NORDIC VOLCANOLOGICAL INSTITUTE 78 14
UNIVERSITY OF ICELAND

# SUBSIDENCE EVENTS IN THE KRAFLA AREA

## PRELIMINARY REPORT BASED ON TILT AND DISTANCE MEASUREMENTS

by

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ABSTRACT

In the inflation-deflation sequence of the Krafla magma chamber since its beginning in 1975, 10 deflation or subsidence events have been identified until July 1978. 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 suggested Krafla caldera to form a dike 3 to 5 meter 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 10 events, is estimated as $392 \times 10^6$ $m^3$, whereof $318 \times 10^6$ $m^3$ are estimated to have flowed northwards, $72 \times 10^6$ $m^3$ southwards and about $2 \times 10^6$ $m^3$ came to the surface as basaltic lava.

## INTRODUCTION

The volcano-tectonic sequence, which started in 1975 in the Krafla-Mývatn area, is characterized by repeated uplift and subsidence of an area centered near Leirhnjúkur in the central part of the suggested 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 event, which started on December 20, 1975 (Björnsson et al., 1977; Björnsson, 1977; Sigurdsson, 1976), when the ground in the Krafla region subsided more than two meter over a period of some two months. There are some indications that tectonic unrest had been increasing in the Krafla region for some years before 1975.

A slight earthquake was felt in the Mývatn area on September 16, 1953 (Tryggvason, 1954), which apparently originated in the Krafla area. Its magnitude was estimated 3.8. This is the first instrumentally recorded earthquake from this area and no information are on felt earthquakes, which may have originated in the Krafla area during the preceeding decades.

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 & Björnsson, 1971), indicating great fluctuations in the seismic activity in the Krafla region.

Repeated geodetic measurements of high precision show that slight horizontal contraction of the Krafla-Mývatn area probably took place between 1965 and 1971, but significant horizontal expansion occurred between 1971 and 1975 (Gerke, 1977; Gerke et al., 1978). This expansion may be viewed as a sign of inflation of the Krafla area prior to

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## OBSERVATIONS

This report is primarily based on tilt and distance observations, which have been conducted by the staff of the Nordic Volcanological Institute since the summer of 1977, and by the University Science Institute in 1976 and 1977.

The tilt measurements are of three types. A water tube tiltmeter of two components was installed in the Krafla power house on August 20, 1976, and has been observed daily since then with a few exceptions. During times of rapid subsidence of the Krafla area, additional readings are made. The length of the north-south arm of this tiltmeter is 68.95 meter and the east-west arm is 19.50 meter long (Björnsson et al., 1978).

Two electronic continuously recording tiltmeters (Sindrason & 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 one kilometer 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). Observation 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 25.0 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 bolt to the next around the circle. Under favourable conditions the leveling accuracy is approximately 0.1 mm. Minor movements of the bolts together with observational errors make the probable error of tilt roughly 5 microradians.

The Nordic Volcanological Institute initiated a program of repeated geodimeter measurement in the Krafla-Mývatn area in early 1977 (Tryggvason, 1978b). The present

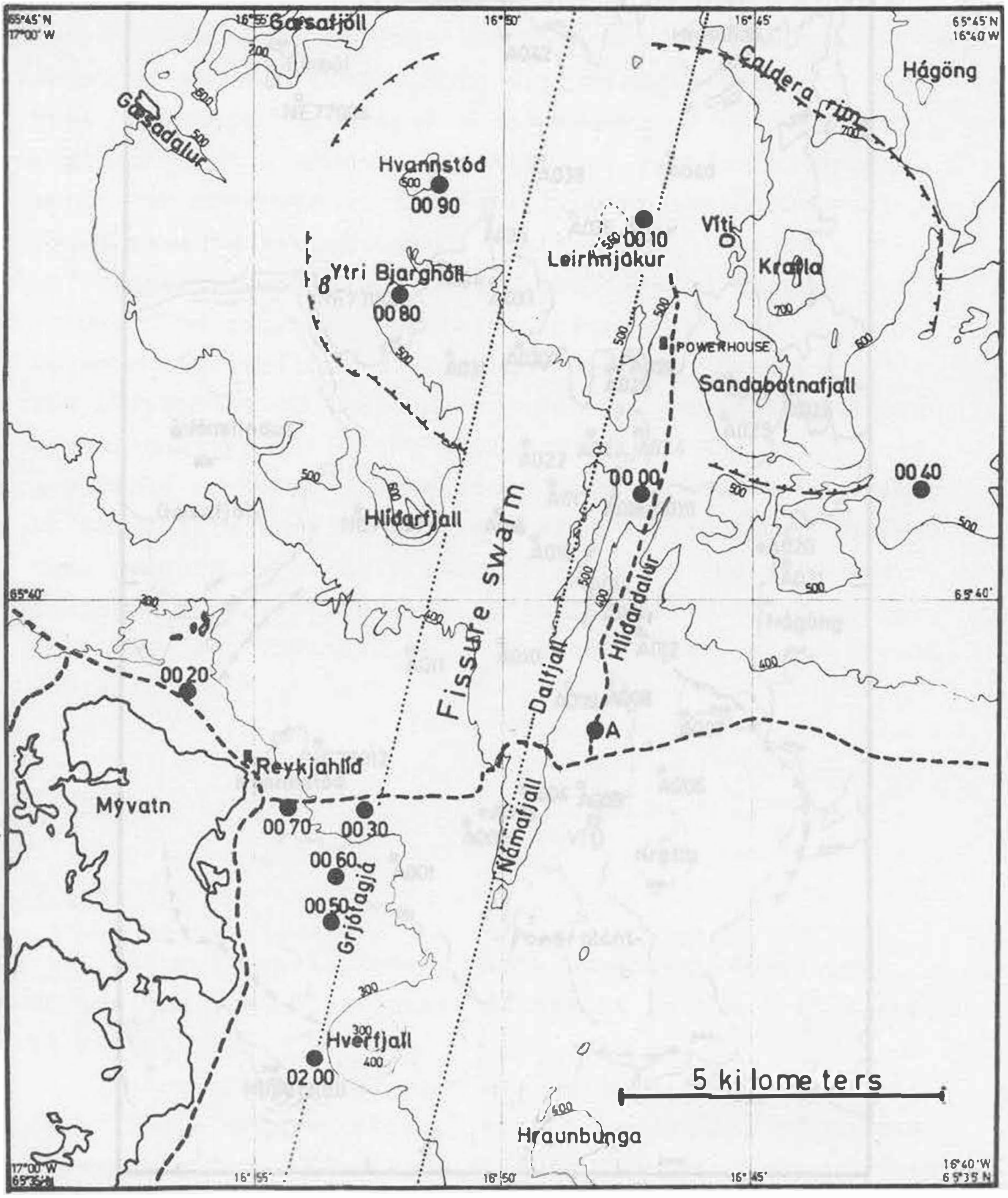


Fig. 1. Location of the spirit level tilt stations in the Krafla-Mývatn area (filled circles) and the electronic tiltmeters at the Krafla power house and Reynihlíd (near Reykjahlíd). The rim of the suggested Krafla caldera (Björnsson et al., 1977) is shown for reference on this and all subsequent maps.

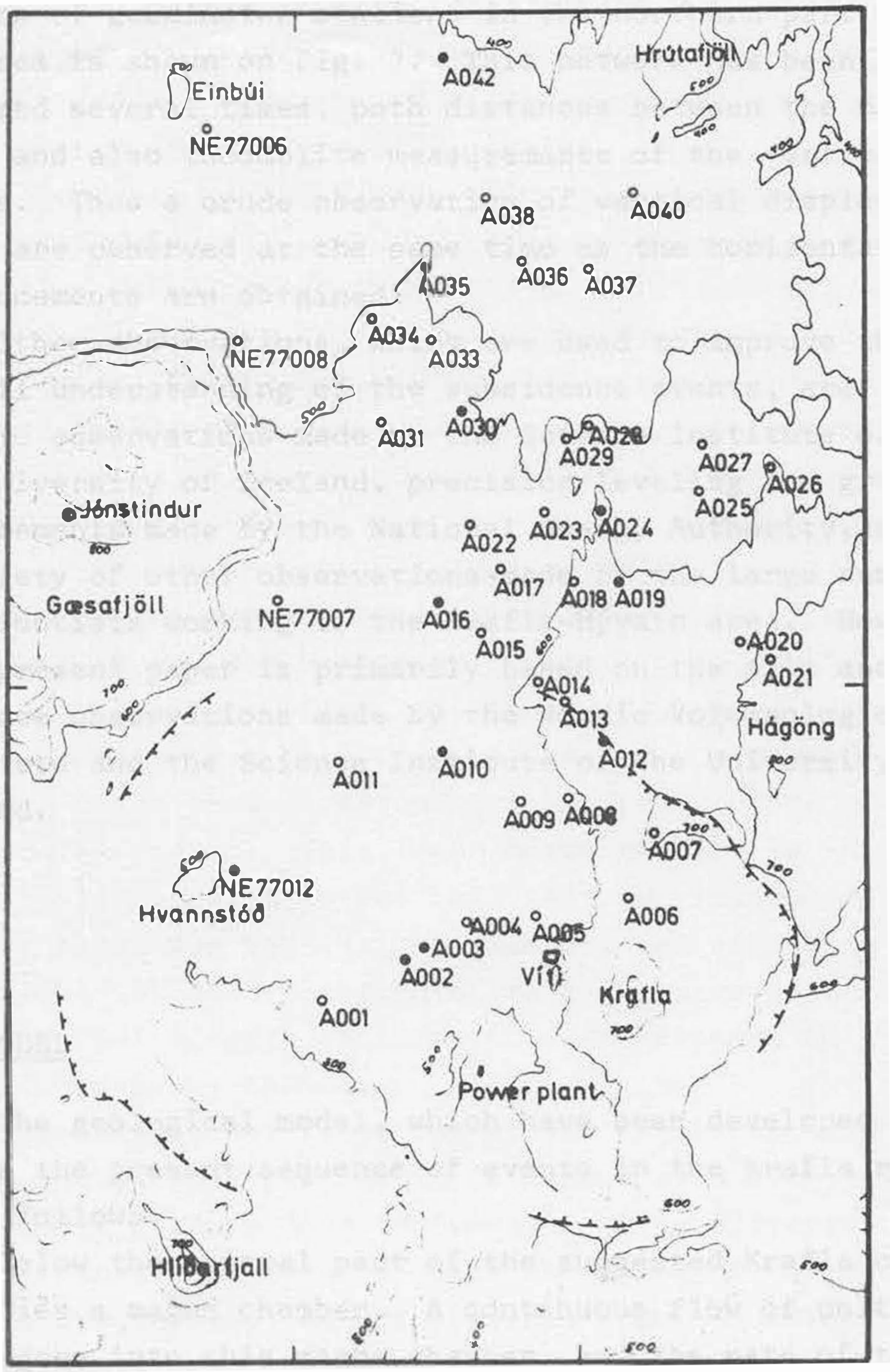


Fig. 2. Location of the stations used in distance measurements with geodimeter in the Krafla-Gjástykki area. Filled circles are stations occupied by geodimeter in 1978, and open circles are stations, which were only occupied by reflectors during the 1978 surveys.

network of geodimeter stations in the northern part of the area is shown on Fig. 2. This network has been measured several times, both distances between the markers, and also theodolite measurements of the vertical angles. Thus a crude observation of vertical displacements are observed at the same time as the horizontal displacements are obtained.

Other observations, which are used to improve the overall understanding of the subsidence events, are seismic observations made by the Science Institute of the University of Iceland, precision leveling and gravity measurements made by the National Energy Authority, and a variety of other observations made by the large number of scientists working in the Krafla-Mývatn area. However, this present paper is primarily based on the tilt and distance observations made by the Nordic Volcanological Institute and the Science Institute of the University of Iceland.

## THE MODEL

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

Below the central part of the suggested Krafla caldera lies a magma chamber. A continuous flow of molten magma goes into this magma chamber, 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, causing subsidence of the ground in the Krafla area. The rate of outflow can be estimated from observed rate of subsidence. The magma flow out of the magma chamber follows the fissure swarm, which goes through the central part of the suggested Krafla caldera in direction N10°E to N15°E. This flow is horizontal, either towards north or towards south, with occasional minor flows of lava to the surface (Björnsson et al., 1977; Björnsson, 1977; Björnsson et al., 1978; 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 best depth estimates are close to 3.0 km to the center of a spherical chamber (Tryggvason, 1978a; Björnsson et al., 1978). The assumption of a spherical magma chamber is certainly not correct, but observations of tilt and variations in ground elevation fit rather well such a model. 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 continuous flow into the Krafla magma chamber is supposedly from below. Thus the model accounts for another magma chamber of unknown but great depth below the Krafla region. This lower magma chamber is so large, that no limits have as yet been seen for its capacity to supply magma for the shallow chamber. An effort to use tilt observations to estimate its depth gave inconclusive results, but a depth of 10 km or somewhat more is indicated (Tryggvason, 1978a).

The magma that flows out of the Krafla magma chamber during subsidence periods is deposited as a dike below the Krafla fissure zone (Björnsson, 1977; Björnsson et al., 1978). The velocity with which the front of the forming dike moves forward, can be obtained from the movement of earthquake epicenters (Brandsdóttir & Einarsson, 1978) and from the time of formation of new fissures or opening of old ones (Björnsson et al., 1978). This velocity is approximately 0.5 m/sec in the cases studied.

The location of the portion of the dike that is formed during each subsidence event is seen from location of seismic epicenters (Brandsdóttir & Einarsson, 1978) and from location of new or reopened ground fissures and new or intensified steam vents (Björnsson et al., 1978). The depth to the dike can be estimated from the width of zone of new or reopened fissures, and the width from the widening of the fissure zone. However, the widening of the fissure zone as measured on the surface may be greater than the width 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 then assumed that the magma chamber does not change with time, neither its shape nor its location. 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 2.93 km.

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

c) The total uplift of the ground surface at the point of greatest uplift was calculated as 110 cm.

d) The total north component of tilt at the Krafla power house was 312 microradians during this inflation period.

Thus one microradian tilt at the Krafla power house corresponds to $0.19 \times 10^6$ $m^3$ of magma influx. In light of the inaccuracies in this determination, especially in the depth of the magma chamber, the rounded value of $0.2 \times 10^6 m^3$ 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 microradian per day during inflation periods, the average influx of magma into the Krafla magma chamber is about $0.4 \times 10^6$ $m^3$ per day or about 5 $m^3$/sec. It is assumed that the influx continues during subsidence periods, so the outflow is slightly greater than the comparisons of tilt before and after the subsidence periods give.

The rate of tilt at the Krafla power house can be converted into rate of magma flow. This is done for inflation periods in Fig. 3, where influx during subsidence periods is estimated. There seem to be considerable fluctuations in the inflow rate. It is very noticeable that the influx rate appears to be much higher first after a subsidence event, and low before such an event. There is no clear trend in the inflow rate during the 2 year period, although there is a slight indication of a decrease in this rate, but this decrease is less than 5 per cent in two years.

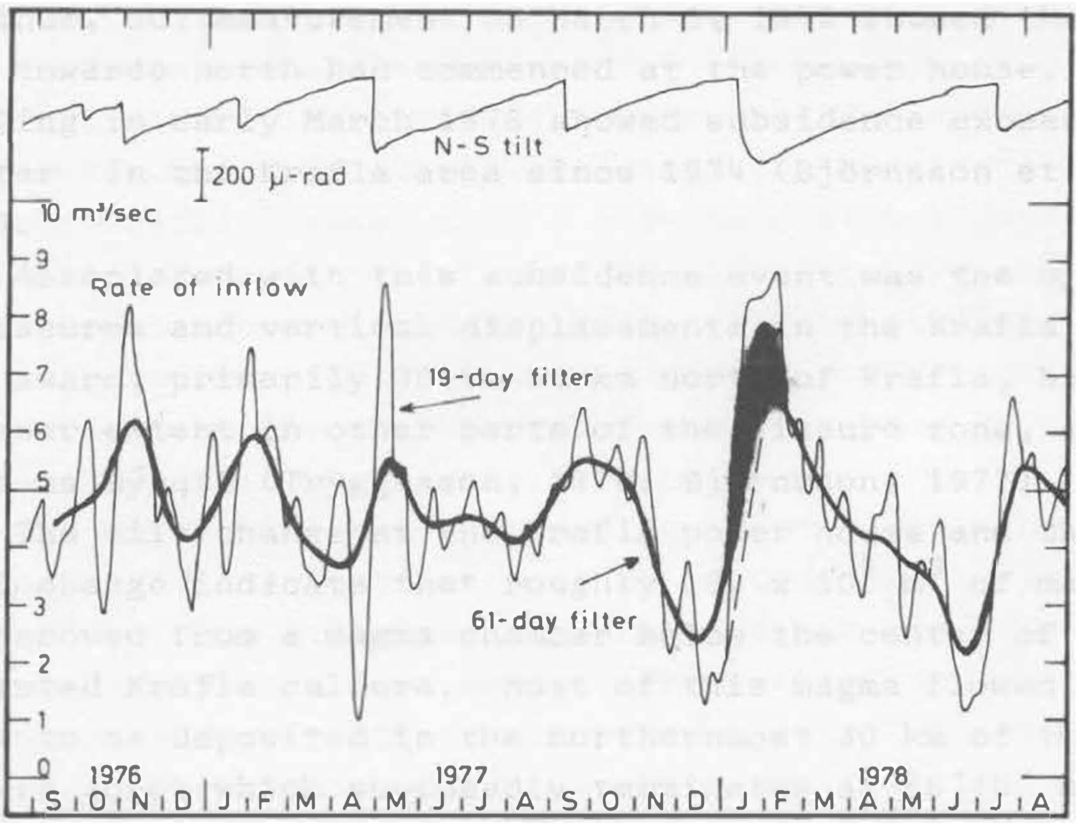


Fig. 3. The north component of tilt measured by the water tube tiltmeter in the Krafla power house (upper trace). Uplift to the north is up on the graph. The lower traces show the rate of tilt converted into rate of volume increase (inflow) of the Krafla magma chamber. This rate is filtered with a low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

## THE SUBSIDENCE EVENT OF DECEMBER 1975 TO JANUARY 1976

The first subsidence event of the present volcano-tectonic sequence in the Krafla area is believed to have started on December 20, 1975 simultaneously with observed volcanic tremor. There were no recording equipment in the area which showed the event, except seismometers, but leveling of the area had been carried out in 1974 and the base of the Krafla power house had been leveled. Repeated leveling of the base of the power house in January and February 1976 showed tilt of approximately 750 micro-radians 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 up-lift towards north had commenced at the power house. Leveling in early March 1976 showed subsidence exceeding 2 meter in the Krafla area since 1974 (Björnsson et al., 1977).

