NORDIC VOLCANOLOGICAL INSTITUTE 78 02
UNIVERSITY OF ICELAND

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# 1976-1977

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## ABSTRACT

Observations of ground tilt in the Krafla-Mývatn area in North Iceland since early 1976 show continuous swelling of the center of the Krafla caldera interrupted by short periods of rapid subsidence. The uplift fits into a model which assumes inflation of a spherical body within homogeneous elastic halfspace. The center of this hypothetical body lies at a depth of approximately 2900 meters below the earth´s surface and the rate of volume increase is approximately 400.000 $m^3$ per day or 5 $m^3$/sec. The maximum tilt rate is about 2.4 microradians per day, but at distances exceeding 10 km from the center of inflation, the tilt is not measureable with the method used. The periods of rapid subsidence of the Krafla caldera usually last for less than 48 hours and happen at intervals of one to five months. These are associated with uplift of the ground outside the Krafla caldera, at different locations for different subsidence events, but always associated with the fissure swarm which cuts through the center of the caldera from N´15°E to S´15°W.

## INTRODUCTION

The accumulation of magma at shallow depth beneath active volcanoes can be observed by repeated levelings, gravity observations or by repeated or continuous tilt observations. The tilt observations have been prooven to be very effective in determination of the location and depth of the hypothetical magma chamber below a volcano (Eaton, 1959). The rate of inflow of magma into a hypothetical shallow magma chamber can also be obtained from tilt observations, assuming a model of spherical chamber, using the equations presented by Mogi (1958).

The eruption in the Krafla area, North Iceland on December 20, 1975 (Björnsson et al., 1977) was associated with very significant ground movements, both horizontical and vertical. Continuation of volcanic unrest in that area offers a opportunity to observe the magnitude and time sequence of the subsurface mass movement associated with this unrest. Various observational techniques have been applied in these observations, but this paper concentrates on the ground tilt observations, which were started in early 1976 and have since been continued and expanded.

The system of tilt measurements was developed in light of the available instrumentation and the experience at other volcanic areas, especially Hawaii (Kinoshita et al., 1974). Water tube tilt meters were considered, but the long freezing season in winter makes them not suitable for frequent measurements around the year. However, one permanent water tube tiltmeter was installed in the Krafla Power House in August, 1976, where daily readings are taken.

The technique adopted was a modification of the spirit-level telescopic tilt observations as employed in Hawaii (Kinoshita et al., 1974). The modification is that the fixed markers at each tilt station are 5 or 6, instead of three in Hawaii, and the level telescope is placed in the center of a circle formed by the bench marks. One invar leveling rod is carried from one marker to the next around the circle, usually two times in opposite directions during each observation. The optical level used is Wild N-3 with Kern invar rods. The sight distances are all of equal length, 25.0 meter.

With leveling accuracy of 0.1 mm, the precision in tilt observations should be 2 to 4 microradians, if all bench marks move as if they were on a single rigid basement. As more than 3 bench marks are employed at each tilt station, the observations also show if the ground behaves as rigid body within the 50 m diameter circle of the station. During the summer of 1976, six spirit level tilt stations were under observation and six more stations were added in early summer of 1977. Two of these tilt stations are not of the circular type. Tilt observations were made approximately once every month during the summer, but very few observations have been made during the winter due to the snow cover on the tilt stations.

It became clear in 1977 that many details of the tilt changes were lost due to infrequent observations, especially during the winter. Even the daily readings of the water tube tiltmeter in the Krafla Power House were not sufficient to show the variations in rate of tilting during the rapid subsidence of the Krafla caldera. Therefore, continuously recording tiltmeters were constructed and installed, one near the Krafla Power House and another near Reykjahlíd during the summer and fall of 1977. These tiltmeters are of a new design, which uses magnetoresistors and suspended permanent magnet in the transducer. The sensitivity of these tiltmeters appears to be approximately $10^{-8}$ radians, but their temporal stability is as yet unknown.

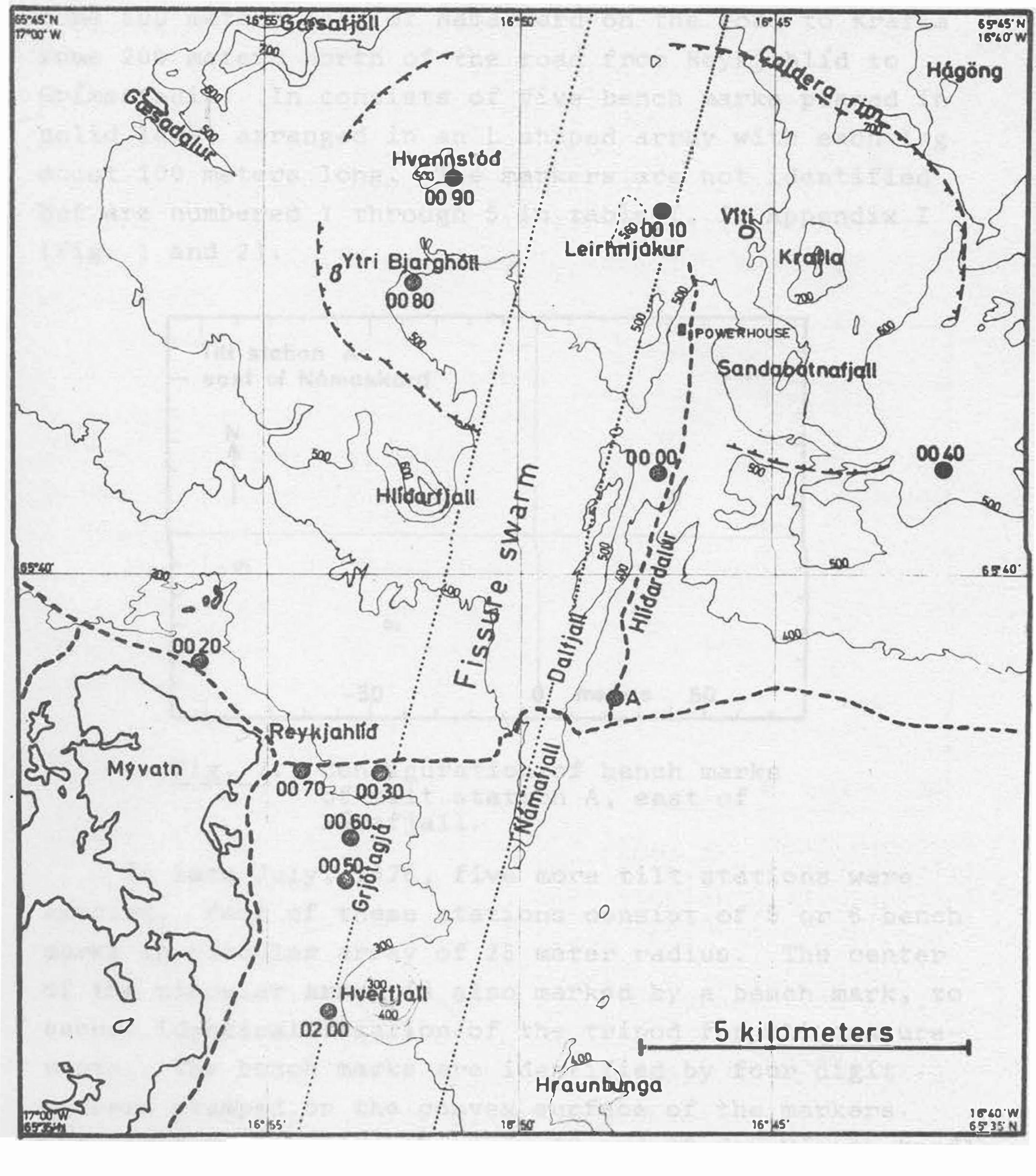

Fig. 1. Location of spirit level tilt stations in the Krafla-Mývatn region.

## THE TILT STATIONS

The first tilt station in the Mývatn-Krafla area was constructed in late January, 1976, about one month after the 1975 eruption. This tilt station is located some 500 meters east of Námaskard on the road to Krafla some 200 meters north of the road from Reykjahlíd to Grímsstadir. In consists of five bench marks placed in solid lava, arranged in an L shaped array with each leg about 100 meters long. The markers are not identified but are numbered 1 through 5 in table I, 1, Appendix I (Fig. 1 and 2).

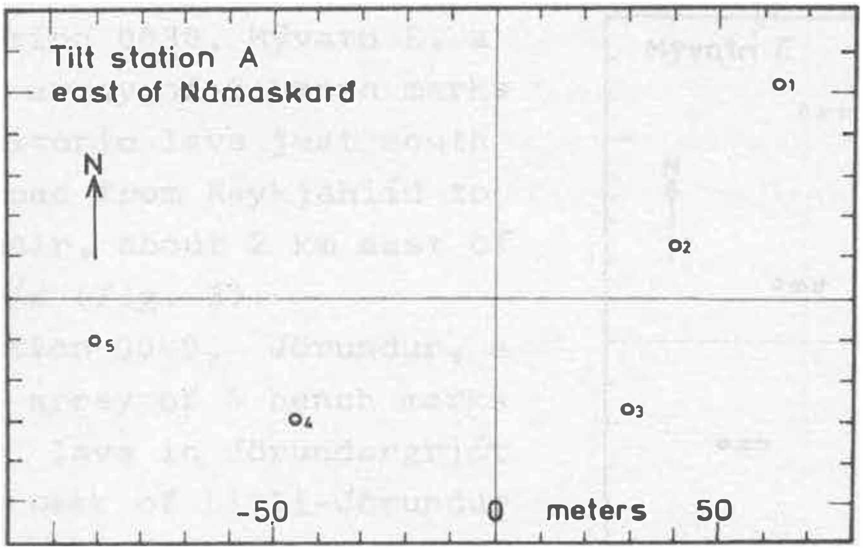

Fig. 2. Configuration of bench marks of tilt station A, east of Námafjall.

In late July, 1976, five more tilt stations were erected. Four of these stations consist of 5 or 6 bench marks in circular array of 25 meter radius. The center of the circular array is also marked by a bench mark, to secure identical location of the tripod for all measurements. The bench marks are identified by four digit numbers stamped on the convex surface of the markers. Two first digits give the area 00 and 02 for Mývatn-Krafla area. The third digit identifies the tilt station and the fourth digit identifies the bench mark within each station (1 through 5 or 1 through 6; with 0 on the central marker).

The tilt stations founded in July, 1976, are (Fig. 1):

Station 0000, Hlídardalur, circular array of 6 bench marks located on the Mývatn lava of 1727-1729 in Hlídardalur, by Hvítholaklif.

Station 0010, Leirhnjúkur, circular array of 5 bench marks located on the Mývatn lava of 1727-1729 east of Leirhnjúkur.

Station 0020, Mývatn N, a circular array of 5 bench marks on the Mývatn lava of 1727-1729 just north of the road from Reykjahlíd to Húsavík, some 1.5 km from Reykjahlíd.

Station 0030, Mývatn E, a T-shaped array of 5 bench marks on prehistoric lava just south of the road from Reykjahlíd to Grímsstadir, about 2 km east of Reykjahlíd (Fig. 3).

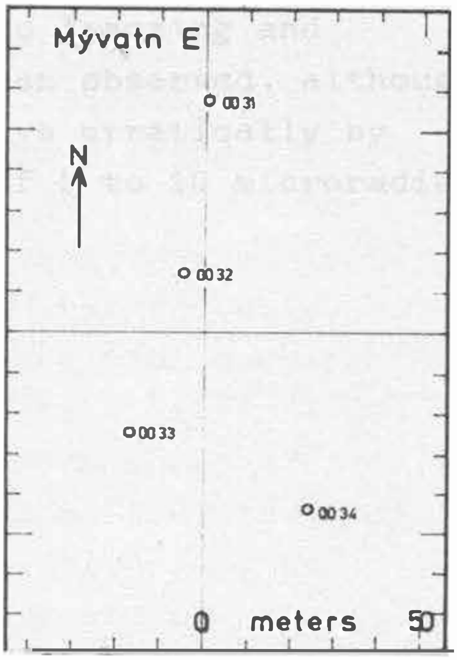

Fig. 3. Configuration of bench marks of tilt station 0030, east of Reykjahlíd.

