Post-eruptive gravity changes from 1990 to 1996 at Krafla volcano, Iceland

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Abstract

The 1975–1984 Krafla rifting episode was a major lava- and dyke-producing event associated with the release of extensional strain accumulated over more than 200 years at the divergent plate boundary in North Iceland. The present work provides a unique example of gravity decreases and increases sustained over a long period following a major eruptive episode at a rift volcano. After height correction, persistent net gravity decreases over the source of observed Mogi-type deflation occur with gravity increases occurring further away from this centre of deformation. Gravity decreases are interpreted in terms of drainage from a shallow magma chamber. The net gravity decreases require that at least 4×10^{10} kg of magma must have been drained during the 6-year observation period. Assuming a density of 2700 kg m^{-3}, this magma would occupy 1.5×10^{7} m^3 and by analogy with results obtained for Kilauea, this implies a magma chamber volume change of 4.1×10^{6} m^3. This is consistent with the chamber volume change deduced from ground deformation data assuming a Poisson's ratio of 0.25 and a Mogi source. Net gravity increases are more spatially extensive and are most likely caused by migration of the steam–water interface and/or closure of micro-fractures in lavas above the magma chamber during post-eruptive cooling and contraction. We present a model for the Krafla magma chamber in which a cooling, contracting and draining magma body causes subsidence at the surface. These results contrast with observations from the Askja caldera, Iceland, where post-eruptive deflation has been shown to be accompanied by negligible net gravity changes above the Mogi-type source in the caldera. Long-term post-eruptive deflation and magma drainage have not been observed at subduction-related volcanoes; this may be a function of a difference in magma viscosity.

Author Keywords: gravity; Krafla volcano; magma

Introduction

The Krafla volcanic system in Northeast Iceland consists of the Krafla central volcano and a 100-km-long transecting fissure swarm. It was last active between 1975 and 1984 when lava was erupted at, and to the north of, the central volcano and dykes were injected along most of the fissure zone. The Krafla volcanic system forms part of the Northern Neovolcanic Zone in Iceland, which is a broadly N–S trending region of active spreading along the axial rift boundary between the European and American plates. The mean half-spreading rate is 10 mm a^{-1}.

An 8 km×10 km caldera has been identified at Krafla (Fig. 1) and is thought to have been formed during an explosive eruption of acidic rocks and the formation of rhyolite and dacite ridges during the last inter-glacial period, about 0.1 Ma ago (Saemundsson, 1998). Post-collapse features such as hyaloclastite ridges and post-glacial activity, including some 35 fissure eruptions (Bjornsson, et al., 1979), have largely obliterated the surface evidence for the caldera, although exploratory drilling and petrologic data (Armannson et al., 1987) have provided supporting evidence. A high-temperature geothermal field (>340°C at 2 km depth) within the caldera (Stafansson, 1981) is exploited by a power plant which produced about 30 MW of electricity throughout the winter months during the present study period.

Although micro-gravity techniques have been applied to the investigation of dynamic processes in various types of volcanoes (e.g., Rymer, 1996), very few studies have been undertaken at spreading rifts. Examples include an earlier study of Krafla volcano (Johnsen et al., 1980) and of Askja caldera in N. Iceland (Rymer and Tryggvason, 1993). In such volcanic settings, the stress field is dominantly tensional and the rock types basaltic in contrast to the andesitic subduction-related systems usually considered. However, the large magma volumes involved and the fact that rift volcanoes tend to be relatively subdued topographically mean that the application of micro-gravity techniques is more straightforward than in many more rugged volcanic settings.

The geology and deformation history of the Krafla system (Sigmundsson et al., 1997) is well-known providing critical and comprehensive constraints on the interpretation of micro-gravity data. Here, we present micro-gravity data for the period 1990–1996, i.e., up to 12 years after the cessation of eruptive activity, which provide valuable insight into post-eruptive processes. When combined with data collected by other workers before and during the rifting and eruptive events, this work completes an excellent record of changes during the largest eruptive episode at Krafla in recent history and demonstrates the continuing dynamic nature of the system.

