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Ground deformation in Askja, Iceland: its source and possible relation to flow of the mantle plume

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Abstract

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The volcano Askja in east-central Iceland erupted several times between 1920 and 1930, following a very large caldera-forming eruption in 1875. The last eruption occurred in 1961. Measurements of the vertical component of ground deformation in Askja were commenced in 1966 and made once each year, 1966 to 1972 and 1983 to 1987. Distance measurements with a geodimeter were first made in 1982. The measurements have shown alternating uplift and subsidence of the central part of the Askja caldera. Two periods of uplift and three periods of subsidence have been identified during the 21 years of observations. Observed vertical displacements agree fairly well with a single point source model at a depth of 1.5-3.5 km below the surface, near the center of the Askja caldera. Deviation from a single point source model can be explained by a secondary source of subsidence beneath the site of the 1961 eruption. This secondary source has been diminishing in intensity and appears to have been exhausted by 1983-1987. Askja has been subsiding at a rate of 6-10 cm per year during the period 1983-1987, but in 1970-1972 rapid inflation was observed possibly as much as 20 cm per year. The period of no levelings, 1972 to 1983, is characterized by deflation, but at a slower average rate than observed in 1983-1987. This suggests continuation of the 1970-1972 inflation into 1973 or 1974.

Introduction

Askja is a caldera in central Iceland, about 65°2′N, 16°47′W. It is roughly circular with an area of 50 km^2. The elevation of the caldera floor is 1100–1200 m and the surrounding mountains, Dyngjufjöll reach 1500 m elevation (Fig. 1).

The Askja volcano produced great amount of lava during the early postglacial era, but its activity has been gradually decreasing. No historic eruptions of Askja are known before 1875, and tephrochronological studies indicate no lava eruptions during the preceding 4 centuries (Annertz et al., 1985). A violent plinian eruption of 1875 was followed by the formation of a 15-km^2 caldera within the older Askja caldera. This 1875 caldera is presently partly filled with water forming the 11-km^2 lake Öskjuvatn.

Recent volcanism includes several lava eruptions of 1921 to 1926 and a last lava flow of 1961 (Thorarinsson and Sigvaldason, 1962).

Precision leveling of a short profile in Askja in 1966–1972 demonstrated that considerable ground deformations occurred during these years, and that the pattern of deformation changed several times. The small areal extent of the leveling profile made any modeling of the results of limited significance, but tilt vectors pointed either towards or away from the central part of the Askja caldera, indicating alternating inflations and deflations. The pattern of ground

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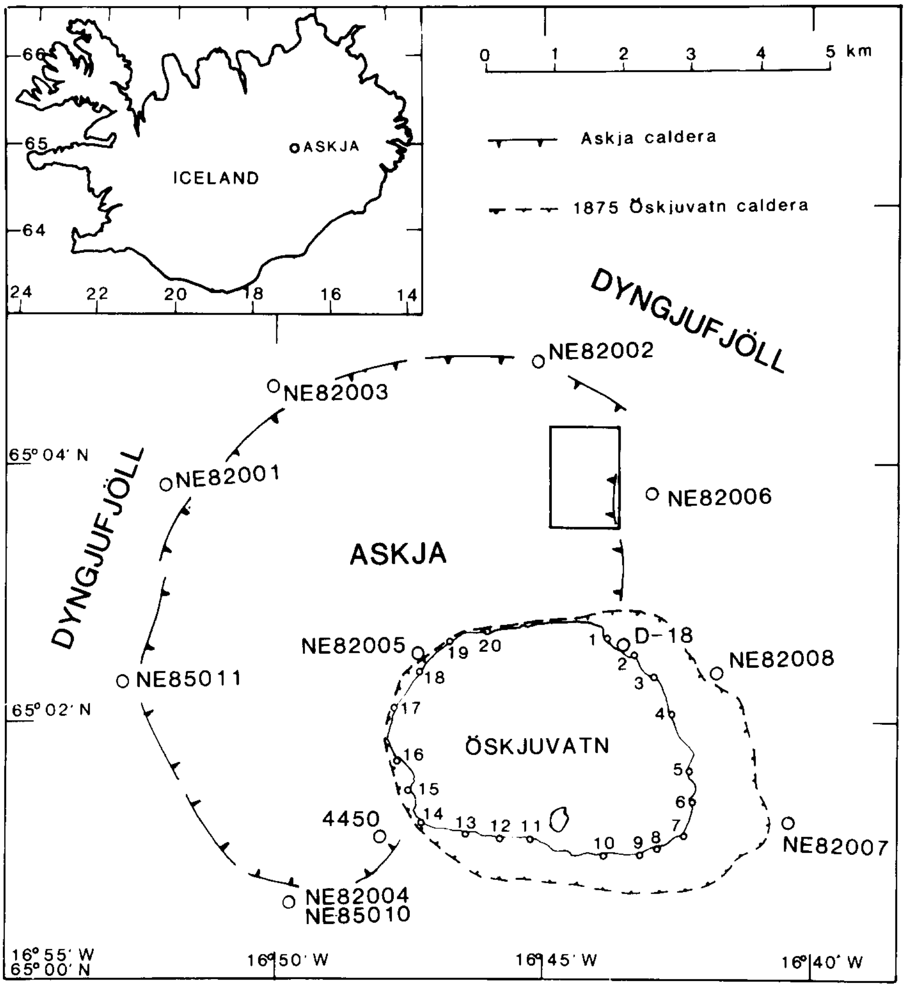