Associated with this subsidence event was the opening of fissures and vertical displacements in the Krafla fis-sure swarm, primarily 30 to 60 km north of Krafla, but to a lesser extent in other parts of the fissure zone, as far south as Mývatn (Tryggvason, 1976; Björnsson, 1977).

The tilt change at the Krafla power house and the level change indicate that roughly 150 x $10^6$ $m^3$ of magma was removed from a magma chamber below the center of the suggested Krafla caldera. Most of this magma flowed north-wards 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

Observations of the water tube tiltmeter in the Krafla power house (Fig. 4) show that this event has two phases or rather that two subsidence events occurred, one lasting from September 29 to the afternoon of September 30, the second lasting from early October 1 to the afternoon of October 4, 1976. The beginning of the first event is poorely recorded as no readings were taken on the tiltmeter between September 25, $10^h$ and September 29, $10^h$ and during these four days tilt rate was very slow, indicating that the subsidence may have started before September 29, $10^h$. The present treatment assumes that the tiltmeter reading on September 29, $10^h$ represents the maximum inflation of the Krafla magma chamber prior to the deflation (subsidence) event.

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 position of the tilt vector before and after the subsidence events.

In estimating the tilt during short lived subsidence events, tilt observations must be reduced to the time of the event. Spirit level tilt observations are made approximately once each month. These observations are normally made soon after a subsidence event, but the time from last observation before such an event to the time of the event varies. The observations of the water tube tiltmeter in the Krafla power house are normally made once a day so extrapolation of these values to the time of subsidence represents only small changes of observed values. Regarding the subsidence events of September 29 to October 4, 1976, power house tilt values are reduced to October 1 using the normal tilt variation during inflation periods

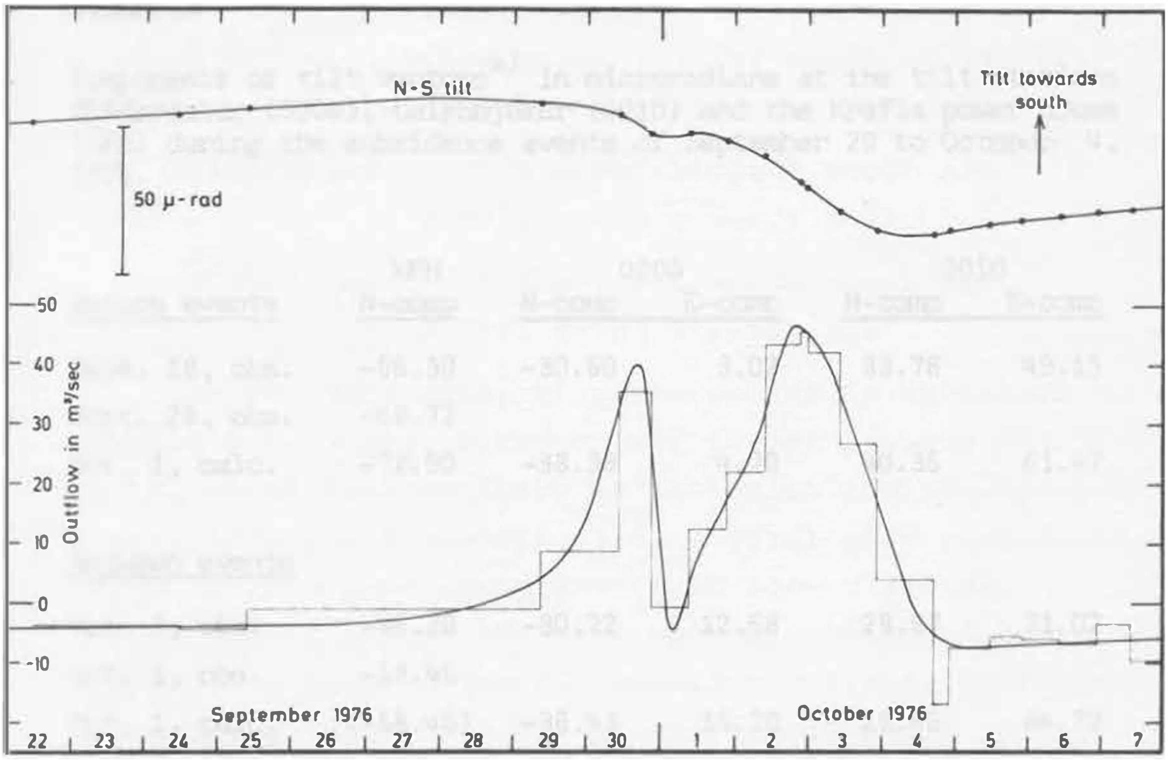


Fig. 4. North-south component of tilt at the Krafla power house and rate of magma outflow from the Krafla magma chamber during the subsidence events of September 29 to October 4, 1976. Filled circles show the actual water tube tiltmeter observations, up is rising to the north. The average rate of outflow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

of 2.09 microradians per day in N-S component of tilt. Thus tilt observation of September 29 of -68.72 μ-rad is reduced to October 1 by subtracting two days normal inflation of 4.18 microradian to become -72.90. Similarily the observation of October 4, immediately after the subsidence event of -24.57 μ-rad, is reduced to October 1 by adding 6.27 microradians to become -18.30 microradians.

Reduction of tilt components at the spirit level tilt stations to the time of the subsidence event is based on the ratio between tilt components at these stations and the north component of tilt at the Krafla power house. The

TABLE I

Components of tilt vectors[x)] in microradians at the tilt stations Hlídardalur (0000), Leirhnjúkur (0010) and the Krafla power house (KPH) during the subsidence events of September 29 to October 4, 1976.

| | KPH | 0000 | | 0010 | |
|---|---|---|---|---|---|
| Before events | N-comp | N-comp | E-comp | N-comp | E-comp |
| Sept. 18, obs. | -56.30 | -30.60 | 3.02 | 33.76 | 49.15 |
| Sept. 29, obs. | -68.72 | | | | |
| Oct. 1, calc. | -72.90 | -38.38 | 4.20 | 40.35 | 61.47 |
| Between events | | | | | |
| Oct. 2, obs. | -46.20 | -30.22 | 12.68 | 28.97 | 71.02 |
| Oct. 1, obs. | -58.45 | | | | |
| Oct. 1, calc. | (-58.45) | -36.43 | 15.20 | 28.69 | 84.73 |
| After events | | | | | |
| Oct. 23, obs. | -61.67 | -37.19 | 10.15 | 47.51 | 73.25 |
| Oct. 4, obs. | -24.57 | | | | |
| Oct. 1, calc. | -18.30 | -16.07 | 6.95 | 29.60 | 39.79 |
| Calculated tilt during events | | | | | |
| First event | 14.45 | 1.95 | 11.00 | -11.66 | 23.26 |
| Second event | 40.15 | 20.36 | -8.25 | 0.91 | -44.94 |

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[x)] The zero point for the tilt components represents the condition during first observation at each station, on July 27, 1976 at Hlídardalur (0000) and Leirhnjúkur (0010), and on August 20, 1976 at the Krafla power house (KPH).

average value of tilt components at Hlídardalur and Leirhnjúkur for each microradian towards south at the Krafla power house during inflation periods is found to be

Hlídardalur: 0.4975 μ-rad towards south and
0.0575 μ-rad towards east

Leirhnjúkur: 0.3974 μ-rad towards north and
0.7422 μ-rad towards east.

The standard error of these values is estimated as roughly 0.05 μ-rad, based on all period between measurements, which fall entirely in inflation periods between August 1976 and September 1978, a total of 8 periods between spirit level measurements at both stations.

The position of the tilt vector at Hlídardalur and Leirhnjúkur between the two subsidence event, is found by assuming that about 69% of the second phase of the subsidence occurred after the tilt measurement of October 2 as indicated by the power house tiltmeter, and that the direction of tilt during this second phase was constant throughout that phase. Thus the observed tilt on October 2 falls on the straight line connecting calculated tilt vector position at the end of the subsidence (1-10-76-III on Fig. 5 and 6) and the calculated tilt vector between subsidence phases (1-10-76-II).

Interpretation of the subsidence event of September 29 to 30, 1976 can be made under the assumption, that observed tilt changes are due to two factors, subsidence of the area, which is uplifted during the inflation periods, and uplift of the same volume of the area where magma was injected. These two factors cannot easily be separated, but it is obvious that tilt measurements at Hlídardalur require uplift of an area west or northwest of that station. Tilt observations at Leirhnjúkur are more difficult to evaluate, but indications are that the uplifted area is approximately towards west of that station. Tilt measurements at the power house give no information of the uplifted area, as no measurements were made of the

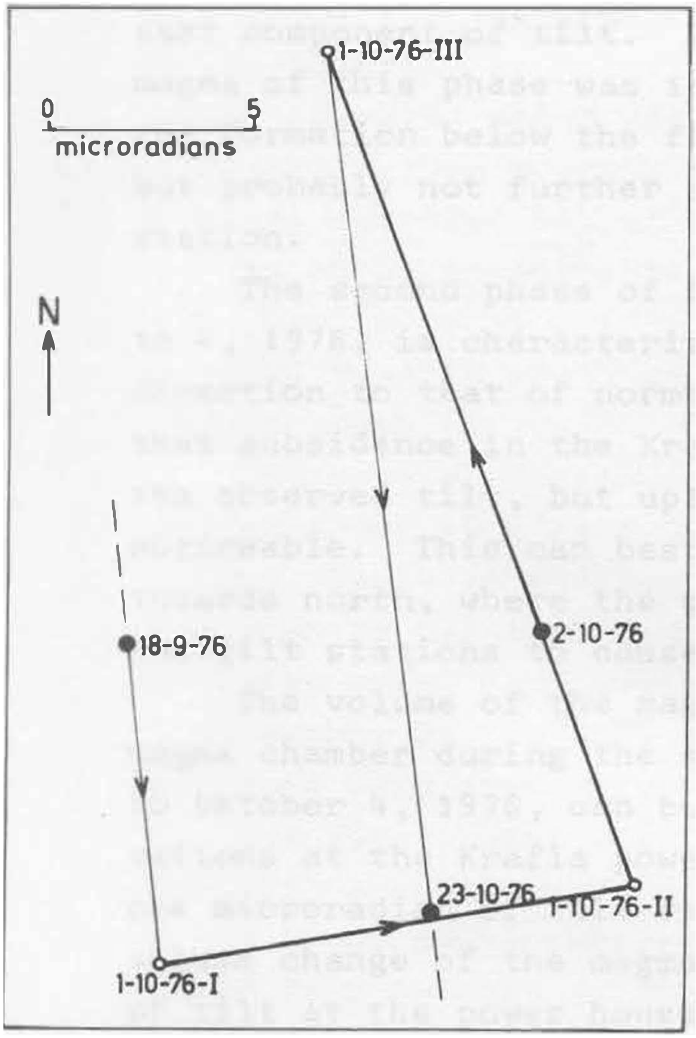


Fig. 5. Observed tilt at the Hlídardalur (0000) tilt station (filled circles) and calculated tilt (open circles) related to the subsidence events of September 20 to October 4, 1976. The tilt is calculated for the beginning of the first event (1-10-76-I), between events (1-10-76-II) and the end of the second event (1-10-76-III), all reduced to a common time on October 1, 1976.

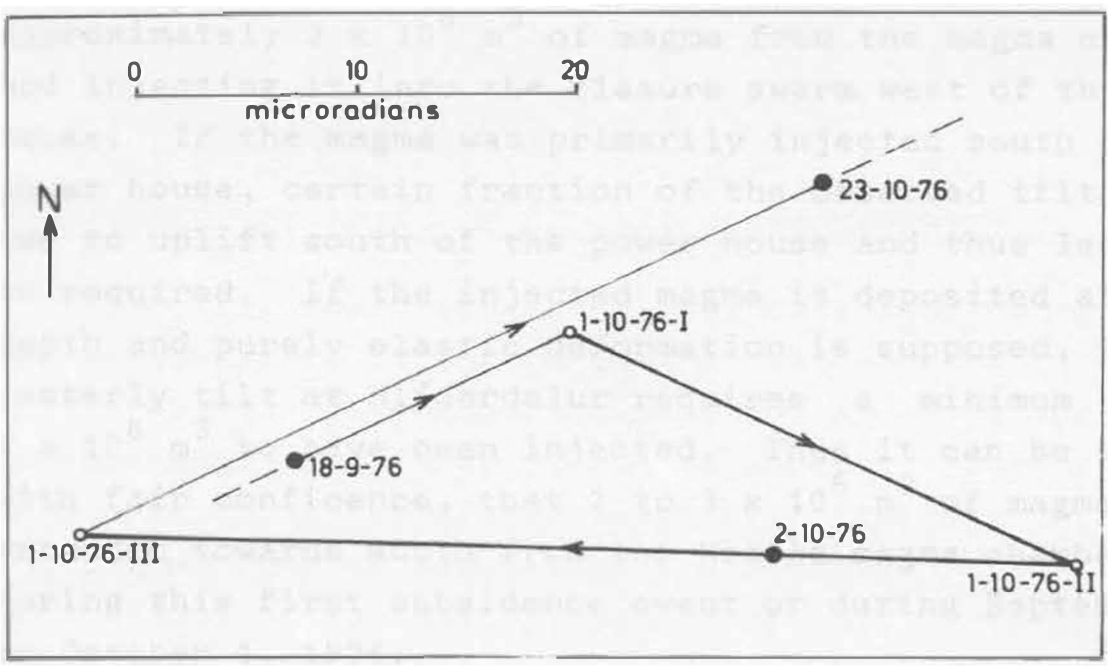


Fig. 6. Observed and calculated tilt at Leirhnjúkur related to the subsidence events of September 29 to October 4, 1976. Notation as on Fig. 5.

east component of tilt. Thus indications are, that the magma of this phase was injected, at least partly, into the formation below the fissure zone south of Leirhnjúkur, but probably not further south than Hlídardalur tilt station.

The second phase of the subsidence event, October 1 to 4, 1976, is characterized by tilt in roughly 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 outflow towards north, where the uplifted area is far enough from the tilt stations to cause only a minor tilt effect.

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. During inflation periods, one microradian of tilt represents roughly $0.2 \times 10^6$ $m^3$ volume change of the magma chamber. 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 subsidence event (September 29 to 30, 1976) is due to removal of approximately $3 \times 10^6$ $m^3$ of magma from the magma chamber and injecting it into the fissure swarm west of the power house. If the magma was primarily injected south of the power house, certain fraction of the observed tilt was due to uplift south of the power house and thus less magma is required. If the injected magma is deposited at 3 km depth and purely elastic deformation is supposed, the easterly tilt at Hlídardalur requires a minimum of $2 \times 10^6$ $m^3$ to have been injected. Thus it can be stated with fair conficence, that 2 to $3 \times 10^6$ $m^3$ of magma was extruded towards south from the Krafla magma chamber during this first subsidence event or during September 29 to October 1, 1976.

The second subsidence event was caused by magma flow towards north and tilt changes are primarily due to subsidence of the caldera. If this subsidence was distributed in the same way as uplift during inflation periods, the volume of magma which was extruded from October 1 to October 4, 1976, was roughly $8 \times 10^6$ $m^3$. Thus the total amount of magma extruded out of the Krafla magma chamber during the two subsidence events of September 29 to October 4, 1976, was 10 to $11 \times 10^6$ $m^3$, whereof 2 to $3 \times 10^6$ $m^3$ was extruded towards south and about $8 \times 10^6$ $m^3$ was extruded towards north.

The rate of outflow of magma, as estimated on Fig. 4, reached about 40 $m^3$/sec during the first event, on October 30, and nearly 50 $m^3$/sec during the second event in the afternoon or night of October 2, 1976. The beginning of the first event may have been before the tilt observation on September 29, $09^h50^m$, possibly 24 hours earlier if it commenced very gradually.

The first event apparently ended on September 30 at about $21^h$ and between that time and October 1, $9^h$ the tilt at the power house changed very little. The second event lasted from October 1, $9^h$ to October 4, $17^h$ approximately, and thereafter the Krafla area started to rise and a new inflation period had begun.

## THE SUBSIDENCE EVENT OF OCTOBER 30 TO NOVEMBER 1, 1976

The tilt measurements showing this subsidence event are measurements of the north and east components of tilt at the Krafla power house twice a day and five additional measurements 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. The reliability of the east component of tilt at the power house is questionable.

