J. Geophys. 47, 132–140, 1980

Journal of Geophysics

Gravity and Elevation Changes Caused by Magma Movement Beneath the Krafla Caldera, Northeast Iceland

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Abstract. Prior to the present activity of the Krafla volcano, which started in 1975, levelling and gravity surveys had been carried out in the area. The network has since been extended, and measurements are carried out about every second month. The measurements reveal a quasi-periodic behaviour of the tectonic activity, characterized by slow inflation of the caldera for several weeks or months at a rate of 6–10 mm/d, interrupted by sudden subsidence events lasting for one or a few days. Elevation changes within the caldera are described by a deflation-inflation swelling with its apex near the center of the caldera. Calculations, using a model of a spherical chamber with varying pressure at 3 km depth, show good agreement with the measured elevation values. Comparison of gravity and levelling data, using a Bouguer type relationship, suggests that inflation and deflation of the floor of the caldera is caused entirely by in- and outflow of magma. Some discrepancies between the levelling and gravity data immediately after subsidence events can be explained by additional mass flow of groundwater.

Key words: Gravity – Elevation changes – Magma flow – Iceland – Current rifting episode.

Introduction

In north Iceland the structure of the neovolcanic zone is characterized by several northsouth oriented fissure swarms running through central volcano complexes. Volcanic and tectonic activity in this region is episodic rather than continuous and each time is confined to one central volcano complex and it's associated fissure swarm (Saemundsson, 1974, 1978; Björnsson et al., 1977). The Krafla fissure swarm, which became active in 1975, extends from Axarfjördur in the north to the mountainous area southeast of Myvatn in the south, some 100 km in length. It's average width is estimated at 5 to 10 km. During the last interglacial period the Krafla central volcano developed a caldera which has been filled to a large extent with eruptive material during the last glacial and postglacial period, see Fig. 1. In postglacial time volcanic activity has remained high in the Krafla fissure swarm. About 35 postglacial eruptive fissures are known along the fissure swarm (Björnsson et al., 1977). A high-temperature geothermal field with temperatures exceeding 340° C at 2 km depth exists within the Krafla caldera. This geothermal field is now being harnessed in a geothermal power plant, see Fig. 2.

During the summer of 1975 it became apparent that the Krafla caldera was in a period of increased seismic activity. Seismic activity kept building up during the summer and fall. On the 20th of December 1975 a major volcano-tectonic event began within the Krafla caldera and part of the associated fissure swarm became active (Sigurdsson, 1976; Björnsson, 1977). A small volcanic eruption took place near the center of the caldera. During the next days and weeks, land subsided some 2.5 m inside the caldera and tectonic movements took place in the northern part of the fissure swarm some 60 km north of the Krafla caldera. Since then the Krafla caldera and the associated fissure swarm have been at

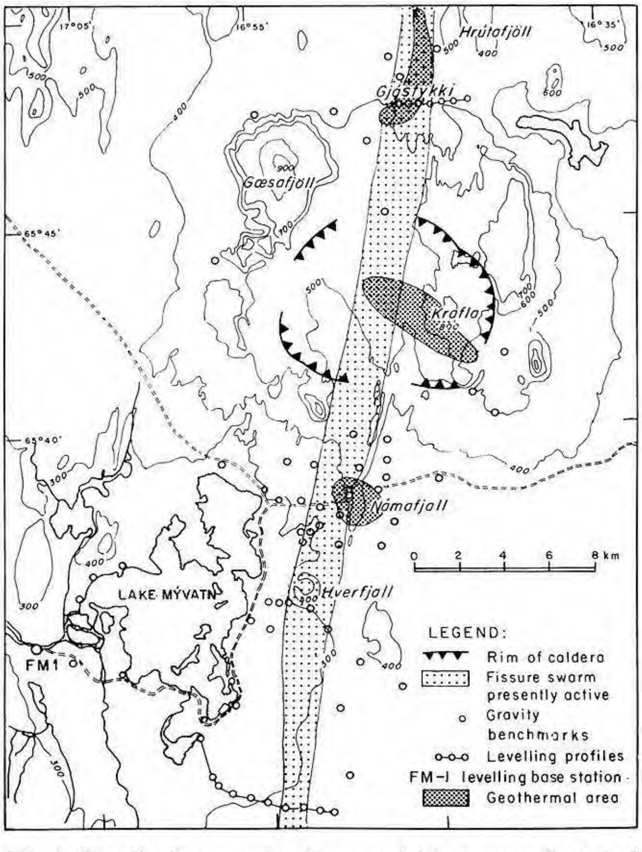

Fig. 1. The Krafla central volcano and it's surroundings in NE-Iceland. The caldera and the center part of the active fissure swarm are shown. *Open circles* show gravity and levelling benchmarks outside the caldera

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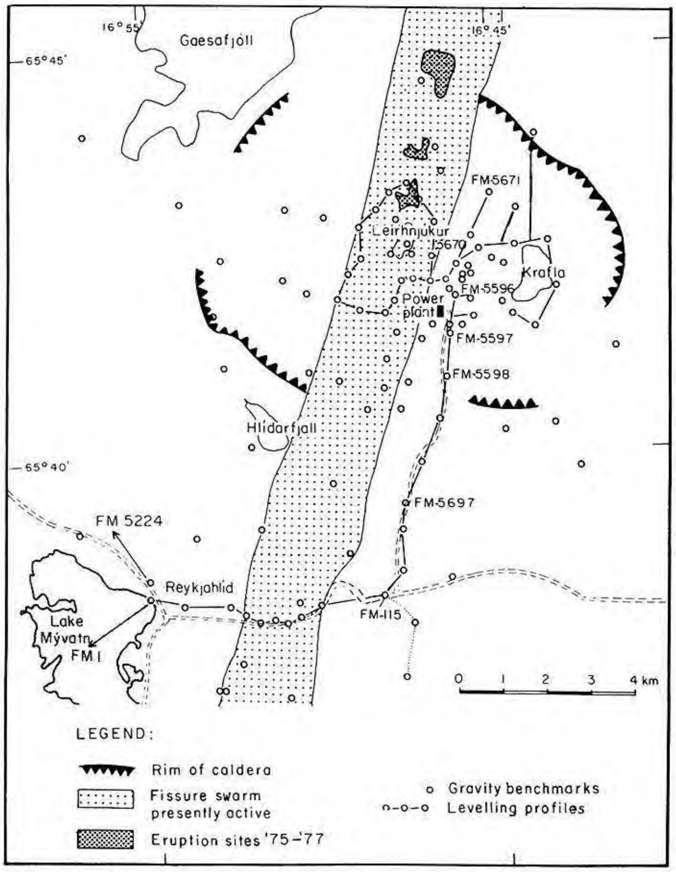

Fig. 2. Gravity and levelling benchmarks inside and around the Krafla caldera. Benchmarks, referred to in the text, are marked with *numbers*. *Arrows* indicate locations of gravity and levelling base stations

unrest. The activity is characterized by slow inflation of the caldera, at a rate of 6–10 mm/d at the center, lasting for several weeks or months, interrupted by sudden subsidence events lasting from one to a few days. The inflation has been interpreted as being caused by inflow of magma from below, at a rate of 5 m^3/s, into a magma chamber at shallow depth. The subsidence of the Krafla caldera is caused by horizontal flow of magma out of the magma chamber along a dike into the fissure swarm towards north or south. This is associated with horizontal and vertical ground movement and seismic activity within a confined part of the fissure swarm outside the caldera (Björnsson et al., 1979; Brandsdóttir and Einarsson, 1979). The existence of a magma chamber beneath the Krafla caldera has further been supported by the observation of a S-wave attenuating zone at a 3 to 7 km depth (Einarsson, 1978).

