NORDIC VOLCANOLOGICAL INSTITUTE 7907
UNIVERSITY OF ICELAND

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IN THE KRAFLA-MÝVATN AREA

PROGRESS REPORT

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EYSTEINN TRYGGVASON

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ABSTRACT

Tilt observations in the Krafla-Mývatn area from 1976 to early 1979 are presented in tables and illustrations. Correlation between tilt at different locations near Krafla is good for inflation periods and for deflation events with magma flow towards north. During deflation events with magma flow towards south, a different and more erratic relation is found between tilt at different stations. Progressive tilt which seem not to be related to the inflation-deflation sequences at Krafla are observed at a few tilt stations, as Jörundur (0040) and Hverfjall (0200). Tilt in the Mývatn area is mostly connected to the subsidence and rifting events of April and September 1977 and slow relaxation after the September 1977 event.

INTRODUCTION

The volcano-tectonic sequence which first became obvious during the volcanic eruption of December 20, 1975 and the immediately following earthquake swarm and rifting on the North Iceland plate boundary is still continuing. Ground deformation in the area of the central volcano Krafla is characterized by relatively constant inflation interrupted at a few months intervals by rapid deflations. The tectonic activity in the fissure zone outside the central volcano appears to be associated only with the subsidence events, but during each subsidence, a portion of the fissure zone becomes active with earthquake swarms, opening of fissures and vertical and horizontal ground movements.

The ground deformation in the Krafla fissure zone and its vicinity has been monitored since early 1976 with increasing effort. The ground elevation and its changes has been measured frequently at a great number of points by the National Energy Authority, which also has measured the gravity and its changes with time (Johnson, 1979). Ground tilt has been observed by the University Science Institute. the National Energy Authority and the Nordic Volcanological Institute (Tryggvason, 1978a and 1978c). Distance measurements have been made by the Nordic Volcanological Institute (Tryggvason, 1978b), the National Energy Authority and the Technical University Hannover (Gerke et al., 1978). Measurements of fissure displacements are made by the National Energy Authority (Björnsson et al., 1979). and seismic observations by the University Science Institute (Brandsdóttir & Einarsson, 1979; Einarsson & Brandsdóttir, 1979).

Several other observations which relate to ground deformation in the Krafla fissure swarm and its vicinity have been made, partly by the institutions mentioned above and partly by other institutions.

This report will present the tilt observations in the Krafla-Mývatn region until March, 1979. Data presented earlier (Tryggvason, 1978a) will not be repeated although they are included in some of the time sequences and illustrations presented.

THE OBSERVATIONS

Three different methods are used to observe ground tilt in the Krafla-Mývatn area, optical observations using precision level, water tube tiltmeter observations and continuously recording borehole tiltmeter.

The optical level tilt stations (spirit level tilt stations, dry tilt stations) are most numerous or 12 in the Krafla-Mývatn area and another two near the north end of the Krafla fissure swarm in Kelduhverfi. Most of these stations (type A in Table 1, Fig. 1) consist of 4 to 6 permanent bench marks placed on the circumferance of a circle with a radius of 25 meter (27.5 m at one station) (Tryggvason, 1978a). Observations are made by placing the precision level in the center of the circle and carry an invar rod from one bench mark to the next two times around the circle.

Two of the optical level tilt stations consist of two short level lines, each nearly 100 m, roughly at right angle to each other (type B in Table 1). One of this stations (0030) has not been occupied since September, 1977 and will probably not be occupied in the future as other stations (0060 and 0070) have been constructed near by.

The spirit level tilt stations in the Krafla-Mývatn area were constructed in 1976 and 1977 and measurements have been made several times each year. The accuracy of the observation depends heavily on the weather, being better than 0.1 mm under favourable conditions, but in bright sunshine or strong wind, the accuracy is 0.1 to 0.2 mm, corresponding to 2 to 4 microradians of tilt. However, the limiting factor for the accuracy of the tilt observations over periods exceeding a few weeks is relative movements of

