm change). Alternatively, a magma volume of 0.06 km$^3$ from 1988 to 2003 could flow into the ductile lower crust and play a role in accommodating widening due to plate spreading across Askja. Over a 15-yr period the plate boundary has spread approximately 30 cm. Given that the visible part of the fissure swarm in our interferograms is about 30 km and assuming a 10-km thickness of the ductile layer, we estimate that up to 0.09 km$^3$ of magma could be accommodated in the ductile lower crust as a result of widening across the plate boundary. This hypothesis is consistent with the suggestion of Menke and Levin (1994) that magma migrates to shallow magma chambers where it is cooled by conductive and hydrothermal mechanisms and it is than being abducted away to deeper depths.

5. Conclusions

Joint inversion of InSAR and GPS data from 1992 to 2000 show that most of the deflation at the Askja caldera can be accommodated by a 3-km-deep ellipsoidal source. The total volume of the preferred ellipsoidal source is about 60 km$^3$. We estimate that the volume change of the shallow magma chamber is 0.0021 km$^3$/yr, if a single shallow source model is used, but this value decreases using two source models. Subsidence of the Askja fissure swarm in addition to the caldera deflation is well observed in several interferograms. We suggest that this signal is due to subsidence of the plate boundary of about 6 mm/yr, but more complicated modeling efforts are needed to resolve its nature.

Large residual uplift, that could accommodate a volume of 0.06 km$^3$ over a 15-yr period, is not visible in any of our residual images. Therefore, if magma is being drained from the shallow Askja magma chamber, it is flowing down to a depth of more than 15 km. This process may contribute to accommodation of plate movements in the ductile lower crust. Magma volume flowing at this depth would not cause any detectable surface deformation in our interferograms.

Acknowledgements

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References