Great effort has been put into studying the present volcano-tectonic episode in the Krafla fissure swarm. The measurements include regular levelling and gravity surveying of the area, tilt measurements, monitoring movement of fissures, distance measurements, monitoring ground temperature and ground water level. A dense seismic network is in operation in the area. Temperature, pressure, and chemical composition of borehole discharge is monitored and gases emitted from fumaroles are analysed. In this paper, however, only the levelling and gravity data from the Krafla caldera and its surroundings will be presented supplemented with tilt measurements from one site inside the caldera.

The land elevation in and around the Krafla caldera has proved to be a most important parameter for understanding the nature of the present volcano-tectonic activity of the Krafla area. It has been possible to delineate the most active area and determine quantitatively the elevation variations, which is the base for further theoretical work. Elevation and seismic activity inside the caldera have been the most important indicators for surveillance of the volcano for the civil defence.

Geodetic and gravimetric measurements were started by Niemczyk (1943) in 1938 in order to observe tectonic movements in NE-Iceland. A high precision gravity profile across the neovolcanic zone in NE-Iceland, established in 1938 and re-observed in 1965, 1970, and 1975 for the investigation of secular gravity variations, indicates an increase of gravity by 0.05–0.1 $\mu m/s^2$ per year in the neovolcanic zone compared with the older plateau basalts to the west (Spickernagel, 1966; Schleusener and Torge, 1971; Torge and Drewes, 1977a; Torge and Kanngieser, 1979). Further measurements by Torge and Drewes (1977b) in 1975 and 1976 and by Björnsson et al. (1979) from 1975 to 1978 showed major changes in gravity and elevation near the caldera and along the active part of the fissure swarm. Repeated geodetic distance measurements of the Krafla-Mývatn area, indicate that slight contraction took place between 1965 and 1971, but significant expansion took place between 1971 and 1975 (Gerke, 1974, 1977; Gerke et al., 1978; Möller and Ritter, 1979).

The Observational Techniques

Levelling was originally carried out in the Krafla area in 1974 along the road from Myvatn to Krafla. Additionally several benchmarks were measured trigonometrically in the area for mapping purposes. The levelling network has gradually been extended and presently it includes some 70 benchmarks (see Figs. 1 and 2). The levelling has been carried out using a Zeiss Ni2 level and wooden measuring rods, which are periodically compared with Wild Invar rods. The standard error is approximately 1.5 $\sqrt{L}$ mm, where L is the length of the forward and backward measured levelling profile in kilometers. All profiles are measured in this manner except a profile around the hill Leirhnjukur, where one way levelling starts and ends at the same benchmark. Regular levelling of the Krafla area, started in early March 1976. Since then large parts of the network have frequently been levelled, usually at intervals of one to two months and the remainder at longer intervals. The main profiles east of Myvatn have a number of times been connected to benchmark FM-1 southwest of the lake by using the surface of the lake as a reference level in very calm weather. This benchmark serves as a base station for the levelling surveys. The levelling is performed by a team of three men. Under favourable weather conditions levelling of all benchmarks takes about a week.

A water tube tiltmeter is operated in the Krafla power house which is situated about 1,300 m south of the apex of maximum elevation changes (see Fig. 2 for location). The reading accuracy is about 1 μrad in the north-south component and readings are made at least once a day. An excellent correlation has been found between the tilt variations at this site and elevation changes of the caldera. Hence it is possible to monitor daily elevation changes during inflation and deflation by using the tilt variations for interpolation between levelling surveys. Further in this way it is possible to estimate the value of maximum subsidence during each subsidence event (Björnsson et al., 1979).

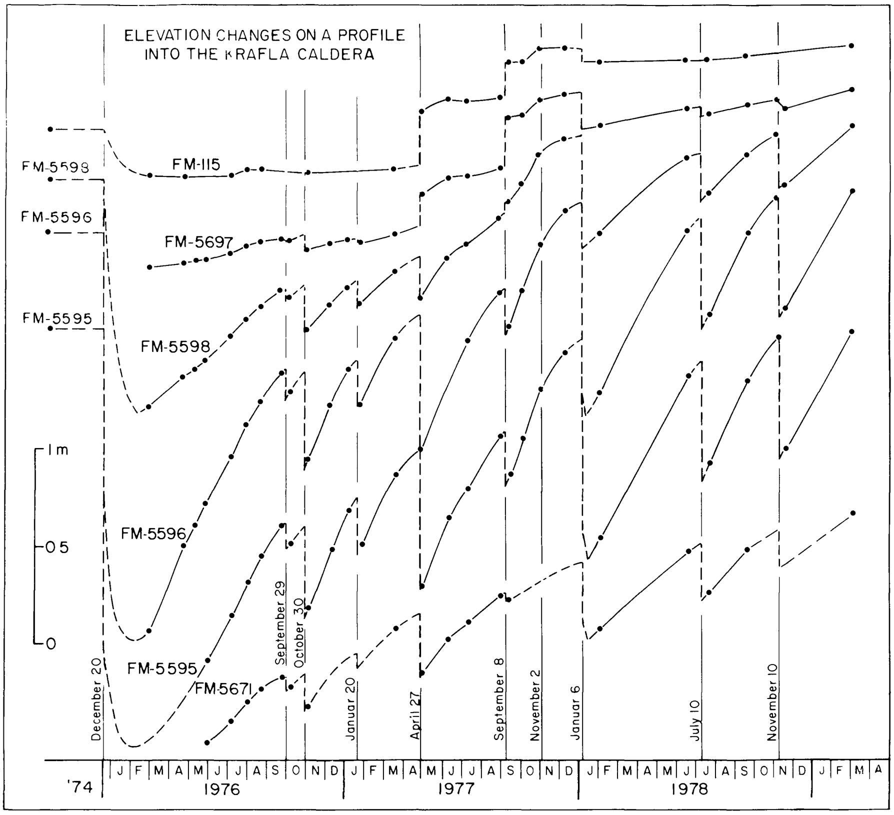

Fig. 3. Measured elevation changes on a 9-km-long profile leading from Námafjall into the Krafla caldera. For location of benchmarks see Fig. 2. *Filled circles* are levelling data and the *connecting lines* interpolations based on daily tilt observations

