Satellite radar interferometry 1993–1999 suggests deep accumulation of magma near the crust-mantle boundary at the Krafla volcanic system, Iceland

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[1] Deep magma accumulation near the crust-mantle boundary (21 km depth) at the Krafla volcanic system is suggested from InSAR observations. A best fit model, derived from four interferograms covering 1993–1999, comprises an opening dike, representing plate spreading and post-rifting deformation, and two Mogi sources. A Mogi source deflating at a rate of ~0.3 × 106 m3/yr coincides with the shallow Krafla magma chamber while a deeper inflating Mogi source, further north, at 21 km depth, inflates at a rate of ~26 × 106 m3/yr. The inflating source is at or near the crust-mantle boundary as identified by seismic studies and is interpreted as accumulating magma.


1. Introduction

[2] Magma accumulation beneath volcanic areas has been studied extensively with various geodetic techniques. Most of these studies locate magma sources at depths within the brittle crust. Only few studies discuss the existence of deeper magma reservoirs. For Krafla volcano, Tryggvason [1986] concluded, from geodetic data spanning the 1984 eruption, that a vertically stacked series of chambers exists at depths of 2.6 km, less than 10 km and deeper than 20 km. At Askja volcano, N-Iceland, 1993–1998 GPS data has been used to infer the location of two magma sources, at 3 and 16 km depth (E. Sturkell et al., 1983–2003 decaying rate of deflation at Askja caldera: Pressure decrease in an extensive magma plumbing system at a spreading plate boundary, submitted to Bulletin of Volcanology, 2004). In this paper we discuss new analysis of Interferometric Synthetic Aperture Radar (InSAR) images from the Krafla area that can be interpreted in terms of magma accumulation at the crust-mantle boundary at 21 km depth.

[3] The Krafla volcanic system in N-Iceland (Figure 1) consists of a central volcano which encompasses a 10 km by 7 km wide caldera, mostly filled by younger lavas. The system is transected by an approximately 100 km long fissure swarm striking N010°E. Detailed seismic studies have been conducted in the Krafla area, e.g., by Brandsdóttir et al. [1997] and Menke et al. [1998]. The crust-mantle boundary underneath Krafla has an asymmetric dome shape. Good seismic reflection originates at the Moho discontinuity. The minimum boundary depth of ~19 km is reached 5 km east of the caldera centre. This depth increases asymmetrically in all directions, at a rate of 1–2 km for each 10 km distance on a north-south profile next to the caldera. Activity at the Krafla volcanic system is characterised by rifting episodes separated by long periods of dormancy. Two historical rifting episodes occurred in 1724–1729 and 1975–1984. During the most recent episode, 9 of 20 deflation/inflation cycles were accompanied by basaltic fissure eruptions in the Krafla fissure swarm.

[4] Geodetic data show that the area around the central volcano was deflating at 5 cm/yr in the 1989–1992 period [Tryggvason, 1994] decaying to 2.4 cm/yr from 1992 to 1995 [Sigmundsson et al., 1997]. A shallow Mogi point source can explain this deflation and its location has been well constrained by several studies at 65.72°N, 16.80°W and 2.7 km depth [Tryggvason, 1986, 1994; Sigmundsson et al., 1997; Arnadóttir et al., 1998]. Krafla is located on the Mid-Atlantic Ridge where the average full spreading rate is ~1.9 cm/yr. GPS measurements in north Iceland have, however, revealed a full spreading rate of 6 cm/yr from 1987 to 1990 in the Krafla area, decaying to 4 cm/yr from 1990 to 1992. This higher rate is attributed to post-rifting relaxation of stresses in the crust after the 1975–1984 rifting episode, and has been modelled e.g., by Foulger et al. [1992] and Pollitz and Sacks [1996].