2. Pre- and syn-eruption ground deformation and gravity changes

Geodetic measurements for the purpose of investigating tectonic movements were made in 1938 and repeated in 1965 on a network running from Akureyri to Grimsstadir (Fig. 1). No significant changes were observed over this period (Bjornsson et al., 1979), but contraction (without vertical deformation) in the period 1965–1971 was followed by extension and uplift between 1970–1975 (Moller and Ritter, 1980; Kanngieser, 1983). Ground deformation during the 1975–1984 rifting episode was characterised by steady inflation interrupted by rapid subsidence within the caldera, accompanied by widening of the fissure swarm. This has been interpreted (Tryggvason, 1984) in terms of pressure increase within a shallow magma reservoir located 2.5 km beneath Krafla (inflation), followed by rupture of the reservoir walls and a rifting event after some critical pressure is reached (subsidence). Although some 0.25 km^3 of magma were erupted during the decade of activity (Saemundsson, 1991), a much larger volume was intruded as dykes in the fissure swarm. Tryggvason (1984) estimates that a total of 1.08 km^3 of magma escaped the Krafla magma chamber during 1975–1981. The rate of inflation was greatest during these early years of the activity, and the rates of elevation change indicate that there was a diminishing magma supply to the shallow reservoir (Ewart et al., 1990) throughout the rifting episode.

Micro-gravity observations (with standard deviations of <20 μGal) extending from Akureyri to Grimsstadir across the Neovolcanic zone, made in 1965, 1970, and 1975, revealed variations of up to ±40 μGal over 5 years together with a gradual increase of up to 5–10 μGal per year (Schleusener and Torge, 1971) along the whole line. Across the Krafla rift itself, over the period 1965–1970, a decrease in gravity of approximately 20 μGal was observed with respect to a station close to the northeastern shore of Myvatn Lake (close to the Hotel station in Reykjahlid referred to later, Fig. 1).

Variations of gravity (with standard deviations of 20 μGal) observed between 1975 and 1978 (Bjornsson et al., 1979) within the caldera and along active parts of the fissure swarm correlated well with observed elevation changes, such that most of the observed gravity variations could be accounted for using a Bouguer-corrected free-air gradient. For example, the gravity–height correlation observed in the period January–June 1978 ranged from −250 μGal m^{-1} during inflation to −166 μGal m^{-1} during the subsequent deflation (Johnsen et al., 1980). These gravity and ground deformation data were interpreted in terms of the inflow and outflow of magma, with small discrepancies between the data sets immediately following subsidence events being attributed to ground-water movements. Inflation events were typically gradual, lasting months, and reflected the build up of magma pressure within the magma chamber. In contrast, deflation events lasted a few hours or days and occurred as the chamber wall ruptured and dykes were emplaced (Bjornsson et al., 1979). The broad agreement of the gravity/height variations with the Bouguer gradient (Johnsen et al., 1980), implies that there was no overall change in sub-surface density i.e., the intruded dykes had an insignificant density contrast with the surrounding material.

3. Post-eruption ground deformation and gravity changes 1990–1996

Deformation measurements made within and outside the Krafla caldera on a regular basis between 1990 and 1996 indicate deflation of the volcano at a rate of about 30 mm a^{-1}, possibly decreasing towards the end of the study period (Tryggvason, 1994; Tryggvason, 1995a and Tryggvason, 1995b; Sigmundsson and Tryggvason, 1995; Sigmundsson et al., 1997). The geodetic data are consistent with a ‘Mogi' point source of pressure (Mogi, 1958) at 65.7150°N and 16.7975°W (Fig. 1) at 2.5 km depth (Tryggvason, 1995a) i.e., in the same location as the deformation source identified during the rifting episode (Tryggvason, 1984). During 1987–1990, horizontal extension was about three times larger than the 19 mm a^{-1} time-averaged plate spreading rate in North Iceland, and reached a maximum about 25 km from the ridge axis (Foulger et al., 1992; Hofton and Foulger, 1996). These observations reflect relaxation of the Krafla system after the rifting episode.