If last measurement before the subsidence event is calculated forewards to the estimated value on November 1,

TABLE II

Components of tilt vectors in microradians at the tilt stations Hlídardalur (0000), Leirhnjúkur (0010) and the Krafla power house (KPH) during the subsidence event of October 30 to November 1, 1976.

| | KPH | | 0000 | | 0010 | |
|---|---|---|---|---|---|---|
| Before event | N-comp | E-comp | N-comp | E-comp | N-comp | E-comp |
| Oct. 23, obs. | -61.67 | | -37.19 | 10.15 | 47.51 | 73.21 |
| Oct. 30, obs. | -80.26 | 1.5 | | | | |
| Nov. 1, calc. | -84.44 | (1.5) | -48.52 | 11.46 | 56.56 | 90.41 |
| After event | | | | | | |
| Nov. 1, obs. | 77.01 | 10.0 | 21.82 | 2.72 | -74.49 | -0.97 |
| Tilt during event | 161.45 | 8.5 | 70.34 | -8.74 | -131.05 | -91.38 |

we get the position of the tilt vector as shown in Table II.

The direction of tilt during this subsidence event is roughly -7.09° at Hlídardalur and 214.98° at Leirhnjúkur, while the average direction of tilt during inflation periods is 173.41° at Hlídardalur and 61.83° at Leirhnjúkur. Thus the tilt during this subsidence event is almost exactly opposite to normal inflation tilt at Hlídardalur, but at Leirhnjúkur the angle between the tilt during this event and the opposite of the tilt during normal inflation periods (241.83°) is about 26.85°. As the Leirhnjúkur tilt station lies very close to the most active fissures in the central part of the Krafla caldera, this discrepancy in angles is considered as insignificant, and observed tilt may be regarded as solely due to subsidence of the same region, as is inflated during the inflation periods. This is interpreted as meaning that the subsidence is entirely due to northward flow of magma, as southward flow would have caused directional effect on the Hlídardalur tilt.

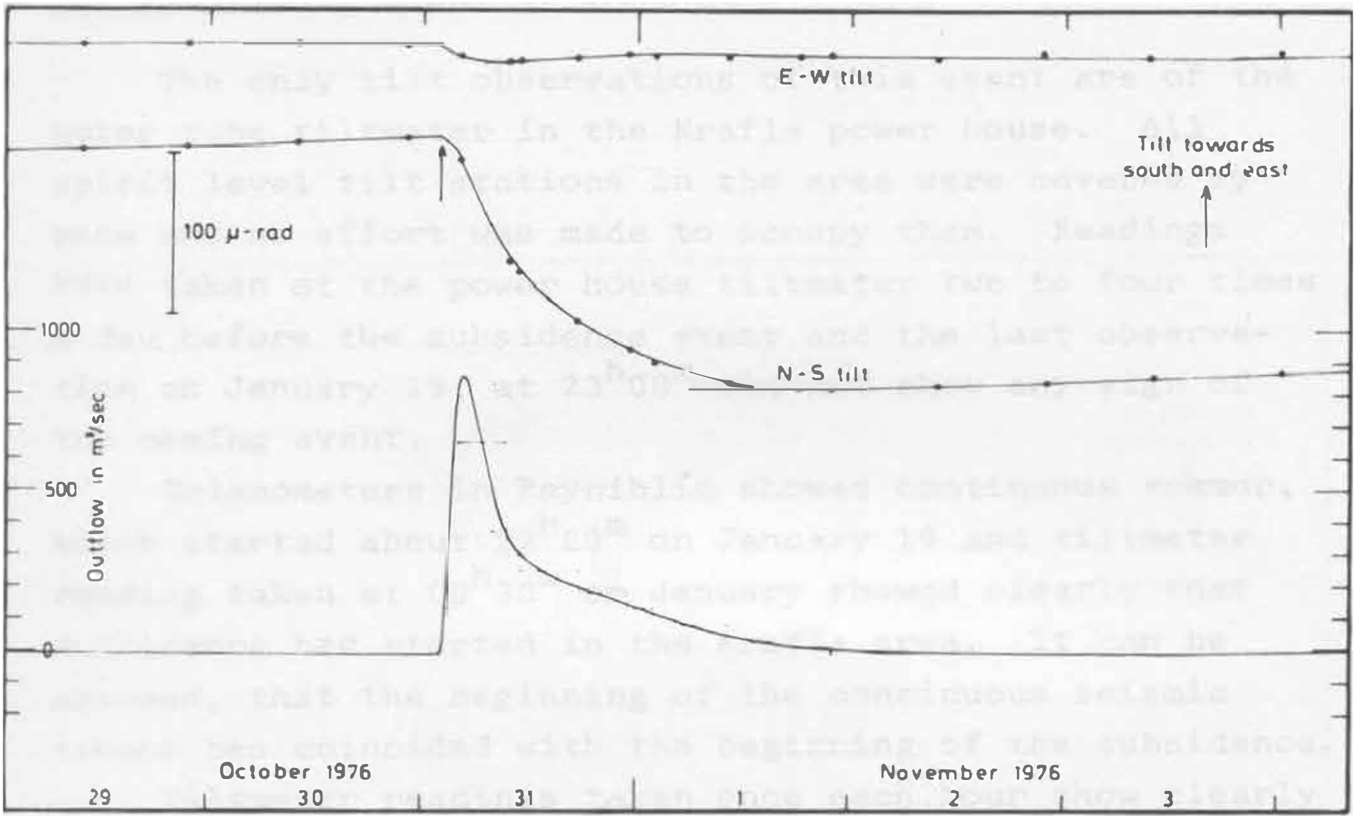


Fig. 7. Tilt in the Krafla power house as observed by the water tube tiltmeter, and the rate of magma flow out of the Krafla magma chamber during the subsidence event of October 31 to November 1, 1976. Notation as in Fig. 4.

Opening of fissures and earthquake swarm north of the Krafla caldera support this view (Björnsson et al., 1977).

The total volume of outflow as calculated from tilt at the power house is 32 x $10^6$ $m^3$ and the rate of outflow probably exceeded 800 $m^3$/sec between $4^h$ and $6^h$ in the morning of October 31 (Fig. 7).

The beginning of the subsidence event is clearly after the tilt observation on October 30, $22^h22^m$ and before October 31, $2^h15^m$. Seismic tremor was observed on seismometers at Húsavík and Reynihlíd on October 31, $2^h0^m$ or a few minutes later. This represents the first sign of the coming subsidence.

The subsidence seem to have ended before the tilt observation on November 1, $21^h45^m$, but after the observation on November 1, $18^h10^m$. Thus the subsidence lasted roughly 42 hours, from October 31, $02^h$ to November 1, $20^h$.

## THE SUBSIDENCE EVENT OF JANUARY 20, 1977

The only tilt observations of this event are of the water tube tiltmeter in the Krafla power house. All spirit level tilt stations in the area were covered by snow and no effort was made to occupy them. 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 $23^h00^m$ did not show any sign of the coming event.

Seismometers in Reynihlíd showed continuous tremor, which started about $23^h50^m$ on January 19 and tiltmeter reading taken at $00^h30^m$ on January showed clearly that subsidence had started in the Krafla area. It can be assumed, that the beginning of the continuous seismic tremor has coincided with the beginning of the subsidence.

Tiltmeter readings taken once each hour show clearly the progress of the subsidence until it almost ceased at $22^h$ on January 20, but minor additional subsidence was observed between $8^h$ and $16^h$ on January 21 (Fig. 8).

The frequent tiltmeter observations during this subsidence events show that the rate of subsidence fluctuated considerably. The maximum rate of subsidence was reached roughly one hour after the subsidence started. This rate corresponds to a rate of magma outflow of approximately 700 $m^3$/sec. The east component of tilt was very small compared to the north component, indicating that the center of subsidence was nearly due north of the power house.

The total tilt at the power house from the beginning of the subsidence event on January 9 at $23^h50^m$ to its end on January 21 at $16^h$ was about 105 microradians corresponding to $21.0 \times 10^6$ $m^3$ of magma flowing out of the magma chamber, provided the tilt was only due to removal of magma from the same region as is inflated during a normal inflation period. 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, as indicated by opening of fissures and earthquake swarm in that area (Björnsson et al., 1977; Sigurdsson, 1977).

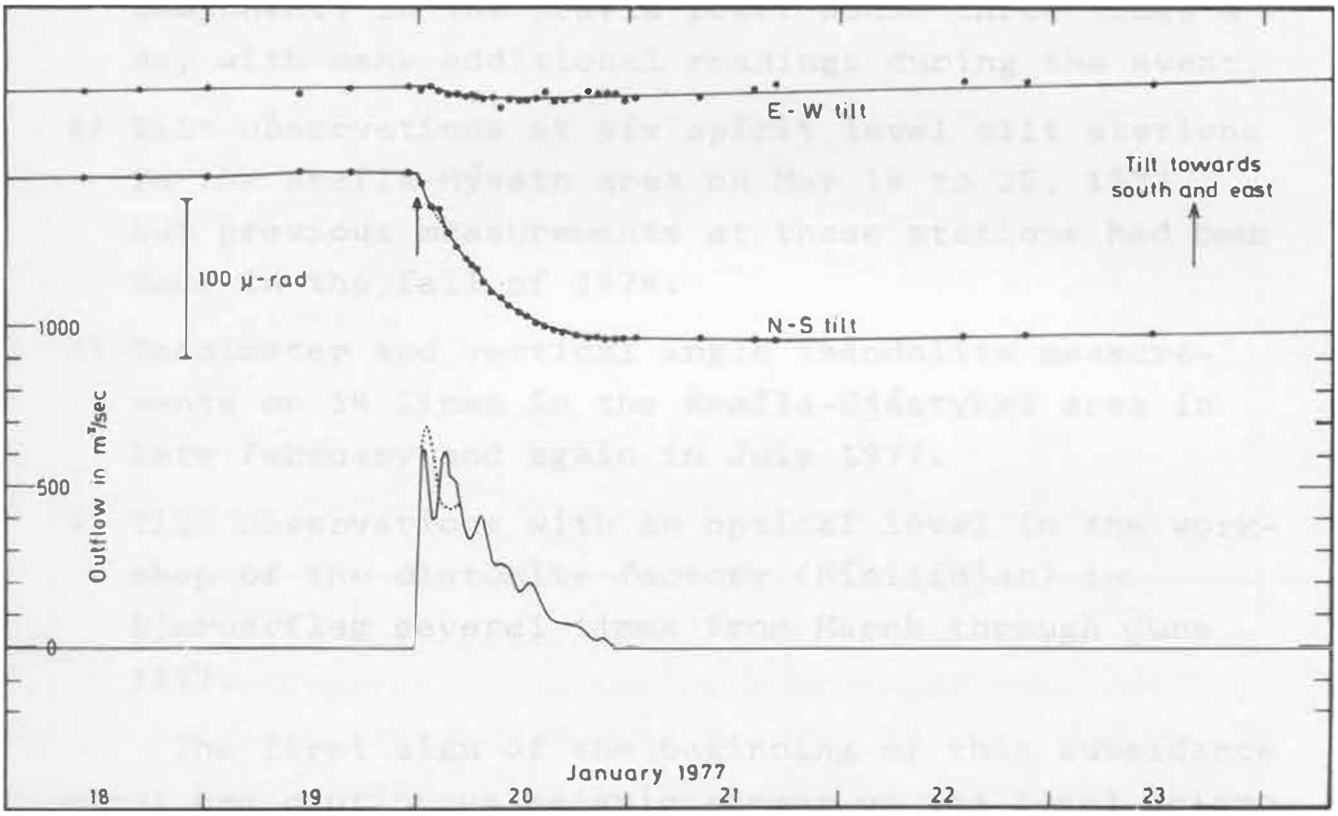


Fig. 8. Tilt in the Krafla power house as observed by the water tube tiltmeter, and the rate of magma flow out of the Krafla magma chamber during the subsidence event of January 20, 1977.

## THE SUBSIDENCE EVENT OF APRIL 27 TO 28, 1977

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

1) Observations of the water tube tiltmeter, N and E component, in the Krafla power house three times a day with many additional readings during the event.
2) Tilt observations at six spirit level tilt stations in the Krafla-Mývatn area on May 16 to 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.
4) Tilt observations with an optical level in the workshop of the diatomite factory (Kísilidjan) in Bjarnarflag several times from March through June 1977.

The first sign of the beginning of this subsidence event was continuous seismic tremor on the local seismometer, which commenced at $13^h17^m$ on April 27 (Sigurdsson, 1977). Tiltmeter reading in the Krafla power house at $8^h30^m$ the same morning did not show any sign of the subsidence, but at $14^h10^m$ the subsidence had started and it continued at rapid rate during the following hours (Fig. 9). The rate of tilt (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 hours after the subsidence started. The total tilt during these 31 hours was some 290 microradians down towards north and some 75 microradians down towards west.

Observations at the spirit level tilt stations at Hlídardalur and Leirhnjúkur were made on November 1, 1976, immediately after the subsidence event, which started October 31, 1976, and again on May 18, 1977. The tilt at

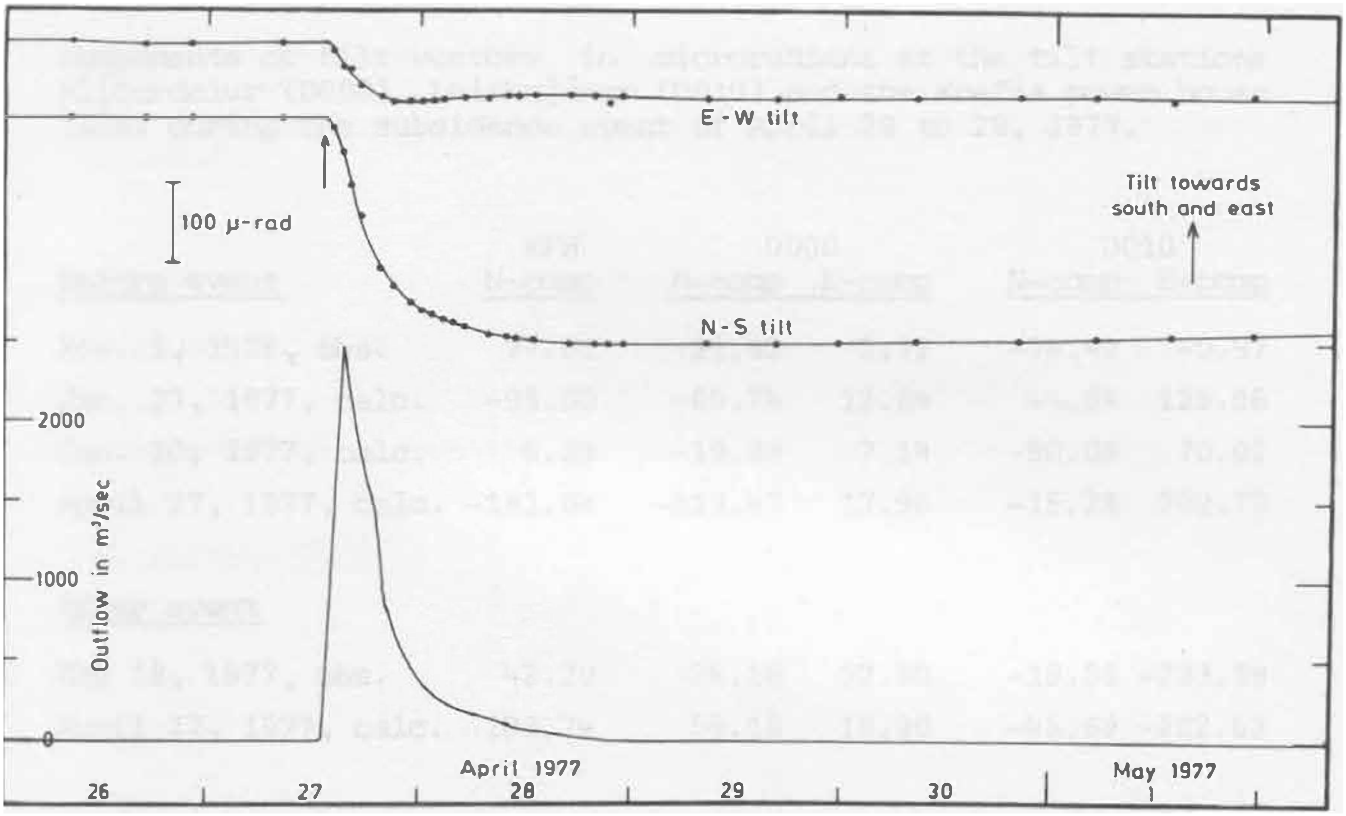


Fig. 9. Tilt in the Krafla power house as observed by the water tube tiltmeter, and the rate of magma flow out of the Krafla magma chamber during the subsidence event of April 27 to 28, 1977. The outflow rate as shown is probably some 10 to 20 per cent too high (see text).

these stations can be reduced to the beginning and end of the subsidence event on January 20, 1977 and to the beginning of the subsidence event on April 27 to 28, 1977, by assuming that normal ratio between tilt components at these stations, and observed north component of tilt at the power house, did prevail during inflation periods and assuming further that the subsidence event of January 20, 1977 behaved as that of October 31 to November 1, 1976, with respect to tilt ratio at these stations and the power house. Furthermore, the position of the tilt vector at the end of the April 27 to 28, 1977 subsidence event can be obtained from the observation of May 18, 1977, and the normal tilt ratios for inflation periods (Table III, Fig. 10).

