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ABSTRACT

Ground tilt measurements demonstrate that Askja is in a state of unrest, and that in the period 1988 - 1991 a maximum 48 +/- 3 µrad tilt occurred down towards the centre of the caldera. This is consistent with 126 mm of deflation at the centre of the caldera with a 2.5 - 3.0 km depth to the source of deformation. The volume of the subsidence bowl is 6.2 x 10^6 m^3. When combined with high precision microgravity measurements, the overall change in sub-surface mass may be quantified. After correction for the observed elevation change using the free air gradient of gravity measured for each station, the total change in mass is estimated to be less than 10^9 kg. A small residual ground inflation and net gravity increase in the eastern part of the caldera may be caused by dyke intrusion in this region. The minimum dimensions of such an intrusion or complex of intrusions are 1 m width, up to 100 m deep and up to several hundred metres thick.

INTRODUCTION

Askja lies on a north - south trending fissure system parallel to the Krafla rift (Figure 1) in central Iceland. The caldera at Askja, in contrast with that at Krafla is quiet prominent, being a circular depression 200 - 300 m deep and 8 km across. Unlike 'conventional' calderas, it seems likely that it grew at least in part by ring and fissure eruption around its margins rather than collapse at the centre (Sigurdsson and Sparks, 1978; Brown et al. 1991). The most recent caldera at Askja, called Oskjuvatn, lies within the main depression. It is a further 200 m deep and 4 km across, formed after explosive activity in 1875 (Figure 2). Most of the volcano developed under ice, although there are extensive lava flows of early post glacial age. Historic activity at Askja includes the plinian event of 1875, and small basaltic lava eruptions during the 1920's and in 1961. In addition, lavas covering the floor of Askja caldera are dated by tephrachronology as being later than 1362 but earlier than 1477 (Annertz et al. 1985). Alternating inflation and deflation have been observed within the caldera since 1966 and the data are consistent with a point source of deformation. This point source, which can be used to account for some 80% of the observed deformation is located just to the north of the recent caldera, at the centre of the main depression (Tryggvason, 1989a). The average rate of ground deformation observed at Askja is greater than at any other quiescent volcano in Iceland, but Tryggvason (1989a) argued that this was not related directly to relaxation after the plinian eruption, but might instead be caused by oscillation of the intensity of convective currents within the Icelandic mantle plume. The period of inflation was accompanied by volcanic and earthquake activity in central Iceland, while the deflation that has been observed since 1983 may relate to magma drainage from the Askja system to Krafla which was active between 1975 and 1985 (Tryggvason 1989a). Indeed, there is evidence from the 1875 explosive eruption that magma stored below Askja travelled 100 km north in underground fissures to erupt contemporaneously at Sveinagja (Sigurdsson and Sparks, 1978). Here we shall consider gravity and ground deformation data for Askja for a three year period and consider the implications for magma injection and drainage.

ASKJA MICROGRAVITY DATA

Microgravity measurements have been made regularly at Askja volcano since 1988. High precision data were obtained by the utilisation of rigourous field procedures (Rymer, 1989), using the same two LaCoste and Romberg model G instruments and the same operators for each survey (H. Rymer for G513 and G. C. Brown for G105). Station pairs were used, so that measurement errors at individual stations were easy to identify. Most of the stations used were either levelling or distance measurement stations established previously by E. Tryggvason.

The reference station was 83001, which lies just outside the northeastern rim of the caldera, on the 1961 lava flow (Figure 2). All gravity data are quoted relative to data at this station, with the assumption that there are no gravity changes at this location. The justifications for using this as the reference are that it is outside the main caldera, but it is close enough to the area of interest that it can be remeasured frequently. In addition, no significant gravity changes have occurred between this station and other reference stations including 83009 (located on figure 2) up to 8 km to the east.