Station 0040, Jörundur, a circular array of 5 bench marks located on lava in Jörundargrjót about 2 km west of Litli-Jörundur and 1.5 km east of Sandabotnafjall.

In mid-May, 1977, three more tilt stations were established, all consisting of 5 bench marks in circular arrays of 25 meter radius. They are:

Station 0050, Grjótagjá S, on the track from Vogar to Grjótagjá, just west of the Grjótagjá fault.

Station 0060, Grjótagjá N, just west of the Grjótagjá fault by the bathing place in Grjótagjá.

Station 0070, Reykjahlíd, just south of the road from Reykjahlíd to Grímsstadir, about 0.5 km east of Reykjahlíd.

In mid-June, 1977, three further tilt stations were constructed, all consisting of 5 bench marks in a circular array of 25 meter radius. They are:

Station 0080, Ytri-Bjarghóll, on the Mývatn lava of 1727-1729 just south of the hill Ytri-Bjarghóll, some 3 km WSW of Leirhnjúkur.

Station 0090, Hvannstód, on the Mývatn lava of 1727-1729 just east of the depression Hvannstód and some 3 km WNW of Leirhnjúkur.

Station 0200, Hverfjall, on a prehistoric lava below the southwest slope of Hverfjall (Fig. 4).

All these 12 tilt stations in the Mývatn-Krafla area are located on Post-Glacial lava (Helluhraun, Aa-lava) thereof 5 on the Mývatn lava of 1727-1729. The location of each bench mark is carefully selected to avoid possible movement of individual markers due to freezing and thawing, and no such movement has been observed, although some of the bench marks appear to move erratically by some 0.2 mm, causing uncertainity of 5 to 10 microradians in the tilt observations.

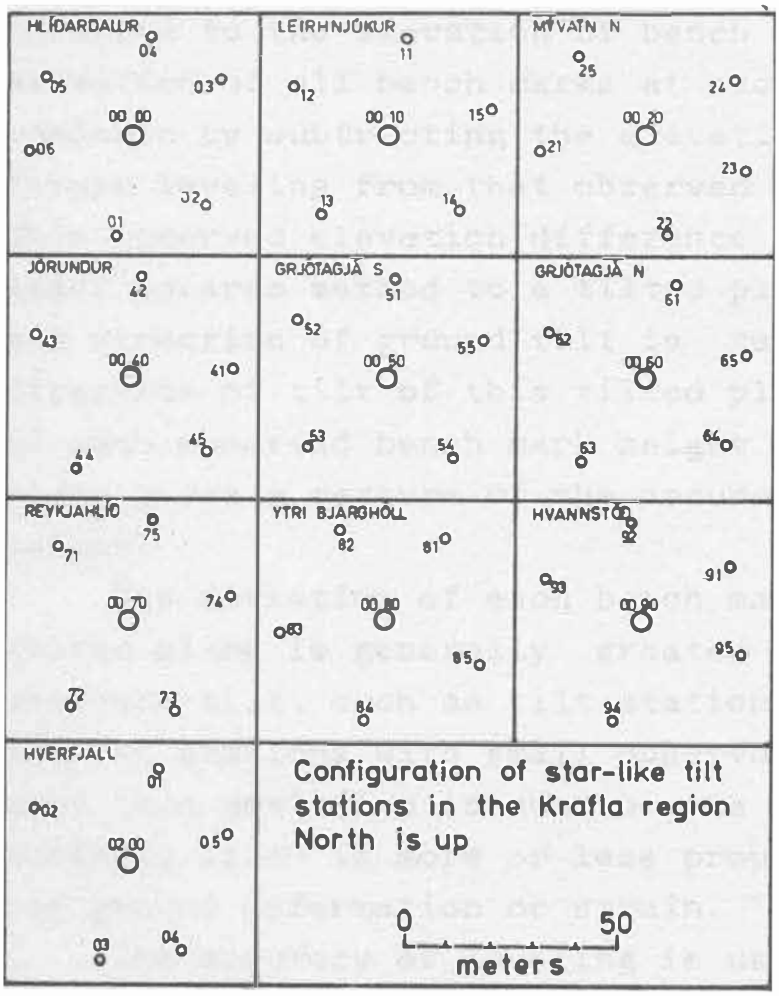

Fig. 4. Configuration of bench marks in the circular array spirit level tilt stations in the Krafla-Mývatn region.

## THE TILT OBSERVATIONS

Optical leveling with Wild N-3 level and Kern invar leveling rods are used to obtain the apparent difference in elevation of the bench marks. On the circular or star-like tilt stations, the tripod with the Wild N-3 level is placed in the center of the circle and one leveling rod is carried from one bench mark to another around the circle and again around the circle in the opposite direction. Thus all bench marks are occupied twice (three times for the starting marker) and additional measurements are made on bench marks if error is indicated when the two measurements are compared.

The L and T shaped tilt stations are leveled by conventional methods using 2 invar rods, placed on the bench marks and the level placed at the same distance from both rods.

The tilt is determined by comparing two levelings. The relative elevation of the bench marks (usually referred to the elevation of bench mark 1 or average elevation of all bench marks at each tilt station) is compared by subtracting the elevation as observed at a former leveling from that observed at a later leveling. This observed elevation difference is fitted by the least squares method to a tilted plane and the amount and direction of ground tilt is taken as the amount and direction of tilt of this tilted plane. The deviation of each observed bench mark height from the best fitted plane gives a measure of the accuracy of the tilt observation.

The deviation of each bench mark from the best fitted tilted plane is generally greater at stations with large observed tilt, such as tilt station 0010, Leirhnjúkur, than at stations with small observed tilt, which indicates that this deviation is due to some warping of the ground surface, which is more or less proportional to the regional ground deformation or strain.

The accuracy of leveling is usually about 0.1 mm, or the standard error of elevation difference of any two bench marks at each station is roughly 0.1 mm. If leveling is performed when weather conditions are unfavourable, such as strong wind or intermittant bright sunshine, the leveling accuracy may be somewhat worse, or some 0.2 mm. However, the accuracy of tilt determination is more dependent on actual relative movement of the bench marks, than on the accuracy of levelings.

For the circular array tilt stations of 25 m radius, the standard error of tilt due to observational errors is thus 2 to 4 microradians, and additional errors due to actual irregular ground warping may be similar for stations which show slight tilt, but larger for stations showing large tilt. This error is, however, difficult to determine as statistical methods are not reliable for the low number of observations at each tilt station, but it may be assumed that the tilt error due to this erratic movement of the bench marks is 10% to 20% of the actual tilt plus some constant which may be about 5 microradians. Thus observed tilt of less than 5 microradians is not significant, but if the observed tilt exceeds 10 microradians it is most likely significant. Fig. 5 shows the observed tilt vectors at the 12 spirit level tilt stations in the Krafla-Mývatn region until October 1977.

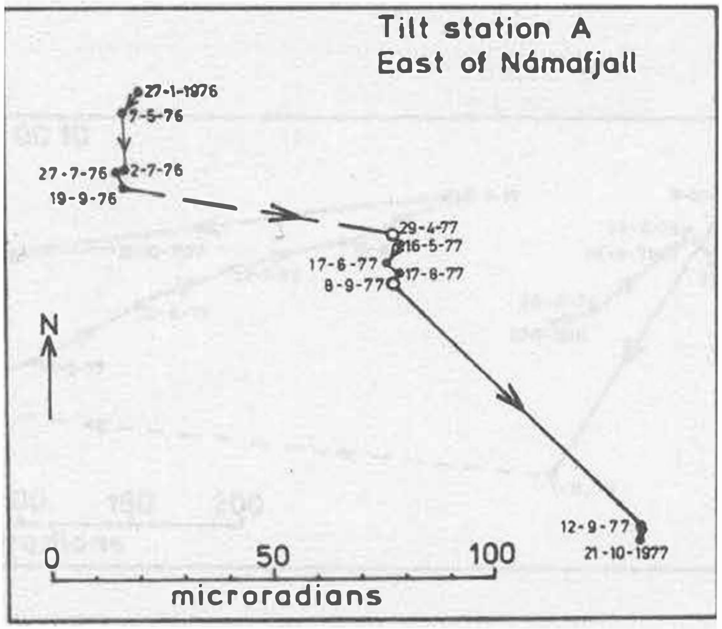

Fig. 5a.

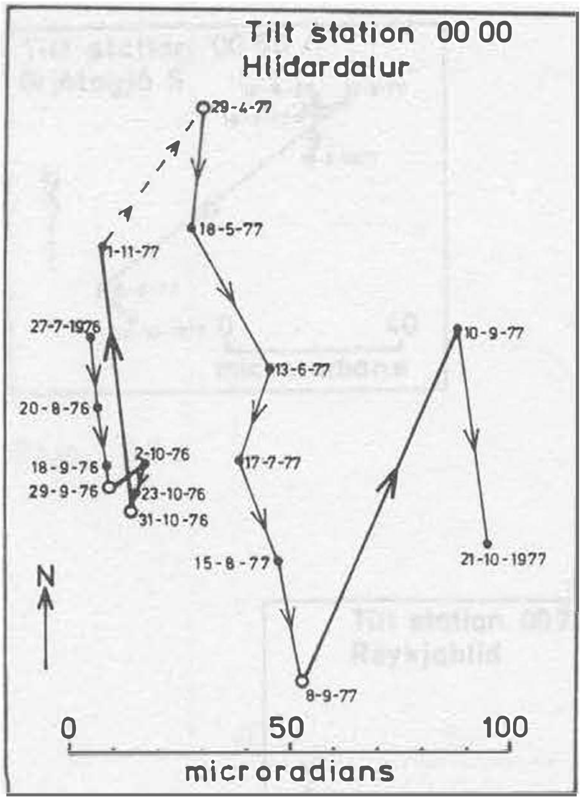

Fig. 5b.

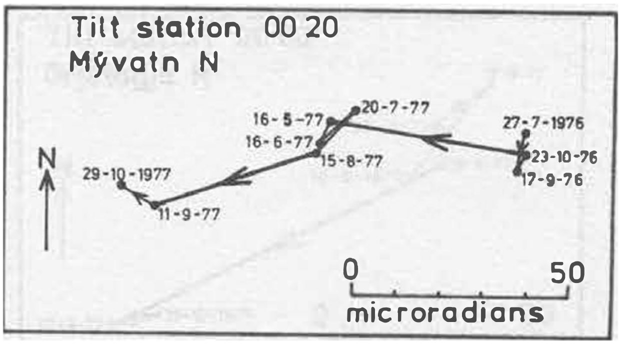

Fig. 5d.

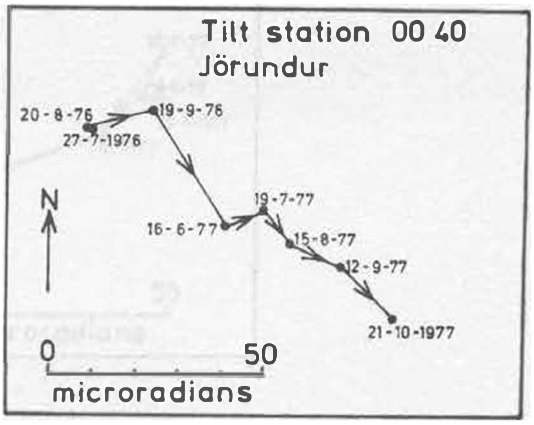

Fig. 5e.