Repeat micro-gravity measurements have been made at stations within the Krafla caldera and along the associated fissure (Fig. 1) every year from 1990 to 1996, except in 1993. The techniques used to obtain the best possible precision (typically ±10 μGal) at Krafla are standard for micro-gravity surveys (e.g., Rymer, 1989 and Rymer, 1994). The same Lacoste and Romberg instrument (sn G513) and operator (HR) were always used. The reference station for the gravity data is located close to the Hotel Reynihlid near Lake Myvatn, because previous observations made during the eruptive period indicated that there were no gravity or elevation changes in this region; the nearby station used by Johnsen et al. (1980) at the church has been destroyed.

From the known ground deformation information, the elevation change at the gravity stations can be calculated with sufficient accuracy simply by knowing the horizontal distance of each station relative to the deformation centre. An error of say 100 m in the horizontal location of the Mogi source corresponds to a maximum uncertainty of <1 μGal in the calculated gravity effect over the whole observation period. Table 1 shows the annual elevation change at each station calculated in this way. One of the inherent problems in correcting micro-gravity data for elevation changes is the choice of gravity/height gradient. The standard end-members are a free-air gradient (FAG) of −308 μGal m^{-1} and a Bouguer-corrected free-air gradient (BCFAG) of ca. −200 μGal m^{-1} (the value depends on the density used, 2600 kg m^{-3} in this case). Use of the BCFAG is more intuitive, however, since deviations from this gradient reflect net density changes which can be attributed to mass transfer. In this case, the largest difference between the FAG and BCFAG over 6 years is 17 μGal, for stations A002 and A003 at which the greatest elevation change occurred; the difference is even smaller for stations where the elevation change is less. Rates of gravity change predicted for each station (from the BCFAG) are shown on Table 1, together with the best-fit rates calculated from the observed data.

The variations of gravity through time at stations on a W–E line (stations A001–A005) and a N–S line (stations 5672–FM115) are illustrated in Fig. 2. For comparison, the gravity changes predicted by the elevation changes assuming a BCFAG are also shown; as the elevation changes diminish rapidly with distance from the source of deformation, the gravity gradients are correspondingly affected.

To assess the significance of the observed gravity changes relative to the predicted gradients, linear fits to the observed data are presented representing the average rate of change of gravity over the 6-year observation period. In most cases, there is a significant difference (at the 95% confidence level, i.e., two standard deviations on the fitted gradient, see Table 1) between the observed and predicted rates of change; stations A1, 5599a and 5672 show smaller differences (significant at the 68% confidence level) and stations A5 and 5595 show no significant differences. Net decreases in gravity, up to −49 μGal over 6 years, with respect to the predicted changes occur at stations A2, A3, A4, and FM115 whereas at other locations there are net gravity increases, reaching a maximum of 62 μGal over 6 years (Fig. 2).

4. Interpretation of 1990–1996 gravity changes

Subsidence identified over the Mogi source may be due to magma drainage, contraction of magma due to solidification (Sigmundsson et al., 1997) or some combination of the two. The gravitational effects of these processes, however, are different. Magma drainage could cause either an increase in density due to the closure (or partial closure) of previously magma-filled channels or a decrease in density due to the expansion of the magma remaining in the chamber. Such density changes would be reflected by corresponding gravity changes with respect to the BCFAG. Solidification, however, would always be associated with densification and hence, a corresponding gravity increase. We observe both gravity increases and decreases; the spatial distribution of the net gravity changes over 6 years, after correcting for elevation changes, shows (Fig. 3) that the gravity decrease is located approximately over the Mogi source while the increases occur at greater distance from the centre of deformation peaking in the data about 2 km to the southeast and may be more widespread around the caldera. Since correction has already been made for elevation changes assuming the BCFAG, departures from this gradient must be interpreted in terms of sub-surface density changes resulting from mass movement. The different wavelength of the gravity changes imply different source depths and/or lateral extents of the sources.