Gravity values relative to the base station (Table 1) indicate that there is a maximum gravity difference of about 15 mGal between the field area and the base. This is within the limits required to obtain the best precision (Rymer, 1989). The figures in parenthesis (Table 1) indicate the standard error on each data point. Where no value is given, this means that only one observation of the gravity difference between the reference station and the field station was made at that time. The standard errors on the data (Table 1) are 10 - 15 μGal at worst for most stations and this is the sort of error expected in a survey of this type (Rymer, 1989) given the climate, the necessary time delay between readings, and the inevitable jolting of the instruments in transit (by back pack) between stations. Where observations differ from previous observations by 10 μGal or more, and if this is recorded by both gravity meters, it is likely at the 68% confidence level that there has been a genuine gravity change.

The survey was designed so that stations could be considered in groups. The locations of the stations (Figure 2) are such that D-19 and (82)005 together represent the caldera centre. This is near the region that has been identified by Tryggvason (1989a) as being the centre of deformation. Both stations seem to behave in much the same way (Figure 3), and although one station value in 1991 appears to be out of line with the others (indicated by an arrow, Figure 3), the overall change in gravity far exceeds the errors on the data. Even the standard deviation on the 'discrepant' point is only 3 μGal (Table 1). There is no obvious explanation for the apparently anomalous points in figure 3, all but one of which are well determined and have a low standard deviation. However, working at the extreme limits of precision of gravity meters, instrumental errors are bound to play an important role in the reliability of data (Rymer 1991). Despite the errors (9 μGal on average, table 1), a clear trend towards increasing gravity is indicated.

The second set of stations lies on a roughly north-south line inside the eastern boundary of the caldera. Stations 412 and 405 are on the 1961 lava flow where it enters the caldera (Figure 2), and there is evidence for an overall very gradual increase in gravity at these stations with respect to the reference outside the caldera. The changes are smaller than for the caldera centre and the errors are larger (Table 1). Once again there is an apparently discrepant data point, (marked by an arrow) but there is some evidence for an overall increase in gravity at these stations.

The third and final set of stations is close to the north east shore of lake Oskjuvatn (Figure 2). There was clearly a significant gravity increase at the eastern two stations between 1988 and 1989 with respect to station 83001 (Figure 3) of around 20 μGal. This was followed by a gravity decrease of about 10 μGal. At the same time, station Kneb showed no such increase, although both gravity meters at all three stations show an overall increase of about 16 μGal (the standard error on this value is 9 μGal) for the three year period as a whole. The discrepant point in 1990 (station IV16, meter G105) has a very small standard error on it (Table 1) and is apparently anomalous. Provisionally it would appear that there have been very slight gravity increases at the southeastern caldera stations during the three year period, although again the errors are larger than for the caldera centre stations (Table 1 and Figure 3).

SUMMARY OF MICROGRAVITY DATA

There is evidence for a gravity increase of 20-25 μGal over the period of observation at the centre of the caldera and to a lesser extent in the northern part of the caldera. A 20 μGal increase between 1988 and 1989 was followed by a 10 µGal decrease at stations close to the north-eastern shore of Oskjuvatn (stations IV16 and D-18). If there were no elevation changes at any of these stations, this would mean that gravity increases represented an overall increase in sub-surface mass and vice versa (Rymer 1991). However, we know that elevation changes have occurred, and these must be interpreted alongside the gravity data. Also, the level of the lake Oskjuvatn is known to change considerably (Tryggvason, 1989b), which could effect gravity at stations near the lake shore by 5-10 µGal.

GROUND DEFORMATION DATA

Observations of ground deformation at Askja since 1966 have revealed alternating inflation and deflation cycles. Since 1983 however, all deformation has been deflation, down towards the centre of the caldera. Although the earlier measurements were largely confined to high precision levelling lines in the NE portion of the caldera, data obtained over the last few years have included optical levelling tilt (dry tilt) and electronic distance measurements as well as precision levelling (Tryggvason, 1989a). Here we present results from an optical levelling tilt network and tilt data derived from the high precision levelling line (station locations are shown on Figure 4) over the three year period from 1988 to 1991.