Fig. 1. Sketch map of Askja, showing lake Öskjuvatn, the Öskjuvatn caldera of 1875 and the older Askja caldera. Shown also are points of distance measurements (large open circles), and points of lake level observations (small circles). Rectangle shows area of Figs. 2 and 3.

deformation is in many aspects similar for any two observational periods, which indicates that a permanent source is causing most of the observed deformation.

Observations of the level of lake Öskjuvatn at 7–20 locations correlate well with the precision levelings, so the observed vertical displacements of the lake shore are clearly caused by the same processes as the observed displacements of the precision leveling profile, which is located about 2 km to the north from the lake.

Resumption of ground deformation measurements in Askja in 1982, and subsequent expansion of the observational program, offers improved opportunity to define a model that can explain the observed deformation. The present report examines if a single point source model can agree reasonably with the observations, and how the parameters of such a model can be determined.

The observations used in defining the model are precision levelings and lake level measurements. The two sets of observations are treated separately because of the greatly different nature of the observations, especially with regard to precision.

A third set of observations, repeated distance measurements, are included in the present study, but because of few observations over a period of only four years, they are of limited use in defining a source model. However, the distance measurements seem to agree with the results obtained from either precision leveling or lake level observations.

Point source model

A single point source model is frequently used in deformation studies of volcanoes. Although a source of deformation of volcanoes is certainly not a point of zero volume, the observed deformation frequently approximates that of point source in elastic half-space. If deformation observations do not deviate from theoretical point source deformation, within the limits set by the accuracy of observation and the bench mark stability, then we can accept the point source model.

A point source of pressure within a perfectly elastic and homogeneous half-space will cause particle displacements of the free surface along a line connecting the surface point and the source, and the magnitude of the displacement is inversely proportional to the square of the slant distance to the source (Mogi, 1958). The equations describing this displacement can be written as:

$$\mathrm{d}z = ChR^{-3}$$
$$\mathrm{d}r = CrR^{-3}$$

where $\mathrm{d}z$ and $\mathrm{d}h$ are the vertical and horizontal (radial) components of ground surface displacements, h is the source depth, r is the horizontal distance to the source and R is the slant distance to the source. The constant C is a measure of the intensity of the source.

Observations of ground tilt in Iceland indicate that the error of observed tilt is roughly proportional to the tilt (Tryggvason, 1983). The standard error of tilt is generally greater than 10% of the observed tilt, and frequently as great as 20%, independent of magnitude of the tilt. This error is partly the result of irregular vertical displacements of the bench marks, caused by the regional ground deformation (Tryggvason, 1983). This means that any deviation of observation from the model is insignificant unless the deviation is greater than about 20% of the observed tilt or displacements.

Tryggvason (1981) argued that a source region at Krafla, Iceland has a radius that exceeds 50% of the calculated source depth, but still the observed ground deformation does not deviate significantly from point source deformation.

While the actual pressure source, causing the observed inflation or deflation, is of finite, possible great volume, the observed deformation is indistinguishable from point source deformation. The pressure decrease during deflations or pressure increase during inflations may be quite small, possibly about one megapascal (10 bar) for each 5 cm of inflation or deflation (Tryggvason, 1981).

Precision leveling; search for a point source

Levelings in Askja before 1982 were confined to an area of 500 m east–west by 1200 m north–south (Fig. 2). Comparisons of any two levelings showed overall ground tilt and its variation from north to south on the irregularly shaped leveling profile. The tilt vectors converged to the west or southwest of the leveling profile, but the variation of tilt in east-west direction could not be determined. Thus the distance to a hypothetical point source could not be estimated with any degree of confidence (Fig. 3).