Net gravity decreases (with respect to the BCFAG) indicate a sub-surface density decrease which we interpret in terms of magma drainage. These gravity decreases require that a minimum of 4×10^{10} kg (calculated simply by integrating the free-air corrected gravity decrease over the area of the anomaly) of magma must have drained. The wavelength of these effects suggests a localised source region for drainage within the larger magma chamber proposed by Brandsdottir et al. (1997) above a central feeder system (the main conduit for drainage). For Kilauea Volcano, Johnson (1987) showed that there was a relationship between magma chamber volume change (ΔV_{ch}) and the volume of magma leaving a chamber (ΔV_m) during deflation. Inelastic effects of magma are involved; the volume of magma drained from a magma chamber is not the same as the volume change of the magma chamber, as the magma remaining in the chamber will expand in response to the pressure release. Assuming that the magma and magma chamber at Krafla behave in a way similar to those on Kilauea (both basaltic systems in extensional regimes), then the relationship ΔV_m=3.6 ΔV_{ch} is expected to hold at least approximately. ΔV_m can be calculated (assuming a magma density of 2700 kg m^{-3}) from the mass loss (4×10^{10} kg) determined from gravity data and so the magma chamber volume change can be estimated to be 0.004 km^{-3}. This can be compared with results from surface deformation measurements. For the 1990–1996 period, these measurements were in broad agreement with a Mogi source at 2.5 km depth and a deflation rate of 30 mm a^{-1}. The integrated surface subsidence according to the Mogi model gives an estimate for the volume change of the volcanic edifice (ΔV_e). Assuming then a Poisson's ratio of 0.25 and the relationship ΔV_{ch}=0.67 ΔVe (Delaney and McTigue, 1994), the geodetic data suggest ΔV_{ch}=0.005 km^3. This is in good agreement with the ΔV_{ch}=0.004 km^3 result from the gravity data.

There are a number of possible explanations for the more widespread gravity increases; increases in sub-surface density could result from closure of micro-fractures in lavas above the magma chamber, a migration of the steam–water interface, or magma solidification (cooling contraction). If these effects are caldera-wide, as would be expected if they are controlled by magmatic processes, then the peak effect is likely to be centred near the focus of Mogi deformation. In this case, both negative and positive components of the anomaly would be underestimated since the two effects would overlap; thus, the previously estimated volume of magma drainage may be too small.

During the eruptive period at Krafla, inflation could have caused micro-fractures to open within the lavas above the inflating magma chamber. Closure of these micro-fractures during post-eruption deflation would produce sub-surface density increases reaching a maximum over the centre of deformation. An average density increase of only 1 kg m^{-3} is required in a conical zone above the deflating Mogi source to account for a gravity increase of 100 μGal.

Alternatively, as the system cooled, steam condensation within the shallow hydrothermal system may have resulted in a migration of the steam–water interface. Assuming an average 10% porosity for the lavas, the interface would need to migrate vertically by only 15 m at most to produce the observed gravity increase. The association of gravity increases with the location of the geothermal field (Fig. 3) suggests that this effect may be the most significant and that the hydrological conditions of the field have amplified these effects.

A final possible cause of the gravity increases is solidification of cooling magma within the chamber producing a density increase. This process can only be a minor contribution to the observed net gravity increases as the data fall well above the free-air gradient (data lie on this gradient when there are no mass changes). This interpretation is consistent with the relatively long wavelength of the observed gravity increases as solidification in the extensive magma chamber modelled by Brandsdottir et al. (1997) would affect a region as wide as the whole caldera.

Station FM115, to the south of the caldera but within the active rift zone, exhibits significant and persistent gravity decreases that cannot be readily explained by magmatic processes. Our observations show a similar decrease to that reported from 1965–1970 in the same location and it may be that this is part of a very long-term effect, perhaps related to the Namafjall hydrothermal system to the south.

