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Subsidence Events in the Krafla Area, North Iceland, 1975–1979

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Abstract. In the inflation-deflation sequence of the Krafla magma chamber since its beginning in 1975, 12 deflation or subsidence events have been identified until May, 1979. The tilt and distance measurements relating to these subsidence events are discussed in some detail. All of these subsidence events are associated with horizontal magma flow along the N-S trending fissure zone, which goes through the central part of the Krafla caldera, to form a dike 3 to 5 m wide, 80 km long, and 1.0 to 2.5 km high from the bottom to the top. The total volume of magma, which flowed out of the Krafla magma chamber during these 12 events, is estimated as 481×10^6 m^3, whereof 407×10^6 m^3 are estimated to have flowed northwards, 72×10^6 m^3 southwards and about 2×10^6 m^3 came to the surface as basaltic lava.

Key words: Krafla volcano Iceland – Ground deformation – Magma flow.

Introduction

The volcano-tectonic sequence, which started in 1975 in the Krafla-Mývatn area, North Iceland, is characterized by repeated uplift and subsidence of an area centered near Leirhnjúkur in the central part of the Krafla caldera (Björnsson et al., 1977). The inflation progresses at a relatively constant rate over periods of several months, to be interrupted by rather sudden subsidence events.

The first very noticeable event in this volcano-tectonic sequence was the subsidence, which started on December 20, 1975 (Björnsson et al., 1977; Björnsson, 1976; Sigurdsson, 1976), when the area around Leirhnjúkur subsided more than 2 m over a period of 1 or 2 months.

There are some indications that tectonic unrest had been increasing in the Krafla region for some years before 1975. During a microearthquake survey in Iceland in 1967, the Krafla area was found to be very active, with higher frequency of microearthquakes than any other surveyed region in Iceland (Ward et al., 1969). However, this high frequency of microearthquakes had subsided by a factor of nearly 100 in 1968 (Ward and Björnsson, 1971). Repeated geodetic measurements of high precision indicate a slight horizontal contraction of the Krafla-Mývatn area between 1965 and 1971, but significant horizontal expansion occurred between 1971 and 1975 (Gerke, 1977; Gerke et al., 1978). Seismic activity increased markedly in the Krafla area in the spring of 1975, and the high activity continued until the beginning of the first subsidence event (Björnsson et al., 1977). These observations indicate, that some signs of the coming volcano-tectonic sequence may have been observed several years before it became obvious on December 20, 1975.

Many individuals from several research institutions have participated in the research of the tectonic unrest in the Krafla area. The first three subsidence events were described in some detail by Björnsson et al. (1977), and these and the subsequent events have been discussed by Björnsson et al. (1979). The first event, which started on December 20, 1975, caused considerable ground movements in Kelduhverfi (Tryggvason, 1976) and elsewhere on the Krafla fissure swarm (Björnsson et al., 1977), and small basaltic lava eruptions occurred (Sigurdsson, 1976). Subsequent subsidence events have been associated with volcanic tremors, earthquake swarms and widening of portions of the fissure swarm, and small volcanic eruptions occurred during two of them, on April 27 and September 8, 1977 (Björnsson et al., 1979). The seismic activity associated with the event of September 8 to 9, 1977, has been described in details by Brandsdóttir and Einarsson (1979). The distance and tilt measurements of the Nordic Volcanological Institute and the University Science Institute in 1976 and 1977 were reported by Tryggvason (1978a and b).

Observations

This report is primarily based on tilt and distance observations of the Nordic Volcanological Institute and the University Science Institute.

The *tilt measurements* are of three types. A water tube tiltmeter of two components was installed in the Krafla power house on August 19, 1976, and has been observed daily since then with few exceptions. During times of very rapid subsidence of the Krafla area, additional readings were made. One arm of this tiltmeter is 68.95 m in direction N13 °E and the other arm is 19.50 m long in direction E13 °S.

Two electronic continuously recording tiltmeters (Sindrason and Ólafsson, 1978) were installed in the Krafla-Mývatn area in 1977, one in the Krafla power house, another in Reynihlíd by Mývatn. A third tiltmeter of the same construction was installed about 1 km north of the explosion crater Víti in 1978.

Twelve spirit level tilt stations were constructed in the Krafla-Mývatn area in 1976 and 1977 (Fig. 1). Observations at these stations have been made approximately once each month during summer, but at longer intervals in the winter (Tryggvason, 1978a). Most of these spirit level tilt stations consist of five bolts in solid bedrock, placed on the circumference of a circle of 25-m radius. When observations are made, an optical level is placed in the center of this circle and invar leveling rod is carried from one

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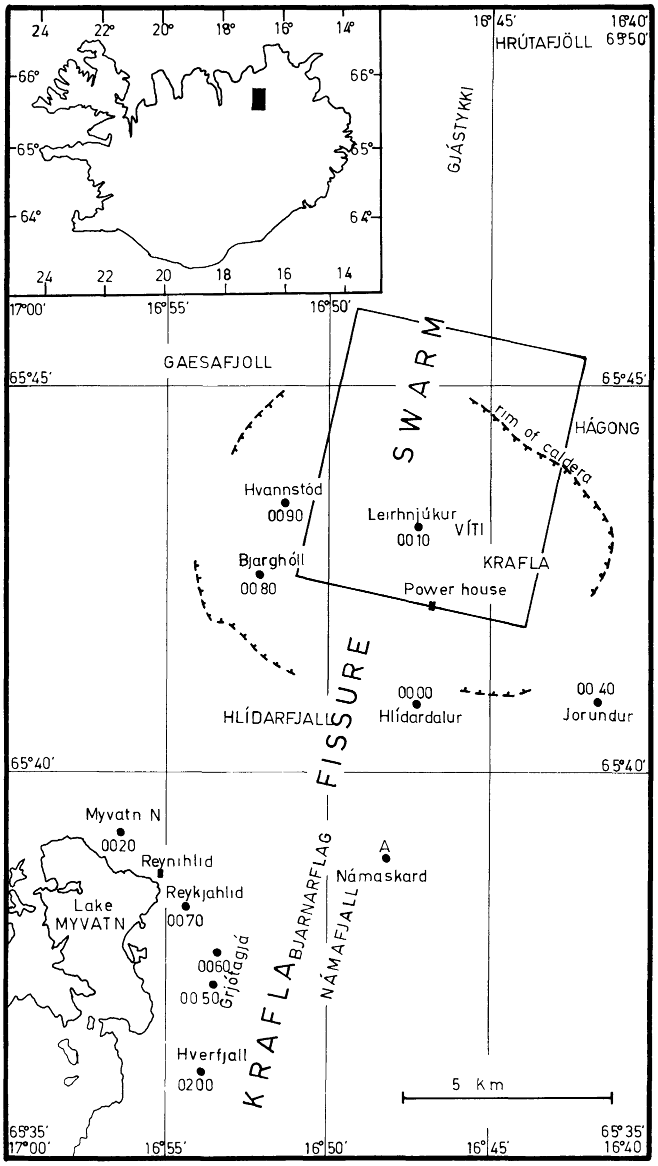

Fig. 1. Location of the spirit level tilt stations in the Krafla-Mývatn area (*filled circles*) and the electronic tiltmeters at the Krafla power house and Reynihlid. The rim of the Krafla caldera is shown for reference on this and all subsequent maps. A rectangle outlines the area covered by the maps on Figs. 9 and 12

bolt to another around the circle. Under favourable conditions the leveling accurancy is approximately 0.1 mm. Minor movements of the bolts together with observational errors make the probable error of tilt roughly 5μ rad.

A program of repeated geodimeter measurements in the Krafla-Mývatn area was initiated in early 1977 (Tryggvason, 1978b). The present stations in the northern part of the area are shown on Fig. 2. This network has been measured several times, both distances between the markers, and also the vertical angles by theodolite. Thus a crude observation of vertical displacements is obtained at the same time as the horizontal displacements.

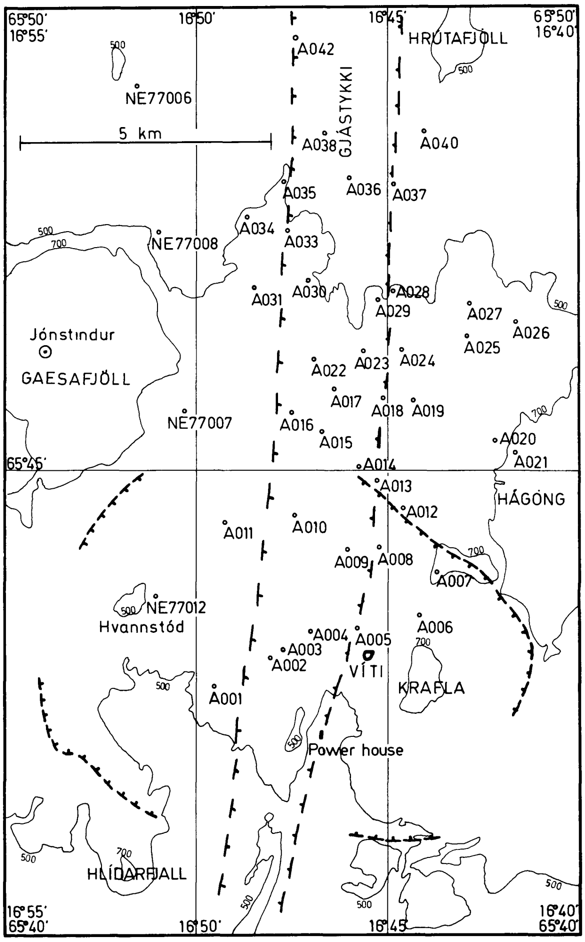

Fig. 2. Location of the stations used in distance measurements with geodimeter in the Krafla-Gjástykki area

Other observations, which improve the overall understanding of the subsidence events, are seismic observations by the Science Institute of the University of Iceland, precision leveling and gravity measurements by the National Energy Authority, and a variety of other observations by the large number of scientists working in the Krafla-Mývatn area.