A computer search for a hypothetical point source of the Askja deformation is based on the Mogi equation (Mogi, 1958). An area is selected, usually about 6 km across, and a source depth is assumed. Some 1500 points, equally spaced within the area, are selected as possible source points. For each of these points the source magnitude is determined which best agrees with the observed vertical ground displacements, and the standard deviation of ob-

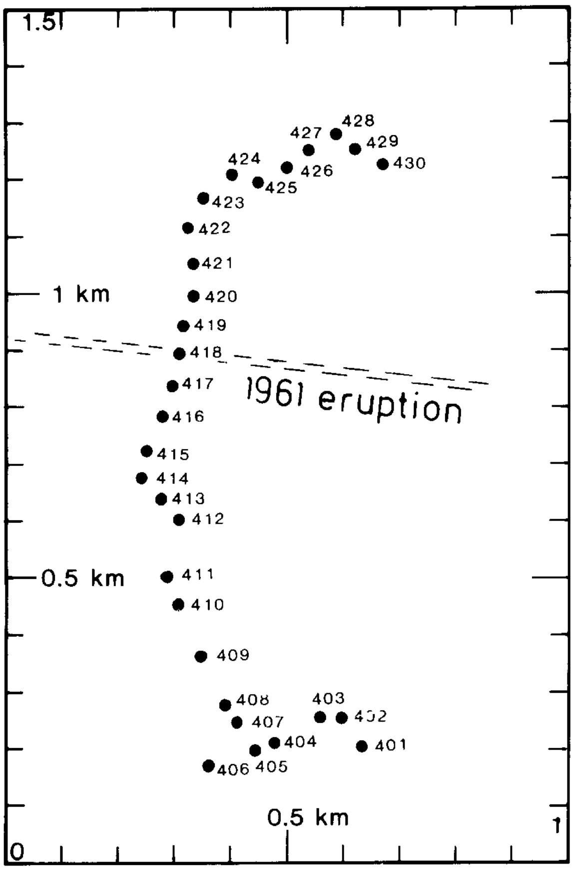

Fig. 2. The profile of precision leveling in Askja before it was extended in 1983. Area of map outlined by rectangle on Fig. 1. The eruption of 1961 occurred on a fissure extending almost east-west at the site of the lettering '1961 eruption'. Bench marks 401 through 412 were constructed in 1966, and the remaining bench marks in 1968.

servations from model displacements. A map is drawn, showing the standard deviation within the selected area, and the minimum value defines the most probable point source. This procedure is repeated for other hypothetical source depths, until the horizontal and vertical coordinates of the most probable source point is found.

The levelings of 1986 and 1987 reached about 3.5 km farther east than the older profile. This extension of the leveling profile helps to control the distance and depth to a hypothetical point source. However, only two levelings of this extended profile, with only one year between the levelings, have been made, so the reliability of this estimate is severely limited.

TABLE 1

Source parameters that best agree with results of precision leveling. D_{h_0} is computed vertical ground displacement directly above the source. R^2 is the correlation coefficient squared between observed and calculated displacement of bench marks. Depth is from ground surface at about 1100 m above sea level.

Period	Horizontal coordinates		Depth (m)	D_{h_0} (mm)	R^2
	north	east			
1968-1970	65°4.0′	16°49.6′	0	*	0.9322
1970-1972	no near solution		deep	*	0.9952
1972-1983	65°3.7′	16°44.8′	1300	−200.1	0.9695
1983-1986	65°3.6′	16°45.0′	1600	−87.1	0.9980
1986-1987	65°3.5′	16°45.0′	2500	−37.0	0.9941

*)No solution.

The mathematically obtained source parameters for a single point source model for various periods are presented in Table 1. The location of the hypothetical point source is poorly defined, and a single point source common for all periods appears not to exist. However, if measurements of 1968 and later are considered, the source location is well defined within a linear strip about 0.5 km wide extending from the precision leveling profile in northeastern Askja west or west-southwest across the Askja caldera floor (Fig. 1). The direction from the profile to the source is well defined by the observations, while the distance and source depth are poorly constrained.

The computed vertical ground displacement above the hypothetical source depends very much on the distance to the source from the leveling line, and also on the source depth, the parameters which are poorly defined. However, a source depth of 2500 m or less apparently agrees better with the observations than a deeper source.