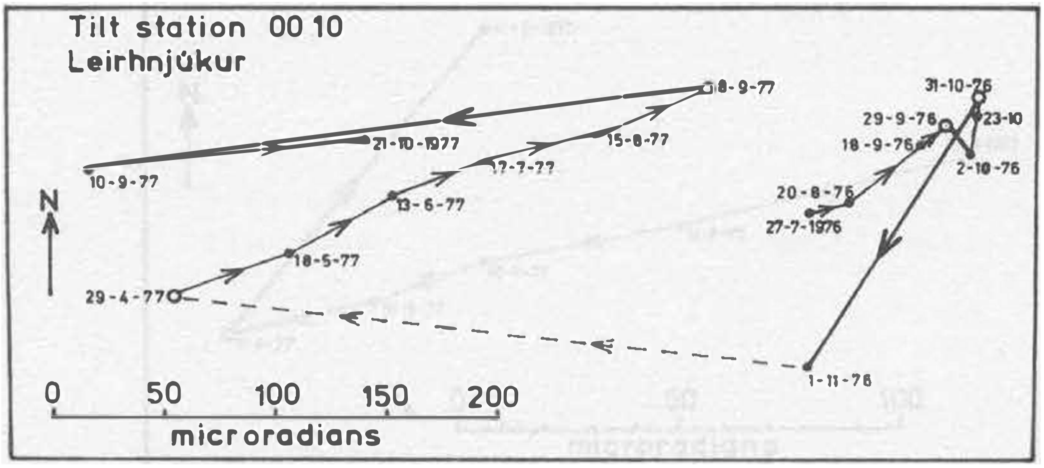

Fig. 5c.

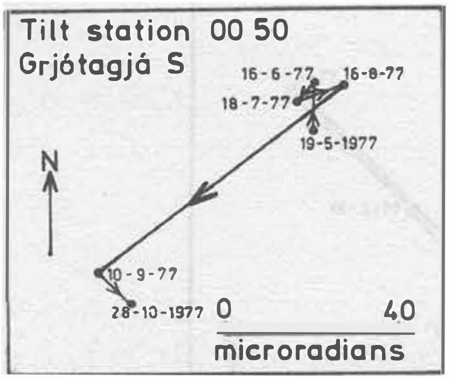

Fig. 5f.

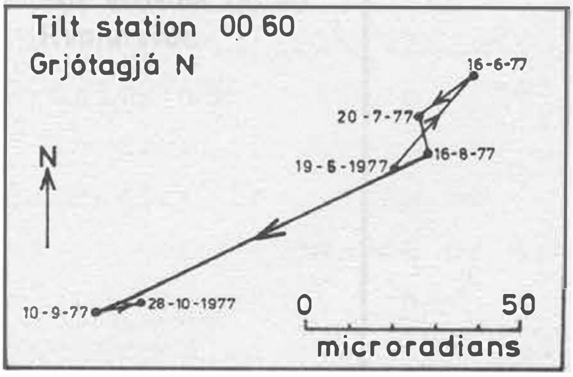

Fig. 5g.

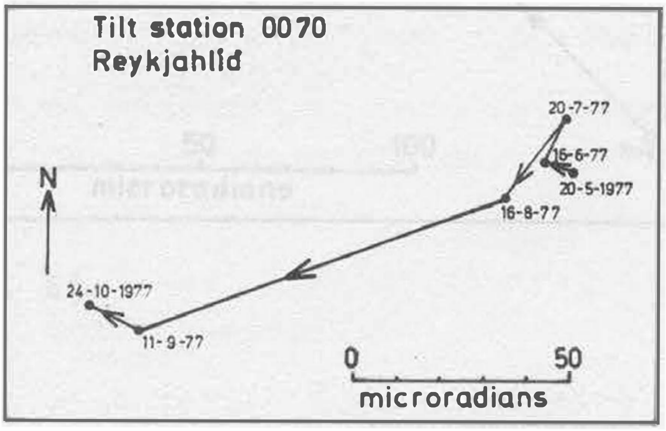

Fig. 5h.

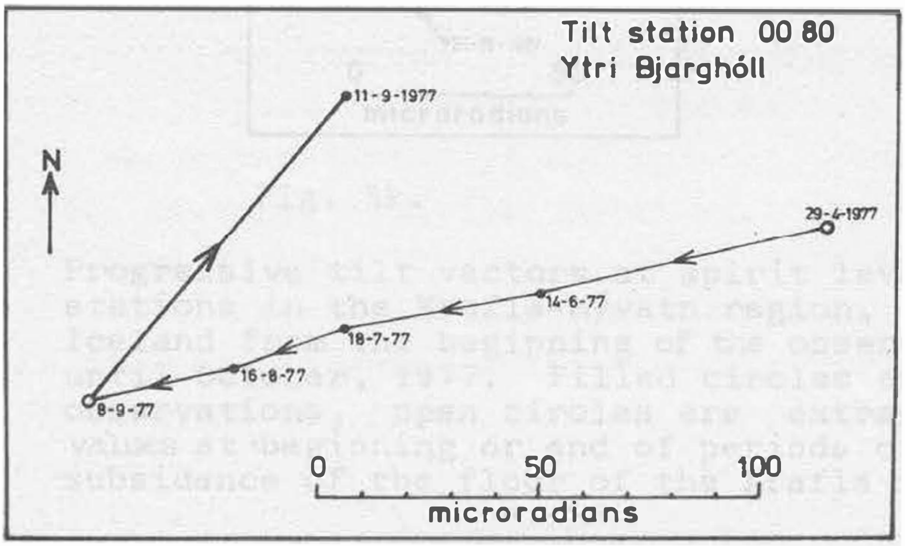

Fig. 5i.

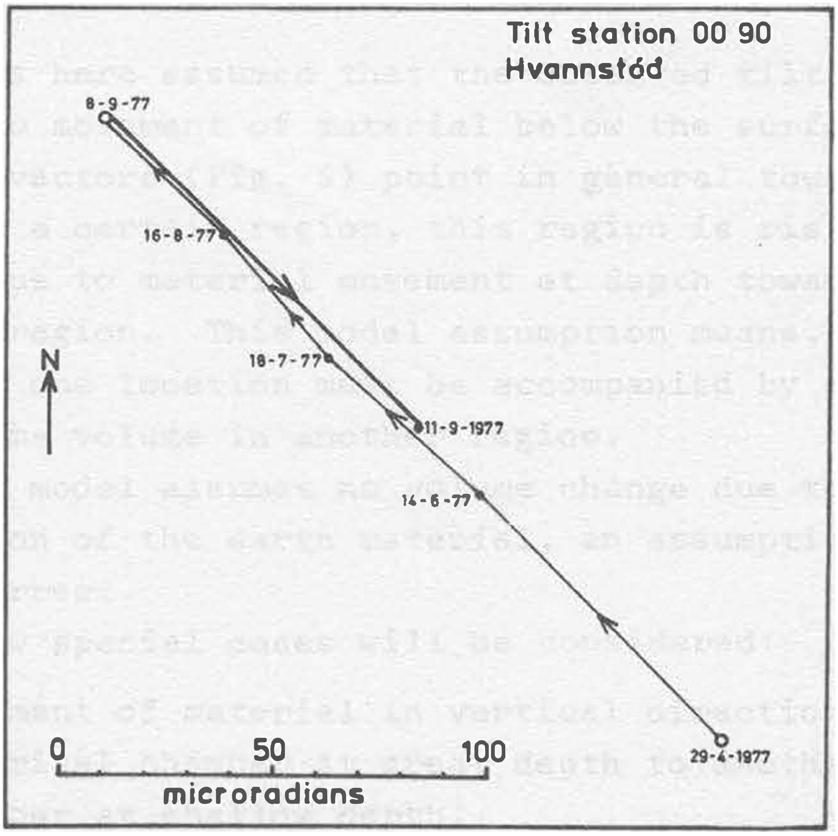

Fig. 5j.

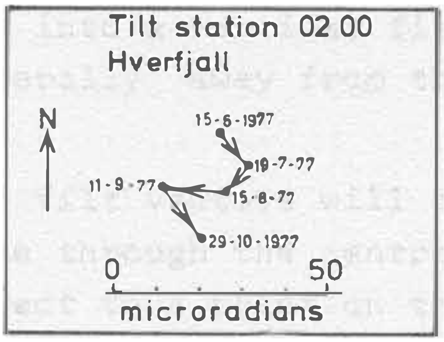

Fig. 5k.

Fig. 5. Progressive tilt vectors at spirit level tilt stations in the Krafla-Mývatn region, North-Iceland from the beginning of the observations until October, 1977. Filled circles are tilt observations, open circles are extrapolated values at beginning or end of periods of rapid subsidence of the floor of the Krafla caldera.

## INTERPRETATION OF THE TILT OBSERVATIONS

It is here assumed that the observed tilt variations are due to movement of material below the surface. If the tilt vectors (Fig. 5) point in general towards or away from a certain region, this region is rising or sinking due to material movement at depth towards or away from the region. This model assumption means, that uplift at one location must be accompanied by subsidence of the same volume in another region.

This model assumes no volume change due to compression or dilation of the earth material, an assumption which may not be correct.

A few special cases will be considered:

I. Movement of material in vertical direction from a spherical chamber at great depth to another spheri- chamber at shallow depth.

II. Movement of material in horizontal direction between two spherical chambers.

III. Movement of material from a spherical chamber at shallow depth into a vertical fissure (dike) extending laterally away from the spherical chamber.

In case I the tilt vectors will be symmetric with respect to any line through the central point and will lie radially with respect to a point on the earth´s surface vertically above the center of the spheres. The variation of tilt with distance from this point will approximately agree with Mogi´s equation (Mogi, 1958). If the lower chamber is much deeper than the shallower chamber, the tilt near the central point will be nearly that of inflation of one spherical volume, while at greater distance from the central point, tilt will be less than the one-sphere model will give.

In case II the tilt will be symmetric with respect to a line through surface points vertically above the two spheres and antisymmetric with respect to a line perpendicular to the line connecting the two sphere, midways between the centers of the two spheres.

In case III a more irregular picture of theoretical tilt will appear, but the tilt will be symmetrical around the dike or tensional fissure.

Tilt due to other causes than material movement may also occur, and the following cases should be considered:

A. Thermal expansion or contraction.

B. Increase or decrease of vapour pressure.

C. Dilatancy.

D. Metamorphism, crystallization or recrystallization.

The observed tilt can be classified into two categories, 1: a slow inflation of the Leirhnjúkur area, and 2: rapid deflation of the same area associated with major deformation outside the Leirhnjúkur area.

During the slow inflation periods, which cover approximately 97 to 98% of the time, the tilt vectors point all away from a location near the south end of Leirhnjúkur and the amount of tilt and its variation with distance from the central point agree with volume increase of a sphere centered at about 3 km depth below the south end of Leirhnjúkur. The tilt is not measurable with the method here used at distances greater than 10 km and at a distance slightly less than 10 km (tilt station A) the observed tilt is considerably less than theory accounts for. This may be interpreted either as effect of the "lower sphere" which is decreasing in volume, and should then be at roughly 10 km depth, or due to deviation from homogeneity in the earth´s crust. The amount of material flowing into the spherical chamber at 3 km depth below Leirhnjúkur is 4.5 to 5.2 $m^3$/sec and has been nearly constant from mid-1976 to mid-1977.

The short periods of subsidence in the Leirhnjúkur area have been associated with major movements on the fissure swarm through Leirhnjúkur but at different location at different times.

The tilt variation during these subsidence events indicates material movement away from the hypothetical spherical chamber below Leirhnjúkur into vertical fissure (dike) towards north or south or both, associated with surface rifting. During the subsidence event at the end of September, 1976, tilt measurements in Hlídardalur indicate some dike formation to the south of Leirhnjúkur, although seismic observations indicate rifting near Hrútafjöll, north of Leirhnjúkur, but in that area no tilt observations were made.