The Model

The geological model, which has been developed during the present sequence of events in the Krafla region, is as follows.

Below the central part of the Krafla area, near Leirhnjúkur, lies a magma chamber. A continuous flow of molten magma enters this chamber from below, and the rate of this flow can be estimated from the rate of uplift during inflation periods. Occasionally, a relatively sudden outflow of magma from this chamber occurs along the fissure swarm, which goes through the Krafla area in direction N10 °E to N15 °E. Minor lava eruptions occurred three times in 1975 and 1977 (Björnsson et al., 1977; Björnsson, 1976; Björnsson et al., 1979; Tryggvason, 1978a; Einarsson, 1978).

The depth of the Krafla magma chamber has been estimated from tilt and level observations using the equations developed by Mogi (1958). The depth estimates, which best agree with the observations are close to 3.0 km to the center of a spherical chamber (Tryggvason, 1978a, Björnsson et al., 1979). The assumption of a spherical magma chamber is certainly not correct, but observations of tilt and variations in ground elevation fit such

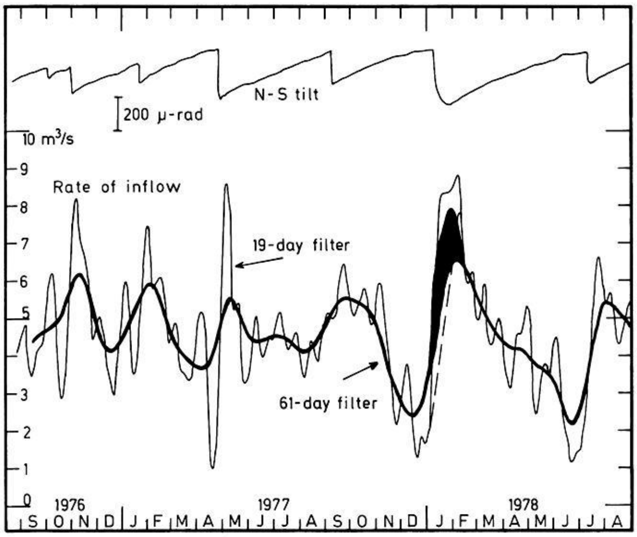

Fig. 3. The north component of tilt measured by the water tube tiltmeter in the Krafla power house (*upper trace*). Uplift to the north is up on the graph. The *lower traces* show the rate of tilt converted into rate of volume increase (*inflow*) of the Krafla magma chamber. This rate is filtered with a low pass filter to clarify the general trend. In January 1978 the inflow rate is uncertain due to prolonged subsidence event

a model rather well. Observations of *S*-wave shadows (Einarsson, 1978) indicate that the top of the magma chamber lies at a depth of approximately 3 km and the bottom at or above 7-km depth.

The observations suggest another magma chamber of great but unknown depth below the Krafla region. This lower chamber is so large, that no limits have as yet been seen for its capacity to supply magma to the shallower chamber.

The magma that flows out of the Krafla magma chamber during subsidence periods is deposited as a dike in the Krafla fissure zone (Björnsson, 1976; Björnsson et al., 1979). The velocity with which the front of the forming dike moves forward, can be obtained from the movement of earthquake epicenters (Brandsdóttir and Einarsson, 1979) and from the time of formation of new fissures or opening of old ones (Björnsson et al., 1979). This velocity is approximately 0.5 m/s in the cases studied.

The portion of the dike that is formed during each subsidence event can be located with seismic epicenters (Brandsdóttir and Einarsson, 1979) and new or reopened ground fissures and new or intensified steam vents (Björnsson et al., 1979). The depth to the dike can be estimated from the width of the zone of new or reopened fissures, and the thickness of the dike from the widening of the fissure zone. However, the widening of the fissure zone as measured on the surface may be greater than the thickness of the new dike due to change in the stress release pattern with depth in the earth's crust. This effect has not been estimated as yet.

In estimating the volume of magma, which flows into and out of the Krafla magma chamber, tilt observations in the Krafla power house are of greatest use. It is assumed that the location of the magma chamber does not change with time. A study of the inflation period between the subsidence events of April 27–28, 1977, and September 8–9, 1977, which is primarily based on tilt observations at 7 stations, including the Krafla power house, gave the following results (Tryggvason, 1978a).

(a) Depth to the center of a spherical magma chamber, which best fitted the observations, was 2.9 km.

(b) The total volume of uplift, assumed to be equal to volume of magma influx, was 59.5×10^6 m^3 during this inflation period.

(c) The calculated uplift of the ground at the point of greatest uplift was 110 cm.

(d) The total north component of tilt at the Krafla power house was 312 μ rad.

Thus one μ rad tilt at the Krafla power house corresponds to 0.19×10^6 m^3 of magma influx. In the light of the inaccuracies in this determination, especially in depth of the magma chamber, the rounded value of 0.2×10^6 m^3 is accepted in this paper as corresponding to one microradian of N-S tilt at the Krafla power house. As the average tilt at the power house is 2.0 to 2.1 μ rad per day during inflation periods, the average influx of magma into the Krafla magma chamber is about 0.4×10^6 m^3/d or about 5 m^3/s. It is assumed that the influx continues during subsidence periods, so the magma outflow is slightly greater than that calculated from tilt during the subsidence periods.

The rate of tilt at the Krafla power house is converted into rate of magma flow in Fig. 3. There seem to be considerable fluctuations in this rate. It is very noticeable that the influx rate appears to be high first after a subsidence event, and low before such an event.

The Subsidence Event of December 1975 to January 1976

The first subsidence event of the present volcano-tectonic sequence in the Krafla area started on December 20, 1975, simultaneously with observed seismic tremor. Repeated leveling of the base of the Krafla power house showed tilt of approximately 750 μ rad down to the north between November 20, 1975, and February 10, 1976. Several measurements between January 18 and February 10, 1976, showed slight northward tilt to continue, but measurement on March 1, 1976, showed that uplift towards north had commenced at the power house. Leveling in early March 1979 along a line from lake Mývatn showed subsidence exceeding 2 m in the Krafla area since 1974 (Björnsson et al., 1977). It may be assumed that this subsidence occurred on December 20, 1975, and the days that followed.

Opening of fissures and faulting was observed in the Krafla fissure swarm, primarily in the Kelduhverfi area 30 to 60 km north of Krafla, but to a lesser extent in other parts of the fissure zone, as far south as lake Mývatn (Tryggvason, 1976; Björnsson, 1976).

The tilt at the Krafla power house and the subsidence indicate that roughly 150×10^6 m^3 of magma was removed from a magma chamber below the Krafla area. If magma entered the chamber from below during this subsidence event at a rate similar to that observed during the following years, the volume of magma entering the fissure swarm during this event may have been as much as 180×10^6 m^3. Most of this magma flowed northwards to be deposited in the northernmost 30 km of the fissure zone, which supposedly terminates at 66° 20′ north. Rifting in the Mývatn area indicates that a minor fraction of the magma flowed southwards.

Subsidence Events of September 29 to October 4, 1976 (Fig. 4)

Observations of the water tube tiltmeter in the Krafla power house show tilt towards north from September 29 to October 4, 1976.