Optical Levelling tilt

Nine new stations (SS, VF, OL, BH, MO, NH, ST, JS and TA; Figure 4) were established in and around the Askja caldera during the summers of 1988 and 1990. Each station consists of 4 or 5 markers cemented into solid rock in a circular pattern of approx. 25 m radius and they are all located on Holocene lavas except MO which is on a palagonite tuff. Of the 9 tilt stations, 2 were first observed in 1988 (VF and SS), while the remaining seven stations were established in 1990, and for these stations, the observed tilt over a period of one year was multiplied by 3 in order to estimate the 3-year tilt 1988-1991. The results (Table 2 and Figure 4) show that with the exception of station MO to the southeast of the caldera, all stations underwent a similar deformation. The maximum tilt over this time interval was recorded at station OL where 12 µrad per year or 36 µrad in the 3-year period up towards the SW was seen. Although the tilt at station MO is not consistent with the other stations, it is much larger than the errors (indicated by the ellipse axes on Figure 4), so it is thought to be genuine but unrelated to the tilt recorded elsewhere.

Precision Levelling

The precision levelling profile was established in 1966 and has been extended on several occasions. It is located on the 1961 lava inside and to the NE of the main Askja caldera, and is about 6 km in total length, but actually covers a distance of only 4.2 km. Deformation along this profile has been used with trigonometric data and lake level measurements to locate the probable source of deformation at Askja and to relate it to the activity at Krafla seen during the first half of the 1980s (Tryggvason, 1989a). In this paper, we are considering tilt, and so we divide the profile into seven components (S1-S7; Figure 4 and Table 2), with some degree of overlap, and deduce a value of tilt for each.

Table 2. *Data for the three year period from the optical levelling tilt stations.*

Tilt station and sections of levelling profile	Tilt observed (see Figure 6) 1988-1991 (μrad)	Azimuth of upslope tilt (degrees)	Standard error on tilt (μrad)	Comments
SS	3.2	131	6.4	Tilt is too small to be significant
VF	12..6	227	1.2	
OL*	37.1	228	4.2 - 8.5	
BH*	24.7	123	5.7	Tilt is probably real
MO*	27.1	12	3.5	Tilt appears to be genuine but unrelated to tilt observed at other stations
NH*	5.4	77	4.2	Tilt too small to be of significance
ST*	15.5	217	5.7	Probably a genuine tilt
JS*	32.1	345	5.8	Likely to be a genuine tilt
TA*	13.4	341	10.2	Result of no significance
S1	47.7	91	0.7 - 2.3	Error depends on exact azimuth assumed
S2	45.0	35	0.5 - 2.7	
S3	31.0	26	0.3 - 2.0	
S4	34.1	25	0.3 - 1.1	
S5	11.8	74	0.3 - 1.8	
S6	11.1	77	0.8 - 4.6	
S7	8.8	98	0.2 - 0.9	

* First observed in 1990. Tilt and standard error is three times that observed in one year.

These data are in good agreement with the optical tilt data which indicate a tilt down towards the centre of the caldera (Figure 4). The largest tilt is seen on section S1 of the previous levelling line, and at stations OL and BH which are closest to the suggested source of deformation and the smallest effects are seen along sections S5, S6 and S7 and stations ST, NH and TA which are outside the caldera boundary.

SEARCH FOR A POINT SOURCE FOR THE GROUND DEFORMATION DATA

Deformation of volcanoes may be attributed to contraction or expansion of the magma reervoir beneath the volcano. The surface deformation expected from this process was evaluated by Mogi (1958), by assuming an homogenous elastic Earth, and a point source reservoir. Although real volcanoes do not fulfill all these requirements, observed deformation of volcanoes is usually similar to the predicted point source deformation. Therefore, the position of a point source can be defined, as the point that will produce ground deformation which is the best approximation to the observed deformation. Certainly, the observed ground deformation always deviates somewhat from the theoretical point source deformation, partly because of the inhomogeneity of the real Earth and partly because the magma reservoir is large and not spherical.

A search for a point source of deformation at Askja is aimed at finding a location where a theoretical point source would cause deformation similar to that observed. A computer program was written which compared observed and theoretical tilt, given the depth and coordinates of the source. The point source is moved iteratively until the difference between the calculated and observed tilt is minimised.