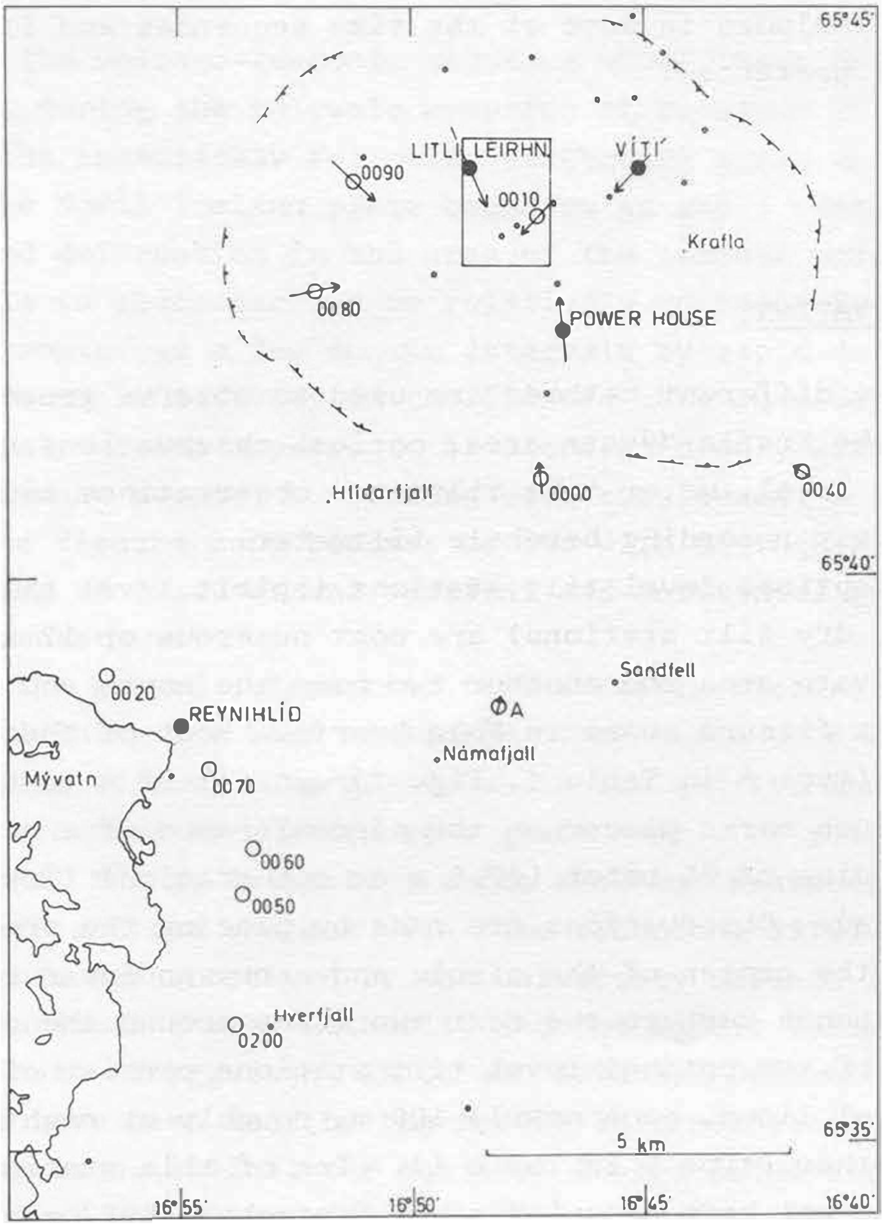

Fig. 1. Location of tilt stations in the Krafla-Mývatn area in February, 1979. Open circles are spirit level tilt stations, filled circles are borehole tiltmeters. Arrows show average tilt during inflation-deflation sequences. Rectangle shows the area of map of Fig. 12.