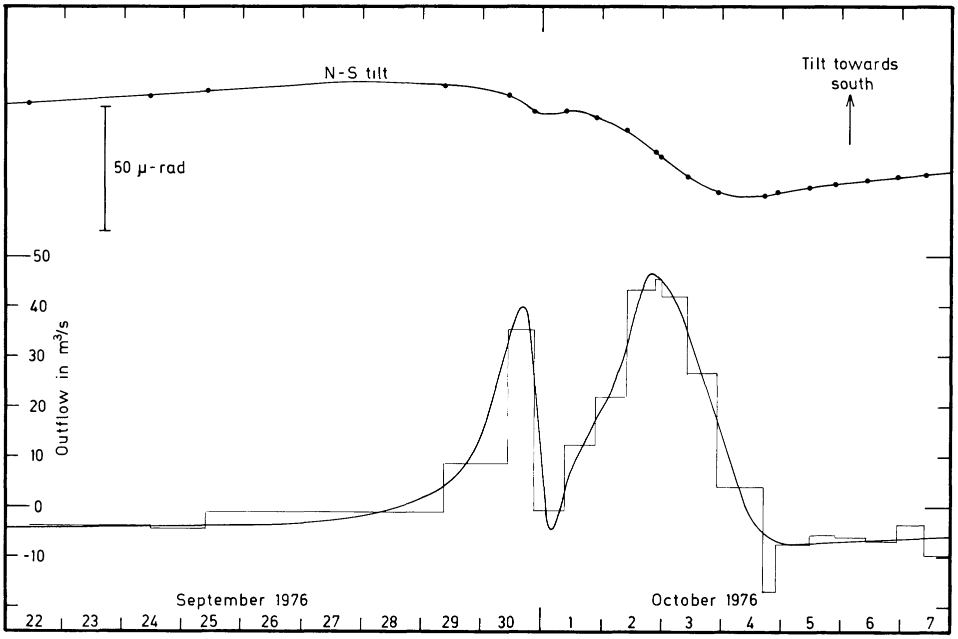

Fig. 4. North component of tilt at the Krafla power house and rate of magma outflow from the Krafla magma chamber during the subsidence events of September 29 to October 4, 1976. *Filled circles* show the actual water tube tiltmeter observations. The average rate of outflow between tilt observations is shown by thin line rectangular curve, while the smooth curve is the authors interpretation

The beginning of this event is poorly recorded as no readings were taken between September 25, 10^h and September 29, 10^h This tilt event seems to be a double event or rather two separate subsidence events (Fig. 4).

Two spirit level tilt stations provide information on these subsidence events, Hlídardalur (0000) and Leirhnjúkur (0010). Observations were made at both stations on September 18, October 2, and October 23, 1976. The good correlation between the tilt at these stations and the N-S component of tilt at the Krafla power house allows us to estimate the tilt during each of these subsidence events.

In estimating the tilt during subsidence events, the observations are reduced to the time of the event. This reduction is based on the average ratio between tilt components at each station and the daily observations of the north component of tilt at the Krafla power house.

The first of these two events, lasting from September 29 (or earlier) to September 30, 21^h appears to have caused a tilt of 11 μ rad towards N80 °E at Hlídardalur and 26 μ rad towards S63 °E at Leirhnjúkur, while the north component of tilt at the Krafla power house was 14 μ rad. The tilt directions indicate that this event was associated with uplift of the Krafla fissure swarm south of Leirhnjúkur but not as far south as Hlídardalur.

The second subsidence event lasted from October 1 to 4, 1976. It caused a tilt of 22 μ rad towards N22 °W at Hlídardalur and 45 μ rad towards west at Leirhnjúkur, while the north component of tilt at the Krafla power house was 40 μ rad. This tilt is roughly in opposite direction to that of normal inflation periods, indicating that subsidence in the Krafla caldera is responsible for the observed tilt, but uplift outside the caldera is not noticeable. This can best be explained by magma flow towards north.

The volume of the magma flowing out of the Krafla magma chamber during the subsidence events of September 29 to October 4, 1976, can best be estimated from tilt observations at the Krafla power house. If the N-S component of tilt at the power house is solely due to volume changes in the magma chamber, the first phase of the subsicence event (September 29–30, 1976) is due to removal of approximately 3×10^6 m^3 of magma. Certain fraction of the observed tilt may have been due to uplift south of the power house and thus less magma is required. The easterly tilt at Hlídardalur requires a minimum of 2×10^6 m^3 to have been injected at 3-km depth. Thus it can be assumed that 2 to 3×10^6 m^3 of magma was injected towards the south from the Krafla magma chamber during this first subsidence event.

Tilt during the second subsidence event is apparently related to subsidence above the magma chamber. If this subsidence was distributed in the same way as uplift during inflation periods, the volume of magma which was emitted from October 1 to 4, 1976, was roughly 8×10^6 m^3

The estimated rate of outflow of magma (Fig. 4), reached about 40 m^3/s during the first event, on October 30, and nearly 50 m^3/s during the second event in the afternoon or night of October 2, 1976.

The Subsidence Event of October 30 to November 1, 1976 (Fig. 5)

The tilt measurements showing this subsidence event are the north and east components at the Krafla power house twice a day and five times in addition on October 31 and November 1, 1976, and measurements at the spirit level tilt stations Hlídardalur and Leirhnjúkur on October 23 and November 1, 1976.

If the last measurement before the subsidence event is extrapolated to November 1, we get the tilt during the event as follows: at the Krafla power house 162 μ rad towards N10 °E, at Hlídardalur 71 μ rad towards N7 °W and at Leirhnjúkur 160 μ rad towards S35 °W The tilt at these stations is nearly in the opposite direction to that observed during inflation periods. This shows that the subsidence is caused by northward flow of magma, as southward flow would have effected the direction of tilt at Hlídardalur. Opening of fissures and earthquake swarm north of the Krafla area support this view (Björnsson et al., 1977). The total volume of outflow as calculated from tilt at the power house is 32×10^6 m^3 and the rate of outflow probably exceeded 800 m^3/s between 4^h and 6^h in the morning of October 31 (Fig. 5).

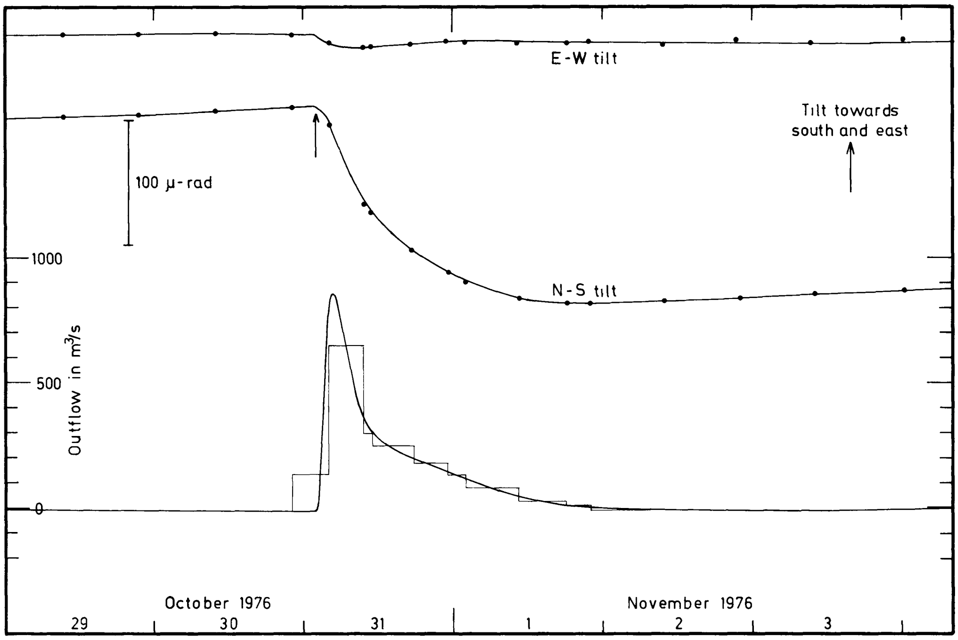

Fig. 5. Tilt in the Krafla power house as observed by the water tube tiltmeter, and the rate of magma flow out of the Krafla magma chamber during the subsidence event of October 31 to November 1, 1976. Notation as in Fig. 4

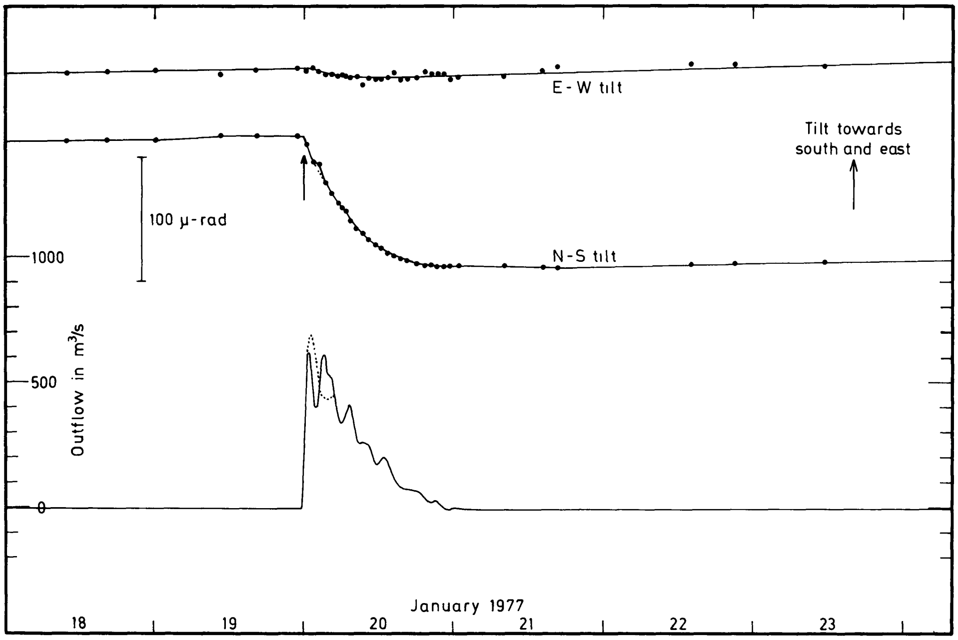

Fig. 6. Tilt in the Krafla power house as observed by the water tube tiltmeter, and the smoothed rate of magma flow out of the Krafla magma chamber during the subsidence event of January 20, 1977. *Dotted portion of curves* is obtained if one suspicious observation is omitted

The beginning of the subsidence event is clearly after the tilt observation on October 30, 22^h22^{min} and before October 31, 2^h15^{min} Seismic tremor was observed on seismometers at Húsavík and Reynihlíd on October 31, 2^h0^{min} or few minutes later. This represents the first sign of the subsidence. The subsidence ended before the tilt observation on November 1, 21^h45^{min}, but after the observation on November 1, 18^h10^{min} Thus the subsidence lasted roughly 42 h, from October 31, 02^h to November 1, 20^h.