The subsidence event on October 31 to November 1, 1976, seems to have been associated with material movement towards north only, and tilt measurements near Leirhnjúkur and farther south show only the effect of the subsidence near Leirhnjúkur, but seismic observations, surface rifting and formation of new steam fields indicate material movement towards the south end of Gjástykki, 10 to 15 km north of Leirhnjúkur.

The subsidence event on January 20-21, 1977, seems to have been very similar to that of October 31 to November 1, although somewhat smaller, with material movement towards north, some 6 to 8 km north of Leirhnjúkur. No tilt measurements were made on the tilt stations discussed here due to the snow cover.

The subsidence event of April 27 to 29, 1977, was associated with a very small eruption about 4 km north of Leirhnjúkur and major surface rifting from the eruption site towards south across Leirhnjúkur, Bjarnarflag and Hverfjall to a point about 20 km south of Leirhnjúkur. The tilt observations indicate that the major material flow was into a dike towards south, but some flow was towards north. The depth to the upper and lower edge of the dike can be approximately determined as 1.5 and 3 km from tilt measurements, widening and width of the rifted zone and subsidence of the rifted zone.

The subsidence event of September 8 to 9, 1977, was associated with a small eruption about 4 km north of Leirhnjúkur, very small eruption through a drilled well in Bjarnarflag and widespread rifting from the eruption site north of Leirhnjúkur towards south across Leirhnjúkur towards Bjarnarflag. Tilt observations indicate that the major material flow was towards south with maximum accumulation some one to two kilometers north of Bjarnarflag. The dike reached a shallower depth than that of April 27 to 29, probably less than one kilometer in the Bjarnarflag area.

Thus all the subsidence events in the Leirhnjúkur area appear to be associated with material (magma) flow into a dike towards north or south or both. The amount of material can be roughly estimated as 10 million $m^3$ for the event at the end of September 1976, 30 million $m^3$ on October 31 to November 1, 1976, 20 million $m^3$ on January 20 to 21, 1977, 50 million m on April 27 to 29, 1977, 20 million $m^3$ on September 8 to 9, 1977 and 2 million $m^3$ on November 2, 1977, but this last event was only observed on tiltmeters in the Krafla Power House and by its seismic effect. Nothing is known about direction of material flow in that event.

During the period from March 1976 to December 1977, some 150 million cubic meters of material has been added to the magma chamber below Leirhnjúkur in addition to the 130 million cubic meters that has flowed away from this magma chamber in six subsidence events. The total inflow of material into the Leirhnjúkur magma chamber in this period of some 650 days is thus some 330 million cubic meters or about 0.4 million cubic meters per day on the average.

## THE INFLATION PERIOD APRIL 28 TO SEPTEMBER 8, 1977

The subsidence event which started on April 27, 1977 at $13^h17^m$ lasted for about 48 hours and measurable inflation commenced again in the afternoon of April 29. This inflation continued without a break until the afternoon of September 8, 1977, when another subsidence event started. This continuous inflation of the Krafla area lasted thus for 132 days. The ground tilt observations made during this period were as follows:

Daily observations of N-S component of a water tube tiltmeter in the Krafla Power House with a break between July 5 and July 10 due to instrument failure.

Daily observations of E-W component of a water tube tiltmeter in the Krafla Power House from the beginning of the inflation period to May 12 and from May 27 to July 4.

Continuous recording of the N-S component of a new electronic tiltmeter with magneto-resistor transducer in the Krafla Power House from August 16, 1977 to the end of the inflation period and daily readings of the E-W component of the same tiltmeter during the same period.

Observations once every month from mid-May to mid-August at 7 tilt stations using optical level and invar rods. Four more such stations were observed once every month from mid-June and two additional stations were observed at less frequent intervals. Only 6 of these dry-tilt stations are sufficiently close to the inflation area to show significant tilt during the inflation period.

The N-S component of the water tube tiltmeter in the Krafla Power House shows continuous tilt down to the south throughout the inflation period, amounting to 18.28 millimeters along a base line of 68.95 meter, or 265 microradians. This tiltmeter is located about 20 meters above ground on the concrete walls, which are insulated on the outside. However, some temperature difference may occur between the north and south walls and the corresponding thermal expansion is known to cause errors of approximately 0.2 millimeters or 3 microradians in extreme cases. Much larger errors (up to 10 microradians) were observed in August and September 1976, prior to the insulation of the Power House.

To obtain the ground tilt at the dry-tilt stations for the whole inflation period, the observed tilt between first and last observation during the inflation period was multiplied by $T_0/T_1$ where $T_0$ is the N-S tilt in the Power House for the whole inflation period and $T_1$ is the Power House tilt for the period between the dry-tilt observations. This method presumes that variations of tilt with time are similar at all tilt stations. The azimuth of the tilt vector is assumed to be the same for the whole inflation period as for the observation period. The tilt for the whole inflation period, thus corrected for time of observation is given in Table 1.

The tilt vectors are shown on a map at the location of the tilt stations (Fig. 6). They all point away from a location near the south end of Leirhnjúkur, which appears to be the center of the inflation. The tilt clearly diminishes with distance from the center of inflation, except for very close distances. This behaviour is expected if the tilt is due to expansion of a relatively small magma chamber lying beneath the center of inflation. If such a magma chamber is spherical and the surroundings behave as homogenous elastic solid the theoretical surface tilt can be calculated.

Taking H as the depth to the center of the spherical magma chamber and h the increase in land elevation at distance r from the center of the inflation bulge, then is (Eaton, 1959):

$$h = K \frac{H}{(H^2+r^2)^{3/2}} \qquad (1)$$

and the ground tilt

$$\tau = \genfrac{}{}{0pt}{}{h}{r} \qquad \genfrac{}{}{0pt}{}{3K}{h^3} \quad \frac{r/h}{1+(r/h)^2 \;\; 5/2} \qquad (2)$$

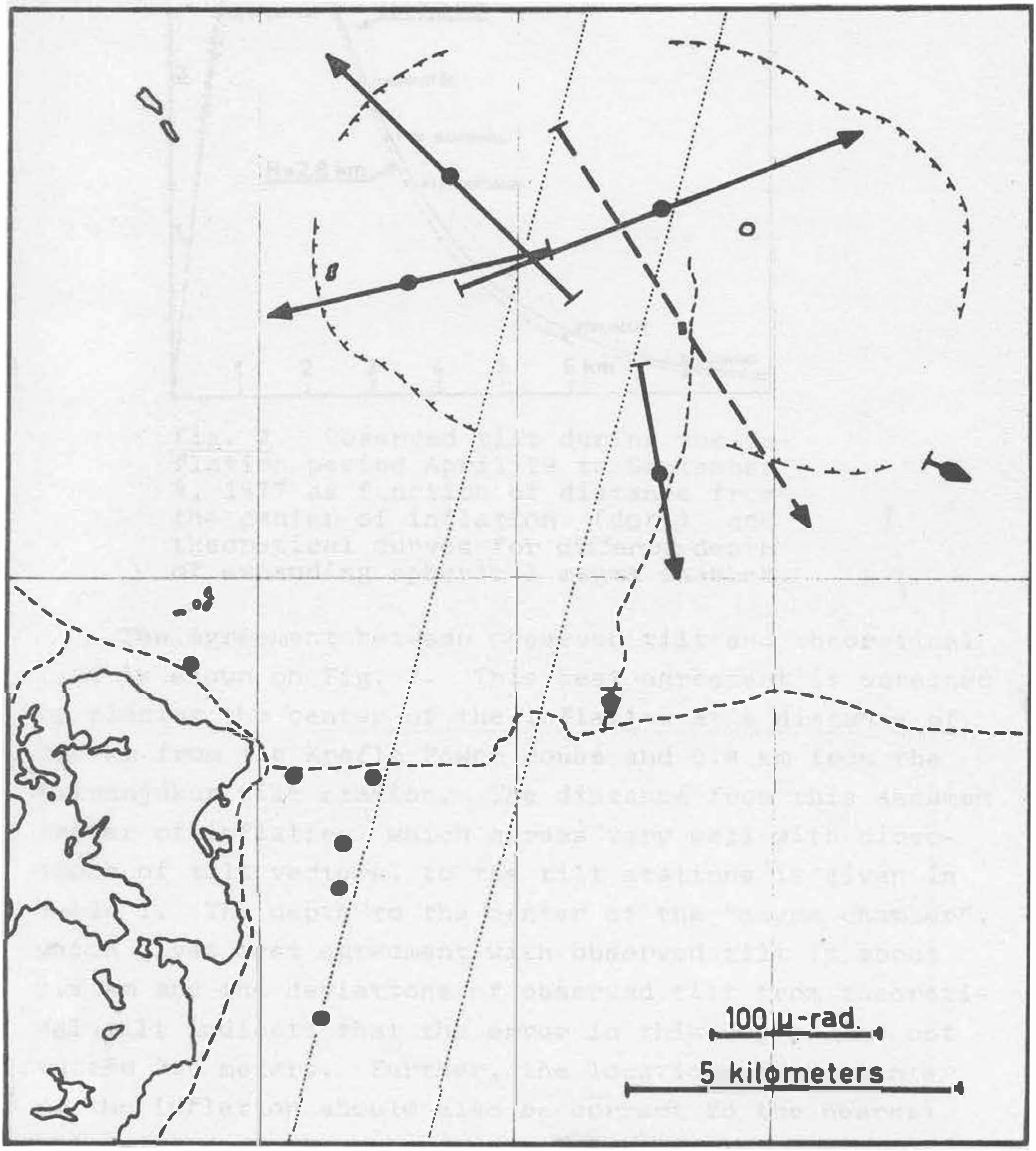

Fig. 6. Tilt vectors during the inflation period April 29 to September 8, 1977. The direction of the tilt at Krafla Power House is taken from the electronic tiltmeter.

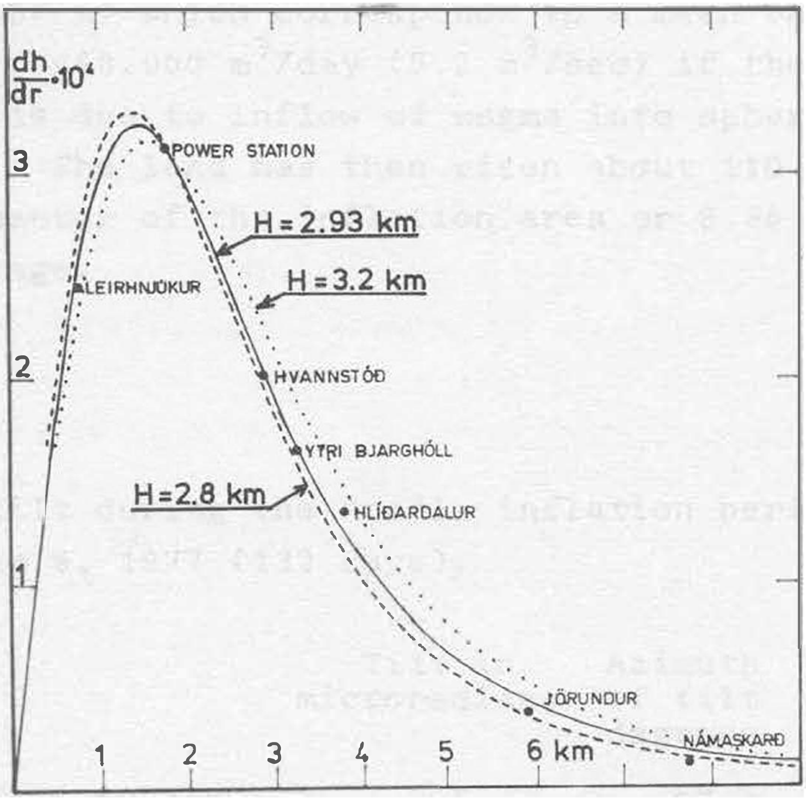

Fig. 7. Observed tilt during the inflation period April 29 to September 8, 1977 as function of distance from the center of inflation (dots) and theoretical curves for different depth of expanding spherical magma chamber.