TABLE 1

Geographic coordinates of tilt stations

Station	N-latitude	W-longitude	Elevation m	Type of station x)
A-Námaskard	65°38.92'	16°48.01'	362	B
0000-Hlídardalur	65°41.12'	16°47.13'	393	A
0010-Leirhnjúkur	65°43.17'	16°47.30'	543	A
0020-Mývatn N	65°39.20'	16°56.44'	292	A
0030-Mývatn E	65°38.30'	16°52.81'	319	B
0040-Jörundur	65°40.90'	16°41.30'	510	A
0050-Grjótagjá S	65°37.20'	16°53.50'	290	A
0060-Grjótagjá N	65°37.59'	16°53.44'	289	A
0070-Reykjahlíd	65°38.32'	16°54.48'	292	A
0080-Bjarghóll	65°42.54'	16°52.07'	498	A
0090-Hvannstód	65°43.49'	16°51.28'	502	A
0100-Hóll	66°02.80'	16°38.00'	40	A
0110-Lón	66°06.00'	16°54.20'	10	A
0200-Hverfjall	65°36.10'	16°53.80'	280	A
Litli Leirhnjúkur	65°43.61'	16°48.80'	549	C
Power house	65°42.22'	16°46.80'	463	C,D
Víti	65°43.62'	16°45.08'	574	C
Reynihlíd	65°38.47'	16°54.90'	316	C

x) A: dry tilt stations with 4 to 6 markers in circular array. B: dry tilt stations with two lines of markers.
C: borehole tiltmeter with continuous recording.
D: water tube tiltmeter.

bench marks or ground surface deformation within the area of each tilt station (Appendix III).

The calculation of tilt is based on the fitting of a tilted plane to the observed elevation changes of the bench marks, using the least squares method. Coordinates of the bench marks (x, y or east and north) are measured from the center of gravity of all bench marks and elevation of each bench mark, h is measured from the average elevation of all bench marks of the station. Thus $\Sigma x = \Sigma y = \Sigma h = 0$. If marker elevation during one observation is h_1, and during a previous observation h_2, the difference is $z = h_2 - h_1$.

The tilted plane, which represent the ground tilt, can be written:

$$z = ax + by$$

where a and b are components of tilt towards east and north. As the elevation change of each individual marker deviates from the tilted plane by some amount u, we write for the marker i:

$$z_i = ax_i + by_i + u_i$$

and the least squares method determines the values of a and b which minimized Σu^2.

This is fulfilled if:

$$a = \frac{\Sigma(zx)\,\Sigma(y^2) - \Sigma(zy)\,\Sigma(xy)}{\Sigma(x^2)\,\Sigma(y^2) - [\Sigma(xy)]^2}$$

and

$$b = \frac{\Sigma(zy)\,\Sigma(x^2) - \Sigma(zx)\,\Sigma(xy)}{\Sigma(x^2)\,\Sigma(y^2) - [\Sigma(xy)]^2}$$

If the horizontal coordinates (x, y) are in meters and the vertical coordinate (z) in micrometers, the tilt as calculated is in microradians.

Continuously recording borehole tiltmeters, designed and constructed at the Nordic Volcanological Institute, were installed at two locations during the summer of 1977, at one location in the fall of 1978 and at a fourth location in February, 1979 (Table 1). The instrument consists of a simple pendulum with a two component magnetoresistor transducer (Sindrason & Ólafsson, 1978). It is placed in a vertical shaft, about 2 m deep with the top of the instrument at roughly one m depth. This type of installation is found to be sensitive to thermal strain, especially during winter when the ground is frozen, but reliable results are apparently obtained during the summer and during mild periods in winter. This report will not deal with the results of the magnetoresistor tiltmeters.

A watertube tiltmeter was permanently installed in the Krafla power house in August, 1976. This instrument is on a shelf about 20 m above ground with a N-S arm (direction about N13°E) 68.95 m long and an E-W arm (E13°S) 19.50 m long (Björnsson et al., 1979). Readings are made every day, with a few exceptions, with an accuracy better than 0.05 mm, corresponding to less than one μ-rad of tilt in N-S direction. However, the height of the instruments above ground, on the concrete walls of the power house, accounts for some error in the tilt observation due to thermal expansion of the walls.

ACCURACY OF THE TILT OBSERVATIONS

The accuracy of tilt observations with an optical level depends on the observational accuracy, the stability of the bench marks and the configuration of the bench mark array. All the spirit level tilt stations in the Krafla-Mývatn area and in Kelduhverfi are located on recent pahoehoe lavas, which appear to be stable with respect to frost action. The bench marks consist of nails of copper alloy cemented in holes drilled directly into the solid lava. None of the bench marks have moved visibly with respect to the lava, indicating that any observed movement represent movement of the lava in which the bench marks are placed.