The Subsidence Event of January 20, 1977 (Fig. 6)

The only tilt observations showing this event are those of the water tube tiltmeter in the Krafla power house. All spirit level stations in the area were convered by snow. Readings were taken at the power house tiltmeter two to four times a day before the subsidence event and the last observation on January 19, at 23^h00^{min} did not show any sign of the coming event.

Seismometers in Reynihlíd showed continuous tremor, which started about 23^h50^{min} on January 19 and the tiltmeter reading taken at 00^h30^{min} on January 20 showed clearly that subsidence had started in the Krafla area. It is assumed, that the beginning of the continuous seismic tremor coincided with the beginning of the subsidence. Hourly tiltmeter readings show clearly the progress of the subsidence until it almost ceased at 22^h January 20, but minor additional subsidence was observed between 8^h and 16^h on January 21 (Fig. 6).

The frequent tiltmeter observations during this subsidence event show that the rate of subsidence fluctuated considerably.

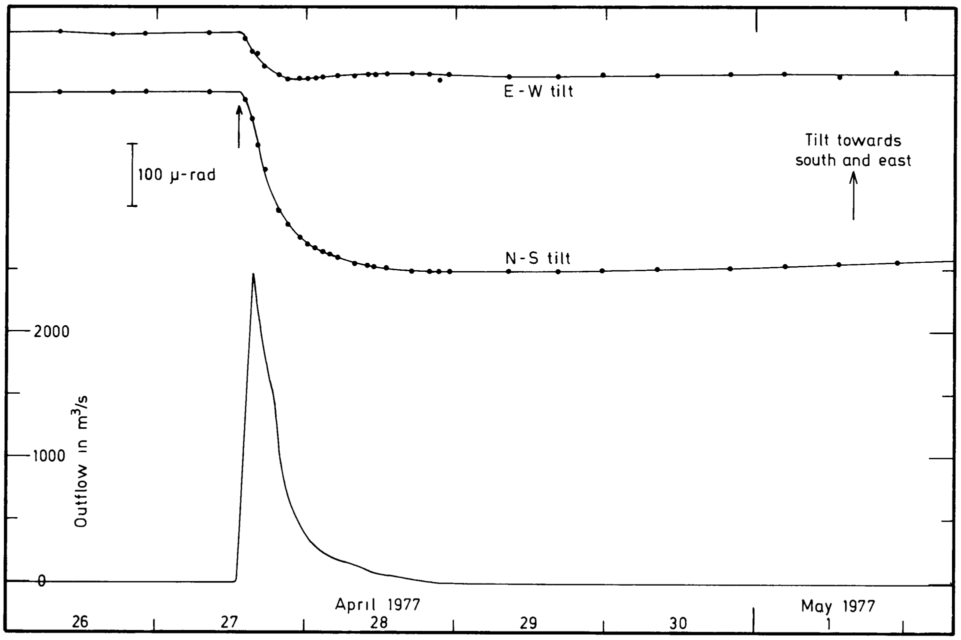

Fig. 7. Tilt in the Krafla power house as observed by the water tube tiltmeter, and the rate of magma flow out of the Krafla magma chamber during the subsidence event of April 27 to 28, 1977. The outflow rate as shown is probably some 10–20% too high (see text)

The maximum rate of subsidence was reached about one hour after the subsidence started. The subsidence rate corresponds to a rate of magma outflow of approximately 700 m^3/s. The east component of tilt was very small compared to the north component, indicating that the center of subsidence was towards N13 °E from the power house.

The total tilt at the power house from the beginning of the subsidence event on January 19 at $23^{\mathrm{h}}50^{\mathrm{min}}$ to its end on January 21 at 16^{h} was about 105 μ rad, corresponding to 21.0×10^6 m^3 of magma flowing out of the magma chamber, providing the tilt was only due to removal of magma from the same region as is inflated during inflation periods. There are no known indications of magma flowing towards south, so it is assumed that the magma movement during this event was towards north only. Opening of fissures and an earthquake swarm north of the Krafla area also show that magma flowed towards north (Björnsson et al., 1977; Sigurdsson, 1977).

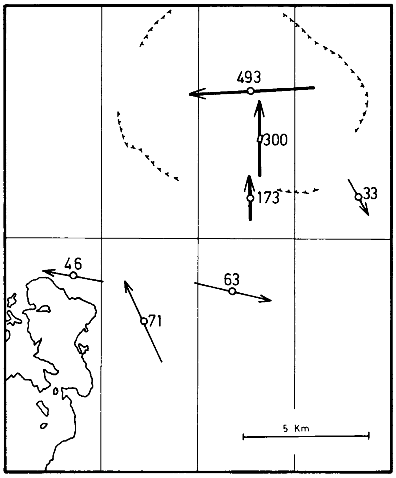

Fig. 8. Tilt vectors related to the subsidence event of April 27 to 28, 1977. Numbers give the estimated tilt in microradians

The Subsidence Event of April 27–28, 1977 (Figs. 7–9)

The tilt and distance observations relating to this subsidence event, are:

(1) Observations of the water tube tiltmeter in the Krafla power house three times a day and additional readings during the event.

(2) Tilt observations at six spirit level tilt stations in the Krafla-Mývatn area on May 16–20, 1977, but previous measurements at these stations had been made in the fall of 1976.

(3) Geodimeter and vertical angle theodolite measurements on 14 lines in the Krafla-Gjástykki area in late February and again in July 1977.

The first sign of the beginning of this subsidence event was continuous seismic tremor on the local seismometers, which commenced at $13^{\mathrm{h}}17^{\mathrm{min}}$ on April 27 (Sigurdsson, 1977). The tiltmeter reading in the Krafla power house at $8^{\mathrm{h}}30^{\mathrm{min}}$ the same morning did not show any sign of the subsidence, but at $14^{\mathrm{h}}10^{\mathrm{min}}$ the subsidence had started and it continued at a rapid rate during the following hours (Fig. 7). The rate of subsidence slowed down towards the evening of April 27, but it did not come to a complete stop until at about 20^{h} on April 28, some 31 h after the subsidence started. The tilt at the power house during these 31 h was some 290 μ rad towards north. The tilt at the spirit level tilt stations during this subsidence event, is estimated with a low degree of accuracy because of few observations prior to the event (Fig. 8).

Distance measurements with a geodimeter in the Krafla-Gjástykki area on February 26–March 3, 1977, and again on July 19–21, 1977, (Tryggvason, 1978b), show distance changes on 14 lines, which are believed to have occurred during the subsidence event of April 27–28, 1977. East-west widening of the fissure zone 63 to 93 cm was observed (Fig. 9). The zone that has widened is only about 1 km wide. Outside the zone of east-west extension, contraction of some 2 to 10 cm/km was observed. In the Mývatn area near Reykjahlíd other measurements showed 2.0 m widening of the fissure zone and 1.0 m shortening of a 7.2 km line outside the active fissure zone (Björnsson et al., 1979).

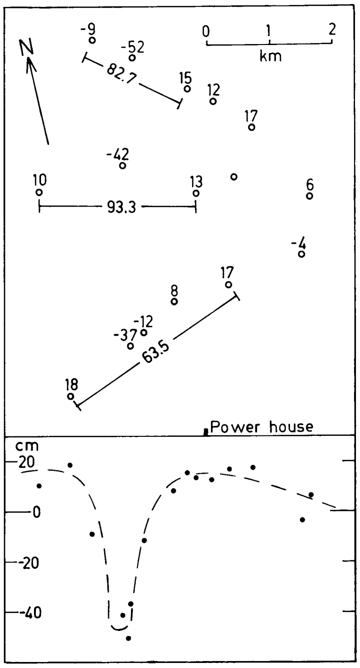

Fig. 9. Lengthening of three lines in the Krafla area and vertical displacements during the subsidence event of April 27 to 28, 1977. The *upper part* is a map (see Fig. 1 for location) showing the three lines across the active fissure zone, giving the calculated lengthening in centimeters, and the numbers by the stations give the vertical displacements in centimeters. On the *lower part* are the vertical displacements projected on a line parallel to the lower edge of the map

Elevation of the geodimeter points in the Gjástykki network were observed with a theodolite. These show about 60 cm subsidence of the active part of the fissure zone, relative to the surrounding area (Fig. 9). Similar vertical movements were observed on a leveling line from Reykjahlíd towards east across Námaskard, where the flanks of the fissure zone were uplifted about 40 cm, while the fissure zone subsided some 80 cm (Björnsson et al., 1979).