A gravity survey was first carried out in the Krafla area in August 1975. The purpose was to monitor gravity variations that might accompany the utilization of fluid from drillholes in the Krafla high temperature geothermal field. The network included some 30 benchmarks and was measured with a LaCoste-Romberg gravity meter, G-10. In March and June 1976 this network was remeasured using an old Worden gravity meter, W-68. Since September 1976 gravity surveys have been carried out with a LaCoste-Romberg gravity meter, G-445. Gravimeter readings are corrected for tidal effects using the method of Longman (1959). Correction is made for instrumental drift by using a looping technique. The accuracy of the gravity values is about $\pm 0.2\ \mu\text{m/s}^2$ for the G-gravity meters. Gravity changes are always measured with respect to stations within the Icelandic gravity base station network (Pálmason et al., 1973). Base station FM-5276 at the church of Reykjahlid was used for this purpose. After the subsidence event in April 1977 change was noted at this station in relation to the general network and the base station was transferred to FM-5224 at Husavik airport, some 40 km away from the Krafla caldera. Since June 1976 the gravity network has gradually been extended and presently includes some 150 gravity benchmarks (see Figs. 1 and 2). Most gravity surveys are carried out at the same time as levelling. The whole gravity network may under favourable conditions be covered by one man in about one week's time.

Characteristics of the Elevation and Gravity Changes

A levelling survey carried out in early March 1976 showed that up to 2 m subsidence had occurred within the Krafla caldera, accompanying the volcano-tectonic activity, which started on December 20, 1975. Further levelling surveys, carried out in the summer of 1976, showed that the floor of the Krafla caldera was rising. The rate of inflation had an average value of 6.5 mm/d at benchmark FM-5596 near the power house. In a similar manner a gravity survey, carried out in June 1976, showed considerable increase in gravity near the center of the caldera compared with measurements from 1975. Decrease in gravity was observed from June to September 1976 in correlation with the increasing elevation. In late September 1976 another volcano-tectonic event occurred within the Krafla fissure swarm. After a period of continuous inflation, lasting for eight months, land subsided within and around the Krafla caldera, and tectonic rifting took place in the fissure swarm, in Gjástykki. Since then eight other subsidence events have occurred in the area.

Figure 3 shows the elevation variations at several benchmarks on a 9 km long north-south profile stretching from Námafjall into the Krafla caldera (for location see Fig. 2). Tilt measurements have been used to interpolate between the levelling data. It is evident from Fig. 3 that the maximum elevation variations are taking place at the benchmarks FM-5596 and FM-5595 near the center of the caldera. At benchmark FM-115 near Námafjall, about 8 km south of the center of the caldera, the elevation variations are an order of magnitude smaller. The first subsidence event in December 1975 is accompanied by the greatest subsidence, while the event in November 1977 was too small to be shown on this scale. The subsidence events in April and September 1977 are the only ones associated with activity in the fissure swarm south of the caldera and hence having the greatest effect on eleva-

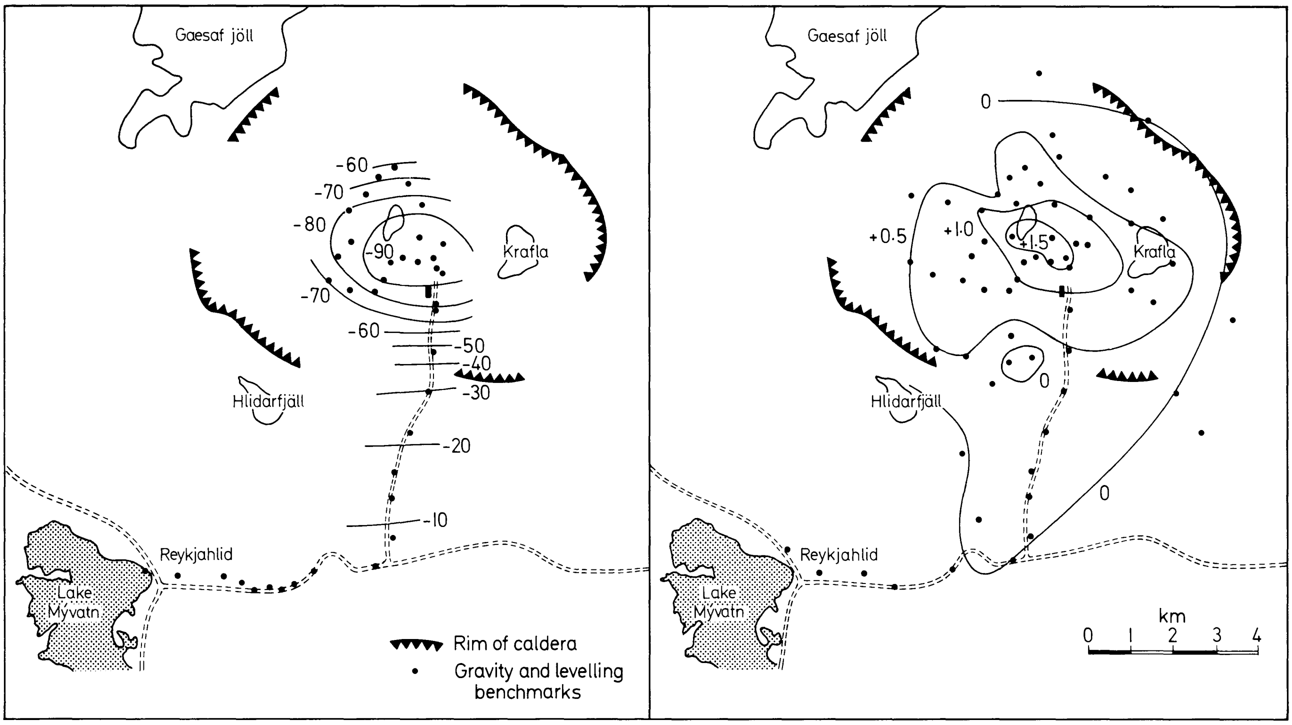

Fig. 4. Measured elevation changes in cm (*left*) and gravity changes in μm/s^2 (*right*) during the subsidence event in January 1978. *Filled circles* show the benchmarks occupied at the time