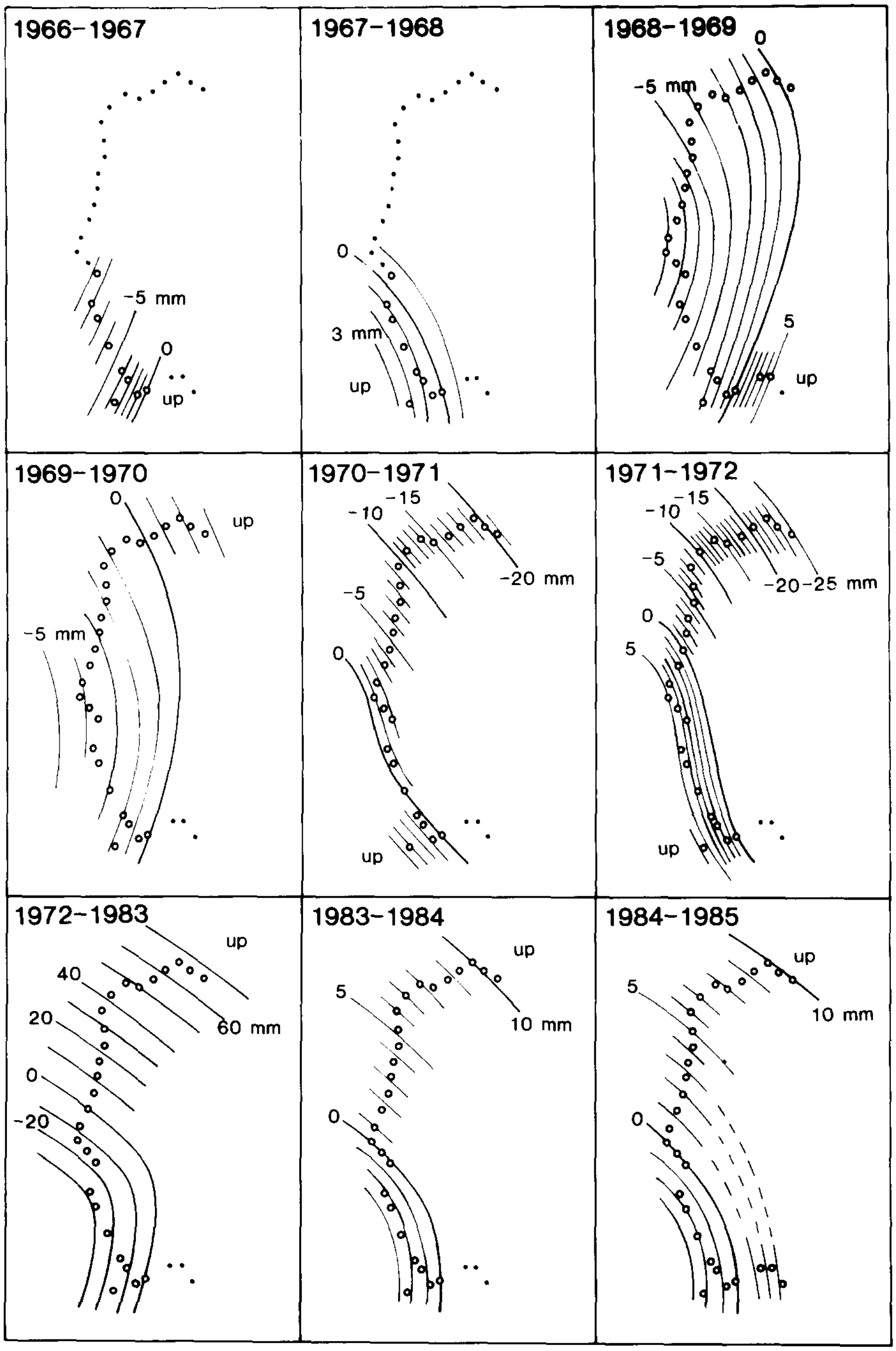

Fig. 3. Vertical displacements relative to bench mark 404 (see Fig. 2) for periods between succeeding levelings. Levelings of 1986 and 1987 showed similar pattern of deformation as the levelings of 1983 to 1985. All levelings were made in late July or August. Open circles indicate observed bench marks.

Lake-level measurements

The Öskjuvatn lake level was observed at 7–20 points each year in 1968 to 1972 and in 1985 and 1986 (Fig. 4). Twenty markers were placed at the shore line in 1968, but several of these