As each tilt station consists of 4 to 6 bench marks, but only three markers are needed for determination of ground tilt, there are possibilities for multiple tilt determination at each station. If these agree within limits, which are in agreement with observational accuracy of roughly 0.1 mm for each marker, the error in the observed tilt depends only on the observational technique and the configuration of the station markers. Calculation of tilt based on different triangles of bench mark within each station frequently show discrepancies which far exceed those which can be explained by the observational technique. This is explained as due to local ground deformation within the area covered by each station, usually within a circle of 25 m radius (Appendix III).

The five triangles at each station, consisting of two adjacent markers and the opposite marker, may be used to evaluate the accuracy of the tilt observations. Table 2 gives the average tilt components and the standard deviation of these, based on observations taken three weeks apart in August 1979 (a_1 and b_1) and on the first observation at each station in 1976 or 1977 and the last observation in August 1979 (a_2 and b_2). There are obviously great differences between the stations. Considering the short period, six of the 10 type A stations have standard deviations, σ , of the tilt components as calculated from the 5 triangles, smaller than 2 μ-rad, while two stations have σ in excess of 4 μ-rad. The standard error of tilt calculated by the least squares method from all markers should be about $\sigma/\sqrt{5}$. Thus the standard error of the calculated tilt over a three weeks period is less than 1 μ-rad at six stations and 1.0 to 2.5 μ-rad at the other four stations. This difference between stations can hardly be contributed to difference in observational accuracy, but is more likely due to local ground deformation of the area of some of the tilt stations.

The effect of local ground deformation is more evident if tilt between the first observation at each station and the last observation in August 1979 is considered (a_2, b_2 in Table 2). At most stations the standard deviation of tilt

TABLE 2

Component of tilt at the circular spirit level tilt stations in the Krafla-Mývatn area for a three weeks period in August 1979 (a_1, b_1) and for a two to three year period ending in August 1979 (a_2, b_2).

Station	a_1 (east) mean	a_1 (east) σ x)	b_1 (north) mean	b_1 (north) σ	a_2 (east) mean	a_2 (east) σ	b_2 (north) mean	b_2 (north) σ
0000	-7.5	3.4	6.6	3.7	89.2	17.7	96.5	14.6
0010	-12.3	1.6	-2.9	1.1	42.1	419.2	88.1	408.1
0020	2.1	1.2	7.6	1.1	104.6	22.1	11.2	31.7
0040	0.5	4.6	-0.7	5.0	-74.7	7.2	57.6	8.3
0050	-2.0	3.4	-4.8	3.2	16.7	10.6	53.8	9.7
0060	-2.2	1.1	1.9	1.4	30.8	19.6	35.1	21.4
0070	-3.9	1.9	0.1	1.3	77.2	36.8	5.9	27.1
0080	7.9	6.3	1.0	5.4	164.6	13.3	-15.1	11.4
0090	7.7	1.8	-3.7	1.9	139.0	19.4	-138.6	26.0
0200	4.1	1.1	2.9	0.7	-25.9	19.5	61.6	11.9

x) Standard deviation of tilt based on tilt calculated from each of 5 triangles at each station (14 triangles at station 0000).

components as calculated from individual triangles for this longer observational period is several times larger than that for the three weeks period. The local ground deformation at the tilt stations is by far the greatest at station 0010, Leirhnjúkur, where it apparently occurred mostly during the two subsidence events of April 1977 and September 1977. At the station 0020, Mývatn N, the local deformation also occurred during these same subsidence events (Appendix III), possibly as the result of east-west compression, which was observed in that area (Björnsson et al., 1979; Tryggvason, 1978c). At the station 0000, Hlídardalur, the local ground deformation increase during the inflation periods and decreases during deflation events. The occurrence of the local deformation has not been studied at other stations, but these few observations indicate a close correlation between regional deformation (inflation-deflation-rifting) and local deforamtion within each station.

The data presented in Table 2 indicates that the accuracy of tilt is roughly one microradian if no local ground deformation takes place between observations. If the interval between observation exceeds a few weeks, local ground deformation limits the accuracy of observed tilt. This local deformation varies greatly from one station to another making the standard error of calculated tilt over 2 to 3 years period about 5 μ-rad at good stations (0000, 0040, 0050, 0080 and 0200), between 5 and 15 μ-rad at poor stations (0020, 0060, 0070 and 0090) and greater than 100 μ-rad at very poor stations (0010).