TABLE III

Components of tilt vectors in microradians at the tilt stations Hlídardalur (0000), Leirhnjúkur (0010) and the Krafla power house (KPH) during the subsidence event of April 28 to 29, 1977.

| | KPH | 0000 | | 0010 | |
|---|---|---|---|---|---|
| Before event | N-comp | N-comp | E-comp | N-comp | E-comp |
| Nov. 1, 1976, obs. | 77.01 | 21.82 | 2.72 | -74.49 | -0.97 |
| Jan. 20, 1977, calc. | -99.00 | -65.74 | 12.84 | -4.54 | 129.66 |
| Jan. 20, 1977, calc. | 6.38 | -19.83 | 7.14 | -90.08 | 70.02 |
| April 27, 1977, calc. | -181.84 | -113.47 | 17.96 | -15.28 | 209.72 |
| After event | | | | | |
| May 18, 1977, obs. | 42.20 | 26.18 | 22.30 | -19.53 | -233.39 |
| April 27, 1977, calc. | 108.74 | 59.18 | 18.90 | -45.89 | -282.63 |
| Tilt during event | 290.58 | 172.65 | 0.94 | -30.61 | -492.35 |

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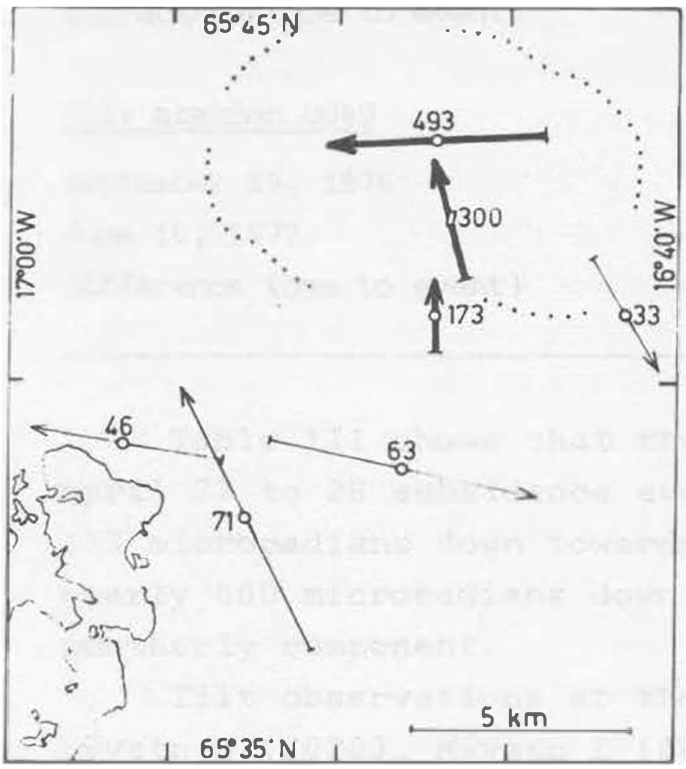



Fig. 10. Tilt vectors related to the subsidence event of April 27 to 28, 1977. Numbers give the amount of tilt in microradians. The last spirit level tilt observation before the event was made in the fall of 1976, causing considerable doubt in the tilt immediately before the event.

TABLE IV

Observed components of tilt in microradians before and after the subsidence event of April 27 to 28, 1977 at the tilt stations A (east of Námaskard), 0020 (Mývatn N), 0030 (Mývatn E) and 0040 (Jörundur).

| Tilt station A | N-component | E-component |
|---|---|---|
| September 19, 1976 | -23.87 | -3.39 |
| May 16, 1977 | -38.13 | 58.34 |
| Difference (due to event) | -14.26 | 61.73 |
| **Tilt station 0020** | | |
| October 23, 1976 | -4.52 | 0.05 |
| May 16, 1977 | 2.79 | -44.94 |
| Difference (due to event) | 7.31 | -44.99 |
| **Tilt station 0030** | | |
| September 19, 1976 | -7.51 | -1.70 |
| May 20, 1977 | 57.40 | -30.73 |
| Difference (due to event) | 64.91 | -29.03 |
| **Tilt station 0040** | | |
| September 19, 1976 | 4.86 | 13.88 |
| June 16, 1977 | -23.54 | 30.40 |
| Difference (due to event) | -28.40 | 16.52 |

Table III shows that the estimated tilt during the April 27 to 28 subsidence event at Hlídardalur is about 173 microradians down towards north, and at Leirhnjúkur nearly 500 microradians down towards west with a slight southerly component.

Tilt observations at the stations Námaskard (A), Mývatn N (0020), Mývatn E (0030) and Jörundur (0040), where tilt observations were made during the summer of 1976 and again in May 1977, show hardly any significant tilt during inflation periods nor during subsidence events with magma flow towards north, as the events of October 31 to November 1, 1976 and January 20, 1977 are believed to have been. Therefore the observed tilt from the last observation in 1976 to the first observation in 1977 at these stations, is assumed to be largely associated with the subsidence event of April 27 to 28, 1977 (Table IV, Fig. 10).

Distance measurements with a geodimeter in the Krafla-Gjástykki area on February 26 to March 3, 1977 and again on July 19 to 21, 1977 in the southern part of the network (Tryggvason, 1978b), show distance changes on 14 lines, which are believed to be primarily associated with the subsidence event of April 27 to 28, 1977. East-west widening of the fissure zone amounting to 63 to 93 cm was observed on three lines crossing the fissure zone in the northern part of the Krafla caldera (Fig. 11). The zone that has widened is probably only about one kilometer wide. Outside the zone of east-west extension, contraction of some 2 to 10 centimeter per kilometer was observed. In the Mývatn area near Reykjahlíd other measurements showed about 2.0 meter widening of the fissure zone and 1.0 m shortening of a 7.2 km line outside the active fissure zone (Björnsson et al., 1978).

Vertical displacements of the geodimeter points in the Gjástykki network were observed with a theodolite at the same time as the geodimeter measurements. These show subsidence of some 60 cm of a narrow strip, coinciding with the most active part of the fissure zone, relative to the surrounding area (Fig. 11).

Similar but somewhat larger vertical movements were observed on a leveling line from Reykjahlíd towards east across Námaskard. The flanks of the active fissure zone in Bjarnarflag were uplifted about 40 cm, while the fissure zone subsided some 80 cm (Björnsson et al., 1978).

Leveling of the foundation of the workshop of the diatomite factory in Bjarnarflag, within the active fissure

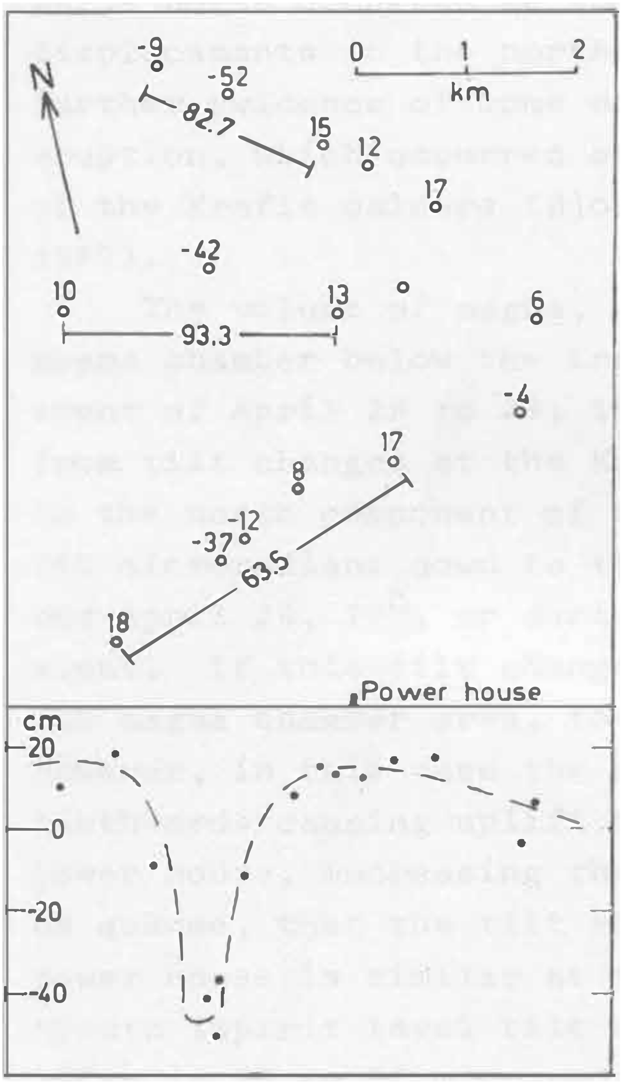



Fig. 11. Lengthening of three lines in the Krafla area and vertical displacements during the subsidence event of April 27 to 28, 1977. The upper part is a map (see Fig.12 for location) showing the three lines across the active fissure zone, giving the lengthening in centimeter, and the number by the markers give the vertical displacements in centimeter. On the lower part are the vertical displacements projected on a line parallel to the lower edge of the map.

zone, showed large and progressive tilting towards west. This had reached 2900 microradians at noon on April 29 and 3250 microradians that same evening. Repeated measurements on May 20 and June 16, 1977 showed increasing tilt towards west with a slight southerly component. On May 20 the tilt had reached 4040 microradians and 4300 microradians on June 16.

All these observations are interpreted as due to magma flow out of the magma chamber beneath the Krafla area into fissure or fissures below the most active part of the Krafla fissure swarm. The major part of this magma flowed southwards as evidenced by the large tilts and widening of the fissure zone in the Mývatn area, but a minor flow towards north occurred as shown by the widening and vertical displacements in the northern part of the Krafla area. A further evidence of some northward flows is the small lava eruption, which occurred on April 27, at the northern edge of the Krafla caldera (Björnsson et al., 1978; Sigurdsson, 1977).

The volume of magma, which was extruded out of the magma chamber below the Krafla area during the subsidence event of April 28 to 29, 1977, can be crudely estimated from tilt changes at the Krafla power house. The change in the north component of tilt at the power house was about 290 microradians down to the north between April 27 $13^h$ and April 28, $20^h$, or during the time of the subsidence event. If this tilt change is solely due to subsidence of the magma chamber area, the volume is about $58 \times 10^6$ $m^3$. However, in this case the majority of the magma moved southwards 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 south of the power house is similar at the power house as the tilt near Mývatn (spirit level tilt stations A, 0020 and 0030), which is 50 to 70 microradians, the tilt change at the power house because of subsidence to the north of the station may be estimated as 220 to 240 microradians, corresponding to total outflux of magma of 44 to $48 \times 10^6$ $m^3$

The rate of outflow of magma is shown on Fig. 9, based on the assumption that tilt changes at the Krafla power house are solely due to subsidence north of the power house. This shows a maximum rate of magma flow of some 2500 $m^3$/sec approximately two hours after the beginning of the subsidence event. As a fraction of the tilt change, possibly 20%, is due to land uplift to the south of the power house, this flow rate may be lower by this factor. Thus the maximum rate of outflow during this event was probably about 2000 $m^3$/sec of magma.

The total length of the area, which was widened during this event, was about 20 km. Its north end is roughly 2 km

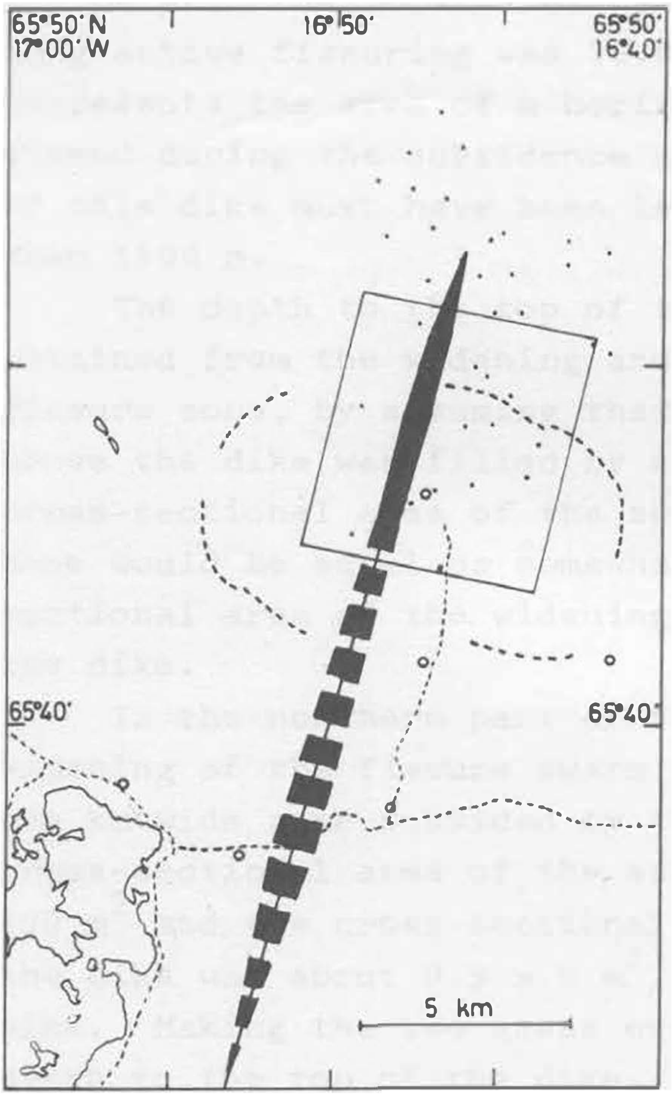



Fig. 12. Map of the Krafla-Mývatn area showing the zone of rifting during the April 27 to 28, 1977 subsidence event. A rectangle shows the area covered by the map in Fig. 11.

north of the northernmost geodimeter line (Fig. 11) measured in July, 1977. This was found in later geodimeter measurements, which showed only about 10 cm east-west extension of the fissure zone three km north of the northernmost line of July 1977 between February 1977 and March 1978, although additional subsidence events had occurred during that time. The south end of the widening is not well known, but open ground fissures formed as far south as the south edge of the map on Fig. 12.

The widening was measured as 70 to 90 cm in the northern part of the active zone and about 200 cm east of the north shore of Lake Mývatn. This indicates that the average widening was about or exceeded one meter. Assuming that the average widening of the fissure zone lay between 1.0 and

1.5 meter, the total area of the expansion of the 20 km long active fissuring was 20.000 to 30.000 $m^2$. If this represents the area of a horizontal cut through the dike formed during the subsidence event, the average height of this dike must have been less than 2500 m, but more than 1500 m.

The depth to the top of the new dike can be crudely obtained from the widening and the subsidence of the fissure zone, by assuming that the volume of the fissure above the dike was filled by slumpings of the walls. The cross-sectional area of the subsidence of the fissure zone would be equal or somewhat smaller than the cross-sectional area of the widening of the fissure swarm above the dike.

In the northern part of the Krafla caldera the widening of the fissure swarm was roughly 90 cm and about one km wide zone subsided on the average of 60 cm. The cross-sectional area of the subsidence was thus roughly 600 $m^2$ and the cross-sectional area of the fissure above the dike was about 0.9 x h $m^2$, where h is the depth to the dike. Making the two areas equal we get roughly 700 m depth to the top of the dike.

East of the north coast of Mývatn the subsided zone was about 2 km wide, and the average subsidence relative to the flanks was 100 to 120 cm, making the cross-sectional area of the subsidence exceeding 2000 $m^2$. The widening of the fissure zone was about 2.0 m, so the depth to the dike, calculated as above, slightly exceeded 1000 meter.

## THE SUBSIDENCE EVENT OF SEPTEMBER 8 TO 9, 1977

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

1. Readings of the water tube tiltmeter in the Krafla power house once a day, with eight additional readings on September 8 to 10. Only the north component was observed.
2. Continuous recording of an electronic tiltmeter north component at the Krafla power house. The east component of the same tiltmeter was manually switched on several times a day for short periods each time (Sindrason & Ólafsson, 1978).
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 also in the Mývatn area to the south of the caldera.
5. Tilt observations with optical level in the workshop of the diatomite factory in Bjarnarflag.

The water tube tiltmeter in the Krafla power house showed tilt down towards north of 190 microradians between reading of September 8, $08^h50^m$ and September 10, $16^h40^m$. The east component of this tiltmeter was not in operation.