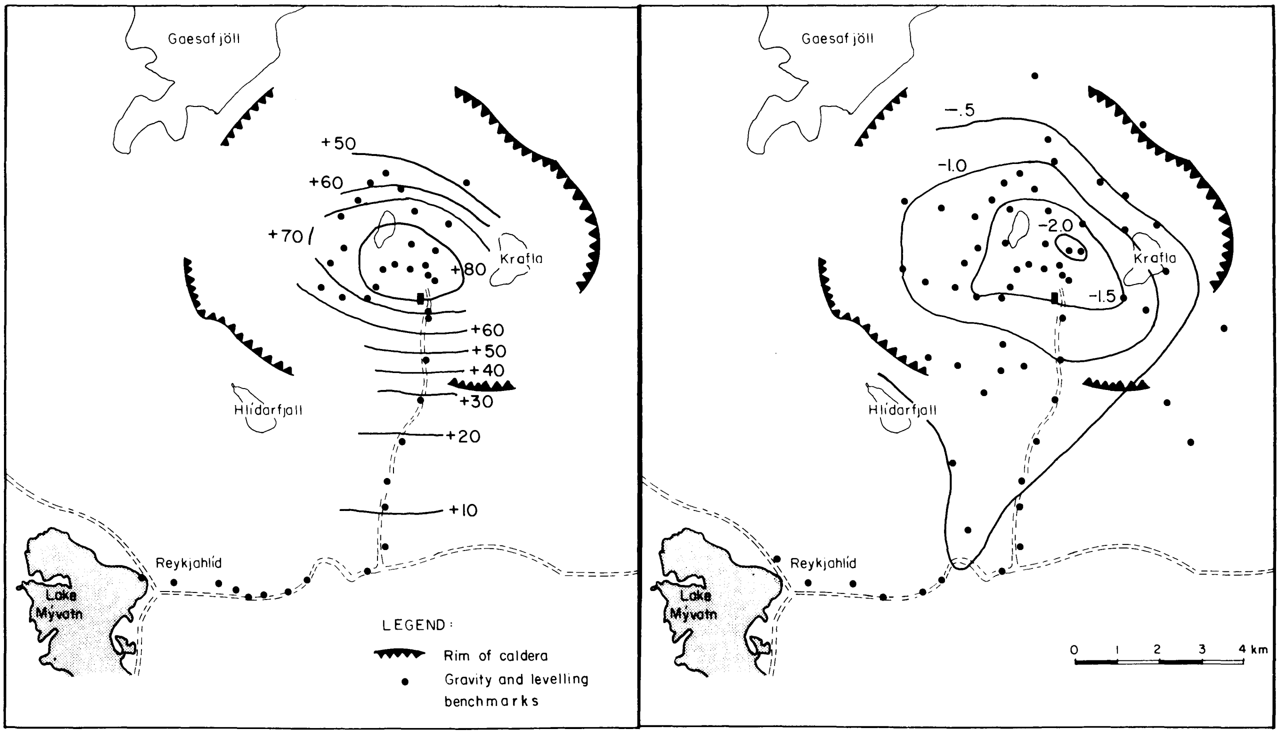

Fig. 5. Measured elevation changes in cm (*left*) and gravity changes in μm/s^2 (*right*) during the inflation period from January to June 1978. *Filled circles* show the benchmarks occupied at the time

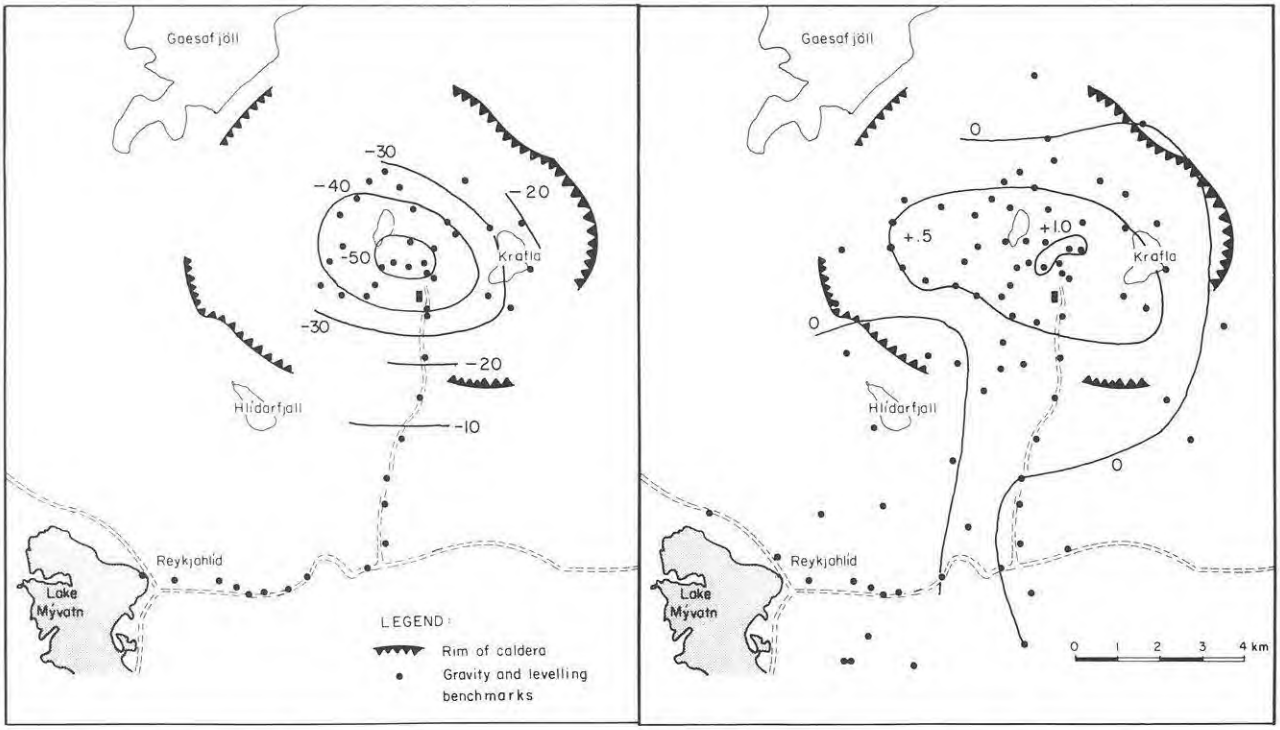

Fig. 6. Measured elevation changes in cm (*left*) and gravity changes in $\mu m/s^2$ (*right*) during the subsidence event in July 1978. *Filled circles* show the benchmarks occupied at the time