All these observations are interpreted as due to magma flow out of the magma chamber beneath the Krafla area into a fissure or fissures. The major part of this magma flowed southwards as indicated by the large tilts and widening of the fissure zone in the Mývatn area. Evidence of some northward flows in the small lava eruption on April 27, at the northern edge of the Krafla caldera (Björnsson et al., 1979; Sigurdsson, 1977).

The volume of magma, which was removed from the magma chamber can be crudely estimated from the 290 μ rad tilt at the Krafla power house. If this tilt is solely due to subsidence above the magma chamber, the volume of the subsidence bowl is about 58×10^6 m^3 However, in this case the majority of the magma moved southward causing uplift of the area south of the Krafla power house, increasing the tilt by an unknown amount. If we assume, that the tilt effect of the uplift is similar at the power house as the tilt near Mývatn (spirit level tilt stations A, 0020 and 0030, Fig. 8), which is 50 to 70 μ rad, the tilt at the power house related to subsidence to the north is estimated as 220 to 240 μ rad, corresponding to the removal of 44 to 48×10^6 m^3 of magma.

The rate of outflow of magma as shown on Fig. 7 is based on the assumption that the tilt is solely due to subsidence north of the power house. This shows a maximum rate of magma flow of some 2500 m^3/s, about 2 h after the beginning of the subsidence event. As a fraction of the tilt is due to uplift to the south of the power house, the actual flow rate is lower. Thus the maximum rate of outflow during this event was probably about 2000 m^3/s.

The Subsidence Event of September 8–9, 1977 (Figs. 10–12)

The tilt and distance observations, which provide information on this subsidence event, are:

1. Readings of the water tube tiltmeter in the Krafla power house once a day, with eight additional readings on September 8–10. Only the north component was observed.
2. Continuous recording of an electronic tiltmeter at the Krafla power house (Sindrason and Ólafsson, 1978). This tiltmeter is oriented parallel to the water tube tiltmeter.
3. Tilt observations at 11 spirit level tilt stations once a month.
4. Distance measurement with a geodimeter and vertical angle measurements with a theodolite on several lines inside the Krafla caldera and in the Mývatn area to the south of the caldera.

The water tube tiltmeter in the Krafla power house showed tilt towards north of 190 μ rad between the readings of September 8, $08^{h}50^{min}$ and September 10, $16^{h}40^{min}$ The new electronic tiltmeter with the sensor in a concrete cellar a few meters west of the power house, showed the beginning of the subsidence to be on September 8, $15^{h}40^{min}$ or possibly some five minutes earlier. The rate of subsidence increased rapidly until $17^{h}10^{min}$, when it reached about 35 μ rad/h, whereafter the subsidence rate decreased even more rapidly to become zero at $18^{h}00^{min}$. Then the tiltmeter indicated uplift to the north of the power house for 20 min, whereafter the subsidence started again and increased rapidly to reach maximum of about 50 μ rad/h at $18^{h}50^{min}$ Following this maximum the subsidence rate decreased gradually to zero on September 9, 15^{h}, whereafter slight inflation commenced. The total tilt according to the electronic tiltmeter was 198 μ rad towards N3 °W (Fig. 10).

Observations of the spirit level tilt stations were made on August 15–17, some 25 days before, and on September 10–12, 1977, immediately after the subsidence event. The tilt vectors at these stations (Fig. 11) clearly indicate subsidence in the western part of the Kraftla caldera and uplift around the active fissure swarm south of the caldera.

Distance measurements with a geodimeter made in July and August before the subsidence event and again in September and October, after the event, show considerable lengthening of lines crossing the Krafla fissure swarm. Within the Krafla caldera the widening is 70–100 cm (Fig. 12) and the zone that widened is roughly 1 km wide. South of the Krafla caldera only two measuring lines crossed the fissure swarm, one from Reykjahlíd to Námafjall, which increased in length by 104.9 cm, and another some 6 km farther south, which increased in length by only 7.4 cm, indicating that this line is at the southern end of the strip, which widened. An east-west line, 7250 m long, wholly outside the active part of the fissure zone from Reykjahlíd to Vindbelgur, was shortened by 25.4 cm, or about 3.5 cm per km. Short lines east of the active fissure zone within the Krafla caldera showed no systematic length changes during the event, but these lines regularly expand and contract as the magma chamber is inflated and deflated, so their length depends on the inflation stage at the time of measurements.

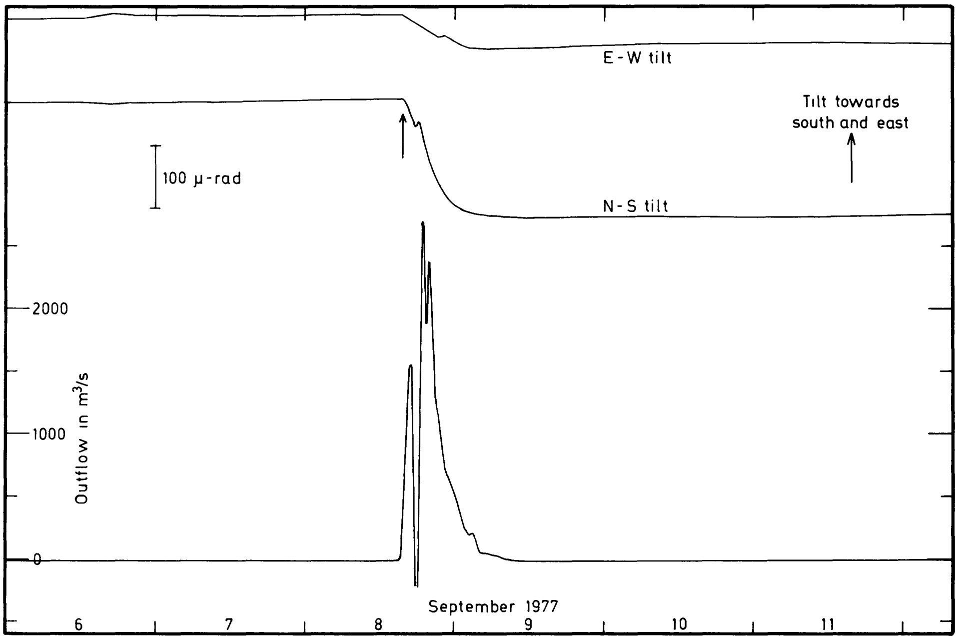

Fig. 10. Tilt in the Krafla power house as measured by the electronic tiltmeter, and the rate of outflow of magma from the Krafla magma chamber during the subsidence event of September 8 to 9, 1977. The outflow rate as shown may be 40–50% too high (see text)

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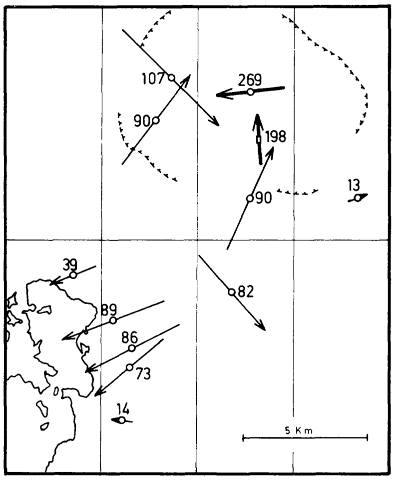

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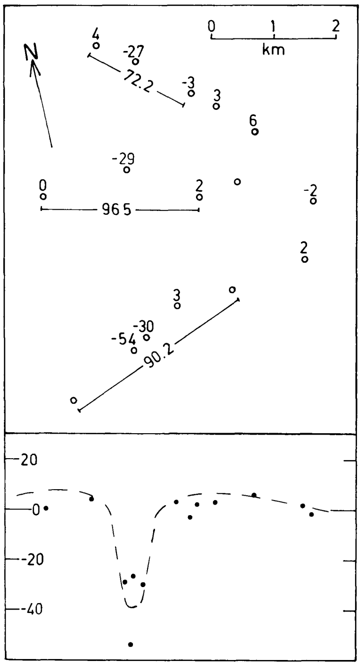

Fig. 11. Tilt vectors related to the subsidence event of September 8 to 9, 1977. *Numbers* give the calculated tilt in microradians

Fig. 12. Lengthening of geodimeter lines and vertical displacements of stations during the September 8 to 9, 1977 subsidence event. See Fig. 9 for explanation

The total volume of magma, which flowed out of the magma chamber during the event, can be estimated roughly from the observed tilt. The *N* component of tilt at the Krafla power house was about 194 µ rad. Part of this tilt is due to uplift south of the power house. If this part is equal to the maximum tilt near the south end of the injected zone (about 90 µ rad) the remaining part, about 100 µ rad, is due to subsidence of the Krafla caldera. This means that about 20×10^6 m^3 of magma moved out of the Krafla magma chamber. This number may be in error by some 20% due to the uncertainity of the effect of the uplift south of the power house.