5. Discussion and conclusions

Post-eruptive gravity changes have been recorded at several volcanoes (typically for less than 1 year immediately following eruption) and invariably show only gravity decreases which are attributable to shallow magma withdrawal associated with incomplete collapse of drained voids (e.g., Etna: Rymer et al., 1995; Mihara: Iida et al., 1952; Kilauea: Jachens and Eaton, 1980). The present work provides a unique example of both gravity decreases and gravity increases sustained over a long period following a major eruptive episode at a rift volcano. The net gravity–height gradients at Krafla reported in this paper are considerably larger than those reported during the syn-eruption stage (Johnsen et al., 1980) and are persistent up to 12 years after the end of the eruptive period.

During this post-eruptive period of deflation we have observed gravity–height gradients ranging from +32 μGal m^{-1} (station A002) to −844 μGal m^{-1} (station 5597). All the current data fall well outside the more narrow range observed throughout the eruption during periods of both inflation and deflation (Johnsen et al., 1980). Since our observations are significantly different from those predicted by the BCFAG, they must represent substantial sub-surface density changes that, unlike the data of Johnsen et al. (1980), cannot be modelled in terms of Mogi-type deformation.

Ground deformation data from Krafla indicate that deflation centred on a point near the caldera centre has occurred at a consistent rate of approximately 30 mm a^{-1} for the 12 years since the end of the last eruption. This suggests post-eruptive collapse above a Mogi-type source, identified during earlier inflation events as a shallow magma chamber. Net gravity decreases have been used to quantify magma drainage of 4×10^{10} kg which is equivalent to a magma chamber volume change of 0.004 km^{-3}, consistent with calculations from deformation alone, and endorses the notion that the magma remaining must be expanding to support the magma chamber. The areal extent of gravity increases appears to be larger than that of the decreases and they form a more consistent pattern in time and space; the most likely significant causes are a migration of the steam–water interface and/or closure of micro-fractures in lavas overlying the magma chamber with a minor contribution due to magma solidification.

In summary, we envisage a cooling, solidifying and therefore, contracting magma body producing subsidence at the surface. The central part of the magma body has also undergone at least 4×10^{10} kg of drainage and the observed subsidence can be attributed principally to drainage rather than contraction.

These results contrast with observations from the Askja caldera 80 km to the south of Krafla where post-eruptive deflation of about 50 mm a^{-1} has been shown to be accompanied by negligible net gravity changes above the Mogi-type source in the caldera centre (Rymer and Tryggvason, 1993). This suggests that excess mass movements at Askja either did not occur after the last eruption in 1961 or have since ceased. Thus, it could be anticipated that the magnitude of the observed gravity changes at Krafla will diminish. Long-term post-eruptive deflation and magma drainage have not been observed at subduction-related volcanoes; this may be a function of magma viscosity and tectonic stress regime and hence, magma chamber depth.

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Figures and captions

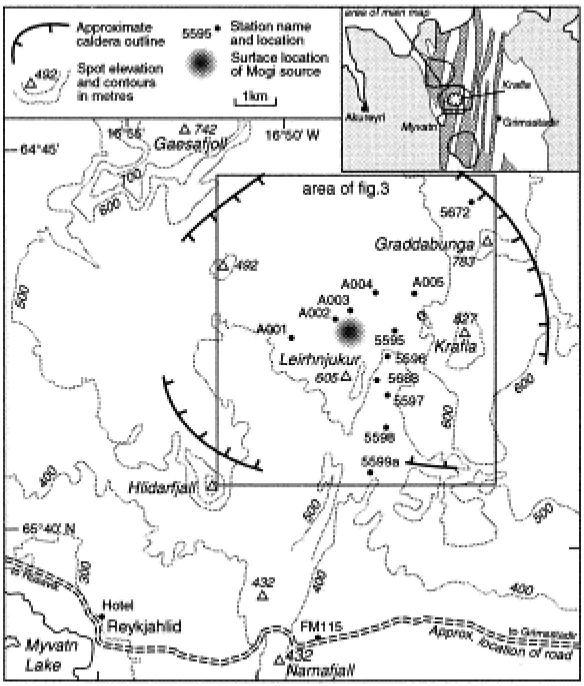

Fig. 1. Gravity station location map for Krafla region. Inset shows position of Krafla in Iceland and the neovolcanic zone. The stations used have been previously monumented by Orkustofnun, the National Energy Authority (personal commun. Axel Bjornsson) or by the Nordic Volcanological Institute (personal commun. Eysteinn Tryggvason).