CORRELATION BETWEEN TILT AT DIFFERENT STATIONS

Ground tilt between observations at the spirit level tilt stations have been compared with the N component of tilt in the Krafla power house as obtained by the water tube tiltmeter. The obtained relation is presented in Table 3 and Figs. 2 to 6.

The two subsidence events with magma flow towards south in April and September, 1977 (Tryggvason, 1978c) seem to have caused tilt at a number of stations, which does not fit the general correlation between tilt at different stations. Tilt observations, which cover the period of these events, are shown by open triangles on Figs. 2 to 6 and are not used in obtaining the relation with tilt at the power house.

Tilt at stations in the Mývatn area (0020, 0050, 0060, 0070, 0200) shows no correlation with the tilt at the power house, while tilt at stations in the Krafla area (0000, 0010, 0080, 0090) shows very clear correlation (Table 3).

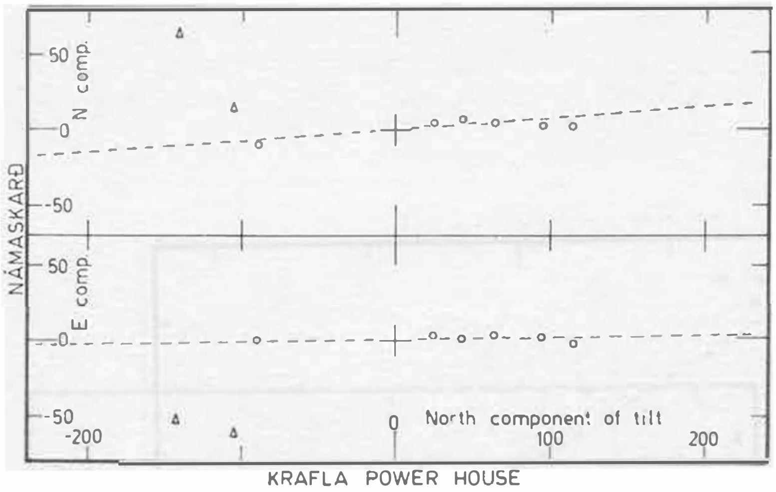

Fig. 2. North and east components of tilt between observations at the tilt station Námaskard (A) plotted against the north component at the Krafla power house as measured by the water tube tiltmeter. Scales are in microradians and increasing numbers represent uplift towards north and east. Open circles are observations over periods of inflation or deflation with northward magma flow. Triangles are observations over periods which include deflation associated with southward magma flow. Dashed lines show the apparent relation between tilt components based only on periods of inflation or deflation with northward magma flow.

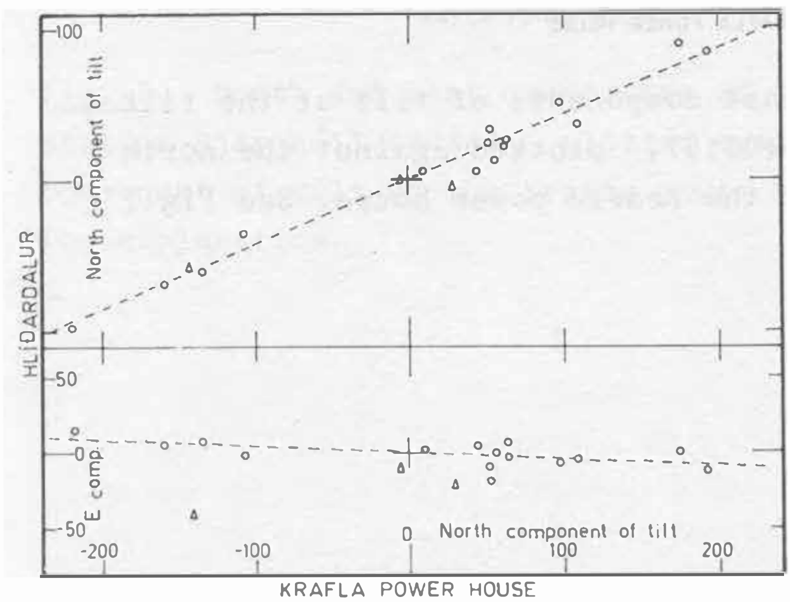

Fig. 3. North and east components of tilt at the tilt station Hlídardalur (0000) plotted against the north component of tilt at the Krafla power house. See Fig. 2 for explanation.