The rate of outflow as calculated from the tilt change at the power house alone, is about 2700 m^3/s at its maximum (Fig. 10). This estimate is certainly too high, due to the effect of land rise to the south of the power house. If the calculated rate of flow is reduced by the same factor as the tilt in the discussion above, the maximum rate of magma outflow was about 1400 m^3/s.

It is obvious from the tilt and distance measurements, that the majority of the magma moved southwards. However, the widening of the fissure zone within the northern part of the Krafla caldera and the eruption of some 2×10^6 m^3 of lava near the northern edge of the caldera (Sigurdsson, 1977), shows that some magma flowed towards north. A rough estimate, based on widening of the fissure swarm, indicates that 80% of the magma flowed southwards, 10% flowed northward into subsurface fissures and 10% came to the surface as lava.

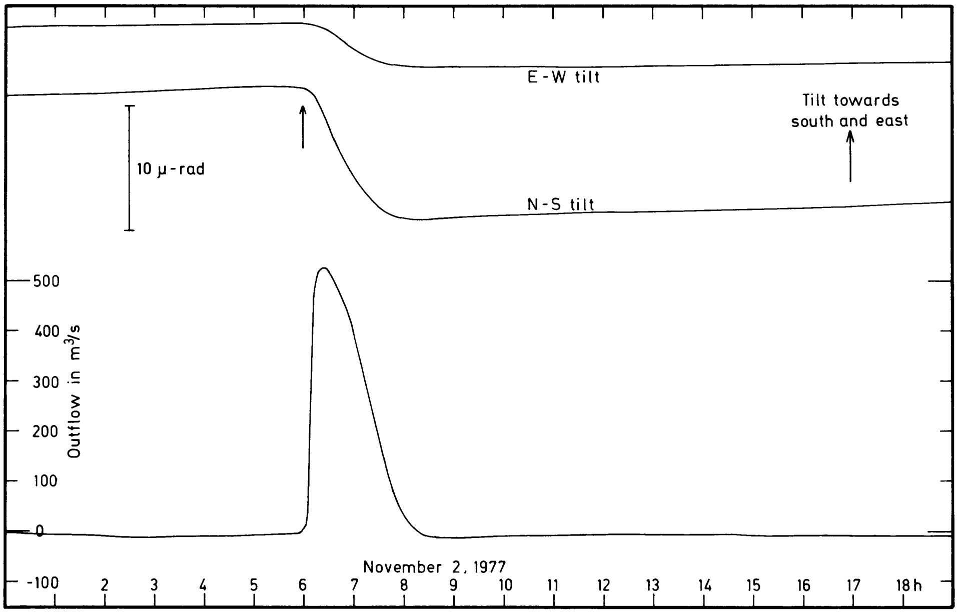

Fig. 13. Tilt in the Krafla power house as measured by the electronic tiltmeter, and the rate of outflow of magma from the Krafla magma chamber during the subsidence event of November 2, 1977

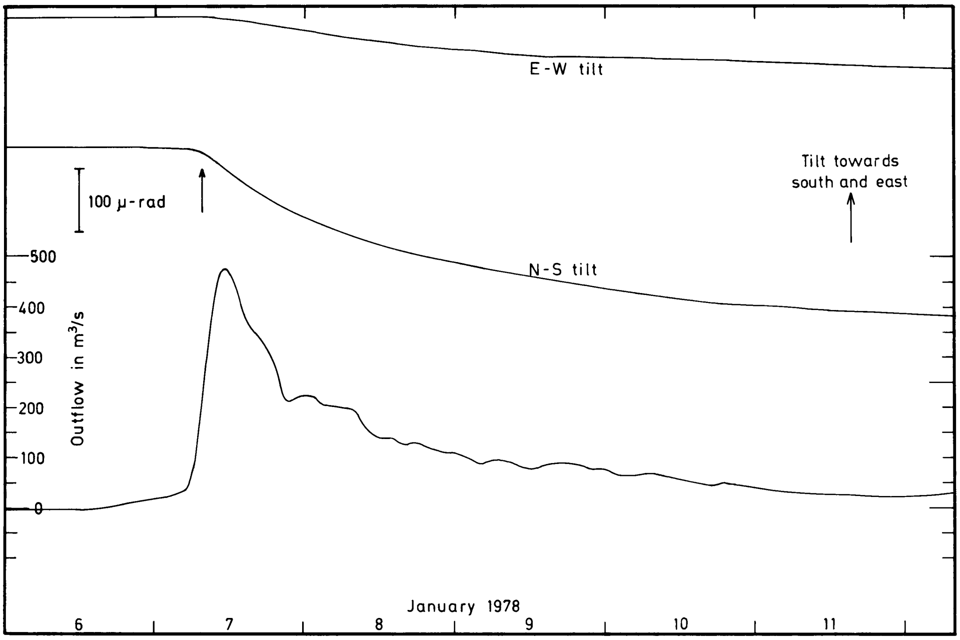

Fig. 14. Tilt in the Krafla power house as measured by the electronic tiltmeter, and the rate of outflow from the Krafla magma chamber during the first days of the January 1978 subsidence event

The Subsidence Event of November 2, 1977 (Fig. 13)

This event was small and the only clear observations of it were the recordings of the electronic tiltmeter at the Krafla power house, and the local seismometers. The subsidence started at about 6^h00^{min}, and the rate of tilt reached a maximum of about 10 µ rad/h at 6^h20^{min}, whereafter it decreased and the subsidence ceased altogether between 8^h00^{min} and 8^h30^{min} The total tilt at the Krafla power house was about 11 µ rad towards N6 °W. This represents a removal of 2×10^6 m^3 of magma from the Krafla magma chamber and the maximum rate of flow was about 500 m^3/s (Fig. 13). The direction of the magma flow is not known with certainty, but the ratio of north and east components of tilt at the Krafla power house is very similar to that of the inflation periods, which indicates flow towards north.

The Subsidence Event of January, 1978 (Figs. 14–16)

The following tilt and distance observations were made:

1. the water tube tiltmeter at the Krafla power house once a day;
2. Continuous recordings of the electronic tiltmeters at the Krafla power house and at Reynihlíd,
3. 11 spirit level tilt stations in the Krafla-Mývatn area before, during, and after the subsidence event;
4. distance with geodimeter in the Krafla-Gjástykki area before and after the event, and
5. tilt at two spirit level tilt stations in Kelduhverfi before and after the event.

The water tube tiltmeter at the Krafla power house showed tilt down to the north to commence before the observation on January

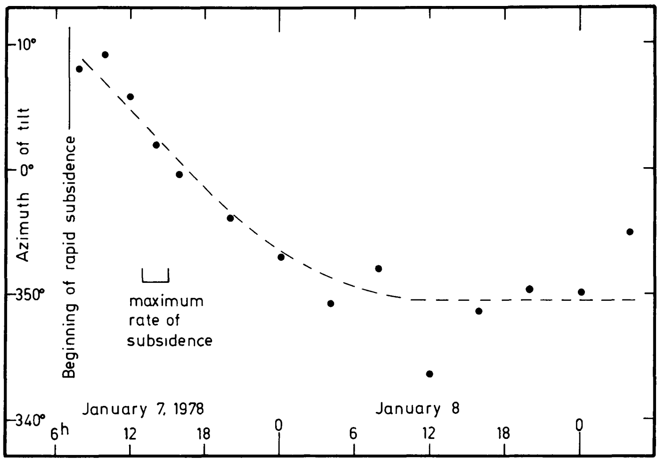

Fig. 15. Direction of tilt at the Krafla power house during the first two days of the January 1978 subsidence event. *Filled circles* give average directions over 2–4 h periods. The *dashed* line is the authors interpretaition of the variation of tilt azimuth with time

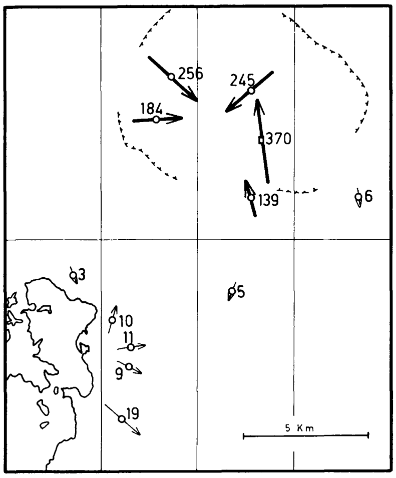

Fig. 16. Tilt vectors related to the subsidence event of January 1978. Numbers give the estimated tilt in microradians

7, 07^{h}, but after the observation on January 6, 09^{h}. The tilt continued until January 25, and had then reached 317 μ rad. The east component of the water tube tiltmeter did not operate.