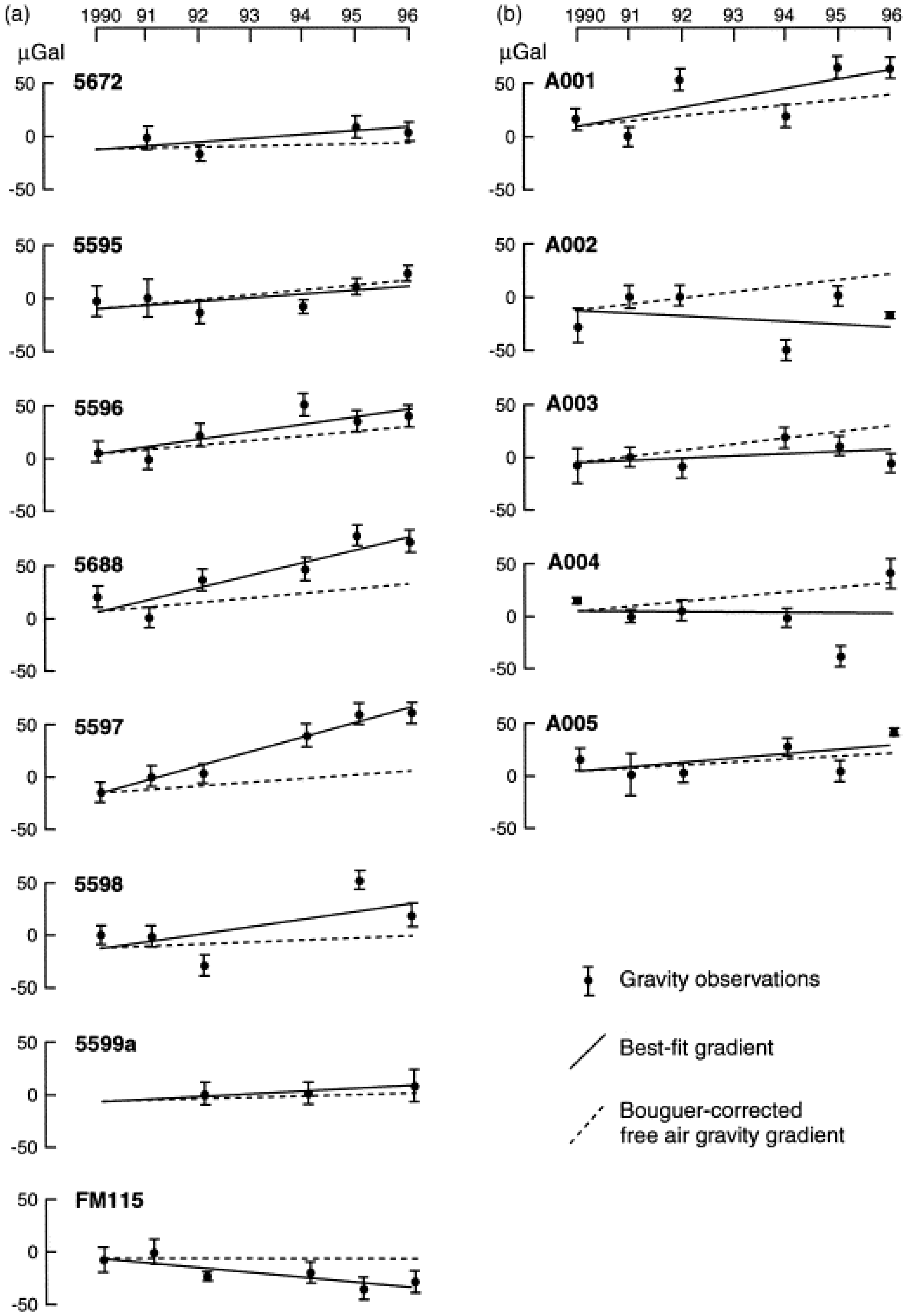

Fig. 2. Variations in gravity (µGal) through time (a) at stations on a roughly N–S line along the recently active rift and extending south across the Krafla caldera boundary and (b) at stations on a W–E line crossing the recently active rift and within the Krafla caldera. Station locations are identified on Fig. 1. The observed data (with error bars denoting standard deviations on repeat measurements) are marked with dots. The solid line shows the linear least-squares fit to the data and the dashed line shows the expected change in gravity calculated from the elevation change using the Bouguer-

corrected free-air gradient (see Table 1). The data are expressed relative to station Hotel near Reykjahlid.

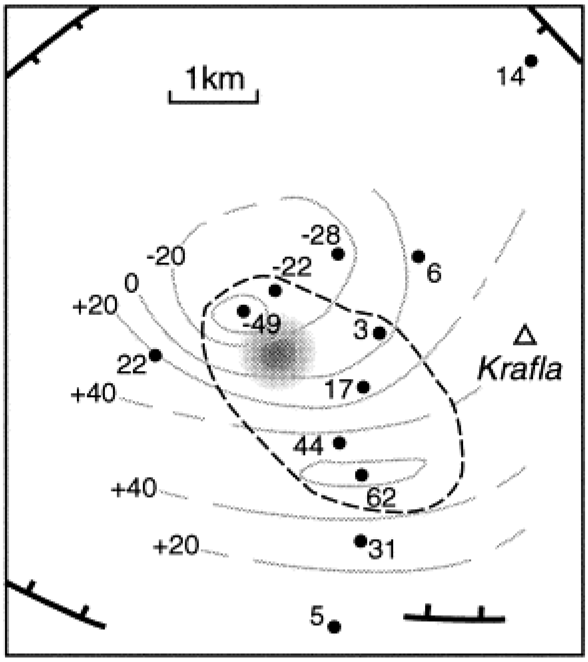

Fig. 3. Spatial variations of cumulative gravity changes over the period 1991–1996 after correction for height changes using a Bouguer-corrected free-air gradient of −200 μGal m^{-1}. Data have been expressed with respect to station Hotel (as in Fig. 2). The area of this figure is defined in Fig. 1; contour interval is 20 μGal. Shaded area denotes the position and possible lateral extent of the Mogi source (i.e., shallow magma chamber), dashed line is the approximate boundary of the geothermal field.