The agreement between observed tilt and theoretical tilt is shown on Fig. 7. This best agreement is obtained by placing the center of the inflation at a distance of 1.6 km from the Krafla Power House and 0.8 km from the Leirhnjúkur tilt station. The distance from this assumed center of inflation, which agrees very well with directions of tilt vectors, to the tilt stations is given in Table 1. The depth to the center of the "magma chamber", which gives best agreement with observed tilt is about 2.9 km and the deviations of observed tilt from theoretical tilt indicate that the error in this depth does not exceed 200 meters. Further, the location of the center of the inflation should also be correct to the nearest 200 meters.

The total volume of the uplift during the 132 days of inflation is in the above best model calculated to be

59.5 x $10^6$ $m^3$ which corresponds to a mean rate of magma inflow of 450.000 $m^3$/day (5.2 $m^3$/sec) if the whole inflation is due to inflow of magma into spherical magma chamber. The land has then risen about 110 centimeters at the center of the inflation area or 8.36 mm/day on the average.

TABLE 1

Ground tilt during the Krafla inflation period April 29 to September 8, 1977 (132 days).

| Station | Tilt in microradians | Azimuth of tilt degrees | Distance from center of uplift, km |
|---|---|---|---|
| Leirhnjúkur (0010) | 245 | 67 | 0.8 |
| Krafla Power House | 312 | 150 | 1.8 |
| Hvannstód (0090) | 202 | 317 | 2.9 |
| Ytri-Bjarghóll (0080) | 165 | 255 | 3.25 |
| Hlídardalur (0000) | 135 | 172 | 3.8 |
| Jörundur (0040) | 36 | 115 | 5.9 |
| Námaskard (A) | (11) | (180) | 7.25 |

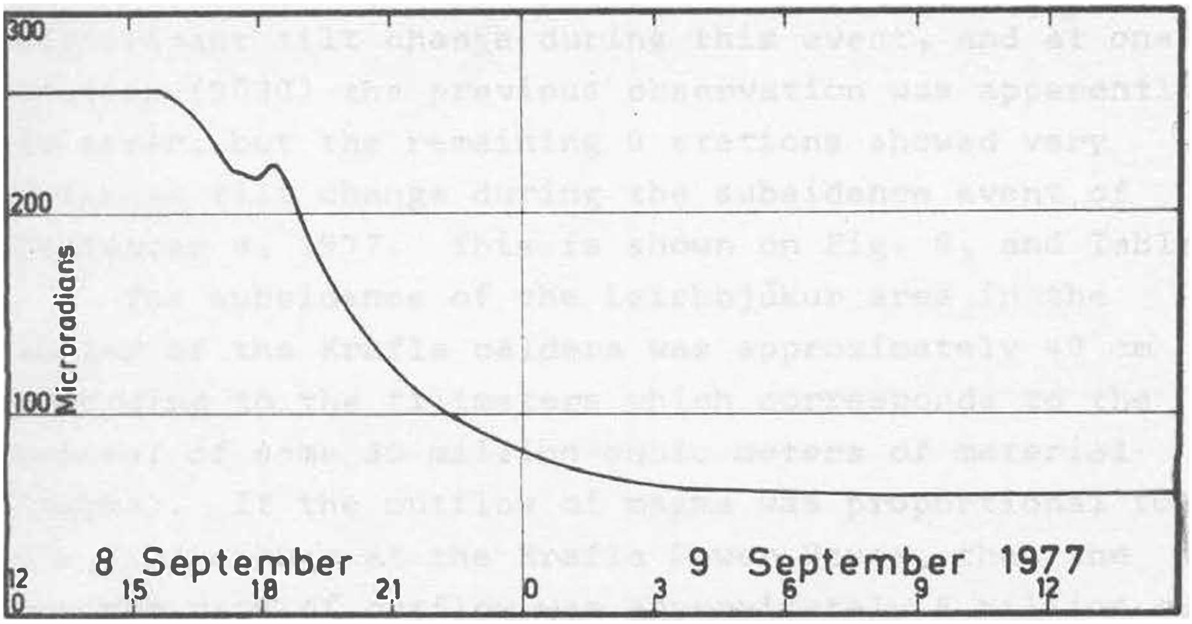

Fig. 8. Tilt record of the N-S component of the electronic tiltmeter in the Krafla Power Station during the subsidence event of September 8-9, 1977.

## THE SUBSIDENCE EVENT OF SEPTEMBER 8, 1977

The recording tiltmeter in the Krafla Power House showed a prominent and sudden reversal in the tilt on September 8, 1977 at $16^h40^m$ local time. The normal pattern of the tiltmeter record is rising to the north or north-northwest at a rate of approximately 2 microradians per day, but during the tilt reversal there was a subsidence to the north amounting to approximately 200 microradians in less than 24 hours (Fig. 8). This subsidence was accompanied by continuous tremor (volcanic tremor) on the local seismometers, outpouring of lava, which started at about $18^h$ local time some 4 km north of the previous center of inflation and a very small eruption through a borehole in Bjarnarflag some 8 km south of the center of inflation at about $22^h30^m$.

The sprit level tilt stations in the Krafla-Mývatn area had been occupied regularly during several months prior to the September 8 subsidence event, so their tilt, immediately prior to this event can be determined with fair accuracy. A new observation was made on all these tilt stations during September 10 to 12, which gave the tilt immediately after the subsidence event. Two of the stations (0040 and 0200) showed no or barely significant tilt change during this event, and at one station (0030) the previous observation was apparently in error, but the remaining 9 stations showed very definite tilt change during the subsidence event of September 8, 1977. This is shown on Fig. 9, and Table 2.

The subsidence of the Leirhnjúkur area in the center of the Krafla caldera was approximately 40 cm according to the tiltmeters which corresponds to the removal of some 30 million cubic meters of material (magma). If the outflow of magma was proportional to the tilt change at the Krafla Power House, then the maximum rate of outflow was approximately 6 million cubic meters per hour or more than 1500 $m^3$ per second.

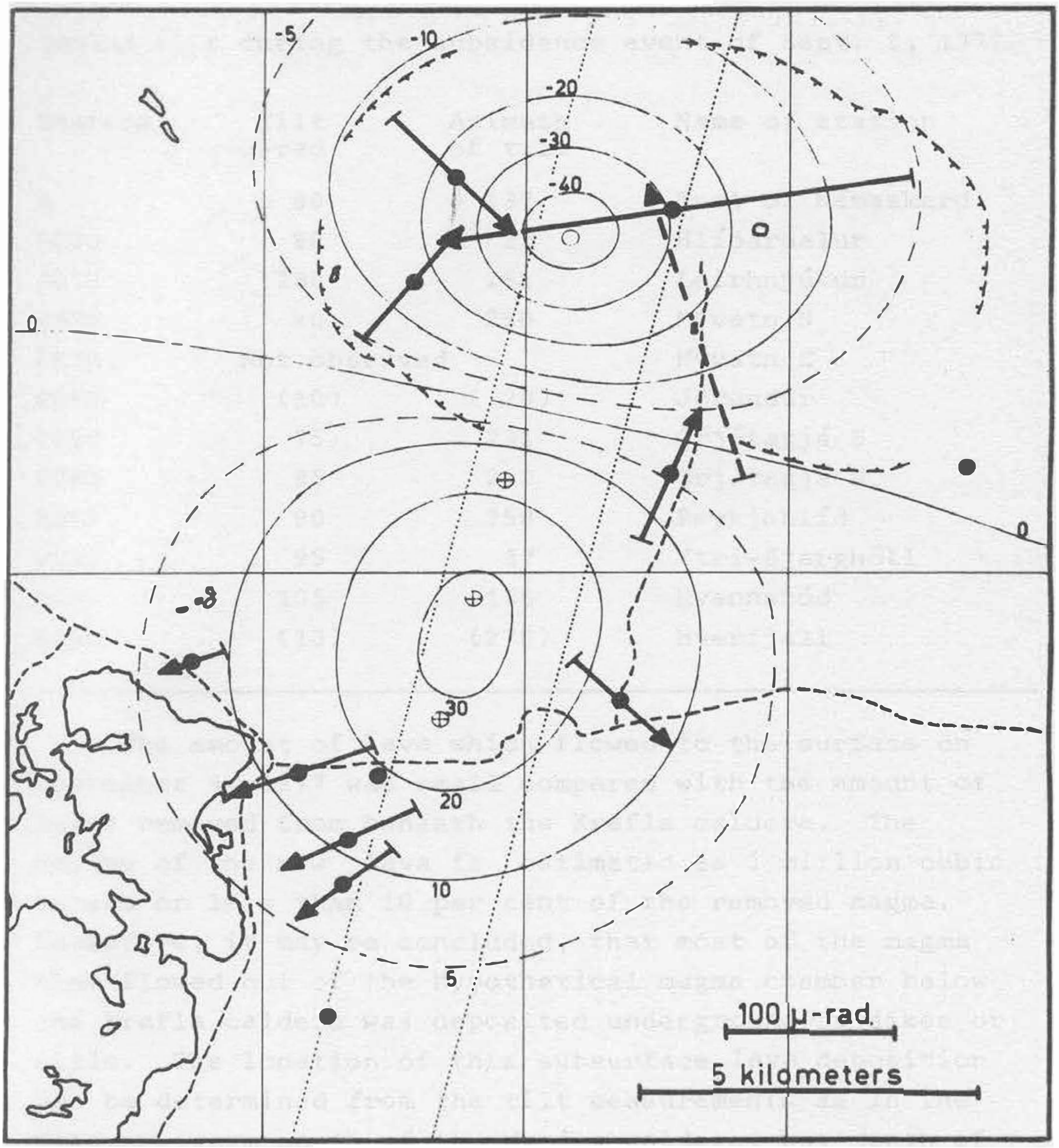

Fig. 9. Tilt vectors associated with the subsidence event of September 8-9, 1977. Curves show vertical ground movement in centimeters if 28.3 x $10^6$ $m^3$ of magma was removed from a spherical chamber at Leirhnjúkur (open circle) and distributed equally in 3 spherical chambers (circles with crosses) south of Leirhnjúkur.

TABLE 2

Ground tilt during the subsidence event of Sept. 8, 1977

| Station | Tilt u-rad | Azimuth of tilt | Name of station |
|---|---|---|---|
| A | 80 | 137 | East of Námaskard |
| 0000 | 90 | 23 | Hlídardalur |
| 0010 | 280 | 261 | Leirhnjúkur |
| 0020 | 40 | 250 | Mývatn N |
| 0030 | Not observed | | Mývatn E |
| 0040 | (10) | (120) | Jörundur |
| 0050 | 75 | 231 | Grjótagjá S |
| 0060 | 85 | 242 | Grjótagjá N |
| 0070 | 90 | 250 | Reykjahlíd |
| 0080 | 95 | 37 | Ytri-Bjarghóll |
| 0090 | 105 | 136 | Hvannstód |
| 0200 | (10) | (270) | Hverfjall |

The amount of lava which flowed to the surface on September 8, 1977 was small compared with the amount of magma removed from beneath the Krafla caldera. The volume of the new lava is estimated as 2 million cubic meters or less than 10 per cent of the removed magma. Therefore, it may be concluded, that most of the magma that flowed out of the hypothetical magma chamber below the Krafla caldera was deposited underground in dikes or sills. The location of this subsurface lava deposition can be determined from the tilt measurements as in the fissure swarm south of the Krafla caldera, but north of Bjarnarflag.