Of course there are biases in the data since stations are unevenly distributed within the area of interest, and some observations are less reliable than others. An additional problem is that not all of the observed ground deformation is necessarily attributable to a single point source. For this reason, four separate data sets were used and the results compared. Tilt stations where the computed tilt error is similar to or greater than the computed tilt are excluded, and also the station MO, because observed tilt there appears to be unrelated to tilt at other stations.

set 1 includes all acceptable tilt data, 5 optical levelling tilt stations and 7 sections of the precision levelling line (Figure 4). Set 2 includes the same 5 optical levelling tilt stations and also 3 sections of the levelling line. Set 3 includes only the 5 optical levelling tilt stations. Set 4 includes only the 7 sections of the precision levelling line.

Computations made for data sets 1 and 2 predict a point source for the tilt at a depth of about 3 km, or slightly less, while data set 3 predicts a deeper source and data set 4 predicts a shallower source. All predict a source to the north of lake Oskjuvatn, slightly northeast of the centre of the main caldera. Similar results are obtained by minimising the standard deviation of observed tilt from theoretical tilt, and by maximising the correlation between the radial components of observed tilt and theoretical tilt (Table 3).

The standard deviation of observed tilt from theoretical tilt is much larger than the standard error of observed tilt, signifying that the point source cannot be used to account for all of the observed tilt. In fact, the hypothetical point source at a depth of 2.8 km and coordinates 16.7 km east, 15.7 km north (65^0 3.19' N, 16^0 46.10' W) could cause about 80% of the observed ground deformation of Askja. The residual tilt, the difference between theoretical and observed tilt is greatest for some sections of the precision levelling line (Figure 5). This suggests that there may be a second source of deformation near the eastern cladera boundary.

Table 3. *Computed points of (a) minimum standard deviation between observed tilt and theoretical tilt, and of (b) maximum correlation between radial component of observed tilt and theoretical tilt for various source depths and station selections. D is assumed source depth (km); X is computed east coordinate of the source (in km, coordinates are shown on figures 2,4 and 5); Y is the computed north coordinate of the source (in km); H is maximum 3 year vertical ground displacement (in mm); sd is minimum standard deviation of tilt (in µrad); R is maximum coefficient of correlation squared. Unacceptable solutions are in parentheses.*

(a)	(a)	(a)	(a)	(a)	(b)	(b)	(b)	(b)
D	**X**	**Y**	**H**	**sd**	**X**	**Y**	**H**	**R**
Data set 1								
2.0	16.87	15.79	-98	14.02	16.75	16.00	-99	0.752
2.5	16.87	15.79	-109	13.09	16.49	15.79	-117	0.721
3.0	16.62	15.58	-141	12.98	16.24	15.58	-155	0.709
3.5	16.62	15.79	-171	15.18	15.98	15.58	-195	0.684
Data set 2								
2.0	16.75	16.21	-104	13.80	16.75	16.21	-104	0.884
2.5	16.87	16.21	-108	12.64	16.62	16.21	-112	0.840
3.0	16.62	16.00	-128	11.95	16.49	16.00	-130	0.797
3.5	16.49	15.79	-162	12.53	16.24	15.79	-167	0.770
Data set 3								
2.0	15.86	14.73	-191	15.10	16.49	16.42	-83	0.973
2.5	16.11	14.94	-129	13.52	16.36	16.42	-76	0.966
3.0	16.24	15.15	-131	12.20	(17.00	12.83	-152	0.951)
3.5	16.49	15.73	-134	11.18	(17.25	12.83	-165	0.964)
Data set 4								
2.0	17.25	16.00	-104	12.72	15.35	14.73	-537	0.881
2.5	16.62	15.58	-160	15.07	14.84	14.31	-632	0.873
3.0	15.86	15.15	-249	17.56	14.08	13.67	-907	0.886
3.5	15.10	14.73	-367	20.49	(19.16	16.31	-919	0.990)