[5] Analysis of InSAR images acquired by ERS1 and ERS2, has proven a valuable tool when studying the ongoing deformation at Krafla [Sigmundsson et al., 1997; Henriot et al., 2001]. Previous work concentrated on the readjustment of the Krafla spreading segment e.g., crustal deformation after the last rifting episode. In this paper we analyse interferograms covering the Krafla region from 1993 to 1999. A signal previously unaccounted for, associated with small but widespread uplift, is attributed to deep accumulation of magma. An alternative model,
formation of twelve interferograms, with reasonable coherence. Four of these, spanning from 2 to 6 years, were selected for modelling (Table 1 and Figure 2). A Digital Elevation Map from the Icelandic Land Survey and post-computed orbits from the European Space Agency were used to correct for topographic effects. Residual orbital fringes were removed by subtracting linear range-change gradients.

[7] Four interferograms (Table 1, Figures 2a–2d) are analysed here. Pair-wise comparison [Massonnet and Feigl, 1998] was used to confirm deformation signals and discriminate them from atmospheric and topographic artifacts. Three different deformation signals can be distinguished: a linear fringe pattern aligned along the rift axis, localized concentric fringes in the centre of the Krafla caldera and a widespread concentric fringe pattern centered 15 km north of Krafla. Each phase fringe represents a range change of 28 mm. Small atmospheric artifacts are present in the upper left corner of Figure 2d.

[8] The linear fringe pattern is at least 20 km long, striking N010°E and most likely shows the combined effect of plate spreading and post-rifting relaxation. The concentric fringes in the centre of the caldera cover an area 3 km across. The increase in range suggests deflation in this area, amounting to ~5 cm in the 1993–1999 interferogram. Both these features have been previously described [Sigmundsson et al., 1997; Hervig et al., 2001]. The widespread concentric fringes 15 km north of the Krafla centre (8 cm in the 1993–1999 interferogram) have, however, not been identified before. The signal shows a decrease in range, representing inflation, and covers a roughly circular area 50 km across.

3. Modelling

[9] Processes contributing to the widespread uplift signal may include post-rifting stress relaxation and/or deep accumulation of magma. To evaluate the effect of post-rifting relaxation, the models of Pollitz and Sacks [1996] were considered. The average 1992–2000 velocity field was calculated (F. Pollitz, personal communication, 2004) using an Earth model with one of the “acceptable” viscosity structures of Pollitz and Sacks [1996] (with \( \eta_a = 2 \times 10^{19} \) Pa s, and \( \eta_m = 4 \times 10^{18} \) Pa s), and considering rifting along their south and central Krafla segments (see their Figure 10). The results predict horizontal postrifting opening rates of ~1 cm/yr on both sides of the rift and a

## Table 1. Best Fit Model Parameters of Displayed Interferograms

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### Notes:

- The M1 Mogi source is located at 65.83°N, 16.73°W at 21 km depth, M2 is located at 65.72°N, 16.78°W at 2.4 km depth. The modelled dislocation has a length of 53 km and a width of 85 km; the strike is N11°E and the dip 78°W. The centre of the upper edge of the dislocation is located at 65.64°N, 16.84°W at 4.6 km depth. Strike-slip and dip-slip components are fixed at 0 cm. ha is the altitude of ambiguity of the interferograms.

- These parameters are the outcome of the simulated annealing algorithm. The derivative-based method did in this case not improve the result.
maximum uplift of $\sim$2 mm/yr (F. Pollitz, personal communication, 2004). This is only $\sim$15% of the observed inflation rate so this model can therefore not explain the InSAR observations. We explore if the widespread uplift can be attributed to deep magma accumulation, utilizing elastic deformation models. These are simple representations of the short-term response to magma accumulation that takes place well below the brittle-ductile transition, within a viscoelastic regime. Because of its anticipated small effect, the contribution of post-rifting adjustment to the observed uplift was not considered in these models.

[10] The InSAR data were unwrapped and the data size was reduced using a two-dimensional quad-tree partitioning algorithm [e.g., Welstead, 1999]. An inversion procedure using a simulated annealing algorithm followed by a derivative based method [Cervelli et al., 2001] was then applied. Initially we modelled the observed widespread fringe pattern, assuming one inflating Mogi source in an elastic half-space.
[Mogi, 1958], with loose initial model bounds. The four modelled interferograms showed similar source locations, 65.87° ± 0.18°N, 16.71° ± 0.76°W with a depth of 21 ± 3 km. A uniformly opening sill model was also tested, but did not yield a better fit. Best results were found considering the three suggested deformation processes: two Mogi point sources and an opening dislocation aligned along the rift axis.