The new electronic tiltmeter in the power house (the sensor is in a concrete cellar a few meter west of the power house), showed the beginning of the subsidence to be on September 8, $15^h40^m$ or possibly some five minutes earlier. The rate of subsidence increased rapidly until $17^h10^m$, when it reached about 35 μ-rad/hour, whereafter the subsidence rate decreased even more rapidly to become zero at $18^h00^m$. Then the tiltmeter indicated uplift to the north of the power house of some 20 minutes, whereafter the subsidence started again and increased rapidly

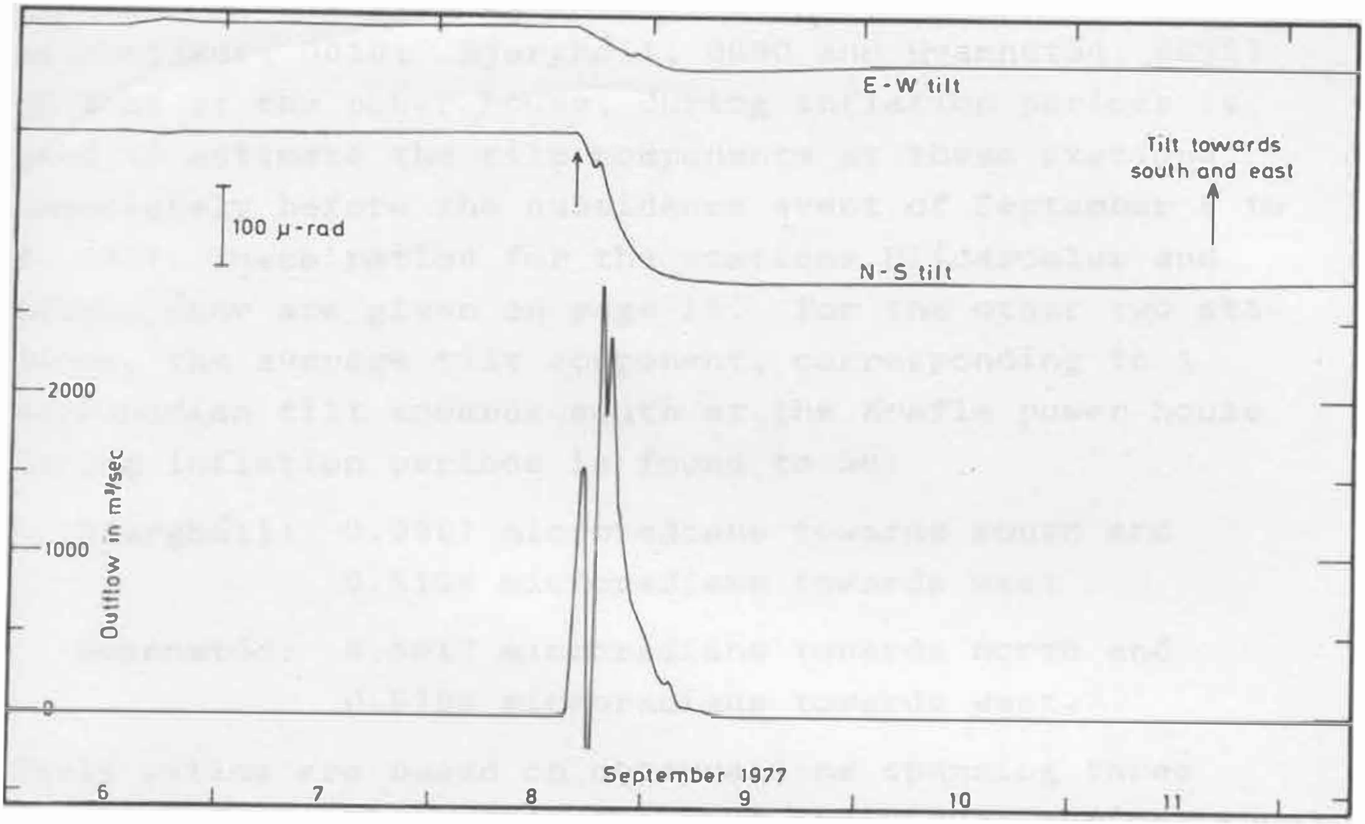



Fig. 13. Tilt in the Krafla power house as measured by the electronic tiltmeter, and the rate of outflow of magma from the Krafla magma chamber during the subsidence event of September 8 to 9, 1977. The outflow rate as shown may be 40 to 50 per cent too high (see text).

to reach maximum of about 50 microradians per hour at $18^h50^m$. Following this maximum the subsidence rate decreased gradually to zero at September 9, $15^h$, whereafter slight inflation commenced. The total tilt change according to the electronic tiltmeter was 190 microradians towards north and 55 microradians towards west (Fig. 13).

Observations of the spirit level tilt stations were made on August 15 to 17, some 25 days before the subsidence event of September 8 to 9, and on September 10 to 12, 1977, immediately after the subsidence event. The observed tilt at the four stations nearest the center of uplift, correlates rather closely with the north component of tilt at the Krafla power house during inflation periods. The average rate of tilt at these stations (Hlídardalur, 0000; Leirhnjúkur, 0010; Bjarghóll, 0080 and Hvannstód, 0090) to that at the power house, during inflation periods is used to estimate the tilt components at these stations immediately before the subsidence event of September 8 to 9, 1977. These ratios for the stations Hlídardalur and Leirhnjúkur are given on page 15. For the other two stations, the average tilt component, corresponding to 1 microradian tilt towards south at the Krafla power house during inflation periods is found to be:

Bjarghóll: 0.0801 microradians towards south and
0.6104 microradians towards west

Hvannstód: 0.5817 microradians towards north and
0.6108 microradians towards west.

These ratios are based on observations spanning three periods of totalling 245 days, but individual periods show that the ratios are not constant and may vary systematically with both time and the observed tilt. Therefore, the estimated tilt at the start of the subsidence event (Table V) may be in error by some 10 mciroradians.

At other spirit level tilt stations, the tilt variations during inflation periods are not or barely noticeable, so the difference in tilt from last observation before the subsidence event to the first observation after the event is taken as the tilt caused by the subsidence event of September 8 to 9, 1977. The observed tilts are given in Table VI.

The tilt vectors at all these tilt stations are shown on a map (Fig. 14), which clearly indicates subsidence in the western part of the Krafla caldera and uplift around the active fissure swarm south of the caldera.

Distance measurements and simultaneous vertical angle measurements were made before and after the subsidence event on a number of lines within the Krafla caldera and south of it.

TABLE V

Components of tilt vectors in microradians at the tilt stations Hlídardalur (0000), Leirhnjúkur (0010), Bjarghóll (0080), Hvannstód (0090) and the Krafla power house (KPH) during the subsidence event of September 10 to 11, 1977.

| | KPH | 0000 | | 0010 | |
|---|---|---|---|---|---|
| Before event | N-comp | N-comp | E-comp | N-comp | E-comp |
| Aug. 15, obs. | -128.14 | -54.09 | 42.31 | 39.87 | -95.09 |
| Sept. 8, calc. | -175.02 | -77.42 | 45.01 | 58.50 | -60.29 |
| After event | | | | | |
| Sept. 10, obs. | 14.68 | 2.04 | 82.92 | 20.89 | -323.59 |
| Sept. 8, calc. | 18.85 | 4.12 | 82.68 | 19.23 | -326.69 |
| Tilt during event | 193.87 | 81.54 | 37.67 | -39.27 | -266.40 |

| | KPH | 0080 | | 0090 | |
|---|---|---|---|---|---|
| Before event | N-comp | N-comp | E-comp | N-comp | E-comp |
| Aug. 16, obs. | -131.18 | -18.02 | -69.04 | 64.61 | -59.18 |
| Sept. 8, calc. | -175.02 | -21.53 | -95.82 | 90.11 | -85.96 |
| After event | | | | | |
| Sept. 11, obs. | 13.56 | 48.80 | -44.24 | 16.85 | -14.14 |
| Sept. 8, calc. | 18.85 | 49.23 | -41.01 | 13.77 | -10.91 |
| Tilt during event | 193.87 | 70.76 | 54.81 | -76.34 | 75.05 |

TABLE VI

Observed components of tilt in microradians before and after the subsidence event of September 8 to 9, 1977, at the tilt stations A (east of Námaskard), 0020 (Mývatn N), 0040 (Jörundur), 0050 (Grjótagjá S), 0060 (Grjótagjá N), 0070 (Reykjahlíd) and 0200 (Hverfjall)

| Tilt station A | N-component | E-component |
|---|---|---|
| August 17, 1977 | -45.19 | 58.60 |
| September 12, 1977 | -107.34 | 112.59 |
| Difference (due to event) | -62.15 | 53.99 |
| **Tilt station 0020** | | |
| August 15, 1977 | -4.96 | -48.39 |
| September 11, 1977 | -18.18 | -85.06 |
| Difference (due to event) | -13.22 | -36.67 |
| **Tilt station 0040** | | |
| August 15, 1977 | -38.02 | 45.61 |
| September 12, 1977 | -33.50 | 57.45 |
| Difference (due to event) | 4.52 | 11.84 |
| **Tilt station 0050** | | |
| August 16, 1977 | 11.25 | 7.50 |
| September 10, 1977 | -34.27 | -49.36 |
| Difference (due to event) | -45.52 | -56.86 |
| **Tilt station 0060** | | |
| August 16, 1977 | 3.66 | 7.81 |
| September 10, 1977 | -35.36 | -68.84 |
| Difference (due to event) | -39.02 | -76.65 |
| **Tilt station 0070** | | |
| August 16, 1977 | -6.41 | -15.90 |
| September 11, 1977 | -38.56 | -99.23 |
| Difference (due to event) | -32.15 | -83.33 |
| **Tilt station 0200** | | |
| August 15, 1977 | -15.22 | 1.32 |
| September 11, 1977 | -13.70 | -13.03 |
| Difference (due to event) | 1.52 | -14.35 |

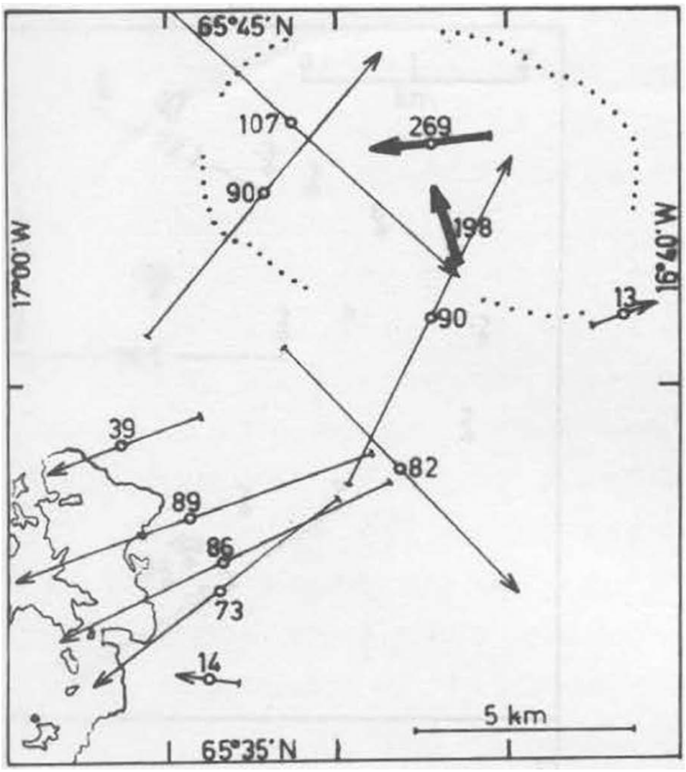



Fig. 14. Tilt vectors related to the subsidence event of September 8 to 9, 1977. See Fig. 10 for explanation.

Distance measurements with a geodimeter made in July and August before the subsidence event of September 8 to 9, 1977 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 to 100 cm (Fig. 15) and the zone that widened is roughly 2 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 six km farther south, which increased in length by only 7.4 cm (Fig. 16), indicating that this line is at the southern end of the strip, which widened during the event. 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 pr km.

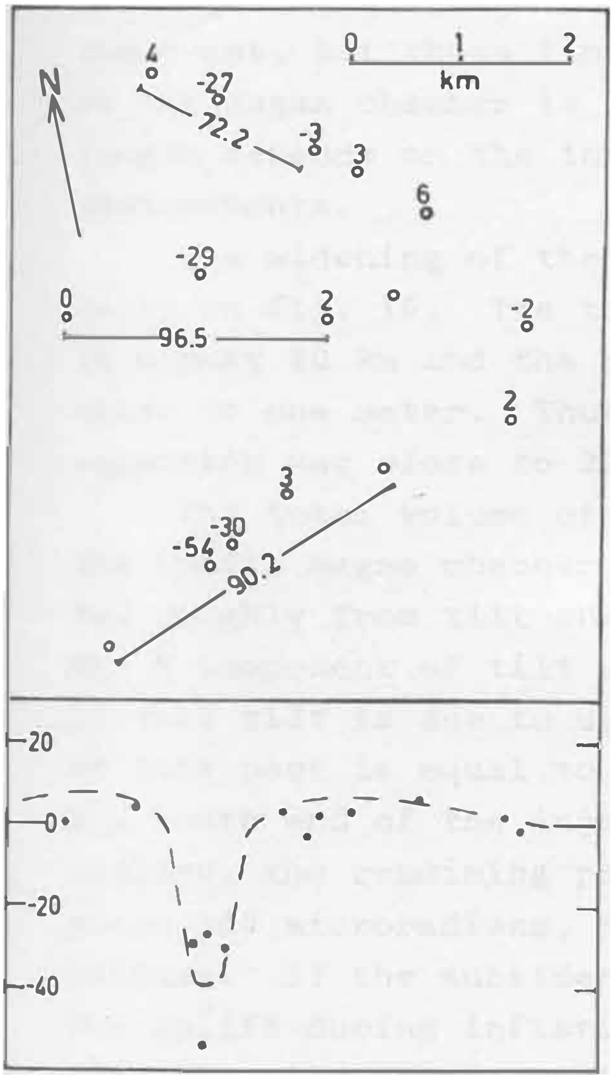



Fig. 15. Lengthening of geodimeter lines and vertical displacements of markers during the September 8 to 9, 1977 subsidence event. See Fig. 11 for explanation.

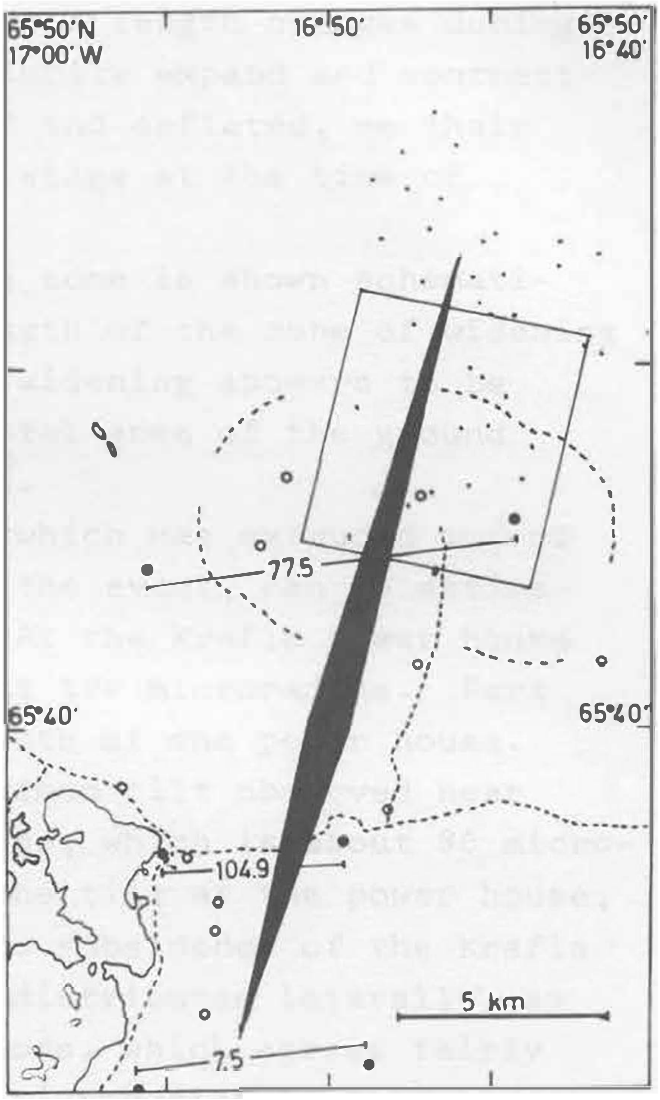



Fig. 16. Map of the Krafla-Mývatn area showing the zone of rifting during the September 8 to 9, 1977 subsidence event. Lengthening of three geodimeter lines in centimeter is shown. A rectangle shows the area covered by the map in Fig. 15.

Short lines east of the active fissure zone within the Krafla caldera showed no systematic length changes during the event, but these lines regularily expand and contract as the magma chamber is inflated and deflated, so their length depends on the inflation stage at the time of measurements.

The widening of the fissure zone is shown schematically on Fig. 16. The total length of the zone of widening is almost 20 km and the average widening appears to be close to one meter. Thus the total area of the ground expansion was close to 20.000 $m^2$

Tht total volume of magma, which was extruded out of the Krafla magma chamber during the event, can be estimated roughly from tilt changes. At the Krafla power house the N component of tilt was about 194 microradian. Part of this tilt is due to uplift south of the power house. If this part is equal to the maximum tilt observed near the south end of the injected zone, which is about 90 microradians, the remaining part of the tilt at the power house, about 100 microradians, is due to subsidence of the Krafla caldera. If the subsidence was distributed laterally, as the uplift during inflation periods, which agrees fairly with all tilt measurements, one microradian in tilt change at the power house represents 200.000 $m^3$ of magma moving out of the magma chamber. Thus the roughly 100 microradians tilt change at the power house due to subsidence to the north, means that about 20 x $10^6$ $m^3$ of magma moved out of the Krafla magma chamber during the subsidence event of September 8 to 9, 1977. 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 $m^3$/sec at its maximum (Fig. 13). This estimate is certainly too high, due to the above mentioned effect of land rise to the south of the power house. If the 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 $m^3$/sec.

It is obvious from the tilt and distance measurements, that the majority of the magma moved southwards out of the magma chamber. However, the widening of the fissure zone within the northern part of the Krafla caldera and probably slightly farther north, and the eruption of some $2 \times 10^6$ $m^3$ 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 some 80% of the magma flowed southwards, some 10% came to the surface, and some 10% flowed northward into subsurface fissures.

The total area of ground expansion of some 20.000 $m^2$ and the total amount of magma filling dikes beneath the expanded ground of some $18 \times 10^6$ $m^3$ (total magma extruded minus magma erupted), indicates that the dike height is on the average some 900 meter. The subsidence of the fissure swarm and the width of the subsided part of the swarm (Fig. 15), indicates a depth down to the dike of some 500 m within the Krafla caldera.