GRAVITY-HEIGHT CORRELATIONS AT ASKJA

The rate of change of gravity with height or the free air gradient (FAG), may be measured in situ by making repeated observations of gravity on top of a tripod or similar stable but portable structure and on the ground beneath it. The elevation difference between the two positions of the gravity meter is carefully measured, and then the free air gradient is simply calculated. The FAG at Askja ranges from -360 μGal m^{-1} at stations D-19 and 005 in the centre of the caldera, to -240 μGal m^{-1} at IV16 and D-18 to -330 μGal m^{-1} at station 83001 (Figure 2). These values are largely explained by the caldera centred Bouguer negative gravity anomaly, and positive anomaly associated with the fissure swarm that runs through the eastern side of the caldera close to stations IV16 and D-18 (Figure 6 and Brown et al. 1991). The Bouguer gravity anomaly falls again towards the east at 83009 (Figures 2 and 6) making the FAG there more negative. Microgravity data are height corrected by the observed FAG rather that the theoretical value of -308.6 μGal m^{-1} to avoid the introduction of errors in interpretation caused by ignoring the Bouguer gravity anomaly (Rymer, 1991; Berrino et al. 1992). Residual gravity changes after correction for height changes may then be interpreted in terms of sub-surface mass changes.

Overall gravity changes (Δg) measured between 1988 and 1991 are given with elevation changes (Δh) deduced from the point source model in table 4. Since the residual tilts were mostly quite small, the actual difference between this deduced Δh and the real elevation changes will be only a few mm over the three year period. Figures in parenthesis are the standard errors on the gravity changes. The expected gravity change for a given elevation change may be predicted by multiplying the elevation change by the observed FAG. The difference between the predicted gravity change and the observed gravity change is called the residual gravity ($\Delta g_{residual}$) change. Although the errors are rather large, it is clear that there is a small $\Delta g_{residual}$ at stations 005 and D-19 in the centre of the caldera. The increase on the eastern side, is rather larger and there is good evidence for a small but finite increase of the order of 10 μGal. This increase in gravity in the eastern part of the caldera after correction for height changes must reflect an overall increase in sub-surface mass beneath that region.

Table 4 *Observed gravity changes (Δg in μGal) with the standard error on the data given in parenthesis for the whole period 1988-1991. Discrepant points highlighted on figure 3 have been ignored for this calculation. The elevation changes (Δh in mm) are calculated from the point source model. The residual change is the difference between the observed and predicted changes; the predicted change is calculated from the Δh values multiplied by the observed FAG (in μGal) for each station pair.*

Station	Δh	Δg	FAG	$\Delta g_{residual}$

005 D-19	-0.047	26 (9)	-360	+9
412 405	-0.026	13 (9)	-240	+7
IV16 D-18	-0.007	17 (9)	-240	+16

These results indicate that over the three year period under investigation there has probably been an overall gravity increase, although the errors (in parenthesis) are rather large. The net gravity change after correction for height changes at stations in the centre of the caldera closest to the point source of deflation is 9 +/- 9 µGal. However, in the eastern part of the caldera there has been a more convincing net gravity increase of 16 +/- 9 µGal. Confidence in this conclusion despite the rather large errors comes from the fact that all the stations in this region indicate a net increase and the results would therefore not appear to be random (figure 3).

MODELLING OF RESIDUAL GRAVITY CHANGES

It is tempting to try to interpret the gravity changes in terms of the same source that accounted for the majority of the deformation data. The gravitational effect (Δg) of mass changes (ΔM) at a spherical source whose depth is much greater than its radius buried beneath the surface may be calculated simply;

$$\Delta g = G\ \Delta M \frac{d}{(r^2 + d^2)^{3/2}}$$

where G is the Universal gravitational constant, d is the depth to the point source and r is the horizontal distance to it. Gravity changes are calculated (Table 5) for (a) a point vertically above the source's centre of mass; (b) a point at the surface but 1.5 km horizontally away (to predict the effect at stations 005 and D-19) and (c) a point at the surface but 2 km horizontally away (to predict the effect at stations on the eastern side of the caldera) for the depth range deduced from the tilt data .