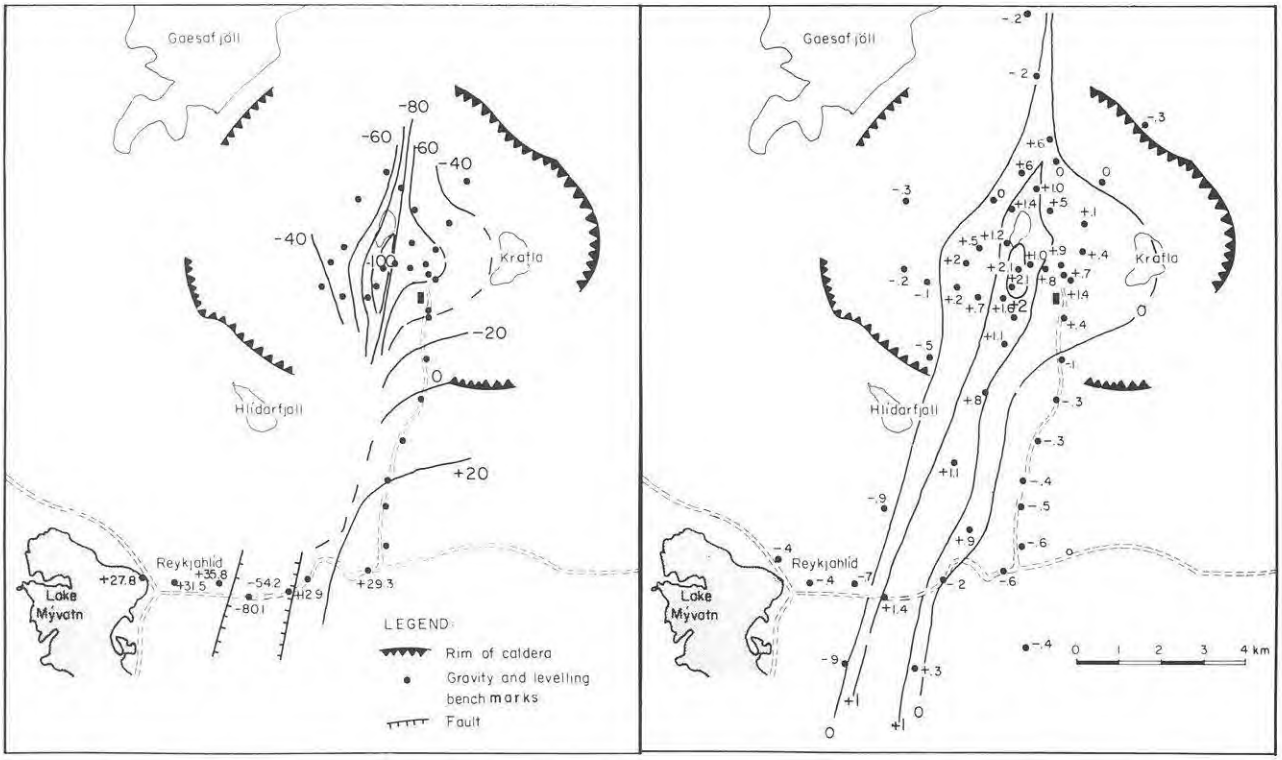

Fig. 7. Measured elevation changes in cm (*left*) and gravity changes in $\mu m/s^2$ (*right*) during the subsidence event in April 1977. *Filled circles* show the benchmarks occupied at the time

tion at the southernmost benchmarks. The inflation periods range from less than one to more than seven months. Elevation variations from other benchmarks in the measuring network give similar results as shown in Fig. 3.

In order to better demonstrate the elevation and gravity changes of the Krafla area we have chosen four sets of survey data covering two subsidence events and one inflation period. Figure 4 illustrates the subsidence event in January 1978, Fig. 5 the following, 6 months long inflation period, and Fig. 6 the subsidence event in July 1978. These figures are typical for the elevation and gravity changes in the Krafla area. A common feature of all three figures is a deflation-inflation bowl, the center of which is a somewhat elongated northwest-southeast oriented plateau, where maximum elevation changes occur. This plateau is situated between the hill Leirhnjukur and the southern slopes of the mountain Krafla. This area coincides with the Krafla high temperature geothermal field. The rate of elevation changes on this plateau during periods of inflation is 6–10 mm/d and the size of the area is approximately 4 km^2 Elevation changes diminish rapidly as one leaves the plateau and has dropped to about 40% of its maximum value at the southern rim of the caldera and to less than 5% at a distance of 10 km from the apex of uplift. Gravity surveys usually cover a greater area than levelling. Maximum gravity changes usually occur in the same area as maximum elevation changes, sometimes distorted, though, in a north-south direction along the fissure swarm.

As indicated in Fig. 3, measured elevation changes during the volcano-tectonic events in April and September of 1977 were somewhat different compared with other events. This is due to the fact that these events activated the southern branch of the fissure swarm within and just south of the caldera and hence influenced the elevation and gravity changes inside the caldera much more than activity further away during other subsidence events. Figure 7 illustrates the elevation and gravity changes during the subsidence event in April 1977. The subsidence bowl inside the caldera can still be seen, but major movement within the fissure swarm just south of the caldera are superimposed on the circular subsidence bowl. From gravity, levelling and distance measurements both south and north of the Krafla caldera it is known, that the activity in the fissure swarm is characterized by subsidence of the central part of the fissure swarm, while the flanks on each side are uplifted. This is accompanied by expansion over the most active part of the fissure swarm, up to 2 m each time resulting in the formation of new fissures and new geothermal areas, while a much larger area outside the fissure zone is contracted (Björnsson et al., 1979; Gerke et al., 1978). This tectonic rifting of the fissure swarm is usually also accompanied by an earthquake swarm (Brandsdóttir and Einarsson, 1979). Elevation changes of this sort were first detected gravimetrically in Gjástykki in January 1977.

Discussion

Elevation Variations – The Mogi Model

Björnsson et al. (1979) have shown that model calculations, using Mogi's (1958) model of a spherical chamber (magma chamber) with varying pressure within a homogeneous elastic half-space shows good agreement between calculated and observed elevation variations from the Krafla area. Thereby the elevation changes, Δh, at the distance x from the apex of a circular bowl is given by

$$\Delta h = h_o \cdot d^3 \cdot (d^2 + x^2)^{-3/2} \qquad (1)$$

where h_o is the elevation variation at the center of the inflation/deflation bowl and d is the depth to the center of the spherical chamber. Best agreement was found for $d = 3$ km. By integrating over the inflation/deflation bowl the volume increase or decrease can be estimated. For the inflation periods a mean value of 5 m^3/s was found for the volume increase. Assuming no compression of the magma or the crustal rock, i.e., that the volume increase of the magma chamber is identical to the volume change at the surface, this corresponds to about $1.25 \cdot 10^4$ kg/s mass flow from below into the magma chamber, if a density of $2.5 \cdot 10^3$ kg/m^3 is used. Similarly mass flow out of the magma chamber during subsidence events can be estimated. Table 1 gives a summary of the elevation variations at the apex of the inflation/deflation bowl. Tilt variations in the power house which is about 1,300 m south of the apex have been used to extrapolate the maximum values at the apex, from the measured values at benchmark FM-5596, which is about 800 m south of the apex. Further, the table gives an estimate of the total volume change during inflation and deflation and the direction of the magma flow into the fissure swarm during subsidence events.