First we modelled the interferogram with the longest time-span (6 years), leaving all model bounds loose. It displays the strongest deformation signals and hence the best signal to noise ratio. Resulting model parameters (see caption Table 1) are well constrained and the model (Figure 2e) reduces the RMS of the data from 2.97 cm for a null-model to 0.63 cm (Figure 2i and Table 1). The parameters found for the deflating Mogi source agree with those found by previous studies [Sigmundsson et al., 1997; Henriot et al., 2001]. The opening dislocation is a simplified model reproducing the effects of plane spreading and superimposed post-rifting deformation. We fix the source location parameters from the inversion of the 1993–1999 interferogram, during inversion of the other three data sets, and optimise only for the two Mogi volumes and the opening of the dislocation source. The residual signal is less than 1 cm for all interferograms.

The results of the inversion are displayed in Figures 2e–2h and summarized in Table 1. The yearly opening decays from 3.4 cm/yr from 1993 to 1999 to an average of 2.5 cm/yr from 1996 to 1999. Post-rifting relaxation is expected to decay with time. The deflating Mogi source, representing a shallow magma chamber, has a depth of 2.4 km and an average volume change of −0.31 × 10^6 m^3/yr, corresponding to surface subsidence of 8.6 mm/yr. This subsidence can be caused by cooling/contraction of the chamber, magma drainage from the chamber or geothermal exploitation of the Krafla area [Sigmundsson et al., 1997; Rymer et al., 1998]. The inflating Mogi source has a depth of 21 km and an accumulation rate of 25.9 × 10^6 m^3/yr which is two orders of magnitudes larger than the yearly volume change of the deflating Mogi source. The depth of it is close to the crust-mantle boundary where we visualise magma to be accumulating.

4. Discussion and Conclusions

We take the relatively good fit of our simple models as an indication that magma accumulation is responsible for the widespread uplift, and suggest that post-rifting deformation and plate movements are mostly mimicked by the opening dislocation. The deep Mogi source then suggests that from 1993 to 1999 a total of ~0.15 km^3 magma accumulated at 21 km depth beneath the Krafla area. This volume may be a low estimate because elasticity is assumed, rather than rheological properties appropriate for ductile crust. The lower crust is likely to accommodate part of the magma accumulation by ductile flow, limiting the effect on the surface. The volume inferred to have accumulated from 1993–1999 is already a significant fraction of the volume of 1 km^3 thought to have moved from a deeper source during the Krafla fires [Tryggvason, 1995].

Our results suggest accumulation of magma at deep levels under Krafla in the decades after termination of a rifting episode. We suggest that co-rifting pressure decrease of the deeper source stimulates this subsequent inflow of magma. The density contrast between the lower crust and mantle may trap magma there, regardless of the lower than average contrast of 90 ± 10 kg/m^3 [Gudmundsson, 2003]. The shallowing of the Moho towards the Krafla rift axis [Brandsdóttir et al., 1997] may focus magma flow towards it. When pressure in the deep source reaches a critical value, magma migrates to the shallow magma chamber from where it can eventually erupt. This complex magma plumbing system is consistent with long periods of dormancy (200–1000 yr) between rifting events.

Our results derive from a relatively simple model. Another simple model would consider the deep magma source as a pressure source at the base of a thin elastic plate. This we consider, however, not suitable in our case as the “plate” overlying the magma source is thick (~21 km) and its lower half is viscoelastic, as well as the mantle beneath it. A more sophisticated Earth model would use brittle and ductile layers which might modify the results. Another improvement would be to use existing GPS data [e.g., Völkelsen, 2000] to calibrate the interferograms. Further studies should also consider if post-rifting adjustment may eventually contribute to the observed signal.

This paper demonstrates the possibility to study deep accumulation of magma using InSAR, despite minimal expressions of such sources at the surface. Our observations are consistent with a deep magma source beneath Krafla, as suggested by previous tilt studies [Tryggvason, 1986]. Such deep sources may play a major role at Icelandic volcanic systems, and elsewhere, and have to be considered to fully understand the dynamics of magmatic systems.

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