The electronic tiltmeter at the Krafla power house showed slight subsidence to commence on January 6, at 15^{h} approximately, but this was very slow the first 16 h, when the tilt had reached only 4 μ rad. On January 7, at about 07^{h}, the subsidence rate started to increase dramatically, and the maximum rate of *N*-tilt of 8.9 μ rad/h was reached between 12^{h} and 15^{h} on January 7, or 5–8 h after the rapid increase in tilt rate. The subsidence continued, although its rate fluctuated greatly, unit about January 22, when the observed tilt had reached 370 μ rad towards N7 °W (Fig. 14). Both *N* and *E* components of this tiltmeter showed great fluctuations in rate during this event and for several weeks after, indicating that some processes associated with the event continued for a month or more after the subsidence of the Krafla region ceased on January 22–25, 1978. The direction of tilt during the first hours showed continuous variation from N10 °E at the very beginning of the rapid subsidence to about N12 °W a day later (Fig. 15).

The electronic tiltmeter at Reynihlíd showed great irregularities during this subsidence event, so the tilt cannot be determined with accurancy.

The spirit level tilt stations 0000, 0010, 0080, and 0090 show the event clearly, although observations were not made after the event until mid May, 1978. The other spirit level tilt stations in the Krafla-Mývatn area showed no definite tilt due to this subsidence event, probably because no observations were made after the event until mid May 1978 (Fig. 16).

Distance measurements with the geodimeter on 24 lines in the Krafla-Gjástykki area in October and November 1977, and again in March 1978, show irregular length changes, usually less than 5 cm on each line, although shortenings of 6 to 17 cm were observed on 6 lines near the center of subsidence. These length changes are largely or wholly the result of vertical ground displacements and associated bending of the elastic crust. They do not indicate any widening of the fissure zone, as was observed during the subsidence events of April and September 1977.

Tilt observations at two spirit level tilt stations in Kelduhverfi were made on July 15, 1977, before the subsidence event, and on May 21, 1978, after the event. At the station Höll (66°02′.8 N, 16°38′.0 W) a tilt of 210 μ rad towards south (azimuth 180.0°) was observed, while at the station Lón (66°06′.0 N, 16°54′.2 W) the observed tilt was about 14 μ rad towards WNW (azimuth 284.2°).

The near zero ground deformation in the Mývatn area together with large scale ground deformation and a major earthquake swarm in Kelduhverfi some 40 km north of Krafla, shows that the magma flowed northward from the Krafla magma chamber. Some of it reached the tilt station Höll, 39 km north of the center of subsidence.

As no magma was deposited in the southern part of the fissure system north of Krafla, the tilt at the Krafla power house is a rather reliable indicator of the volume of the magma, which left the chamber. However, the subsidence event lasted for approximately 3 weeks, so it may be assumed that a considerable amount of magma flowed into the chamber from below at the same time. Under these assumptions, the total volume of the magma, which flowed out during the subsidence event, is estimated 70 to 75×10^6 m^3 The rate of flow reached a maximum of approximately 500 m^3/s near noon on January 7 (Fig. 14), and decreased irregularly towards the end of January 1978. There were several noticeable increases in the outflux rate, especially on January 14–15 and on January 19, when it reached 60 to 70 m^3/s and on January 30 and February 2, when it reached approximately 40 m^3/s.

The Subsidence Event of July 10–12, 1978 (Figs. 17–21)

The tilt and distance observations showing this event are:

1. daily readings of the water tube tiltmeter in the Krafla power house;

2. continuous recording of electronic tiltmeters in the Krafla power house and in Reynihlíd,

3. observation of 11 spirit level tilt stations in the Krafla-Mývatn area about once each month, and

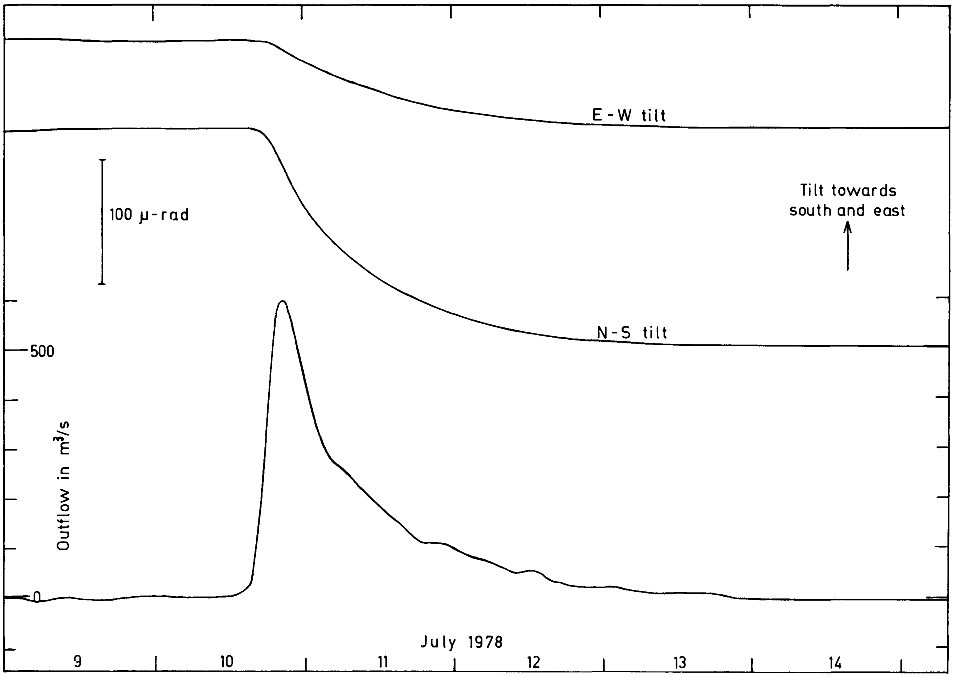

Fig. 17. Tilt in the Krafla power house as measured by the electronic tiltmeter, and the rate of outflow from the Krafla magma chamber during the July 10 to 12, 1978 subsidence event

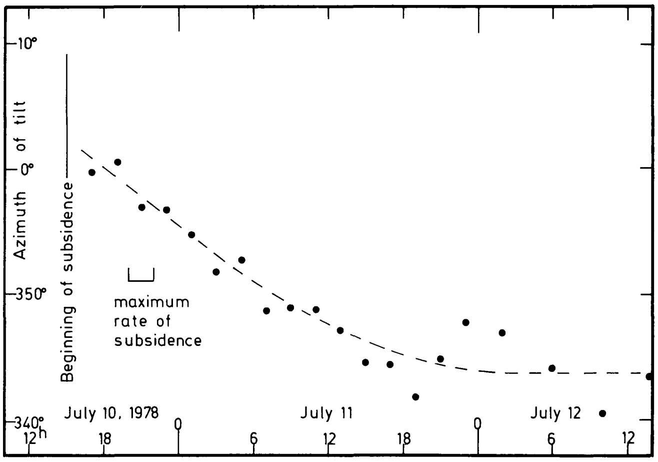

Fig. 18. Direction of tilt at the Krafla power house during the subsidence event of July 10 to 12, 1978. See Fig. 15 for explanation

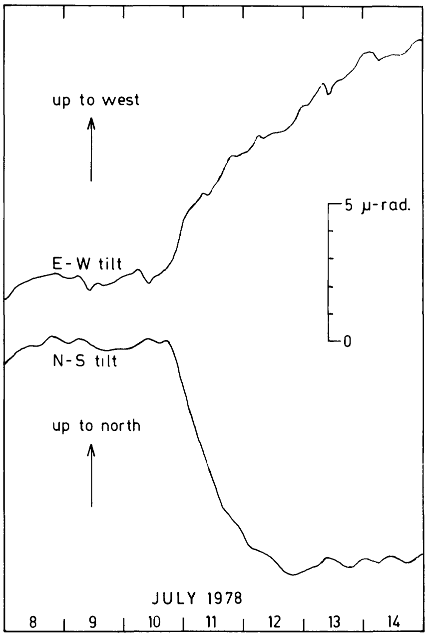

Fig. 19. Redrawn traces of the electronic tiltmeter in Reynihlíd during the July 10 to 12, 1978 subsidence event

4. distance measurements with a geodimeter on about 100 lines in the Krafla-Gjástykki area and similtaneous theodolite observations of elevation differences.

The water tube tiltmeter in the power house shows a total tilt of 177 μ rad towards north between July 10, 9^h and July 13, 13^h40^{min} The east component of the water tube tiltmeter showed no significant tilt.