Table 1. Elevation and volume changes, direction of magma flow during subsidence events

Dates of Subsidence events	Maximum elevation changes at the apex	Estimated total volume change	Main direction of flow
December 20, 1975 to January, 1976	−230 cm +140 cm	$130 \cdot 10^6$ m^3 80 m^3	N (eruption)
September 29 to October 4, 1976	− 17 cm + 18 cm	9 m^3 10 m^3	N
October 30 to November 1, 1976	− 51 cm + 56 cm	29 m^3 32 m^3	N
January 20–21, 1977	− 32 cm + 59 cm	18 m^3 33 m^3	N
April 27–28, 1977	− 81 cm + 95 cm	46 m^3 54 m^3	S (eruption)
September 8–9, 1977	− 24 cm + 48 cm	14 m^3 27 m^3	S (eruption)
November 2, 1977	− 3 cm + 27 cm	2 m^3 15 m^3	?
January 6–25, 1978	−119 cm +108 cm	67 m^3 61 m^3	N
July 10–12, 1978	− 64 cm + 76 cm	36 m^3 43 m^3	N
November 10–15, 1978	− 72 cm	41 m^3	N

Mass Movement Beneath the Krafla Caldera Inferred From the Gravity Data

During the early stages of the present volcano-tectonic episode in the Krafla area some debate took place on the causes of the observed elevation changes. One model explained the inflation of the caldera by inflow of magma from below into a magma

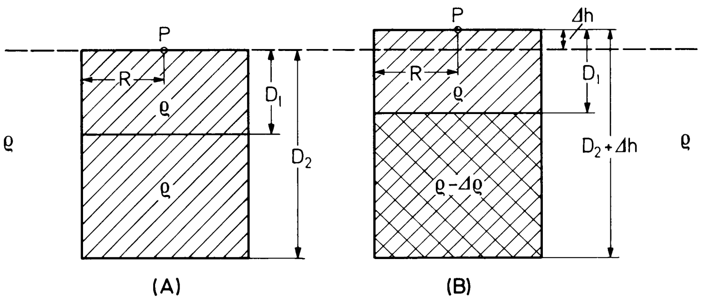

Fig. 8. Model of gravity change due to an expanding vertical cylinder. *A*. before expansion. *B*: after expansion. *P*· point of observation

chamber at shallow depth and the deflation events by flow of magma from the magma chamber into the fissure swarm to the north or south. In another model the inflation and deflation were interpreted as being caused by generation and condensation of steam in the geothermal water system. It is possible to test these models by converting measured elevation changes, Δh, into gravity values, Δg, using some assumption on mass distribution, and plot them along with measured gravity values as a function of time. As the changes in mass distribution accompanying level and gravity changes are not known we have used two simple models:

(1) A free air model described by the equation $\Delta g = -3.086\ \Delta h$, where Δg is measured in $\mu m/s^2$ and Δh in m. A change in gravity of 0.1 $\mu m/s^2$ will thus be obtained by an elevation change of approximately 3 cm.

(2) A Bouguer model described by the equation $\Delta g = -3.086\ \Delta h + 0.0004191\ \rho\ \Delta h$ where the density, ρ, is measured in kg/m^3 Using the value $\rho = 2.5\ 10^3\ kg/m^3$ leads to $\Delta g = -2.038\ \Delta h$. A change in gravity of 0.1 $\mu m/s^2$ will thus be obtained by an elevation change of approximately 5 cm.

If the elevation changes are entirely accompanied by complete mass (magma) compensation inflow or outflow the Bouguer model is clearly the more appropriate one. The relevance of the free-air model may, on the other hand, be judged from the simple case where we assume that the elevation change is caused by a uniform expansion or contraction within a vertical cylinder of radius R, which is situated directly under the point of observation, the depth to the top of the cylinder being D_1 and the depth to the bottom being D_2 before the expansion (contraction) and $D_2 + \Delta h$ after the expansion (contraction) (see Fig. 8). In this case the gravity change Δg due to the change Δh in elevation is approximately given by

$$\Delta g = 3.086\ \Delta h + 0.0004191\ \rho\ \Delta h\ c \qquad (2)$$

where

$$c = \frac{(D_1 + D_2)/R}{\sqrt{1 + (D_1/R)^2} + \sqrt{1 + (D_2/R)^2}} \qquad (3)$$

This can be seen from the fact that the gravitational attraction at P in Fig. 8 is

$$g_1 = 2\pi G \rho D_2$$

before expansion and

$$g_2 = 2\pi G(\rho(D_2 + \Delta h) - \Delta\rho$$
$$(D_2 + \Delta h - D_1 + \sqrt{R^2 + D_1^2} - \sqrt{R^2 + (D_2 + \Delta h)^2}))$$

after expansion with $\Delta\rho \simeq \Delta h \rho/(D_2 - D_1)$. After some arithmetic and neglect of small terms:

$$\Delta g = g_2 - g_1 \simeq 2\pi G \rho \Delta h\ \ c \text{ with}$$

$$c = (\sqrt{1 + (D_2/R)^2} - \sqrt{1 + (D_1/R)^2})/[(D_2 - D_1)/R]$$

which is identical to (3) as can be verified easily.

If $c = 0$ as becomes the case when $D_2/R \rightarrow 0$ we get the free air model, whereas if $c = 1$ as becomes the case when $D_2/R \rightarrow \infty$ we get a Bouguer model. Typical intermediate cases are, for example:

$R = 2$ km, $D_1 = 0$ km, $D_2 = 2$ km,
i.e., $D_1/R = 0$, $D_2/R = 1$ giving $c = 0.41$

$R = 2$ km, $D_1 = 0$ km, $D_2 = 4$ km,
i.e., $D_1/R = 0$, $D_2/R = 2$ giving $c = 0.62$

$R = 2$ km, $D_1 = 2$ km, $D_2 = 4$ km,
i.e., $D_1/R = 1$, $D_2/R = 2$ giving $c = 0.82$.

It is further clear that if inflation is caused both by magma inflow and rock expansion, and deflation by magma outflow and rock compression and ρ represents both the density of the magma and the rock, then the relationship (2) will still remain valid with a value of c less than 1 If, on the other hand, magma inflow is accompanied by rock compression and magma outflow by rock expanison (2) remains valid with a value of c larger than 1. We refer below to the factor c as the *correction factor*.

Figure 9 shows the result of the free air model and the Bouguer model with $\rho = 2.5\ 10^3\ kg/m^3$ at benchmark FM-5597 (for location see Fig. 1). The comparison indicates that the Bouguer model is the more appropriate if we observe:

(a) the increase in gravity that occurs during deflation

(b) the rate of decrease of gravity during inflation apart from a relatively short period immediately after the deflation event.