Table 5. *Calculated gravitational effect Δg (µGal) of a mass change ΔM (kg) in a spherical source at depths of 2.5 - 3.0 km (a) immediately beneath the station, (b) 1.5 km away horizontally and (c) 2 km away horizontally.*

Depth	ΔM	Δg (a)	Δg (b)	Δg (c)
2.5 km	10^8	1.06	0.67	0.50
2.5 km	10^9	10.6	6.7	5.0

2.5 km	10^{10}	106	67	50
2.5 km	10^{12}	106 x 10^{2}	67 x 10^{2}	50 x 10^{2}
3.0 km	10^{8}	0.74	0.53	0.42
3.0 km	10^{9}	7.4	5.3	4.2
3.0 km	10^{10}	74	53	42
3.0 km	10^{12}	74 x 10^{2}	53 x 10^{2}	42 x 10^{2}

It is the trends between the rows and the columns here that is important, and not the actual numbers themselves as these depend strongly on the *exact* depth chosen. These calculations show that from a gravitational point of view, the difference between a point source at 2.5 km depth and one at 3 km depth cannot be resolved using the available data. The gravity data however do not dispute the conclusion drawn from the tilt data that a source buried between 2.5 and 3.0 km beneath the centre of the caldera is responsible for at least some of the geophysical observations. Moreover, the gravity data can be used to quantify this source. After correction for the effects of elevation changes, the gravity change is small, just 9 +/- 9 µGal and so for our model to be plausible, the calculated Δg (Table 5) must also be of this order. For a ΔM of 10^8 kg, the calculated gravity change is negligible but is of the order of a few tens of µGal for $\Delta M = 10^{10}$ kg and for $\Delta M = 10^{12}$ kg, the gravity effect is of the order of 10^2 µGal. However, for $\Delta M = 10^9$kg, the calculated gravity change at stations immediately above, 1.5 and 2.0 km from the source is of the order of a few µGal, just as we observed.

Thus a likely cause of the observed deflation in the centre of the caldera associated with no significant residual gravity change, is a source 2.5 - 3.0 km beneath the surface undergoing a mass increase of no more than 10^9 kg. However, the net mass increase in the east must be accounted for separately as there is a larger increase than can be accounted for using the point source model. This region coincides with a proposed zone of intense dyking, representing the passage of a fissure swarm through Askja (Brown et al. 1991). The residual gravity increases and tilt in this region may therefore reflect dyke intrusion. Dykes exposed in other parts of the Askja complex range in width from 10 cm to 1 m, and we have calculated the gravitational effect of such dykes at depths of 10 m, 100 m, 500 m and 1000 m of height 0 - 3000 m. A density contrast of 300 kg m^{-3} has been used for these calculations on the assumption that the dykes infiltrate a region composed of lava flows, dykes and hyaloclastite deposits. For a dyke 10 cm wide, the gravitational effect at the surface above it is always less than 5 µGal even when the dyke extends from 10 m below the surface to 3000 m below. For a 1 m wide dyke however, the surface gravitational effect may exceed 20 µGal even if the dyke is over 100 m beneath the surface. It is therefore possible that the small residual gravity increases represent dyke intrusion to within 100 m of the surface, with dyke widths in excess of 10 cm and probably up to 1 m. Dyke intrusion can explain the residual gravity increases and the residual inflation at stations on the eastern side of the caldera after the effects of the point source model have been removed.

SUMMARY

Gravity increases of up to 32 µGal have been observed at stations within the Askja caldera between 1988 and 1991 (Figure 3). Tilt data obtained at the same time indicate overall deflation within the caldera (Figure 4). Eighty per cent of this deflation may be attributed to a pressure decrease in a spherical Mogi type source 2.5 to 3.0 km below the surface at the point marked with a cross on figure 5. This model has been used to calculate elevation changes at gravity stations to within a few mm. The free air gradient of gravity measured at the field stations is then used to calculate the expected or predicted gravity change. The residual gravity change (Table 4) is the difference between the observed and predicted change. The residual gravity changes indicate that although the pressure source depth cannot be resolved any better than with the tilt data, it can be quantified to be less than 10^9 kg increase in mass. Residual tilt after removal of the pressure source effects indicates inflation in the eastern part of the caldera. There is also a residual gravity increase in this region, which may be modelled in terms of dyke intrusion. The proposed intrusion is of average width 1 m, and reaches to between 10 m and 100 m of the surface. This need not be a single dyke of these dimensions, but may comprise several smaller, thinner intrusions with the same net effect.