## THE SUBSIDENCE EVENT OF NOVEMBER 2, 1977

This event was a small one and the only clear observations of it were the recordings of the electronic tiltmeter at the Krafla power house, and the local seismometers, which recorded continuous tremor. The subsidence started at about $6^h00^m$, and the rate of tilt reached a maximum of about 10 microradians per hour at about $6^h20^m$, whereafter it decreased and the subsidence ceased altogether between $8^h00^m$ and $8^h30^m$ (Fig. 17). The total tilt at the Krafla power house was about 10.5 microradians down to the north and 3.4 microradians down to the west. This represents a removal of $2 \times 10^6$ $m^3$ of magma from the Krafla magma chamber and the maximum rate of flow was about 500 $m^3$/sec (Fig. 17).

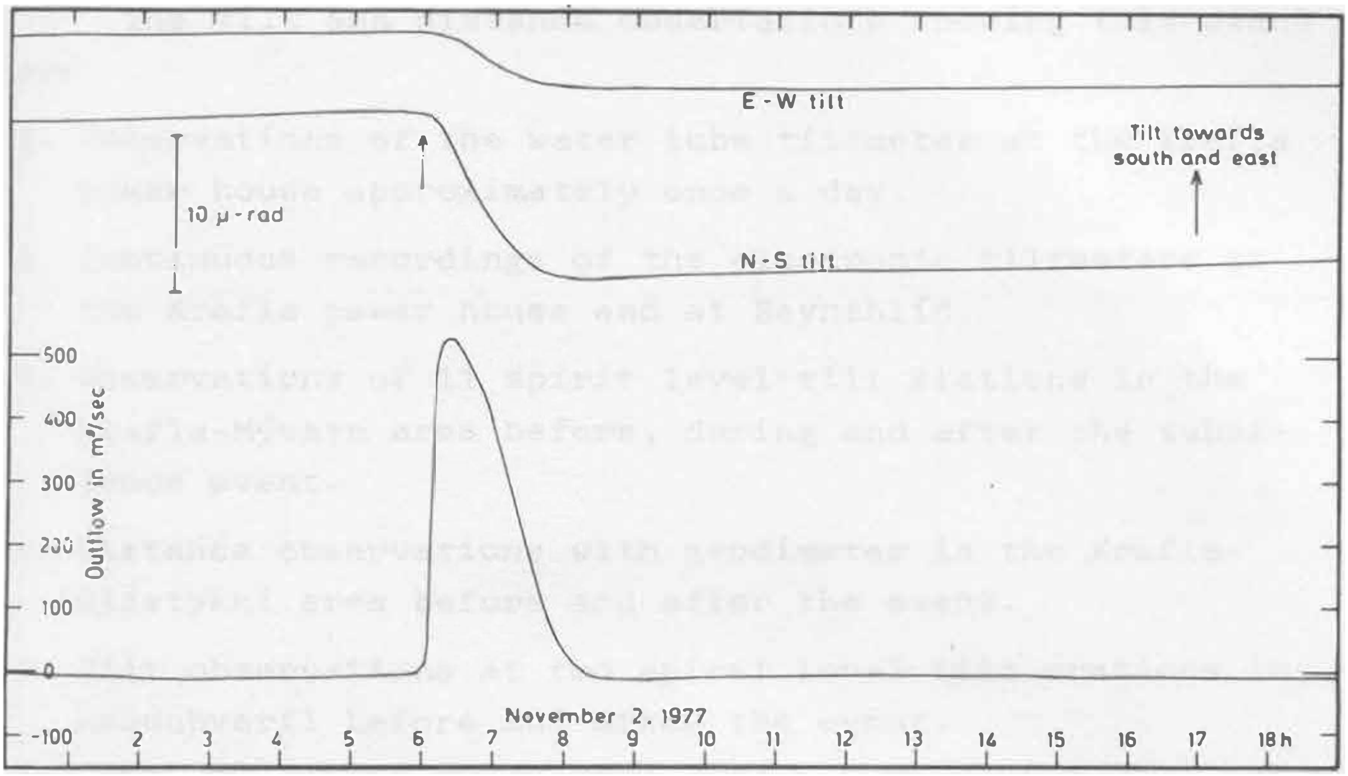



Fig. 17. Tilt in the Krafla power house as measured by the electronic tiltmeter, and the rate of outflow of magma from the Krafla magma chamber during the subsidence event of November 2, 1977.

The direction of the magma flow is not known with certainty, but the ratio of north and east component of tilt at the Krafla power house is very similar as for inflation periods, which indicates northward flow, as otherwise different direction of the tilt vector can be expected.

## THE SUBSIDENCE EVENT OF JANUARY, 1978

The tilt and distance observations showing this event are:

1. Observations of the water tube tiltmeter at the Krafla power house approximately once a day.
2. Continuous recordings of the electronic tiltmeters at the Krafla power house and at Reynihlíd.
3. Observations of 11 spirit level tilt stations in the Krafla-Mývatn area before, during and after the subsidence event.
4. Distance observations with geodimeter in the Krafla-Gjástykki area before and after the event.
5. Tilt observations 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 clearly before the observation on January 7, $07^h$, but after the observation on January 6, $09^h$. The tilt down to the north continued until January 25, and had then reached 317 microradians. The east component of the water tube tiltmeter was not operating porperly during this event.

The electronic tiltmeter at the Krafla power house showed slight subsidence to commence on January 6, at $15^h00^m$ approximately, but this was very slow the first 16 hours, when the tilt change had reached only 4 microradians. On January 7, at about 07 , the subsidence rate started to increase dramatically, but the maximum rate of N-S tilt change of 8.9 microradians per hour was first reached between $12^h$ and $15^h$ on January 7, or 5 to 8 hours after the rapid increase in tilt rate occurred. The subsidence continued, although its rate fluctuated greatly, until about January 22, when the observed tilt had reached 348 microradians down towards north and 126 microradians down to the west (Figs. 18 & 19). Both N-S and E-W components of this tiltmeter showed great fluctuations in the rate of

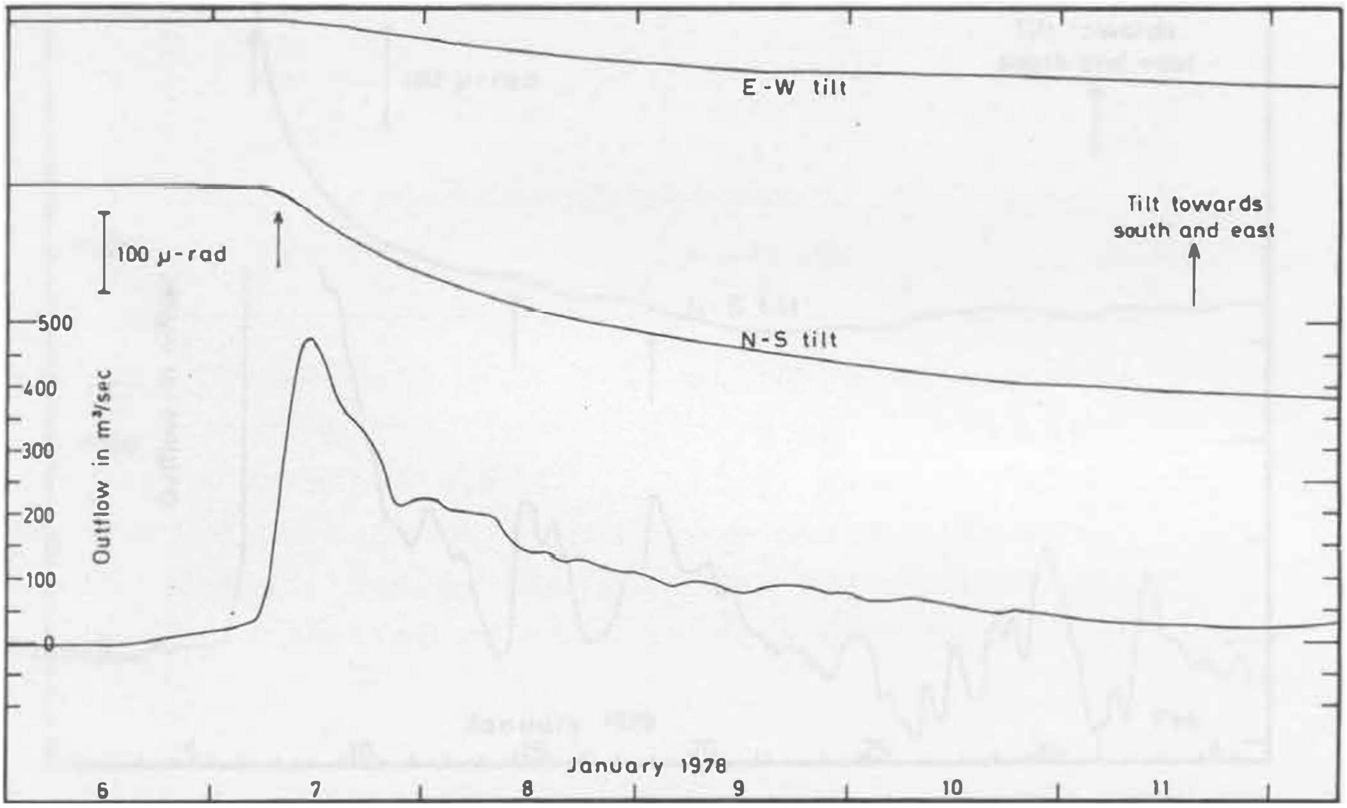



Fig. 18. Tilt in the Krafla power house as measured by the electronic tiltmeter, and the rate of outflow of magma from the Krafla magma chamber during the first days of the January 1978 subsidence event.

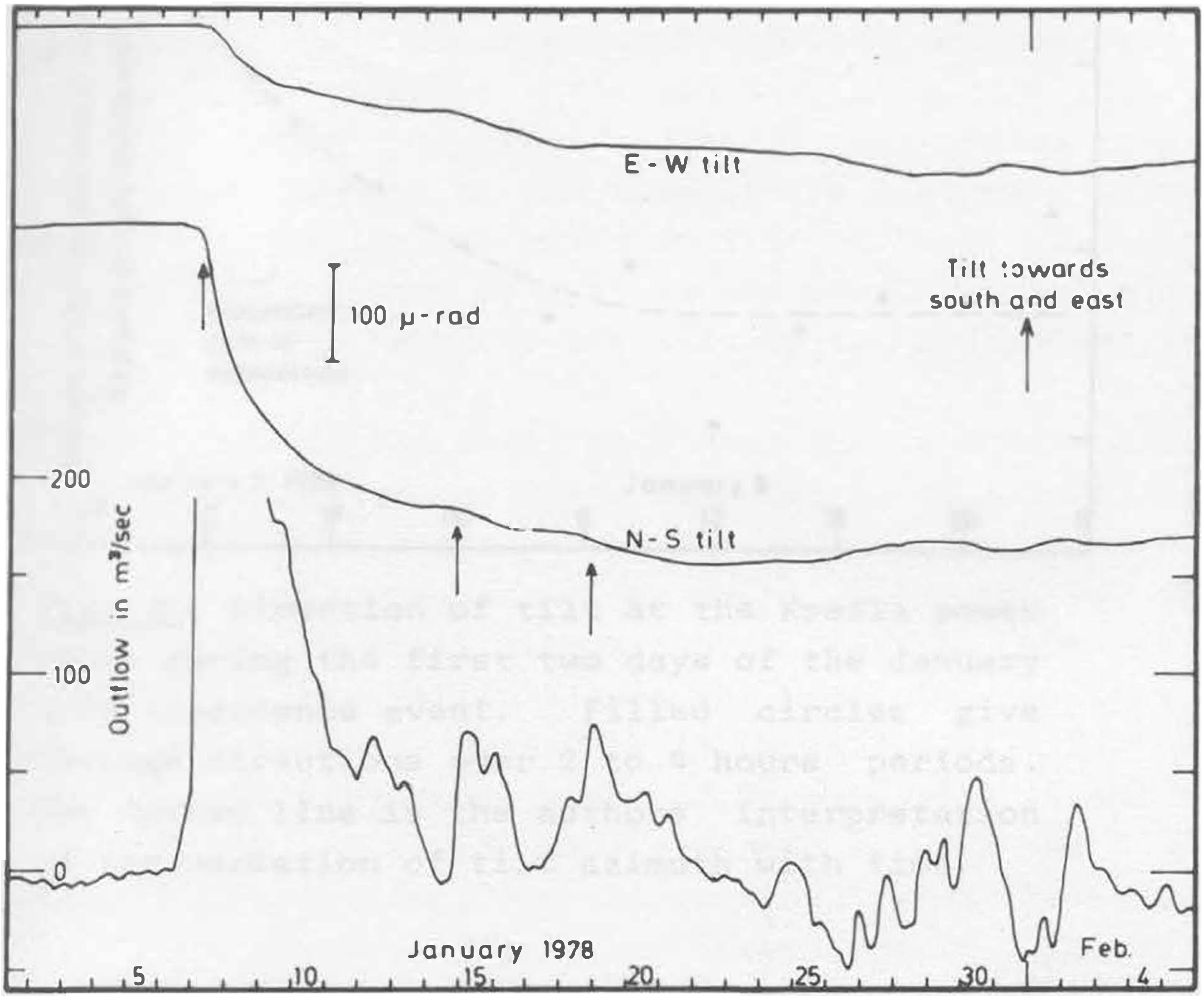



Fig. 19. Tilt in the Krafla power house as measured by the electronic tiltmeter, and the rate of outflow of magma from the Krafla magma chamber during the January 1978 subsidence event. For details of the first days of the event, see Fig. 18. The arrows show times of noticeable continuous tremors on the local seismographs.

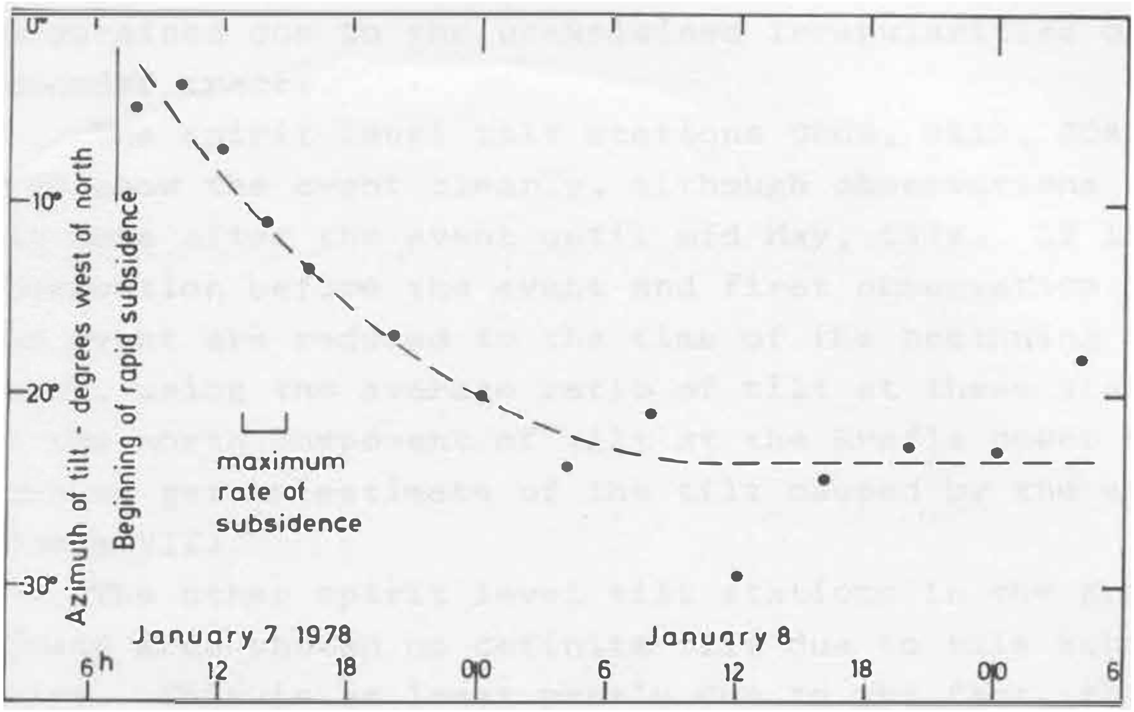



Fig. 20. Direction of tilt at the Krafla power house during the first two days of the January 1978 subsidence event. Filled circles give average directions over 2 to 4 hours periods. The dashed line is the authors interpretation of the variation of tilt azimuth with time.

tilt during this subsidence event and for several weeks after it, indicating that some of the processes associated with the event continued for a month or more after the subsidence of the Krafla region ceased on January 22 to 25, 1978. The direction of tilt, during the first hours of rapid tilt, showed continuous variation from near north at the very beginning of the rapid subsidence to about 25° west of north a day later (Fig. 20).