In fact, the closest agreement between gravity and elevation changes is in general found by using a value for $\rho \cdot c$ that lies in the range from approximately $3 \cdot 10^3\ km/m^3$ to over $4 \cdot 10^3\ km/m^3$ The regional value of density of basalts within the neovolcanic zone in NE-Iceland, based on seismic refraction work (Pálmason, 1971) and on rock weighing and Nettleton profiles (Schleusener et al., 1976) is considered to be $2.3 \cdot 10^3\ kg/m^3$ On the other hand, Ito and Kennedy (1971) have discussed a relation between the density of molten basaltic magma and pressure, indicating that for molten basalts, density values of around $3.0 \cdot 10^3\ kg/m^3$ may be quite realistic. In any case, there is clearly little justification for assuming that the correction factor, c, should take on a value any lower than one. This supports the theory that the inflation and deflation of the Krafla caldera is caused by in- and outflow

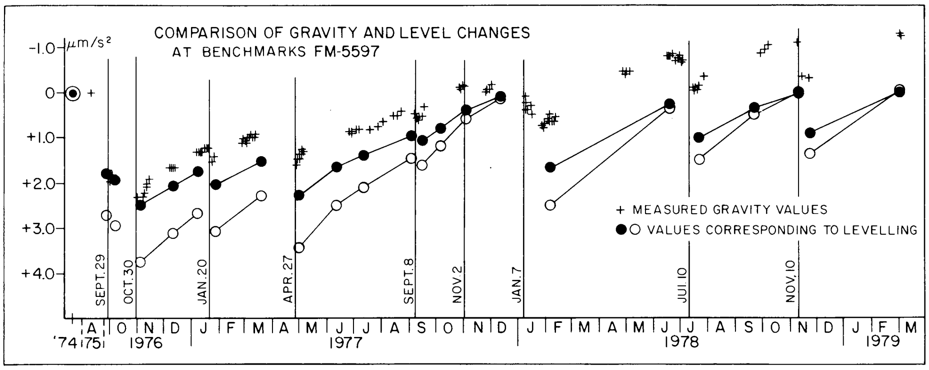

Fig. 9. Comparison of gravity and elevation changes with time at benchmark FM-5597, for location see Fig. 2. *Crosses* are measured gravity values. *Filled circles* are gravity values calculated from measured level values assuming a Bouguer model. *Open circles* are gravity values calculated from level values using a free air model

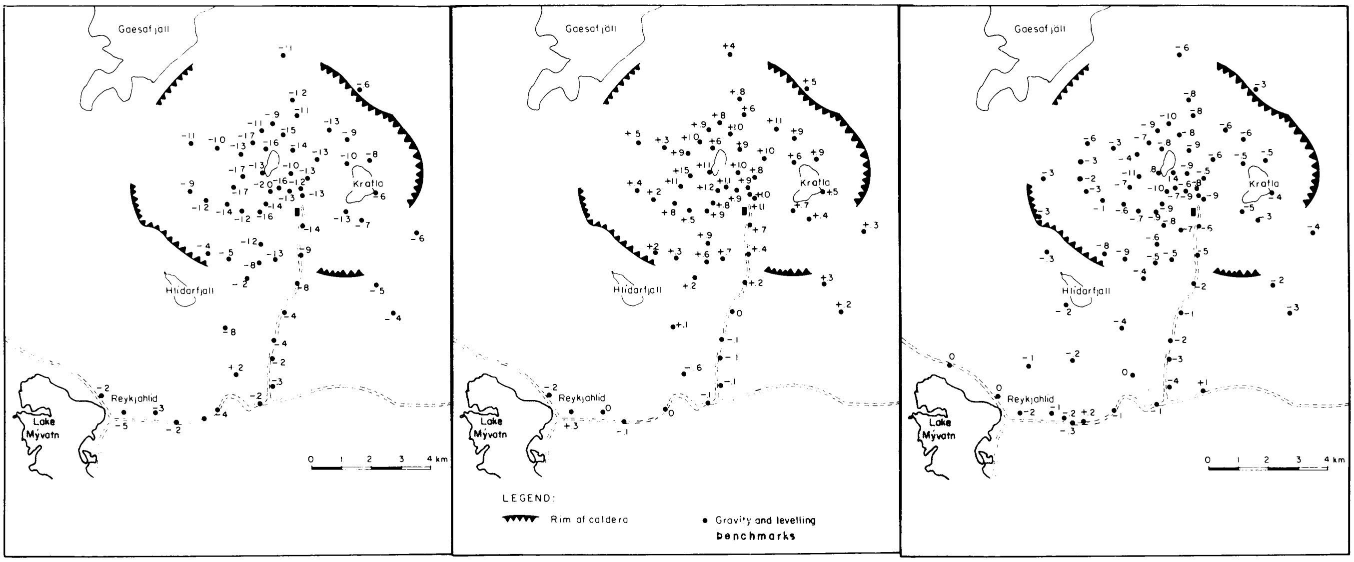

Fig. 10. Reduced gravity values in μm/s², for the time periods shown in Figs. 4–6. Reduced gravity is the difference between measured gravity and gravity calculated from levelling using a free air model

of magma into a chamber. We observe, however, also that immediately after the deflation there usually occurs a rapid decrease in gravity with the gap between observed and calculated gravity persisting during inflation and thus, after each deflation event, increasing with time. The rate of gravity decrease is such that it cannot even be explained by a correction factor of 0. Thus, although some expansion of crustal rocks due to, e.g., steam generation or intrusion of magmatic gases, may take place after deflation this cannot be the sole explanation. Another plausible explanation is a rapid sinking of the groundwater level after each deflation event. Such sinking could be caused by the rifting and opening of new fissures in the area and hence the flow of groundwater from the Krafla central volcano. In order to explain the difference between measured and calculated gravity values in 1979 the accumulated sinking of groundwater level must amount to some 20 m assuming a porosity of 15%. If less were observed some permanent rock expansion would be indicated. Unfortunately there are no groundwater data available to test this.

Gravity observations at other benchmarks are much less detailed than those at benchmark FM-5597. In general we only have one observation in the short period after the deflation event when the rapid decrease in gravity has been observed at benchmark FM-5597 and this observation most often takes place towards the end of that period. Observations at other benchmarks thus do not shed any additional light on the nature of the rapid decrease in gravity. They do however indicate that it is not confined to benchmark FM-5597 in that

(a) estimates of the density of the compensating mass based on the Bouguer model and observations over a deflation event in general give a higher value than those based on observations during an inflation period,

(b) a comparison of two gravity observations, many deflation events apart, that correspond to approximately the same elevation value reveals, in general, a decrease in the gravity value.