DISCUSSION AND CONCLUSIONS

The definition of caldera unrest is a change from the normal state (Newhall and Dzurisin, 1988). Whatever the 'normal' state for Askja is , it has clearly changed in historic times and so by definition is a caldera in a state of unrest. Like other well studied calderas such as Campi Flegrei, Rabaul, Long Valley and Yellowstone, (summarised by Berrino at al. 1992) Askja has undergone considerable ground deformation. As much as 5 m of uplift occurred on the northeast shore of lake Oskjuvatn relative to the southeast shore between 1960 and 1968, probably during the 1961 eruption (Tryggvason, 1989b). There is archeological evidence from Rabaul and Campi Flegrei that considerable (several metres) subsidence has occurred in the past, but the recent crises at these calderas have involved considerable inflation (about 1 m) followed by relatively little subsidence. Only at Krafla (also in Iceland) was the deflation of the same order of magnitude as the preceding inflation (about 1 m), while at Campi Flegrei it was less than a quarter and at other calderas the deflation has been negligible or very limited. The tectonic regime in Iceland is extensional and the relationship between caldera dynamics and magma chamber pressure may well be more complicated for Icelandic volcanoes than for volcanoes elsewhere because of the extensive rifting system and proximity of other active volcanic centres. In other words, the presence of an active rifting system allows magma to flow away from the central volcano.

Long term monitoring of ground deformation at Askja has revealed that periods of inflation and deflation occur without any change in surface activity. In fact during the period of investigation (1966 - 1991), thermal activity has been confined to the shores of Oskjuvatn caldera and the pit crater Viti formed in the 1875 eruption. Variable amounts of snow melt make precise measurements difficult, however it is clear that surface activity has been static or declining rather than increasing over this time. It is possible that the cooling in Viti lake is directly associated with magma drainage.

Ground deformation over the period 1988 - 1991 was measured as tilt reaching a maximum of 48 µrad indicating a source of deflation in the centre of the caldera. The best fitting model of this source is 65^0 3.19' N, 16^0 46.10' W at 2.8 km depth with an error margin of about 0.3 km. The maximum deflation above the source is 126 mm, which corresponds to a total subsidence volume of 6.2×10^6 m^3. This corresponds to a contraction of 9.3×10^6 m^3 of the magma chamber according to the Mogi model. A small residual inflation in the eastern part of the caldera indicates another source of deformation within the caldera, but it is poorly defined and will be the subject of further study. Gravity data support the spherical source model for deflation in the centre of the caldera, and have been used to estimate the magnitude of the change at the source. It is thought to be less than 10^9 kg, and since deflation and very small net gravity increases are observed at the caldera centre, this is the order of magnitude of the mass gained at the source. The source is considered to be part of a magma reservoir located beneath the central part of Askja, and mass increases are most likely to reflect magma intrusion into this sub-caldera chamber. The overall extensional regime means that ground deflation may accompany intrusion.

The residual deformation in the eastern part of the caldera coincides with the positive Bouguer gravity anomaly (Figure 6) which forms a linear feature running north-south parallel to the caldera boundary and then sweeps east at Oskjuop, the opening of the caldera exploited by the 1961 lavas and many other post glacial flows before (Figure 2). It seems likely that the residual ground deformation is associated with this feature. The static Bouguer gravity anomaly was interpreted by Brown et al. (1991) in terms of a relatively high density of intrusions associated with the eastern rift zone as it passes through the Askja caldera. This zone has been the site of recent activity in 1875, 1921-1928 and 1961 (Thorarinsson and Sigvaldason, 1962). A corridor some 0.5-1.0 km wide is envisaged in which basaltic dykes intrude lower density hyaloclastites and lava flows, and the anomaly represents some combination of increased dyking intensity and intrusion to shallower depth. Residual gravity increases in such an area accompanied by minor inflation would be the most likely result of further dyke emplacement. Small gravity increases have been observed in this region (Figure 3 and Table 4). Thus there may have been some intrusive activity within this region during the three year period. There are still some unresolved differences between the deformation and gravity data sets, and these will be addressed in future surveys.