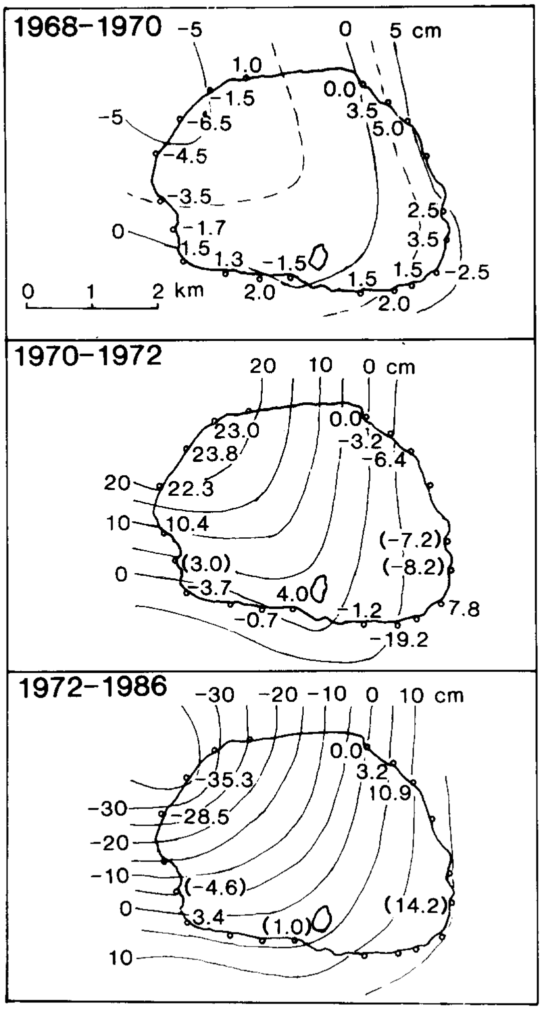

Fig. 4. Observed vertical displacements of bench marks along shore of Öskjuvatn for three periods, August 1968 to August 1970, August 1970 to July 1972, and July 1972 to August 1986. For location see Fig. 1. Numbers by the bench marks are vertical displacements in cm relative to marker 1 on the northeast shore. Numbers in parentheses are estimated displacements based on observations in 1971 or 1985. Lines of equal vertical displacements at 5 (and 2.5)-cm intervals represent my interpretation and should not be taken as observed facts.

have been destroyed by rock falls, inundated by rising lake level or become inaccessible because of changes in the lake or because of semi-permanent snow. Therefore, only 7 of the original bench marks were observed in 1985 and 8 in 1986.

The lake-level observations in 1968 to 1972 were rather crude and the accuracy low. The estimated observational error was about 1.0 cm if weather conditions were favorable, but 2.0 cm under less favorable conditions. In 1985 an improved observational technique was introduced, which had been tested thoroughly at lake Myvatn (Tryggvason, 1987).

The low accuracy of the lake-level observations made a specific model study of limited value, except for periods of greatest displacements. Two periods, 1970–1972 and 1972–1986, had relative vertical displacements that exceeded 20 cm, greatly exceeding the estimated error of observation. A third period, 1968–1970, with much smaller relative vertical displacements, was included in the study for comparison.

A computer search by the same technique as before identified a region below the northwestern part of lake Öskjuvatn as an optimum point source location (Table 2). A rather large range in area and depth gave standard deviations of observations from the model that were only slightly greater than those for the best location.

The lake level observations alone do not give an acceptable solution for the location of a single point source, although they define an area within which the source must lie. The computed shallow depths of Table 2 are of interest. They may not be of great significance, but together with the data of Table 1 they indicate that the source of the observed ground deformation in Askja lies at a shallow depth of 1500–2500 m.

TABLE 2

Source parameters that best agree with the lake level data. For explanation see Table 1

Period	Horizontal coordinates		Depth (m)	D_{h_0} (mm)	R^2
	north	east			
1968–1970	65°2.1′	16°46.7′	1400	−135	0.8666
1970–1972	65°2.2′	16°46.7′	1500	383	0.9319
1972–1986	65°2.3′	16°46.5′	2200	−657	0.9751

A common solution for a point source

As neither precision leveling nor lake level observations gave an unequivocal solution for a single point source, a combination of both types of measurements was investigated. The vastly different nature and precision of the two types of observations make a common solution somewhat dubious.

The acceptable location of a single point source must lie within the long and narrow area defined by the precision levelings as well as the wide elliptical areas defined by the lake level observations (Fig. 5). But there must be a further criterion, that the computed vertical displacement above the source is the same within a reasonable margin for both types of observations. A line can be defined for any preset source depth where this criterion is fulfilled. This line cuts across or lies near the area acceptable by both types of observation if the source depth is about 2500 m.

The combination of both types of data thus defines a small area near the center of the Askja caldera where the hypothetical single point source can lie. The geographic coordinates of this location are about 65°03.2′ north, 16°46.4′ west with a probable error of about 250 m horizontally, but the depth is less well defined. A depth of 2500 m with an error margin of 1000 m appears acceptable.