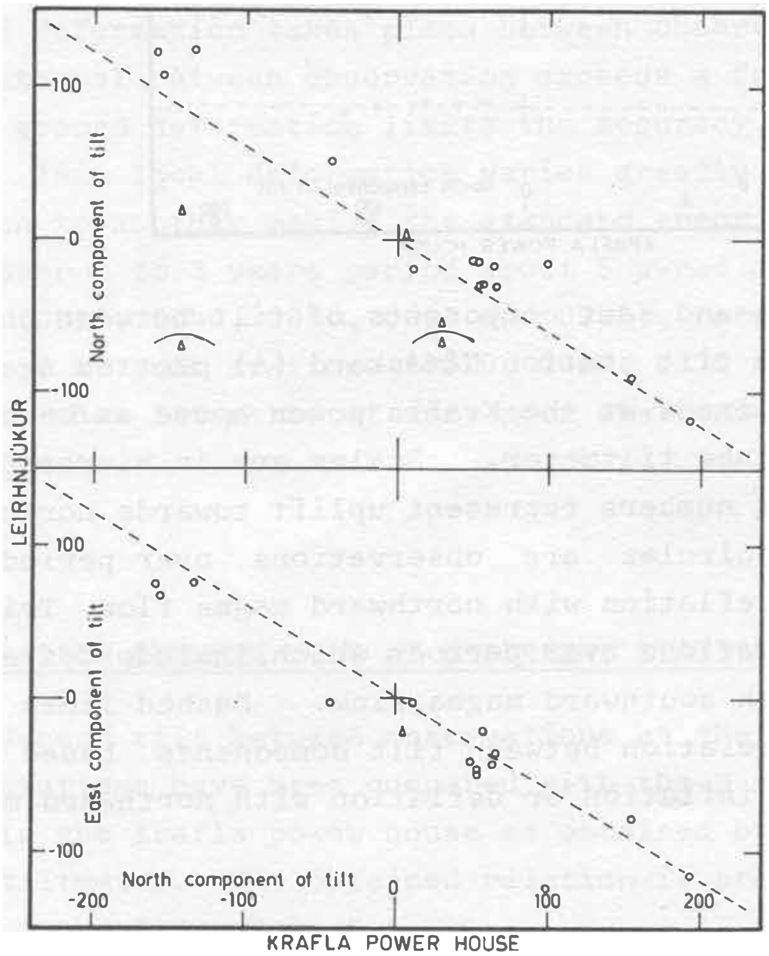

Fig. 4. North and east components of tilt at the tilt station Leirhnjúkur (0010), plotted against the north component of tilt at the Krafla power house. See Fig.2 for explanation