Hunt (1976) has outlined a simple method to estimate total mass variation by comparing measured elevation and gravity changes. The procedure used is as follows: First the measured elevation changes are converted into gravity changes using the normal free air gravity reduction ($\Delta g = -3.086 \cdot \Delta h$). Then the free air gravity value is subtracted from the measured value of gravity, obtaining a reduced gravity value, Δg_c. Finally applying Gauss' potential theorem in the form $M = (\Sigma\, \Delta g_c \cdot \Delta S)/2\pi G$ where M is the mass not recovered, ΔS is the area corresponding to the reduced gravity change and G is the gravitational constant, an estimate of total change of mass can be found. This can be applied both to periods of inflation, to determine the rate of inflow into

Table 2. Mass and volume changes and estimated density of mass flow between November 27, 1977 and July 21, 1978

Dates of observations	Changes in total mass from gravity measurements	Changes in total volume from the Mogi model	Estimated density by full mass compensation
November 27, 1977			
	$-2.43 \cdot 10^{11}$ kg	$-56 \cdot 10^{6}$ m^3	$4.3 \cdot 10^{3}$ kg/m^3
February 5, 1978			
	$+1.69 \cdot 10^{11}$ kg	$+56 \cdot 10^{6}$ m^3	$3.0 \cdot 10^{3}$ kg/m^3
June 22, 1978			
	$-1.64 \cdot 10^{11}$ kg	$-30 \cdot 10^{6}$ m^3	$5.5 \cdot 10^{3}$ kg/m^3
July 21, 1978			

the caldera, and also to subsidence events for estimating the related total change in mass. The results, at least theoretically, are not affected by possible mass redistribution due to, e.g., rock expansion or compression.

Figure 10 shows gravity values for the three periods of time shown in Figs. 4–6, i.e., for the two deflation events in January and July 1978 and the inflation period between these events. Levelling and gravity surveys are not always carried out at the same time, but the levelling data can be interpolated to the same date as the gravity data using the daily tilt observations. The Mogi model can subsequently be used to calculate volume change corresponding to the mass changes obtained from the gravity measurements. The results are presented in Table 2.

Estimates of density are based on the assumption that both inflation and deflation are entirely caused by mass inflow and outflow. Keeping in mind an earlier remark about the lack of detail in gravity observations after the deflation events, this is in good agreement with the inference made from the observations at benchmark FM-5597, i.e., that one is justified in assuming that inflation and deflation are accompanied by mass (magma) inflow and outflow provided one can further assume that some additional mass (groundwater) outflow takes place immediately after deflation.

Acknowledgements. We are thankful to G. Thorbergsson for drawing the attention of the authors to the relation (2), and to A. Gunnarsson for carrying out the levelling measurements.

Reference

Björnsson, A. Jardhraeringar vid Kröflu (in Icelandic with English summary). Natturufraedingurinn **46**, 177–240, 1977

Björnsson, A., Johnsen, G.V., Sigurdsson, S., Thorbergsson, G., Tryggvason, E.: Rifting of the plate boundary in North Iceland 1975–1978. J. Geophys. Res. **84**, in press, 1979

Björnsson, A., Saemundsson, K., Einarsson, P., Tryggvason, E., Grönvald, K.: Current rifting episode in North Iceland. Nature **266**, 318–323, 1977

Brandsdóttir, B., Einarsson, P.. Seismic activity associated with the September 1977 deflation of the Krafla central volcano in NE-Iceland. J. Volc. Geotherm. Res. in press; 1979

Einarsson, P.: S-wave shadows in the Krafla caldera in NE-Iceland, evidence for a magma chamber in the crust. Bull. Volcanol. **41**, 1–9, 1978

Gerke, K.: Crustal movements in the Myvatn- and the Thingvallavatn-area, both horizontal and vertical. In: Geodynamics of Iceland and the North Atlantic area, L. Kristjansson, ed. pp. 263–275. Dordrecht, Boston: D. Reidel Publishing Company 1974

Gerke, K.. Über neuere horizontale und vertikale Krustenbewegung in Island. Mitteilungen der Technischen Universität Carolo-Wilhelmina zu Braunschweig XII, Heft III/IV, 1977

Gerke, K., Möller, D., Ritter, B.. Geodätische Lagemessungen zur Bestimmung horizontaler Krustenbewegungen in Nordost-Island. In: Festschrift für W. Höpcke, Wiss. Arb. d. Lehrst. f. Geodäsie, Photogramm. u. Kartogr. an d. T.U. Hannover, Nr. **83**, Hannover 1978

Hunt, T.M.. Recharge of water in Wairakei geothermal Field determined from repeated gravity measurements. N. Z. J. Geol. Geophys. **20**, 307–317, 1976

Ito, K., Kennedy, G.C.: An experimental study of the basalt-garnet granulite-eclogite transition. In: The structure and physical properties of the Earth's crust, Vol. 14, J.G. Heacock, ed. pp. 303–314. Washington, D.C. Geophys Monogr. Am. Geophys. Union 1971

Longman, I.M. Formulas for Computing the tidal accelerations due to the Moon and the Sun. J. Geophys. Res. **64**, 2351–2355, 1959

Möller, D., Ritter, B. Geodetic measurements and horizontal crustal movements in the rift zone of NE-Iceland. J. Geophys. **47**, 110–119, 1980

Mogi, K.: Relations between the eruptions of various volcanoes and the deformation of the ground surfaces around them. Bull. Earthq. Res. Inst. **36**, 99–134, 1958

Niemczyk, O.. Spalten auf Island. Stuttgart: Wittwer, 1943

Pálmason, G.: Crustal structure of Iceland from explosion seismology. Soc. Sci. Islandica, Rit XL, 1971

Pálmason, G., Nilsen, T.H., Thorbergsson, G.. Gravity base station network in Iceland 1968–1970. Jökull **23**, 70–125, 1973

Saemundsson, K.. Evolution of the axial rifting zone in Northern Iceland and the Tjörnes Fracture Zone. Geol. Soc. Am. Bull. **85**, 495–504, 1974

Saemundsson, K.. Fissure swarms and central volcanoes of the neovolcanic zones of Iceland. In. Crustal evolution in Northwest Britain and adjacent regions. Geol. J. Spec. Issue **10**, 415–432, 1978

Schleusener, A., Torge, W.: Investigations of secular gravity variations in Iceland. Z. Geophys. **37**, 679–701, 1971

Schleusener, A., Torge, W., Drewes, H.. The gravity field of Northeastern Iceland. J. Geophys. **42**, 27–45, 1976

Sigurdsson, O.. Náttúruhamfarir i Thingeyjarthingi (In Icelandic with English summary). Tyli **6**, 3–20, 1976

Spickernagel, H.: Höhenmessungen in Nord-Island. Mitt. Markscheidewesen **73**, 139–152, 1966

Torge, W., Drewes, H. Gravity variations with time in Northern Iceland 1965–1975. J. Geophys. **43**, 771–790, 1977a

Torge, W., Drewes, H.: Gravity changes in connection with the volcanic and earthquake activity in Northern Iceland 1975/1976. Jökull **27**, 60–69, 1977b

Torge, W., Kanngieser, E.. Gravity and height variations during the present rifting episode in northern Iceland. J. Geophys. **47**, 125–131, 1980

Received May 19, 1979; Revised Version July 9, 1979