Observations before 1970

The precision levelings each year from 1966 through 1970 identified two periods of subsidence and one period of inflation. Subsidence was observed between observations of 1966 and

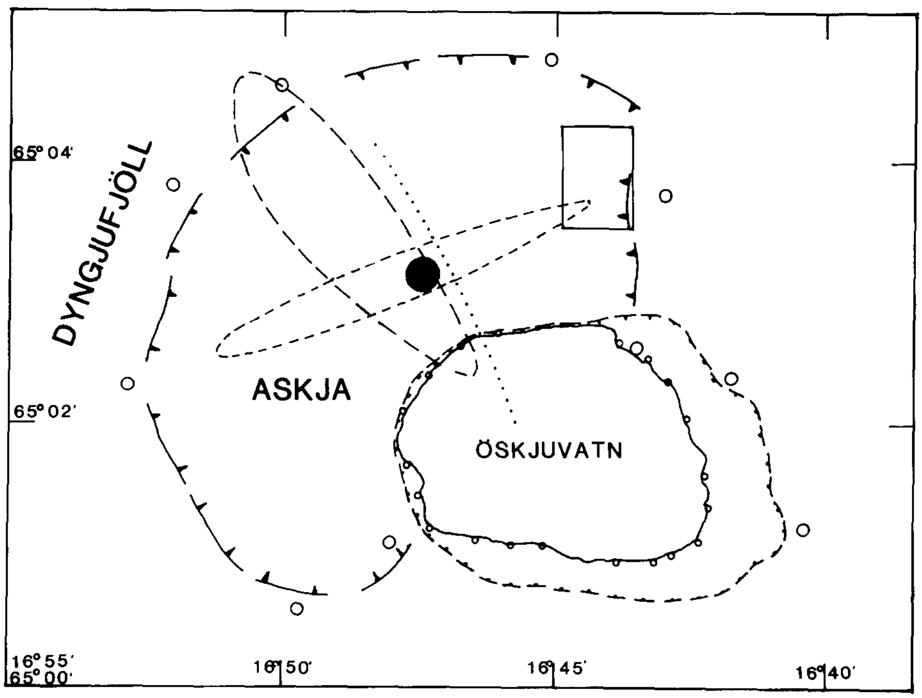

Fig. 5. Map of Askja showing acceptable areas of point source causing the observed deformation of 1972 through 1986. Assumed source depth is 2.5 km. Short-dashed line encloses area where point source of subsidence agrees with precision leveling. Long-dashed line similarly encloses area where point source agrees with lake level observations. These dashed lines are drawn through points where standard deviation of observed vertical displacements from point model displacements is 1.5 times the minimum standard deviation. If a source lies beneath the dotted line, the vertical displacement is the same if computed from leveling data or lake level data. For further explanation, see Fig. 1.

TABLE 3

Vertical ground displacement, D_{h_0}, above a point source computed from a model that agrees with both precision levelings and lake level observations. R^2 is the correlation coefficient squared between observed and computed vertical displacements of bench marks.

Period	From levelings		From lake level	
	D_{h_0}mm	R^2	D_{h_0}mm	R^2
Source location: 65°3.30′N, 16°47.32′W, $z=1500$ m				
1966-1967	−705.9	0.2967		
1967-1968	237.0	0.5654		
1968-1970	−252.1	0.3612	−450.1	0.7033
1970-1972	882.9	0.9872	956.5	0.7466
1972-1983	−1612.4	0.9633 }	−1948.9	0.8884
1983-1986	−591.3	0.9735 }		
1986-1987	−217.0	0.9744		
Source location: 65°3.25′N, 16°47.38′W, $z=2500$ m				
1966-1967	−423.9	0.1863		
1967-1968	142.4	0.6580		
1968-1970	−130.7	0.3391	−222.1	0.7406
1970-1972	457.9	0.9904	572.2	0.8199
1972-1983	−836.7	0.9598 }	−1014.0	0.9296
1983-1986	−300.4	0.9686 }		
1986-1987	−94.7	0.9860		
Source location: 65°3.20′7N, 16°47.44′W, $z=3500$ m				
1966-1967	−412.1	0.0978		
1967-1968	138.4	0.7337		
1968-1970	−114.2	0.3206	−181.2	0.7353
1970-1972	400.0	0.9912	536.9	0.8335
1972-1983	−731.6	0.9562 }	−877.2	0.9336
1983-1986	−258.5	0.9638 }		
1986-1987	−70.8	0.9879		

1967 and 1968–1970 while inflation was observed between observations of 1967 and 1968.

The limited horizontal extent of the observations, especially in 1966 and 1967, did not allow an independent determination of a hypothetical point source, but the observed tilt vectors should point toward or away from the source. These tilt vectors (Table 4) indicate a more northerly source during the first years of observation than later on. If only periods of deflation are considered, the azimuth of the tilt vectors rotated from 285° in 1966–1967 to 250° in 1983–1987. This may be interpreted as gradual southward displacement of the center of subsidence.