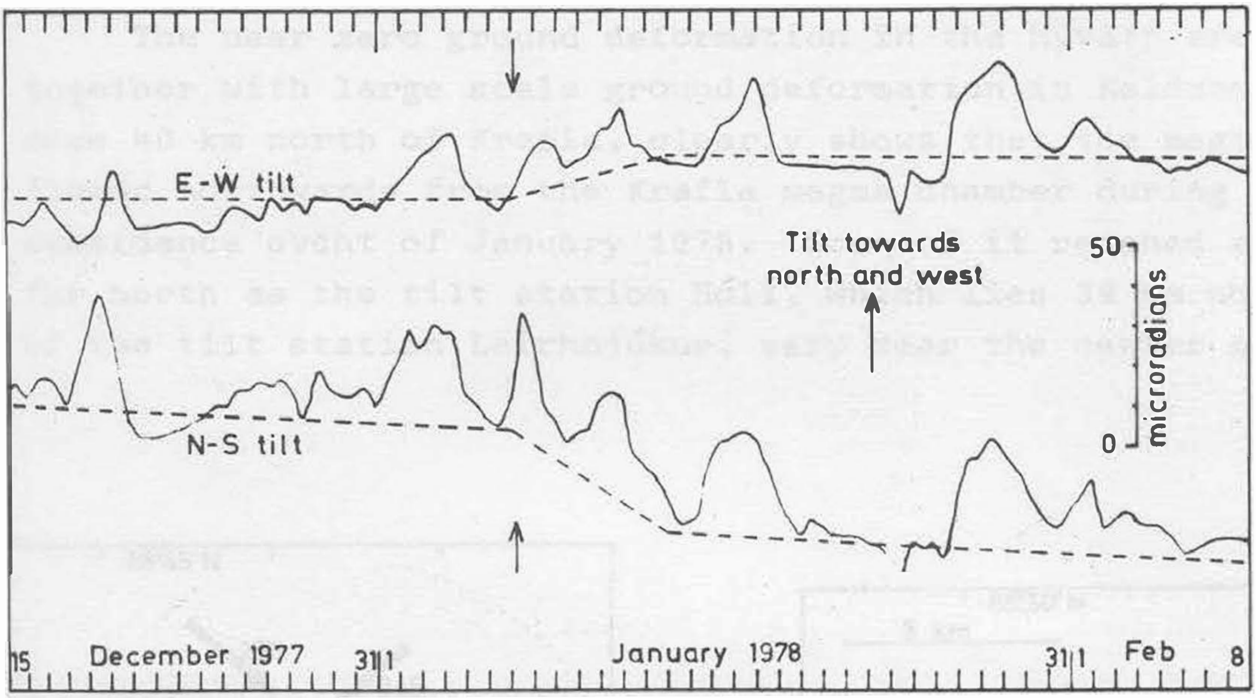
The electronic tiltmeter at Reynihlíd showed great irregularities in the recorded trace during the period of this subsidence event (Fig. 21), so the tilt change due to the event cannot be determined with accuracy. It is estimated that tilt change of approximately 23 microradians down to the north and 12 microradians down to the east is caused by this event. The exact time of this tilt cannot be obtained due to the unexplained irregularities of the recorder traces.

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. If last observation before the event and first observation after the event are reduced to the time of the beginning of the event, using the average ratio of tilt at these stations to the north component of tilt at the Krafla power house, then we get an estimate of the tilt caused by the event (Table VII).

The other spirit level tilt stations in the Krafla-Mývatn area showed no definite tilt due to this subsidence event. This is at least partly due to the fact, that no observations were made after the event, until mid May 1978, and partly due to small tilt at these stations. The tilt from the last observation before the event to the first observation after the event are given in Table VIII. These are due to the subsidence event of January 1978 in addition to other tilts, which may have occurred between the measurements. Further, the observational error of some 5 microradians greatly affects the observed tilt (Fig. 22).

Distance measurements with the geodimeter on 24 lines in the Krafla-Gjástykki area in October and November 1977, and again in March 1978 (Fig. 23), 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 (Table IX). At the station Hóll (66°04.2´N, 16°38.0´W) a tilt of 210 microradians up towards north (azimuth 0.8°)




<u>Fig. 21.</u> Redrawn traces of the electronic tiltmeter in Reynihlíd during the January 1978 subsidence event. The arrows mark the beginning of rapid subsidence as observed by the tiltmeter in the Krafla power house. Tilt due to the event is obscured by large unexplained oscillations, but dashed line shows the authors interpretation of the effect of the subsidence event on the tilt at Reynihlíd.

was observed, while at the station Lón (66°06.0´N, 16°54.2´W) the observed tilt was about 14 microradians, up towards ESE (azimuth 104.2°). These tilt changes in Kelduhverfi apparently occurred simultaneously with the subsidence event of January 1978 in Krafla.

The near zero ground deformation in the Mývatn area together with large scale ground deformation in Kelduhverfi some 40 km north of Krafla, clearly shows that the magma flowed northwards from the Krafla magma chamber during the subsidence event of January 1978. Some of it reached as far north as the tilt station Hóll, which lies 39 km north of the tilt station Leirhnjúkur, very near the center of

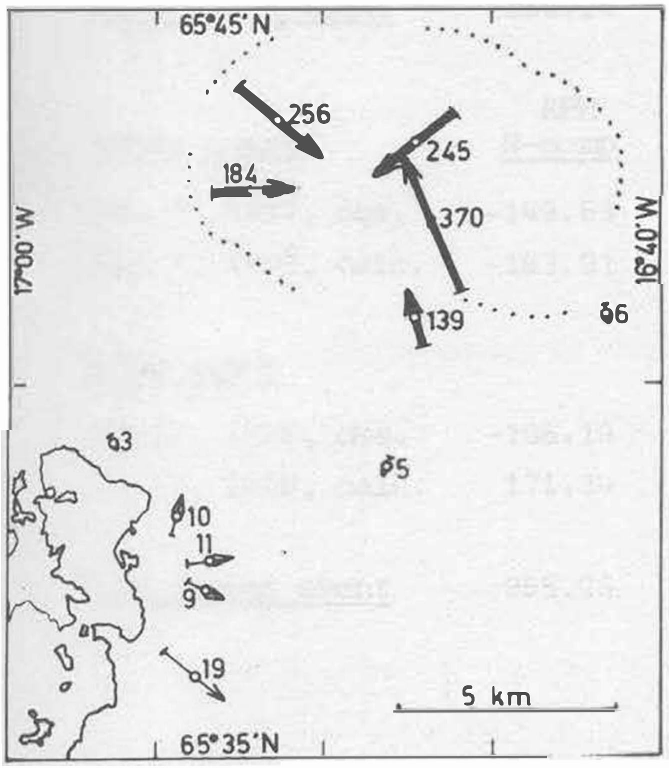



Fig. 22. Tilt vectors related to the subsidence event of January 1978. See Fig.10 for explanation.

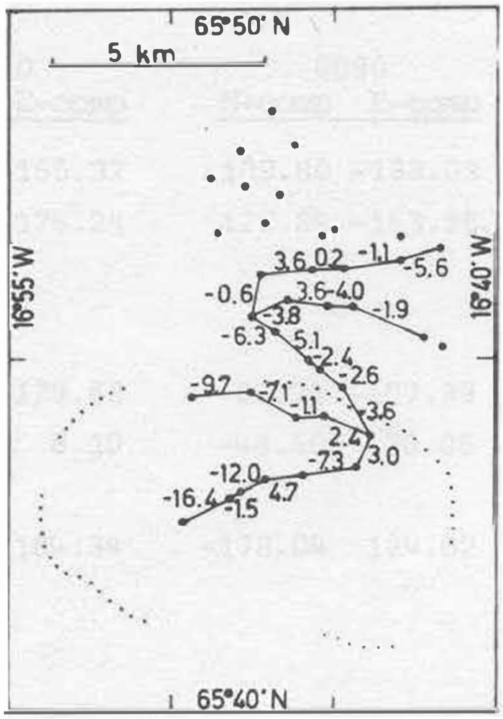



Fig. 23. Length changes of geodimeter lines in the Krafla area between October/November 1977 and March 1978 in cenmeter.

TABLE VII

Components of tilt vectors in microradians at the tilt stations Hlídardalur (0000), Leirhnjúkur (0010), Bjarghóll (0080), Hvannstóð (0090) and the Krafla power house (KPH) during the subsidence event of January 1978.

| | KPH | 0000 | | 0010 | |
|---|---|---|---|---|---|
| Before event | N-comp | N-comp | E-comp | N-comp | E-comp |
| Dec. 1, 1977, obs. | -149.54 | -75.21 | 92.49 | 65.80 | -163.10 |
| Jan. 7, 1978, calc. | -183.91 | -91.31 | 94.46 | 79.46 | -137.59 |
| After event | | | | | |
| May 19, 1978, obs. | -106.19 | -67.91 | 78.06 | 14.24 | -159.40 |
| Jan. 7, 1978, calc. | 171.34 | 44.34 | 65.08 | -75.42 | -326.87 |
| Tilt during event | 355.25 | 135.65 | -29.38 | -154.88 | -189.28 |

| | KPH | 0080 | | 0090 | |
|---|---|---|---|---|---|
| Before event | N-comp | N-comp | E-comp | N-comp | E-comp |
| Dec. 2, 1977, obs. | -149.63 | 29.24 | -155.32 | 109.60 | -133.03 |
| Jan. 7, 1978, calc. | -183.91 | 26.49 | -176.24 | 129.54 | -153.96 |
| After event | | | | | |
| May 19, 1978, obs. | -106.19 | 15.82 | -129.63 | 82.75 | -107.39 |
| Jan. 7, 1978, calc. | 171.34 | 33.90 | 8.10 | -48.50 | 30.06 |
| Tilt during event | 355.25 | 7.41 | 184.34 | -178.04 | 184.02 |

TABLE VIII

Observed components of tilt in microradians before and after the subsidence event of January 1978 at the tilt stations A (east of Námaskard), 0020 (Mývatn N), 0040 (Jörundur), 0050 (Grjótagjá S), 0060 (Grjótagjá N), 0070 (Reykjahlíd) and 0200 (Hverfjall).

| Tilt station A | N-component | E-component |
|---|---|---|
| Oct. 21, 1977 | -110.85 | 112.49 |
| May 21, 1978 | -115.34 | 109.80 |
| Difference (due to event ?) | -4.49 | -2.69 |
| **Tilt station 0020** | | |
| Dec. 2, 1977 | -14.54 | -92.39 |
| May 15, 1978 | -16.97 | -90.85 |
| Difference (due to event ?) | -2.43 | 1.54 |
| **Tilt station 0040** | | |
| Oct. 21, 1977 | -46.06 | 69.78 |
| June 28, 1978 | -52.27 | 70.79 |
| Difference (due to event ?) | -6.21 | 1.01 |
| **Tilt station 0050** | | |
| Dec. 3, 1977 | -40.50 | -37.81 |
| May 20, 1978 | -44.82 | -29.82 |
| Difference (due to event ?) | -4.32 | 7.99 |
| **Tilt station 0060** | | |
| Dec. 6, 1977 | -39.57 | -50.87 |
| May 20, 1978 | -38.03 | -39.62 |
| Difference (due to event ?) | 1.54 | 11.25 |
| **Tilt station 0070** | | |
| Dec. 1, 1977 | -36.20 | -97.64 |
| May 20, 1978 | -25.90 | -94.92 |
| Difference (due to event ?) | 10.30 | 2.72 |
| **Tilt station 0200** | | |
| Oct. 29, 1977 | -26.58 | -4.15 |
| May 21, 1978 | -39.27 | 10.35 |
| Difference (due to event ?) | -12.69 | 14.50 |

TABLE IX

Observed components of tilt in microradians before and after the subsidence event of January 1978 at the Kelduhverfi tilt stations 0100 (Hóll) and 0110 (Lón).

| Tilt station 0100 | N-component | E-component |
|---|---|---|
| July 15, 1977 | 3.65 | 6.68 |
| May 21, 1978 | -206.10 | 3.52 |
| Difference (due to event) | -209.75 | -3.16 |
| **Tilt station 0110** | | |
| July 15, 1977 | 0.28 | 1.13 |
| May 21, 1978 | 3.78 | -12.71 |
| Difference (due to event) | 3.50 | -13.84 |

subsidence. The available observations do not indicate any magma movement towards south.

As the magma movement was apparently entirely towards north, and no magma was deposited in the southern part of the fissure system north of Krafla (Fig. 23), the tilt change at the Krafla power house is a rather reliable indicator of the volume of the magma, which left the magma chamber. However, the subsidence event lasted for a period of approximately 3 weeks, so it may be assumed that the normal influx of some $0.4 \times 10^6$ $m^3$/day flowed into the magma chamber from below at the same time as the magma flowed out of the magma chamber towards north. Under these assumptions, the total volume of the magma, which flowed out of the Krafla magma chamber during the subsidence event of January 1978, was $70 \times 10^6$ to $75 \times 10^6$ $m^3$. The rate of flow reached a maximum of approximately 500 $m^3$/sec near noon on January 7 (Fig. 18), and decreased irregularily 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 the outflux rate reached 60 to 70 $m^3$/sec and on January 30 and February 2, when the outflux rate reached approximately 40 $m^3$/sec.

THE SUBSIDENCE EVENT OF JULY 10 TO 12, 1978

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

The water tube tiltmeter in the Krafla power house shows a total tilt of 177 microradians towards north between July 10, $9^h$ and July 13, $13^h40^m$. The east component of the water tube tiltmeter showed no significant tilt.

The continuously recording electronic tiltmeter at the Krafla power house showed that the tilt started on July 10 at about $11^h$, although it was very slow until about $15^h$ (Fig. 24). The rate of tilt increased rapidly until it reached its maximum between $20^h$ and $21^h$, about 11.1 microradian per hour. Thereafter the rate of tilt decreased gradually until it reached zero on July 12, $20^h$, and a new inflation period started. The total tilt according to the electronic tiltmeter, was 175 microradians towards north and about 68 microradians towards west. In fact, the westward tilt continued at a very slow rate until July 16, when the total westward tilt had reached 72 microradians.

The direction of tilt, according to the electronic tiltmeter, was approximately 10° west of north at the beginning of the subsidence event, and changed gradually to nearly 30° west of north in the afternoon of July 11 (Fig.25).

The electronic tiltmeter at Reynihlíd (Fig. 26) showed definite tilt to start at about $19^h$ on July 10, or several

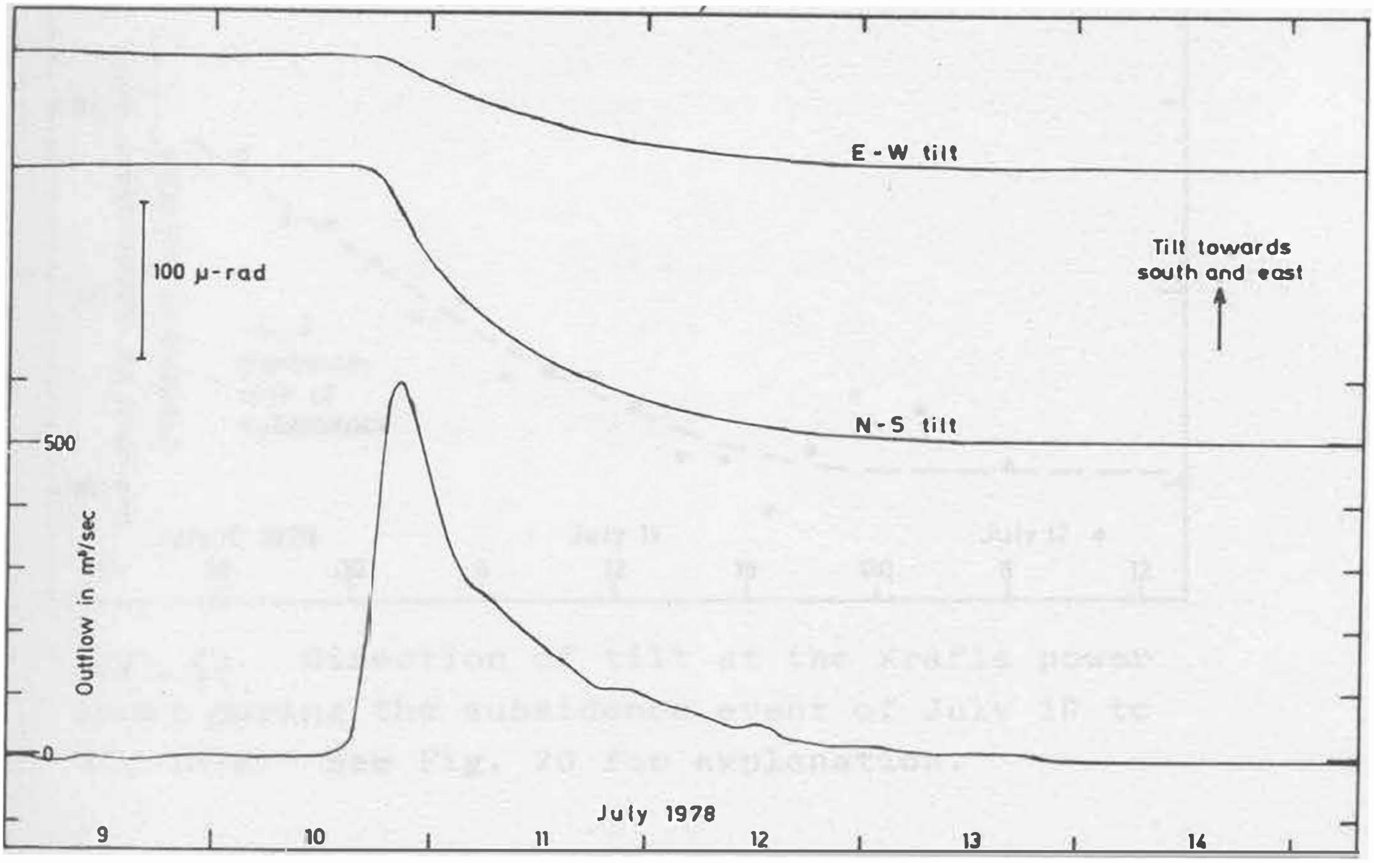



Fig. 24. Tilt in the Krafla power house as measured by the electronic tiltmeter, and the rate of outflow of magma from the Krafla magma chamber during the July 10 to 12, 1978 subsidence event.