Although Askja lies on the actively rifting central portion of Iceland, it has undergone a gradual decline in volcanic activity during post-glacial times (Annertz et al. 1985). The products of the 1875 eruption provided geochemical evidence for a fractionating magma chamber beneath the caldera (Sigurdsson and Sparks, 1981), and the plethora of dykes exposed at eroded Tertiary volcanoes in Iceland indicate that these central volcanoes grow more by intrusion and extension than by surface eruption. It is suggested therefore that excess pressure within the magma chamber at Askja is relieved by intrusion into the eastern dyke system that either erupts within the caldera (1961) or under extensional stress is able to transport magma away from the volcano. Indeed the 1875 eruption was accompanied by a basaltic fissure eruption 70 km north of the caldera thought to have been fed by the Askja dyke system (Sigurdsson and Sparks, 1978).

In summary, the combined gravity and tilt data are thought to indicate that over the three year period 1988 to 1991, magma was intruded into and drained from the central magma chamber some 2.5 - 3.0 km beneath the caldera floor. Magma draining from this reservoir may feed directly into the fissure system in the eastern part of the caldera. From this system, the magma may then flow out of the Askja region altogether. A magmatic 'plumbing' link has already been suggested between Askja and Krafla (Tryggvason, 1989a), indicating that the Askja system is more readily able to respond to changes in mantle magma pressure than others. If this were the case, the Askja chamber would store, then feed the Icelandic rift zone with its replenished magma supply. This is not then a caldera in a state of unrest in the usual sense, but a combination of hot spot volcano and a rift system on thin young lithosphere which yields readily to magmatic pulses and acts as a temporary store rather than the 'end user' of intruded magma.

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FIGURE CAPTIONS

1. Map showing location of Askja volcano in north central Iceland. Askja lies in the neovolcanic zone about 100 km south of Krafla which was active during the 1980's. All the volcanoes in this zone are characterised by extensive rift systems with the focus of activity at a central volcano. Askja and Krafla express en echelon fissures, however, there is a possibility that magma migrates between systems (Tryggvason, 1989a).

2. Gravity station location map for Askja caldera. The outer curve shows the extent of the main caldera, with lake Oskjuvatn, formed after the 1875 eruption in the southeastern part. Viti is the only explosion crater remaining after this eruption, the rest were drowned by the lake. A small island in the south of Oskjuvatn was formed during one of the numerous eruptions in the 1920's. Oskjuop is a channel like feature where the north-eastern boundary of the main caldera is complicated. The most recent eruption, in 1961 occurred between stations 412 and 83001 and lava extended through Oskjuop about 6 km beyond station 83009 and within the caldera stopped between stations 405 and Kneb.

3. Gravity data (in µGal) for the period 1988 to 1991. Data are expressed relative to station 83001 with respect to the gravity difference for each station measured in 1988. For each station, there are two sets of data, one for each of the gravity meters used (LaCoste and Romberg G513 and G105). The error bars indicate the average error on the points shown and arrows indicate points that are 'out of line', although the standard errors on these points is often rather less than the average error (Table 1). The data are grouped into a) central caldera, b) northern and c) southeastern. Although there is a degree of scatter, there would appear to be a small increase over the three year period at the caldera centre (note the smaller error on these data). There are no significant overall changes at the other stations. None of these data have been height corrected at this stage.

4. Observed 3-year tilt at the optical levelling tilt stations in Askja identified by letters, and for portions of the precision levelling profile identified by numbers. Error bars show double standard errors of tilt along minor and major axes of the error ellipses. Lines leading from the stations indicate direction of up-slope tilt and amount of tilt.

5. Residual tilt at stations after the effect of a point source of deflation at 2.5 - 3.0 km depth beneath the point marked has been removed. Since the residual tilt is rather small (indicated by line length) for most stations, it is concluded that about 80% of the observed tilt may be accounted for by a pressure drop in the point source. The larger residual tilt observed in the eastern part of the caldera indicates that there may be a second source of deformation causing minor inflation on the eastern caldera margin.

6. Bouguer gravity anomaly map of the Askja caldera. The overall negative anomaly is perturbed by rather higher gravity values generally inside the caldera and a north-south trending high gravity feature in the eastern part. These anomalies were interpreted by Brown et al. (1991) in terms of basaltic lava flows inside the caldera, and a dyke swarm (to the east) contrasting in density with hyaloclastite ridges forming the caldera boundary.

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