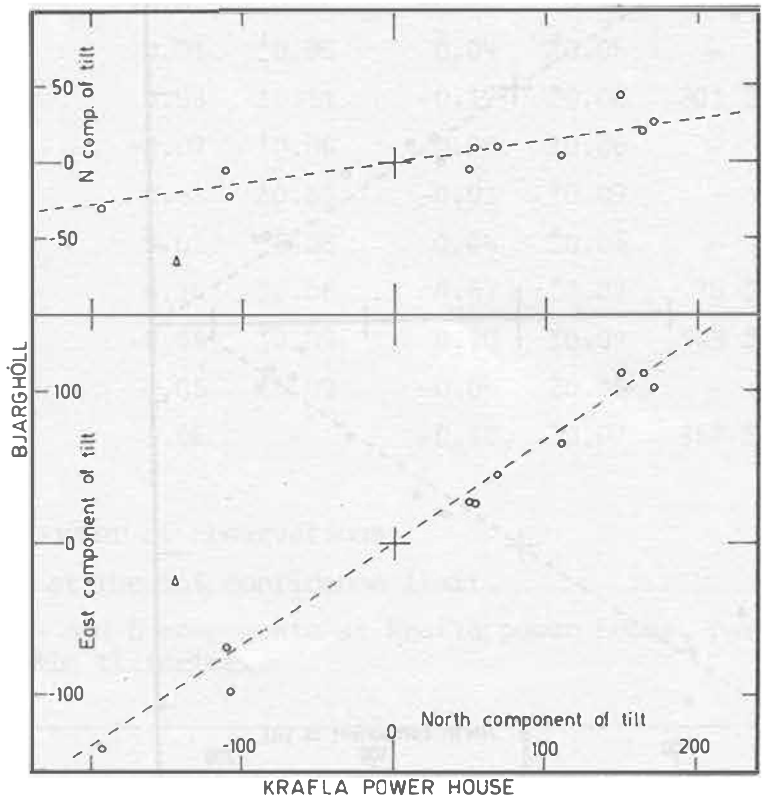

Fig. 5. North and east components of tilt at the tilt station Bjarghóll (0080), plotted against the north component of tilt at the Krafla power house. See Fig.2 for explanation.

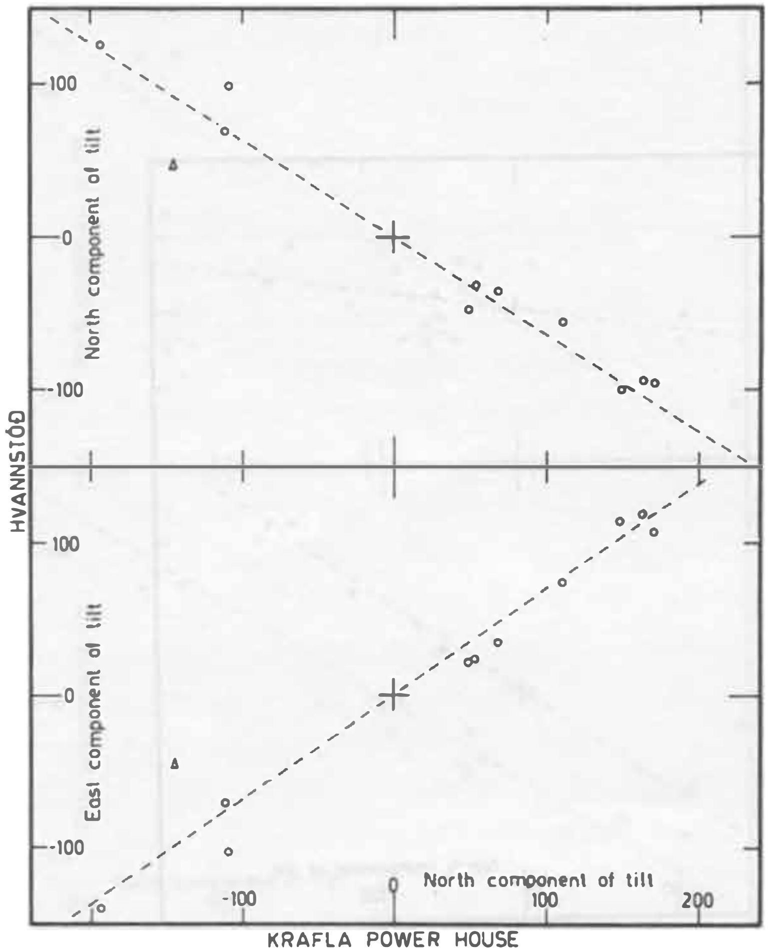

Fig. 6. North and east components of tilt at the tilt station Hvannstóð (0090), plotted against the north component of tilt at the Krafla power house. See Fig.2 for explanation.

TABLE 3

Ratio of tilt at the spirit level tilt stations to the N-component of tilt (N13°E) at the Krafla power house as observed by the water tube tiltmeter.

Station	North component		East component		Azimuth	
A	0.04	±0.01[2]	0.01	±0.03	13 ± 20	6
0000	0.42	±0.05	-0.04	±0.04	354 + 6	14
0010	-0.62	±0.16	-0.58	±0.14	223 + 10	13
0020	0.01	±0.06	0.04	±0.05		8
0040	0.08	±0.11	-0.12	±0.06	301 ± 38	6
0050	-0.02	±0.06	0.00	±0.06		9
0060	-0.01	±0.09	-0.01	±0.09		10
0070	0.01	±0.06	0.04	±0.05		11
0080	0.14	±0.06	0.67	±0.07	79 ± 6	9
0090	-0.65	±0.09	0.70	±0.09	133 + 5	9
0200	0.05	±0.09	-0.04	±0.05		6
Krafla[3]	1.06		-0.15	±0.07	352 + 4	

1) N is number of observations.