TABLE 4

Computed tilt vectors from leveling of bench marks 404 through 412

Years of observations	Azimuth of tilt up-dip (degrees)	Standard error of azimuth	Tilt (micro-rad)	Standard error of tilt (micro-rad)
1966-1967	104.86	1.53	31.55	3.75
1967-1968	245.46*	2.32	24.75	4.64
1968-1969	99.05	1.30	26.25	2.75
1969-1970	93.60	1.53	18.98	2.34
1970-1971	235.98*	1.50	26.07	3.15
1971-1972	255.07*	0.69	40.57	2.27
1972-1983	82.21	2.59	188.45	39.35
1983-1984	72.18	1.56	23.58	2.96
1984-1985	70.97	1.92	22.43	3.46
1985-1986	72.13	2.19	17.80	3.14
1986-1987	70.46	2.31	19.04	3.54

*inflation of Askja.

During periods of inflation, the corresponding up-dip tilt vectors point towards a more southerly source. This difference in azimuth for the inflation and deflation tilt vectors is greater than the expected tilt error and, therefore, it appears to be significant.

The counterclockwise rotation of the deflation tilt by about 35° from 1966 to 1983 is quite significant. This rotation can be explained by two sources of the observed deformation, one permanent source of either inflation or deflation near the center of the Askja caldera, and another source of gradually waning deflation near the site of the 1961 eruption. This would explain the difference in azimuth to the apparent center of deflation in 1966–1967 and 1968–1970, and that of inflation in 1967–1968 and 1970–1972. It also explains the difference in azimuth of tilt during slow inflation of 1967–1968 and 1970–1971 and fast inflation of 1971–1972 (Table 4). The nearly constant azimuth of tilt after 1983 indicates that the secondary source of subsidence near the 1961 eruption site has become inactive.

Distance measurements

Several bench marks were installed in 1982 for geodimeter measurements, and additional stations were established in 1985 (Fig. 1). The distances from bench mark NE82005, near the center of the Askja caldera, to bench marks on or near the caldera rim were measured in August 1982, August 1985 and August 1986.

The principal result of these distance measurements (Table 5) is that all measured lines were shorter in 1986 than in 1982, the difference being 2.1 to 11.7 cm, while the line length ranged from 3.0 to 6.0 km. A shortening of the lines agrees with the subsidence indicated by both precision leveling and lake level measurements, but the distance measurements alone do not suffice to define the parameters of an independent point source model.

The single point source model (the Mogi model) predicts that radial displacement at 3.0 km horizontal distance from a point source is 25.6 and 35.4% of maximum vertical displacement for source depths of 2.0 and 3.0 km, respectively. The corresponding percentages at 6 km distance are 9.5 and 17.9.

TABLE 5

Distances measured with geodimeter in Askja, 1982-1986. All distances are measured from station NE82005 in central Askja to stations on or near the caldera rim. Observational errors are estimated as less than 0.02 m

To station	Aug 28-30, 1982 (m)	Aug 15, 1985 (m)	Aug 18, 1986 (m)
NE82001	4404.125	4404.100	4404.102
NE82003	4518.577	4518.487	4518.454
NE82003	4447.369	4447.341	4447.336
NE82004*	4099.388	4099.296	
NE82006	4130.404	4130.338	4130.315
NE82007	5959.676	5959.654	5959.655
NE82008	4404.292	4404.246	4404.252
NE85010*		4099.570	4099.574
NE85011		4328.333	4328.351
D-18	3009.210	3009.131	3009.093
4450		2718.533	2718.510

*Station NE82004 was on unstable foundation and was replaced by station NE85010 in 1985.

Station NE82005 is located near the center of the Askja caldera (Fig. 1) and also near the center of subsidence as suggested by precision leveling and lake level observations. Hence the contraction from NE82005 to D18 (Table 5) can be equated to radial displacement at 3.0 km horizontal distance from a point source. The observed 11.7 cm shortening corresponds to a subsidence of 46 or 33 cm in 4 years at the place of maximum subsidence, if the underlying point source depth is 2.0 or 3.0 km, respectively. This agrees well with the 30 cm subsidence in 3 years, 1983–1986 as deduced from levelings if source depth is 2.5 km (Table 3).

Similarly, the distance of about 6 km from NE82005 to NE82007 was 2.1 cm shorter in 1986 than in 1982 according to the geodimeter measurements. This corresponds to a maximum subsidence of 21.0 cm if the source depth is 2.0 km, and subsidence of 11.2 cm if the source depth is 3.0 km. This suggests a smaller subsidence than that indicated by precision leveling, but observational errors in both levelings and distant measurements may account for considerable part of this discrepancy. A still shallower source depth will bring this distance measurement in better agreement with the levelings.

Thus the distance measurements support the results of precision leveling and lake level observations, but more observations are needed to obtain an independent model solution from the repeated distance measurements.