Fig. 9 shows the predicted subsidence in the Krafla caldera and the uplift south of the caldera if $28.3 \times 10^6$ $m^3$ of material is removed from a spherical chamber at 3 km depth and deposited at 3 km depth in three locations within the fissure swarm south of the caldera, assuming purely elastic deformation in homogeneous halfspace. This calculated subsidence and uplift is in fair agreement with the observed tilt, so both amount of magma flow and location of outflow and inflow must be similar to that assumed in Fig. 9.

## APPENDIX I

Tables of relative bench mark elevation at spirit level tilt stations in the Krafla-Mývatn region, and change of the relative elevation since the first observation at each station. The relative elevation of a bench mark is the bench mark elevation minus the average elevation of all bench marks at the tilt station in question.

TABLE I, 1 Tilt station A, east of Námaskarð

| Bench marks | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Date of observation | Relative elevation of bench marks in centimeters | | | | |
| 27/1 1976 | -24.394 | 6.612 | -14.402 | 22.574 | 9.610 |
| 7/5 1976 | -24.346 | 6.642 | -14.414 | 22.552 | 9.566 |
| 2/7 1976 | -24.279 | 6.669 | -14.457 | 22.525 | 9.541 |
| 27/7 1976 | -24.277 | 6.697 | -14.476 | 22.527 | 9.529 |
| 19/9 1976 | -24.270 | 6.709 | -14.493 | 22.516 | 9.539 |
| 16/5 1977 | -24.564 | 6.427 | -14.687 | 22.733 | 10.090 |
| 17/6 1977 | -24.530 | 6.475 | -14.718 | 22.732 | 10.040 |
| 17/8 1977 | -24.537 | 6.466 | -14.730 | 22.727 | 10.075 |
| 12/9 1977 | -24.525 | 6.268 | -15.045 | 22.814 | 10.488 |
| 21/10 1977 | -24.505 | 6.273 | -15.058 | 22.810 | 10.480 |
| | Change in relative elevation of bench marks since 27 Jan. 1976 in millimeters. (Relative elevation at given date minus relative elevation on 27 Jan. 1976) | | | | |
| 27/1 1976 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 7/5 1976 | 0.48 | 0.30 | -0.12 | -0.22 | -0.44 |
| 2/7 1976 | 1.15 | 0.57 | -0.55 | -0.49 | -0.69 |
| 27/7 1976 | 1.17 | 0.85 | -0.73 | -0.48 | -0.81 |
| 19/9 1976 | 1.24 | 0.97 | -0.91 | -0.59 | -0.71 |
| 16/5 1977 | -1.70 | -1.85 | -2.84 | 1.58 | 4.81 |
| 17/6 1977 | -1.36 | -1.37 | -3.16 | 1.58 | 4.30 |
| 17/8 1977 | -1.43 | -1.46 | -3.28 | 1.52 | 4.65 |
| 12/9 1977 | -1.31 | -3.44 | -6.42 | 2.40 | 8.78 |
| 21/10 1977 | -1.11 | -3.39 | -6.55 | 2.36 | 8.70 |

TABLE I, 2 Tilt station 0000, Hlíðardalur

| Bench marks | | 0004 | 0002 | 0003 | 0004 | 0005 | 0006 |
|---|---|---|---|---|---|---|---|
| Date of observation | | Relative elevation of bench marks in centimeters | | | | | |
| 27/7 | 1976 | -18.047 | -6.288 | 2.355 | 2.771 | 5.670 | 13.539 |
| 20/8 | 1976 | -18.088 | -6.318 | 2.380 | 2.811 | 5.680 | 13.536 |
| 18/9 | 1976 | -18.107 | -6.374 | 2.422 | 2.856 | 5.707 | 13.496 |
| 2/10 | 1976 | -18.101 | -6.390 | 2.375 | 2.837 | 5.728 | 13.551 |
| 23/10 | 1976 | -18.114 | -6.391 | 2.395 | 2.854 | 5.730 | 13.527 |
| 1/11 | 1976 | -17.974 | -6.264 | 2.337 | 2.724 | 5.624 | 13.553 |
| 18/5 | 1977 | -17.918 | -6.324 | 2.295 | 2.708 | 5.664 | 13.575 |
| 13/6 | 1977 | -18.011 | -6.416 | 2.300 | 2.777 | 5.728 | 13.622 |
| 17/7 | 1977 | -18.078 | -6.455 | 2.332 | 2.745 | 5.761 | 13.595 |
| 15/8 | 1977 | -18.119 | -6.518 | 2.339 | 2.894 | 5.808 | 13.596 |
| 10/9 | 1977 | -18.017 | -6.440 | 2.177 | 2.707 | 5.837 | 13.736 |
| 21/10 | 1977 | -18.131 | -6.565 | 2.222 | 2.842 | 5.900 | 13.731 |
| | | Change in relative elevation of bench marks since 27. July, 1976 in millimeters. (Relative elevation at given date minus relative elevation on 27 July, 1976) | | | | | |
| 27/7 | 1976 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 20/8 | 1976 | -0.41 | -0.29 | 0.24 | 0.40 | 0.10 | -0.04 |
| 18/9 | 1976 | -0.60 | -0.85 | 0.66 | 0.85 | 0.37 | -0.44 |
| 2/10 | 1976 | -0.54 | -1.01 | 0.19 | 0.66 | 0.57 | 0.12 |
| 23/10 | 1976 | -0.67 | -1.03 | 0.40 | 0.83 | 0.59 | -0.12 |
| 1/11 | 1976 | 0.73 | 0.25 | -0.18 | -0.47 | -0.46 | 0.14 |
| 18/5 | 1977 | 1.30 | -0.35 | -0.61 | -0.63 | -0.07 | 0.36 |
| 13/6 | 1977 | 0.36 | -1.27 | -0.55 | 0.06 | 0.58 | 0.82 |
| 17/7 | 1977 | -0.31 | -1.67 | -0.23 | 0.74 | 0.91 | 0.56 |
| 15/8 | 1977 | -0.72 | -2.30 | -0.17 | 1.24 | 1.38 | 0.57 |
| 10/9 | 1977 | 0.30 | -1.52 | -1.78 | -0.64 | 1.67 | 1.96 |
| 21/10 | 1977 | -0.84 | -2.76 | -1.33 | 0.72 | 2.30 | 1.92 |

TABLE I, 3 Tilt station 0010, Leirhnjúkur

| Bench marks | 0011 | 0012 | 0013 | 0014 | 0015 |
|---|---|---|---|---|---|
| Date of observation | Relative elevation of bench marks in centimeters | | | | |
| 27/7 1976 | 10.408 | -4.567 | -2.591 | 2.795 | -6.045 |
| 20/8 1976 | 10.395 | -4.536 | -2.539 | 2.797 | -6.117 |
| 18/9 1976 | 10.335 | -4.519 | -2.425 | 2.793 | -6.184 |
| 2/10 1976 | 10.355 | -4.504 | -2.393 | 2.745 | -6.203 |
| 23/10 1976 | 10.319 | -4.518 | -2.344 | 2.772 | -6.229 |
| 1/11 1976 | 10.616 | -4.513 | -2.689 | 2.636 | -6.049 |
| 18/5 1977 | 10.879 | -5.433 | -2.797 | 3.022 | -5.671 |
| 13/6 1977 | 10.860 | -5.391 | -2.654 | 3.044 | -5.859 |
| 17/7 1977 | 10.806 | -5.344 | -2.493 | 2.954 | -5.923 |
| 15/8 1977 | 10.789 | -5.277 | -2.350 | 2.894 | -6.056 |
| 10/9 1977 | 11.119 | -6.021 | -2.606 | 3.107 | -5.600 |
| 21/10 1977 | 11.163 | -5.860 | -2.274 | 2.925 | -5.954 |

Change in relative elevation of bench marks since 27 July, 1976 in millimeters. (Relative elevation at given date minus relative elevation on 27 July, 1977)

| Bench marks | 0011 | 0012 | 0013 | 0014 | 0015 |
|---|---|---|---|---|---|
| 27/7 1976 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 20/8 1976 | -0.13 | 0.31 | 0.52 | 0.02 | -0.72 |
| 18/9 1976 | -0.73 | 0.48 | 1.66 | -0.02 | -1.39 |
| 2/10 1976 | -0.53 | 0.63 | 1.98 | -0.50 | -1.58 |
| 23/10 1976 | -0.89 | 0.49 | 2.47 | -0.23 | -1.84 |
| 1/11 1976 | 2.08 | 0.54 | -0.98 | -1.59 | -0.04 |
| 18/5 1977 | 4.71 | -8.66 | -2.06 | 2.27 | 3.74 |
| 13/6 1977 | 4.52 | -8.24 | -0.63 | 2.49 | 1.86 |
| 17/7 1977 | 3.98 | -7.77 | 0.98 | 1.59 | 1.22 |
| 15/8 1977 | 3.81 | -7.10 | 2.41 | 0.99 | -0.11 |
| 10/9 1977 | 7.11 | -14.54 | -0.15 | 3.12 | 4.45 |
| 21/10 1977 | 7.55 | -12.93 | 3.17 | 1.30 | 0.91 |

TABLE I, 4 Tilt station 0020, Mývatn N

| Bench marks | 0021 | 0022 | 0023 | 0024 | 0025 |
|---|---|---|---|---|---|
| Date of observation | Relative elevation of bench marks in centimeters | | | | |
| 27/7 1976 | -20.633 | 7.772 | 17.871 | 2.352 | -7.362 |
| 17/9 1976 | -20.652 | 7.753 | 17.874 | 2.359 | -7.334 |
| 23/10 1976 | -20.639 | 7.774 | 17.849 | 2.370 | -7.354 |
| 16/5 1977 | -20.739 | 7.770 | 18.000 | 2.418 | -7.449 |
| 16/6 1977 | -20.758 | 7.755 | 18.012 | 2.419 | -7.428 |
| 20/7 1977 | -20.746 | 7.779 | 18.003 | 2.384 | -7.420 |
| 15/8 1977 | -20.776 | 7.756 | 18.023 | 2.405 | -7.408 |
| 11/9 1977 | -20.864 | 7.711 | 18.123 | 2.478 | -7.449 |
| 29/10 1977 | -20.885 | 7.724 | 18.146 | 2.488 | -7.472 |
| | Change in relative elevation of bench marks since 27 July, 1976 in millimeters. (Relative elevation at given date minus relative elevation on 27 July, 1976) | | | | |
| 27/7 1976 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 17/9 1976 | -0.19 | -0.19 | 0.03 | 0.07 | 0.28 |
| 23/10 1976 | -0.06 | 0.02 | -0.22 | 0.18 | 0.08 |
| 16/5 1977 | -1.06 | -0.02 | 1.29 | 0.66 | -0.87 |
| 16/6 1977 | -1.25 | -0.17 | 1.41 | 0.67 | -0.66 |
| 20/7 1977 | -1.13 | 0.07 | 1.32 | 0.32 | -0.58 |
| 15/8 1977 | -1.43 | -0.16 | 1.52 | 0.53 | -0.46 |
| 11/9 1977 | -2.31 | -0.61 | 2.52 | 1.26 | -0.87 |
| 29/10 1977 | -2.52 | -0.48 | 2.75 | 1.36 | -1.10 |