Table 1

Comparison of observed and predicted rates of gravity changes

Station name	Horizontal distance from Mogi point source (km)	Rate of annual elevation change (m a^{-1})	Predicted rate of gravity change (μGal a^{-1})	Observed rate of gravity change (μGal a^{-1})	Standard deviation on fitted gradient (μGal
FM115	7.600	0	0	−4.5	1.1
A001	1.270	−0.021	4.2	8.1	2.3
A002	0.500	−0.028	5.6	−0.9	0.4
A003	0.600	−0.028	5.6	2.1	0.8
A004	1.250	−0.022	4.4	−0.3	0.1
A005	2.000	−0.014	2.8	3.8	1.3
5599A	3.500	−0.006	1.2	2.0	0.7
5672	4.300	−0.004	0.8	3.1	1.1
5595	1.250	−0.021	4.2	3.6	1.1
5596	1.270	−0.021	4.2	7.1	1.5
5688	1.270	−0.021	4.2	11.5	2.0
5597	1.800	−0.016	3.2	13.5	1.0
5598	2.600	−0.010	2.0	7.1	2.4

Observed rate of gravity change calculated by least-squares linear regression with standard deviation on fitted gradient ([Till, 1974]).

Predicted rate of gravity change calculated from the Bouguer corrected free-air gradient (−200 μGal m^{-1}) assuming a density of 2600 kg m^{-3} and elevation cha deduced from Mogi source dynamics.