Discussion

The observed rate of ground tilt at the site of the precision leveling profile in Askja has usually been 20 to 40 microradians per year during the last twenty years (Table 4). This tilt rate is very much faster than that observed within the active rift zone in southwest Iceland or in the north Iceland rift zone before the 1975–1984 Krafla rifting episode. A tilt rate of 0.2 to 0.6 microradians per year was observed on the flanks of and within the rift zones (Tryggvason, 1974a). The tilt rate in Askja is also much faster than that observed near Katla (Tryggvason, 1973a) or Hekla (Tryggvason, unpublished data).

The volcano Askja thus exhibits much higher rate of ground deformation than has been observed elsewhere in Iceland, if erupting volcanoes are excluded. This makes Askja unique, and an explanation for its uniqueness is desired.

Is the observed ground deformation of Askja in some way related to the great eruption of 1875, or to the much smaller eruption of 1961? I argued above that the rotation of the tilt vector from 1966 to 1983 may be caused by gradually slower subsidence at the site of the 1961 eruption, but the repeated inflations and deflations can not easily be related to any past event. I therefore conclude that most of the observed ground deformation of Askja is not a direct consequence of past eruptions, although the last eruption may have modified the style of deformation for several years. Some sustained process is most likely causing the observed ground deformation, possibly the same process that has caused the eruptions of the past.

Perhaps the observed inflations and deflations of Askja reflect oscillations of the intensity of convective currents within the Iceland mantle plume (Morgan, 1972; Tryggvason, 1974b). This would require that pressure oscillations at an unspecified depth in the mantle plume are transmitted to the shallow magma chamber which acts as a source of the observed deformation.

A pressure increase at the top of the mantle plume will cause some increase in the tensile stress within the elastic crust above the plume. This will increase the probability of tensile rifting and fissure eruptions. If the flow of the mantle plume creates and maintains the stress that is responsible for earthquakes in Iceland, then an increase in flow rate will increase the probability of earthquakes.

If the rapid inflation of Askja in 1970–1972, which may have lasted until 1974, was caused by rapid increase of pressure in the upper mantle, this pressure pulse would be expected to have caused other observable processes. The Heimaey eruption of 1973 was possibly triggered by this pressure pulse in the upper mantle. This was the second eruption in 10 years in the Vestmannaeyjar island group, after a repose period of several thousand years (Tryggvason, 1980). The earthquake sequence of 1974 in Borgarfjördur, west Iceland, may also be related to this pressure pulse. It included one shock of magnitude near 6 in an area of low seismicity. (Einarsson et al., 1977), although in a region where maximum shear stress as caused by the Iceland mantle plume, is predicted (Tryggvason, 1974b). The series of relatively large earthquakes in Bárdarbunga, central Iceland, that commenced in 1974 can possibly be related to this pressure pulse. This sequence included about ten earthquakes of magnitude 5 to 5.5 in ten years, but no earthquakes of similar magnitude had been observed in this region, about 50 km southwest of Askja, for several decades prior to this sequence (Tryggvason, 1973b; Einarsson, 1987). The Krafla rifting and eruptions which commenced in late 1975 (Björnsson et al., 1977) may also be associated with this pressure pulse. Einarsson earlier suggested (1987) that some kind of relation exists between the earthquakes of Bárdarbunga and the eruption of Krafla.

All these geophysical events are spectacular, and they all occurred while the Askja inflation stage indicated high pressure within the presumed Askja magma chamber.

It may be asked if the continuous subsidence of Askja which is known to have lasted from 1983 to 1987, and probably began in 1974 or 1975, is somehow related to the sustained volcanic activity of Krafla. Magma flowed continuously from an unknown source into the shallow Krafla magma reservoir from 1975 to 1985 (Björnsson et al., 1979; Tryggvason, 1986). During this time at least one cubic kilometer of magma entered the Krafla magma chamber and was subsequently distributed between fissures (dikes) and lava.

The hypothetical model that emerges from the above speculations is that the succession of inflations and deflations of Askja in 1966 to 1987 is neither directly related to the 1961 Askja eruption nor to earlier eruptions. It is suggested that a hypothetical magma chamber below the Askja caldera responds easily to pressure fluctuations in the upper part of the Iceland mantle plume. Increased pressure in the upper part of the Iceland mantle plume may also trigger earthquakes (Borgarfjördur 1974, Bárdarbunga 1974–1985) and eruptions (Heimaey 1973, Krafla 1975), but sustained volcanic activity of Krafla in 1975 to 1984 apparently caused continuous subsidence of the Askja caldera.

We will now wait for further evidence for or against this hypothesis. If Askja starts inflating when the activity at Krafla has ceased or if Askja is inflated at the time of the next great earthquake in Iceland and of the next volcanic eruption, then the above hypothesis will be worth considering.

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