TABLE I, 5 Tilt station 0030, Mývatn E

| Bench marks | 0031 | 0032 | 0033 | 0034 |
|---|---|---|---|---|
| Date of observation | Relative elevation of bench marks in centimeters | | | |
| 27/7 1976 | -111.971 | -58.099 | 5.031 | 165.039 |
| 19/9 1976 | -111.927 | -58.093 | 5.009 | 165.010 |
| 20/5 1977 | -112.261 | -58.270 | 5.153 | 165.378 |
| 17/6 1977 | -112.215 | -58.264 | 5.137 | 165.342 |
| 17/8 1977 | -112.280 | -58.392 | 4.992 | 165.680 |
| 12/9 1977 | -111.912 | -58.283 | 4.714 | 165.482 |
| | Change in relative elevation of bench marks since 27 July, 1976 in millimeters. (Relative elevation at given date minus relative elevation on 27 July, 1976) | | | |
| 27/7 1976 | 0.00 | 0.00 | 0.00 | 0.00 |
| 19/9 1976 | 0.44 | 0.06 | -0.22 | -0.29 |
| 20/5 1977 | -2.90 | -1.71 | 1.22 | 3.39 |
| 17/6 1977 | -2.44 | -1.65 | 1.06 | 3.03 |
| 17/8 1977 | -3.09 | -2.93 | -0.39 | 6.41 |
| 12/9 1977 | 0.59 | -1.84 | -3.17 | 4.43 |

TABLE I, 6 Tilt station 0040, Jörundur

| Bench marks | 0041 | 0042 | 0043 | 0044 | 0045 |
|---|---|---|---|---|---|
| Date of observation | Relative elevation of bench marks in centimeters | | | | |
| 27/7 1976 | 31.247 | 13.116 | -2.751 | -13.829 | -27.782 |
| 20/8 1976 | 31.244 | 13.126 | -2.767 | -13.821 | -27.782 |
| 19/9 1976 | 31.216 | 13.109 | -2.733 | -13.787 | -27.805 |
| 16/6 1977 | 31.177 | 13.178 | -2.655 | -13.833 | -27.867 |
| 19/7 1977 | 31.164 | 13.156 | -2.627 | -13.816 | -27.878 |
| 15/8 1977 | 31.145 | 13.210 | -2.596 | -13.847 | -27.912 |
| 12/9 1977 | 31.105 | 13.204 | -2.574 | -13.825 | -27.910 |
| 21/10 1977 | 31.076 | 13.241 | -2.537 | -13.827 | -27.953 |
| | Change in relative elevation of bench marks since 27 July, 1977 in millimeters. (Relative elevation at given date minus relative elevation on 27 July, 1977) | | | | |
| 27/7 1976 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 20/8 1976 | -0.03 | 0.10 | -0.16 | 0.08 | 0.00 |
| 19/9 1976 | -0.31 | -0.07 | 0.18 | 0.42 | -0.23 |
| 16/6 1977 | -0.70 | 0.62 | 0.96 | -0.04 | -0.85 |
| 19/7 1977 | -0.83 | 0.40 | 1.24 | 0.13 | -0.96 |
| 15/8 1977 | -1.02 | 0.94 | 1.55 | -0.18 | -1.30 |
| 12/9 1977 | -1.42 | 0.88 | 1.77 | 0.04 | -1.28 |
| 21/10 1977 | -1.71 | 1.25 | 2.14 | 0.02 | -1.71 |

TABLE I, 7 Tilt station 0050, Grjótagjá S

| Bench marks | 0051 | 0052 | 0053 | 0054 | 0055 |
|---|---|---|---|---|---|
| Date of observation | Relative elevation of bench marks in centimeters | | | | |
| 19/5 1977 | -49.883 | -11.902 | 31.670 | 9.758 | 20.356 |
| 16/6 1977 | -49.908 | -11.915 | 31.689 | 9.799 | 20.334 |
| 18/7 1977 | -49.903 | -11.912 | 31.674 | 9.782 | 20.359 |
| 16/8 1977 | -49.915 | -11.887 | 31.694 | 9.783 | 20.326 |
| 10/9 1977 | -49.794 | -11.965 | 31.510 | 9.761 | 20.487 |
| 28/10 1977 | -49.779 | -11.953 | 31.496 | 9.713 | 20.463 |
| | Change in relative elevation of bench marks since 19 May, 1977 in millimeters. (Relative elevation at given date minus relative elevation on 19 May, 1977) | | | | |
| 19/5 1977 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 16/6 1977 | -0.25 | -0.13 | 0.19 | 0.41 | -0.22 |
| 18/7 1977 | -0.20 | -0.10 | 0.04 | 0.24 | 0.03 |
| 16/8 1977 | -0.32 | 0.15 | 0.24 | 0.25 | -0.30 |
| 10/9 1977 | 0.89 | -0.63 | -1.60 | 0.03 | 1.31 |
| 28/10 1977 | 1.04 | -0.51 | -1.74 | -0.45 | 1.07 |

TABLE I, 8 Tilt station 0060, Grjótagjá N

| Bench marks | 0061 | 0062 | 0063 | 0064 | 0065 |
|---|---|---|---|---|---|
| Date of observation | Relative elevation of bench marks in centimeters | | | | |
| 19/5 1977 | -3.008 | 53.754 | 31.330 | -37.765 | -44.311 |
| 16/6 1977 | -3.075 | 53.762 | 31.435 | -37.792 | -44.331 |
| 20/7 1977 | -3.064 | 53.780 | 31.349 | -37.743 | -44.323 |
| 16/8 1977 | -3.041 | 53.786 | 31.341 | -37.772 | -44.314 |
| 10/9 1977 | -2.951 | 53.671 | 31.098 | -37.703 | -44.115 |
| 24/10 1977 | -2.969 | 53.701 | 31.119 | -37.724 | -44.127 |
| | Change in relative elevation of bench marks since 19 May, 1977 in millimeters. (Relative elevation at given date minus relative elevation on 19 May, 1977) | | | | |
| 19/5 1977 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 16/6 1977 | -0.67 | 0.08 | 1.05 | -0.27 | -0.20 |
| 20/7 1977 | -0.56 | 0.26 | 0.19 | 0.22 | -0.12 |
| 16/8 1977 | -0.33 | 0.32 | 0.11 | -0.07 | -0.03 |
| 10/9 1977 | 0.57 | -0.83 | -2.32 | 0.62 | 1.96 |
| 28/10 1977 | 0.39 | -0.53 | -2.11 | 0.41 | 1.84 |

TABLE I, 9 Tilt station 0070, Reykjahlíð

| Bench marks<br>Date of observation | 0071 | 0072 | 0073 | 0074 | 0075 |
|---|---|---|---|---|---|
| | Relative elevation of bench marks in centimeters | | | | |
| 20/5 1977 | 42.416 | -47.533 | 0.878 | 1.703 | 2.536 |
| 16/6 1977 | 42.411 | -47.558 | 0.914 | 1.706 | 2.528 |
| 20/7 1977 | 42.404 | -47.533 | 0.937 | 1.689 | 2.501 |
| 16/8 1977 | 42.416 | -47.610 | 0.923 | 1.717 | 2.554 |
| 11/9 1977 | 42.281 | -47.784 | 0.908 | 1.927 | 2.668 |
| 24/10 1977 | 42.238 | -47.778 | 0.926 | 1.951 | 2.662 |
| | Change in relative elevation of bench marks since 20 May, 1977 in millimeters. (Relative elevation at given date minus relative elevation on 20 May, 1977) | | | | |
| 20/5 1977 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 16/6 1977 | -0.05 | -0.25 | 0.36 | 0.03 | -0.08 |
| 20/7 1977 | -0.12 | 0.00 | 0.59 | -0.14 | -0.35 |
| 16/8 1977 | 0.00 | -0.77 | 0.45 | 0.14 | 0.18 |
| 11/9 1977 | -1.35 | -2.51 | 0.30 | 2.24 | 1.32 |
| 24/10 1977 | -1.78 | -2.45 | 0.48 | 2.48 | 1.26 |

TABLE I, 10 Tilt station 0080, Ytri Bjarghóll

| Bench marks | 0081 | 0082 | 0083 | 0084 | 0085 |
|---|---|---|---|---|---|
| Date of observation | Relative elevation of bench marks in centimeters | | | | |
| 14/6 1977 | 11.909 | 34.776 | -19.505 | -9.738 | -17.441 |
| 18/7 1977 | 12.024 | 34.716 | -19.599 | -9.775 | -17.366 |
| 16/8 1977 | 12.071 | 34.715 | -19.658 | -9.820 | -17.308 |
| 11/9 1977 | 11.922 | 34.566 | -19.544 | -9.655 | -17.288 |
| | Change in relative elevation of bench marks since 14 June, 1977 in millimeters. (Relative elevation at given date minus relative elevation on 14 June, 1977) | | | | |
| 14/6 1977 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 18/7 1977 | 1.15 | -0.60 | -0.94 | -0.37 | 0.75 |
| 16/8 1977 | 1.62 | -0.61 | -1.53 | -0.82 | 1.33 |
| 11/9 1977 | 0.13 | -2.10 | -0.39 | 0.83 | 1.53 |

TABLE I, 11 Tilt station 0090, Hvannstóð

| Bench marks | 0091 | 0092 | 0093 | 0094 | 0095 |
|---|---|---|---|---|---|
| Date of observation | Relative elevation of bench marks in centimeters | | | | |
| 14/6 1977 | -44.386 | 36.341 | 24.401 | -37.467 | 21.021 |
| 18/7 1977 | -44.367 | 36.321 | 24.315 | -37.426 | 21.158 |
| 16/8 1977 | -44.378 | 36.273 | 24.214 | -37.361 | 21.251 |
| 11/9 1977 | -44.387 | 36.369 | 24.379 | -37.455 | 21.094 |
| | Change in relative elevation of bench marks since 14 June, 1977 in millimeters. (Relative elevation at given date minus relative elevation on 14 June, 1977) | | | | |
| 14/6 1977 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 18/7 1977 | 0.19 | -1.10 | -0.86 | 0.41 | 1.37 |
| 16/8 1977 | 0.08 | -1.58 | -1.87 | 1.06 | 2.30 |
| 11/9 1977 | -0.01 | -0.62 | -0.22 | 0.12 | 0.73 |

TABLE I, 12 Tilt station 0200, Hverfjall

Relative elevation of bench marks in centimeters

| Bench marks<br>Date of observation | | 0201 | 0202 | 0203 | 0204 | 0205 |
|---|---|---|---|---|---|---|
| 15/6 | 1977 | -28.691 | 10.427 | 45.561 | 7.313 | -34.609 |
| 19/7 | 1977 | -28.660 | 10.441 | 45.564 | 7.275 | -34.620 |
| 15/8 | 1977 | -28.636 | 10.439 | 45.533 | 7.280 | -34.616 |
| 11/9 | 1977 | -28.643 | 10.408 | 45.518 | 7.298 | -34.580 |
| 29/10 | 1977 | -28.626 | 10.448 | 45.504 | 7.248 | -34.575 |

Change in relative elevation of bench marks since 15 June, 1977 in millimeters. (Relative elevation at given date minus relative elevation on 15 June, 1977)

| Bench marks<br>Date of observation | | 0201 | 0202 | 0203 | 0204 | 0205 |
|---|---|---|---|---|---|---|
| 15/6 | 1977 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 19/7 | 1977 | 0.31 | 0.14 | 0.03 | -0.38 | -0.11 |
| 15/8 | 1977 | 0.55 | 0.12 | -0.28 | -0.33 | -0.07 |
| 11/9 | 1977 | 0.48 | -0.19 | -0.43 | -0.15 | 0.29 |
| 29/10 | 1977 | 0.65 | 0.21 | -0.57 | -0.65 | 0.34 |

## APPENDIX II

Error in spirit level tilt measurements caused by relative bench marks movement or warping of the ground surface.

As each tilt station consists of 5 or 6 bench marks, the apparent tilt can be calculated from several 3 point groups for each tilt observation. If all combinations of three point tilt agree, there is no warping of the ground, and there is no movement of the markers relative to the "rigid" ground.

Fig. 10 shows the calculated tilt of each triangle of markers in tilt station 0000, Hlídardalur, where triangles of three adjacent markers are omitted, for three periods in 1976. Significant scatter of the calculated tilt vectors is obvious and the standard deviation of individual tilt vectors from that obtained by the least squares methods of all 6 markers increases with increasing length of the period between observations.