The continuously recording electronic tiltmeter at the power house showed that the tilt started on July 10 at about 11^h, although it was very slow until about 15^h (Fig. 17). The rate of tilt increased rapidly until it reached its maximum between 20^h and 21^h, about 11.1 μ rad/h. Thereafter the rate of tilt decreased gradually until July 12, 20^h when a new inflation period started. The total tilt according to the electronic tiltmeter, was 188 μ rad towards N8 °W.

The direction of tilt, according to the electronic tiltmeter, was approximately N3 °E at the beginning of the subsidence event, and changed gradually to N17 °W in the afternoon of July 11 (Fig. 18).

The electronic tiltmeter at Reynihlíd (Fig. 19) showed definite tilt to start at about 19^h on July 10, or several hours later than at the Krafla power house. The tilt was about 8 μ rad towards north and a slightly smaller east component. The north component reached a maximum in the evening of July 12, as at the Krafla power house, while the east component showed progressive tilt for several days. This can be interpreted as change in direction of tilt at Reynihlíd from some 20° east of north at the beginning

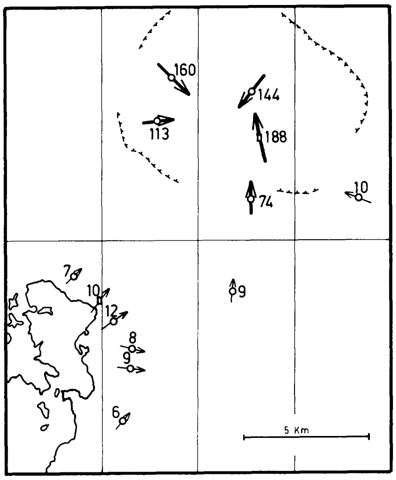

Fig. 20. Tilt vectors related to the subsidence event of July 10 to 12, 1978. Numbers give the calculated tilt in microradians

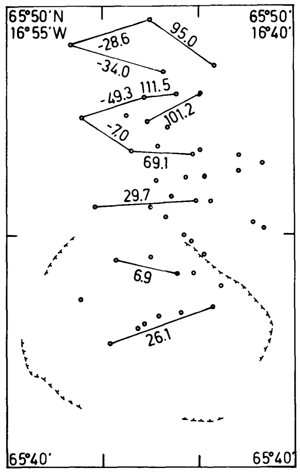

Fig. 21. Length changes of selected geodimeter lines in the Krafla-Gjástykki area between March and August 1978, in centimeters. The changes in the northern part of the area of measurement occurred during the July 10 to 12 subsidence event. See Fig. 2 for location

of the subsidence event towards east and even slightly south of east on July 13.

The spirit level tilt stations were occupied on June 24–29, 1978, before the event and in late July or early August after the event. The tilt at these stations related to the subsidence event are shown on Fig. 20. The tilt in the Mývatn area is so small that observational errors and minor tilt at times other than during the subsidence event may affect the results significantly. However, the very close correlation between observed tilt on the electronic tiltmeter at Reynihlíd and that at nearby spirit level stations (0020 and 0070) supports the opinion that the tilt shown on Fig. 20 is primarily related to this subsidence event.

Distance measurements in the Krafla-Gjástykki area in March 1978, and again in August 1978 (Fig. 21), show no noticeable permenent horizontal deformation within the Krafla caldera, but a widening of the fissure zone of approximately 1 m is observed in the northernmost part of the area of measurements. This widening is accompanied by subsidence of 50–70 cm of the central part of the fissure zone, relative to its flanks, and an east-west shortening of lines immediately outside the fissure swarm. The lengthening of 26 cm across the central part of the Krafla caldera is explained by the different stages of inflation during the two measurements.

The tilt measurements do not indicate any magma flow towards south, while the distance measurements strongly indicate deposition of magma below the southern part of Gjástykki, where the fissure zone was widened by 1 m. The present measurements do not show how far north the magma flow reached.

The total volume of magma, which flowed out of the Krafla magma chamber during the subsidence event, can be estimated from the north component of tilt at the Krafla power house to be about 37×10^6 m^3

The Subsidence Events of November 10–15, 1978, and May 13–18, 1979

These two events were very similar to that of July 10–12, 1978, although slightly larger. A preliminary analysis of the observational data indicates, that 44 to 45×10^6 m^3 of magma flowed out of the Krafla magma chamber during each event. Geodimeter measurements in April 1978 and May 1979 indicated 3.5 m widening of the fissure swarm, 18 km north of Krafla. This widening occurred during three subsidence events, July and November 1978 and May 1979, which all affected the same section of the fissure swarm.

Concluding Remarks

The present interpretation accounts for 12 subsidence events in the Krafla area from December 1975 to May 1979. The number of subsidence events is somewhat questionable. The two events at the end of September and beginning of October 1976 are sometimes considered as only one event (Björnsson et al., 1977). The event on November 2, 1977, is very small and of short duration, so it may be of limited significance in the sequence of events. Still smaller subsidence events may have occurred, without being noticed, espicially before the water tube tiltmeter was installed in the Krafla power house on August 20, 1976.

Of the twelve events, three have been associated with magma flowing primarily towards south and nine with magma flowing mainly or wholly towards north (Table 1). The total amount of magma flowing out of the Krafla magma chamber during these twelve events is estimated as 4.81×10^8 m^3 (0.481 km^3) of which 4.07×10^8 m^3 has been deposited in dikes to the north, and 0.72×10^8 m^3 to the south of the center of the Krafla caldera. About 2.4×10^6 m^3 has erupted.

It is assumed that magma, which flowed into the fissure swarm, formed a dike of width about equal to the widening of the fissure swarm. The subsidence of the central zone of the fissure swarm is supposedly caused by slumping into the void above the dike. Thus the depth to the dike can be estimated from the widening of the fissure swarm and the cross-sectional area of the subsidence. The depth to the dike appears to be 500–1,000 m within the Krafla caldera (Figs. 9 and 12), while a depth of 1,000–1,500 m is indicated in the Mývatn area according to data given by Björnsson et al. (1979). This depth is probably controlled by the cooling affect of groundwater in highly permeable formations. The new and intensified steam fields along the fissure swarm clearly show interaction between magma and the groundwater system.

Table 1. Estimated volume of magma flow in the Krafla subsidence events in 10^6 m^3

Event		Volume of flow towards north	Volume of flow towards south	Volume of lava	Total volume of flow
December 20,	1975	140	10	0.4	150
September 29,	1976		2		2
October 1,	1976	8			8
October 31,	1976	32			32
January 20,	1977	21			21
April 27,	1977	2	44	0.01	46
September 8,	1977	2	16	2	20
November 2,	1977	2			2
January 7,	1978	74			74
July 10,	1978	37			37
November 10,	1978	45			45
May 13,	1979	44			44
Total		407	72	2.4	481

The accumulated widening of the Krafla fissure swarm during the sequence of events which started in 1975 can only be estimated. The only precise distance measurements across the fissure swarm before 1975 were made by German scientists and remeasurements during the summer of 1977 showed lengthening of up to 1.8 m of lines which exceeded 10 km in length (Gerke et al., 1978). If the contraction of the flanks of the fissure swarm and the effect of line direction is added to the line lengthening, a widening of 2 to 3 m of the fissure swarm is estimated. A further widening of about 1 m occurred in the same area in September 1977 to July 1978 (this paper). A widening of 3.2 m in the Mývatn area was measured in two subsidence events (Björnsson et al., 1979; this paper) and some additional widening occurred in December 1975. In Kelduhverfi, 40 km north of Krafla, a widening of 1.5 m was indicated by opening of fissures in December, 1975 (Björnsson, 1976), and similar widening occurred at the same place in January 1978. Thus the widening of the Krafla fissure swarm probably equals or exceeds 3 m throughout its whole length from Mývatn to Axarfjördur. In places it exceeds 4 m.

The contraction of the flanks of the fissure swarm has been measured as 1 m on 20 km line or 5×10^{-5} between 1975 and 1977 (Gerke et al., 1978), 1.25 m on 7.2 km line or 1.7×10^{-4} in April and September, 1977 (Björnsson et al., 1979; this paper) and 0.49 m on 2.7 km line or 1.8×10^{-4} in July, 1978 (this paper). Thus the maximum relative east-west shortening of the flanks of the fissure zone is about 2×10^{-4}

The average cross-sectional area of the new dike is found to be about 6,000 m^2 by dividing the dike volume of 4.8×10^8 m^3 by the total length of the active fissure swarm of about 80 km. An average width of 3 m gives 2 km average height of the dike. With 1 km depth to the top of the dike, its bottom is apparently at only 3 km depth. If the dike narrows downwards, it extends deeper.

Acknowledgements. The observations of the water tube tiltmeter in the Krafla power house have been made by the staff of the National Energy Authority and the tilt observations of the spirit level stations were funded by the Science Institute of the University of Iceland until August 1977. The accomodation for tiltmeters in the Krafla power house is greatly appreciated, and also the assistance and goodwill of Jón Ármann Pétursson, who made it possible to operate a recording tiltmeter in Reynihlíd.

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