hours later that at the Krafla power house. The tilt was about 8 microradians towards north and a slightly smaller east component. The north component of tilt 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, similar to the east component of tilt in the power house. This can be interpreted as change in direction of tilt at Reynihlíd from some 20° east of north at the beginning 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 to 29, 1978, before the event and in late July or early

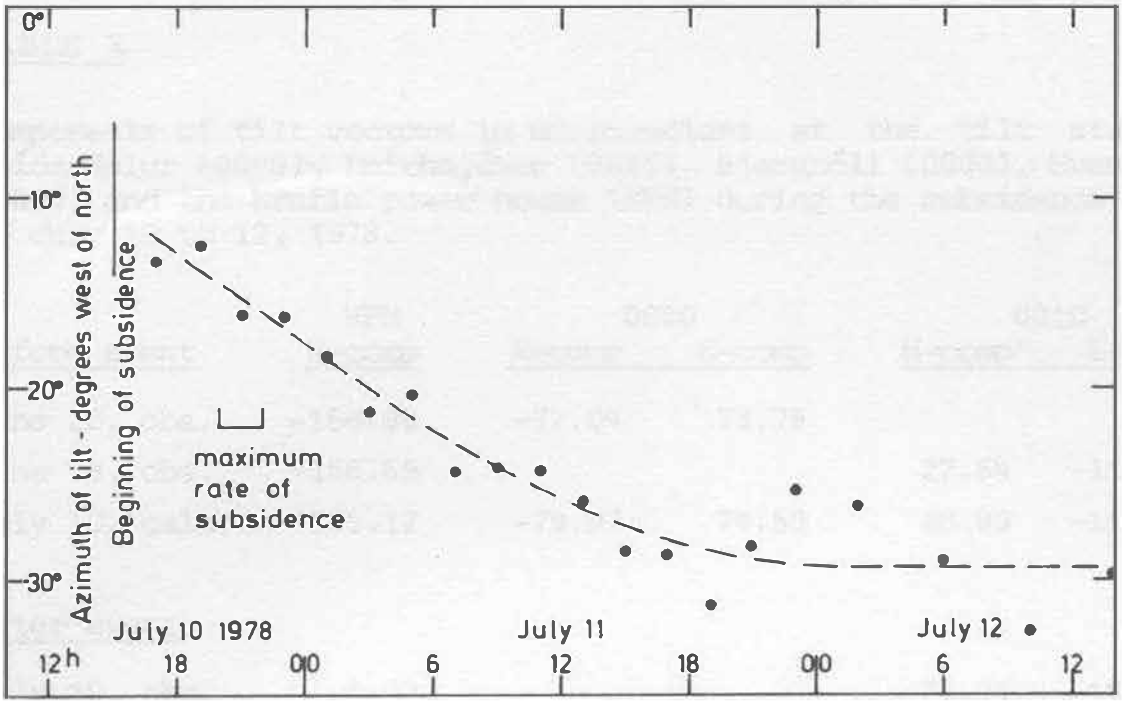



Fig. 25. Direction of tilt at the Krafla power house during the subsidence event of July 10 to 12, 1978. See Fig. 20 for explanation.

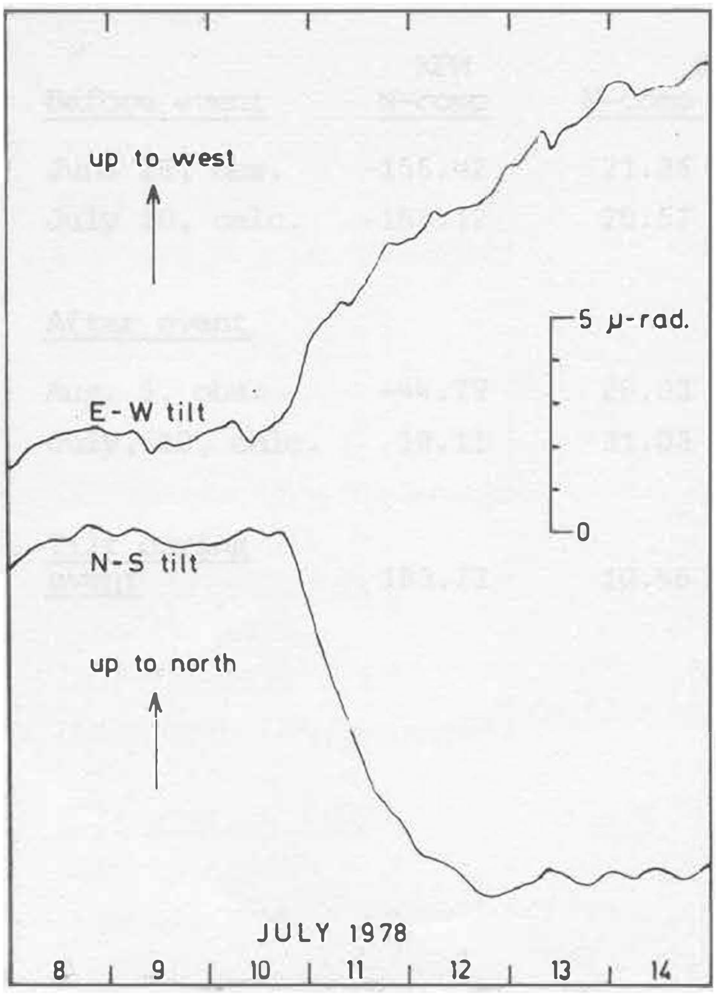



Fig. 26. Redrawn traces of the electronic tiltmeter in Reynihlíd during the July 10 to 12, 1978 subsidence event.

TABLE X

Components of tilt vectors in microradians at the tilt stations Hlídardalur (0000), Leirhnjúkur (0010), Bjarghóll (0080), Hvannstód (0090) and the Krafla power house (KPH) during the subsidence event of July 10 to 12, 1978.

| | KPH | 0000 | | 0010 | |
|---|---|---|---|---|---|
| Before event | N-comp | N-comp | E-comp | N-comp | E-comp |
| June 22, obs. | -150.99 | -72.04 | 73.78 | | |
| June 28, obs. | -156.69 | | | 27.64 | -118.39 |
| July 10, calc. | -165.12 | -79.07 | 74.59 | 30.99 | -112.13 |
| After event | | | | | |
| July 19, obs. | -0.33 | | | -79.91 | -185.04 |
| Aug. 5, obs. | -44.29 | -36.16 | 75.13 | | |
| July 10, calc. | 18.11 | -5.12 | 71.54 | -84.24 | -198.73 |
| Tilt during event | 183.23 | 73.95 | -3.05 | -115.23 | -86.59 |

| | KPH | 0080 | | 0090 | |
|---|---|---|---|---|---|
| Before event | N-comp | N-comp | E-comp | N-comp | E-comp |
| June 28, obs. | -155.42 | 21.35 | -156.34 | 129.80 | -129.36 |
| July 10, calc. | -165.12 | 20.57 | -162.26 | 135.44 | -135.28 |
| After event | | | | | |
| Aug. 5, obs. | -44.29 | 26.03 | -87.36 | 59.90 | -58.74 |
| July, 10, calc. | 18.11 | 31.03 | -44.27 | 23.60 | -20.63 |
| Tilt during event | 183.23 | 10.46 | 112.99 | -111.84 | 114.65 |

TABLE XI

Observed components of tilt in microradians before and after the subsidence event of July 10 to 12, 1978, at the tilt stations A (east of Námaskard), 0020 (Mývatn N), 0040 (Jörundur), 0050 (Grjótagjá S), 0060 (Grjótagjá N), 0070 (Reykjahlíd) and 0200 (Hverfjall)

| Tilt station A | N-component | E-component |
|---|---|---|
| June 24, 1978 | -123.04 | 109.79 |
| Aug. 8, 1978 | -113.81 | 111.12 |
| Difference (due to event) | 9.23 | 1.33 |

| Tilt station 0020 | | |
|---|---|---|
| June 29, 1978 | -17.89 | -93.53 |
| July 19, 1978 | -12.98 | -88.17 |
| Difference (due to event) | 4.91 | 5.36 |

| Tilt station 0040 | | |
|---|---|---|
| June 28, 1978 | -52.27 | 70.79 |
| Aug. 11, 1978 | -49.27 | 61.35 |
| Difference (due to event) | 3.00 | -9.44 |

| Tilt station 0050 | | |
|---|---|---|
| June 29, 1978 | -45.57 | -25.99 |
| Aug. 8, 1978 | -46.37 | -16.92 |
| Difference (due to event) | -0.80 | 9.07 |

| Tilt station 0060 | | |
|---|---|---|
| June 29, 1978 | -34.18 | -39.69 |
| Aug. 6, 1978 | -36.11 | -31.77 |
| Difference (due to event) | -1.93 | 7.92 |

| Tilt station 0070 | | |
|---|---|---|
| June 29, 1978 | -25.45 | -100.33 |
| July 19, 1978 | -18.20 | -90.49 |
| Difference (due to event) | 7.25 | 9.84 |

| Tilt station 0200 | | |
|---|---|---|
| June 29, 1978 | -47.78 | 14.57 |
| Aug. 12, 1978 | -52.73 | 10.97 |
| Difference (due to event) | -4.95 | -3.60 |

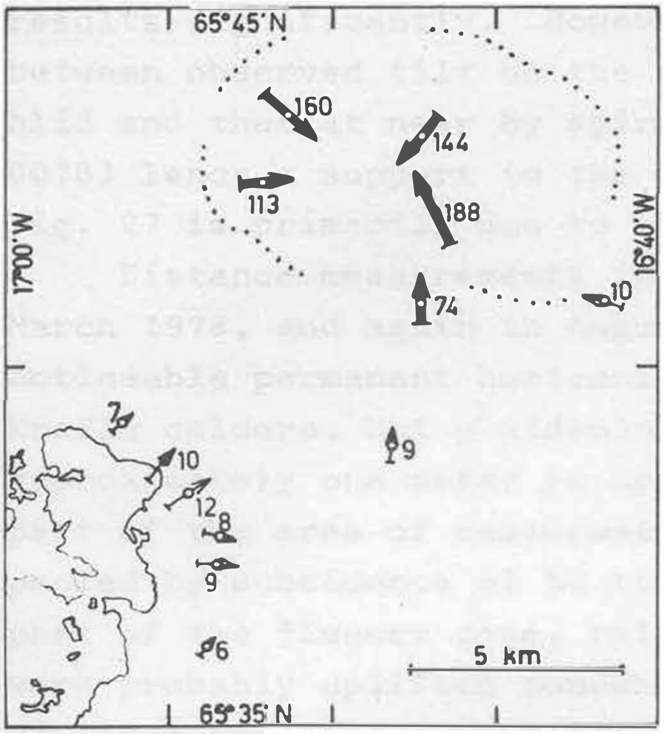



Fig. 27. Tilt vectors related to the subsidence event of July 10 to 12, 1978. The tilt vector at the northeast corner of Mývatn shows the tilt recorded by the electronic tiltmeter in Reynihlíd. See Fig. 10 for explanation.

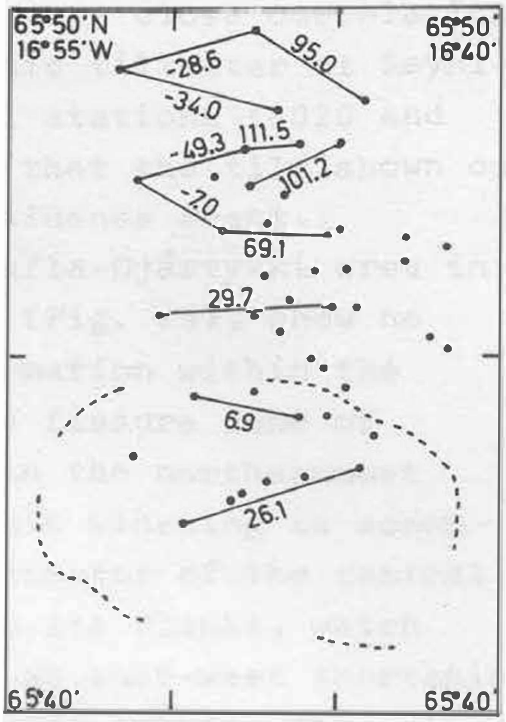



Fig. 28. Length changes of selected geodimeter lines in the Krafla-Gjástykki area between March and August 1978, in centimeters. The changes in the northern part of the area of measurement occurred during the July 10 to 12 subsidence event. The map scale is as in Fig. 23.

August after the event. Bad weather prevented the completion of tilt measurements in July. The tilt at these stations due to the subsidence event are given in Tables X and XI.

The tilt changes in the Mývatn area (Fig. 27, Table XI) are so small that observational errors and minor tilts 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 near by spirit level stations (0020 and 0070) lends a support to the opinion that the tilt shown on Fig. 27 is primarily due to this subsidence event.

Distance measurements in the Krafla-Gjástykki area in March 1978, and again in August 1978 (Fig. 28), show no noticeable permanent horizontal deformation within the Krafla caldera, but a widening of the fissure zone of approximately one meter is observed in the northernmost part of the area of measurements. This widening is accompanied by subsidence of 50 to 70 centimeter of the central part of the fissure zone, relative to its flanks, which were probably uplifted somewhat, 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 purely due to difference of the stage 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 one meter. 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 of July 10 to 12, 1978, can be estimated directly from the north component of tilt at the Krafla power house. This is estimated as $37 \times 10^6\ m^3$.

## CONCLUDING REMARKS

This report gives a rather complete account of the tilt and distance observations in the Mývatn-Krafla-Kelduhverfi area in relation to the 10 subsidence events

TABLE XII

Volume of magma flow in Krafla subsidence events

| Event | Volume of flow towards north | Volume of flow towards south | Volume of lava | Total volume of flow |
|---|---|---|---|---|
| Dec. 20, 1975 | 140 | 10 | 0.4 | 150 |
| Sept. 29, 1076 | | 2 | | 2 |
| Oct. 1, 1976 | 8 | | | 8 |
| Oct. 31, 1976 | 32 | | | 32 |
| Jan. 20, 1977 | 21 | | | 21 |
| April 27, 1977 | 2 | 44 | 0.01 | 46 |
| Sept. 8, 1977 | 2 | 16 | 2 | 20 |
| Nov. 2, 1977 | 2 | | | 2 |
| Jan. 7, 1978 | 74 | | | 74 |
| July 10, 1978 | 37 | | | 37 |
| Total | 318 | 72 | 2.4 | 392 |

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in the Krafla area from December 1975 to July 1978. The number of subsidence events is somewhat questionable. This paper counts two events at the end of September and beginning of October 1976. Other authors have considered these 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, especially before the water tube tiltmeter was installed in the Krafla power house on August 20, 1976.

Of the ten events, three have been associated with magma flowing primarily towards south and in seven events the magma flow was mainly or wholly towards north (Table XII). The total amount of magma flowing out of the Krafla magma chamber during these ten events is here estimated as $3.92 \times 10^8$ $m^3$ ($0.392$ $km^3$), whereof $3.18 \times 10^8$ $m^3$ has been deposited in dikes north of the center of the suggested

TABLE XIII

Duration and subsidence rate in the Krafla subsidence events

| Event | Duration of event hours | Time of max. rate of tilt hours after beginning | Max. tilt rate in Krafla p.h. μ-rad/hr | Maximum flow rate $m^3$/sec |
|---|---|---|---|---|
| Dec. 20, 1975 | (1200) | | | |
| Sept. 29, 1976 | (50) | (40) | | (40) |
| Oct. 1, 1976 | (100) | (50) | | (45) |
| Oct. 31, 1976 | 42 | (2) | (15) | (850) |
| Jan. 20, 1977 | 40 | (2) | 14.9 | 800 |
| April 27, 1977 | 30 | 2.5 | 45 | 2500 x) |
| Sept. 8, 1977 | 23 | 4 | 43 | 2400 x) |
| Nov. 2, 1977 | 2 | 0.5 | 9.5 | 520 |
| Jan. 7, 1978 | 380 | 23 | 8.9 | 500 |
| July 10, 1978 | 57 | 9 | 11.1 | 600 |

x) The rate of flow probably too high due to southward flow, past the tilt station. Values somewhere between 1500 and 2000 are considered more likely.

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Krafla caldera and $0.72 \times 10^8$ $m^3$ south of the center of the caldera. About $2.4 \times 10^6$ $m^3$ has been erupted in three eruptions.

The new dike can be assumed to extend as far towards north and south as significant ground fissures or earthquake epicenters are observed. The total length of this zone is about 80 km. By dividing the dike length into the dike volume, we get the average cross-sectional area of the dike as 4900 $m^2$.

Table XIII shows that the subsidence events with magma flow towards south (April 27, 1977 and September 8, 1977) are associated with maximum tilt rate in the Krafla power house, which is about three times higher than if the flow is towards north. It also appears, that the duration from the beginning of a subsidence event to the time of maximum tilt rate is longer if the subsidence event lasts for a long time. It may be that the time from the beginning of a subsidence event to the time of maximum tilt rate is correlated to the distnace from the Krafla magma chamber to the part of the fissure zone where the magma is deposited.

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NOTE

The north-south component of the water tube tiltmeter in the Krafla power house has a direction, which deviates some 10° to 15° clockwise from true north-south direction. The components of the electronic tiltmeter in the Krafla power house are parallel to and perpendicular to the north-south water tube tiltmeter. Reported tilt directions in the Krafla power house (Fig. 10, 14, 20, 22, 25 and 27, and in text) are not corrected for this deviation of directions in this report.