This increase in the apparent error of tilt measurements with time is also observed at other tilt stations. At tilt station 0020, Mývatn N, the standard deviation of tilt, as calculated from individual triangles, from that obtained by the least squares method of all 5 markers is shown on Fig. 11. Here the error is largely due to erratic behaviour of one single bench mark, 0023, although other markers also take part in the increase of error with time. It is also apparent that large additional error factor was added between the measurements of August 15 and September 11, 1977, but the eruption and subsidence event of September 8, 1877 happened in this time interval.

This may be interpreted as a considerable warping of the area of the tilt station at the time of this subsidence avent. There is a reason to assume, that the tilt errors due to erratic movement of individual markers has some annual cycle and be thus partly due to thermal response of the near surface rock.

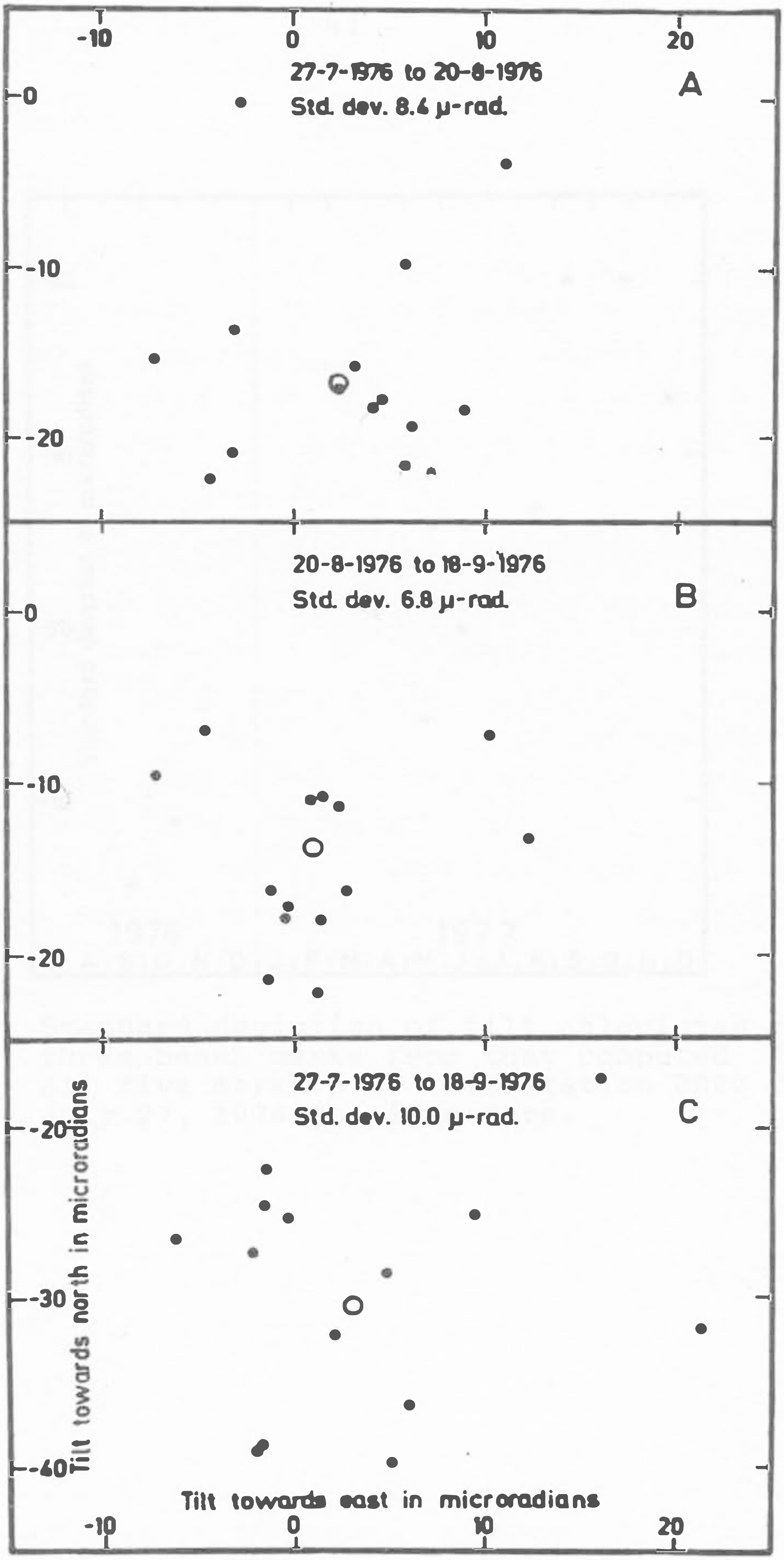

Fig. 10. Tilt at tilt station 0000, Hlídardalur. Dots are tilt as calculated from each triangle within the six-point tilt station and open circles are tilt obtained by the least squares method using all six markers. The scatter of the dots is due to irregular movement of individual bench marks relative to the basement or to warping of the basement.

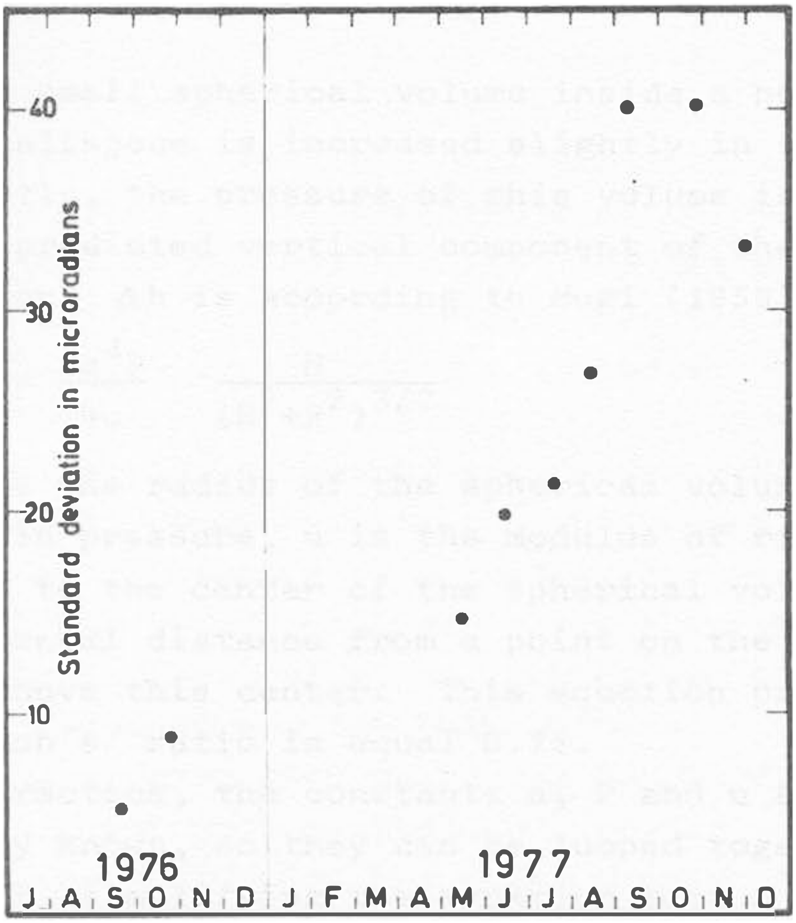

Fig. 11. Standard deviation of tilt calculated from three bench marks from that computed from all five markers of tilt station 0020 from July 27, 1976 to given date.

## APPENDIX III

Surface deformation due to internal pressure source.

If a small spherical volume inside a homogeneous elastic halfspace is increased slightly in volume, or, equivalently, the pressure of this volume is increased, then the predicted vertical component of the surface deformation, $\Delta h$ is according to Mogi (1958):

$$\Delta h = \frac{3a^3P}{4u} \quad \frac{H}{(H^2+R^2)^{3/2}} \qquad (B,1)$$

Where a is the radius of the spherical volume, P is the increase in pressure, u is the modulus of rigidity, H is the depth to the center of the spherical volume and R is the horizontal distance from a point on the surface vertically above this center. This equation presumes that the Poisson´s ratio is equal 0.25.

In practice, the constants a, P and u are unknown or poorely known, so they can be lumped together into one constant K, simplifying the equation to:

$$\Delta h = K \frac{H}{(H^2+R^2)^{3/2}} \qquad (B,2)$$

The corresponding ground tilt $\tau$ becomes:

$$\tau = \frac{\partial \Delta h}{\partial R} = -3K \frac{RH}{(H^2+R^2)^{5/2}} \qquad (B,3)$$

The well known equation for gravity anomaly due to spherical volume of anomalous density is:

$$\Delta g = MG \frac{H}{(H^2+R^2)^{3/2}} \qquad (B,4)$$

or identical to equation (B,2) if we replace the constant K by MG where M is the excess mass and G is the gravitational constant.

It is easy to visualize that the deformation due to two spherical volumes of increased pressure is the sum of the deformation due to each volume, as long as the elastic limit is not reached at any point. Similarily, a large number of bodies will cause a deformation which is the sum of deformation due to each body. As the same rules are valid for gravity, it may be stated, that the vertical component of surface deformation due to change in hydrostatic pressure in any subsurface volume will be identical to gravity effect of the same volume of anomalous density, except for a multiplication factor.

As the gravity effect of various shapes of bodies have been thoroughly studied, these studies are immediately applicable to the surface deformation due to pressure changes in volumes of widely various shapes.

Increase in pressure within a volume inside homogeneous elastic halfspace will increase this volume, and this increase in volume will be nearly identical to the volume of the surface bulge, as long as the elastic limit is not reached and the bulk modulus of the elastic solid is much greater than the pressure change. This statement will not be supported any further.

The volume of a bulge caused by expansion of a spherical volume within a homogeneous elastic halfspace can be found by integrating equation (B,2):

$$V = \int_0^\infty 2\pi R \, \Delta h \, dR = 2\pi H K \int_0^\infty \frac{R \, dR}{(H^2 - R^2)^{3/2}} = 2\pi K \qquad (B,5)$$

The maximum uplift (at R = 0) caused by expansion of a spherical volume within a homogeneous elastic halfspace is found from (B,2) to be

$$\Delta h_o = \frac{K}{H^2} \qquad (B,6)$$

and the maximum ground tilt is found to be at R = H/2 equal to:

$$\tau_{max} = 0.8578 \, \frac{K}{H^3} \qquad (B,7)$$

## APPENDIX IV

### Depth to the lower magma chamber

The observed tilt during the period between the subsidence events of April 26 and September 8, 1977 is in good agreement with expansion of a spherical magma chamber centered at 2900 m depth below the south end of Leirhnjúkur. Tilt measurements east of Námafjall show less tilt than this model accounts for. The total tilt at that station is observed to be about 11 microradians while the theoretical tilt at that location is about 20.5 microradians. Error in observed tilt at this station can be estimated as less than 5 microradians.

At tilt stations 0020, 0050, 0060, 0070 and 0200, no systematic tilt was observed during this time interval, althouth theory predicts a tilt of 5 to 10 microradians, which should have been indicated in the measurements.

This apparent deviation of observed tilt from that predicted by theory can be explained if the magma which did flow into a magma chamber at 2.9 km depth came from another chamber at greater depth.

Assuming that this lower magma chamber was spherical and was located vertically below the upper chamber, then its depth can be roughly estimated.

Observations at station A, east of Námaskard, located at horizontal distance of about 7.25 km from the center of the magma chamber, showed tilt which was 9.5±5 microradians too small. This can be caused by a lower chamber at 9±3 km depth, assuming that the same volume of magma flowed out of this chamber as into the chamber at 2.9 km depth. Such a model would result in very small tilt at stations 0020, 0050, 0060, 0070 and 0200.

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