2) Error at the 95% confidence limit.

3) True N and E components at Krafla power house, partly based on borehole tiltmeter.

At the two stations, Námaskard (A) and Jörundur (0040) the observed tilt correlates poorly with that at the power house, but the correlation appears to be real.

Tilt at the two borehole tiltmeters at Víti and Litli Leirhnjúkur seem to correlate very well with that at the Krafla power house, if only observations during the summer are considered. Thermal strains affect these stations greatly during the winter.

Arrows on Fig. 1 show the average direction and relative magnitude of tilt associated with inflation and deflation of the Krafla area. The arrows point towards the center of inflation or deflation as it is indicated at each station.

OBSERVED TILT AT INDIVIDUAL STATIONS

Krafla power house. The N-S component of tilt as obtained by the water tube tiltmeter is shown on Fig. 7. Up is tilt towards south as indicated by the letter S at the beginning of the tiltmeter trace. The characteristic feature of the tilt is the inflation-deflation pattern with relatively slow inflation and rapid deflation. The rate of tilt during the inflation periods decreases gradually from the beginning to the end of each period and the observed tilt at the end of each inflation period is at nearly the same level for all inflation periods after January 1977.

The E-W component of the water tube tiltmeter has shown very small tilt throughout the period of observation. This indicates that at the location of the power house, the tilt is generally parallel to the Krafla fissure swarm, which has an average direction N13°E or the same as the N-S component of the water tube tiltmeter.

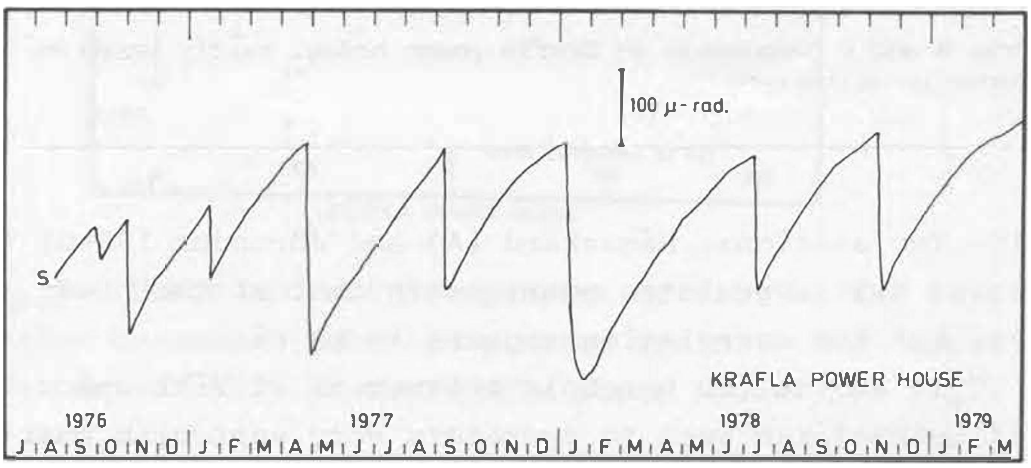

Fig. 7. N-S component of tilt at the Krafla power house based on about two readings every month of the water tube tiltmeter. This and the subsequent four figures are plotted such that the trace is rising if land is rising at the center of tectonic activity in the Krafla region. The letter S at the beginning of the trace means that tilt towards south is up on the graph.

A magnetoresistor tiltmeter, which has been operated in a cellar a few meters west of the power house since August 1977, and is oriented parallel to the water tube tiltmeter, shows that westward tilt amounts to about 15% of the northward tilt. The average azimuth of tilt is N8°W for subsidence events and S8°E for inflation periods, after a correction has been made for the azimuths of the tiltmeter components.

Dry tilt stations in the Krafla area (Figs. 8 and 9). The observed tilt at the four stations 0000, 0010, 0080 and 0090 reflects the inflation-deflation pattern so clearly seen at the power house. The good correlation of tilt at these stations to that at the power house allows an estimate of the variation of tilt with time as shown with traces on Figs. 8 and 9. The subsidence events of April and September 1977 are anomalous as the relation between tilt at the power house and these stations is clearly different from other events. This is most clearly observed at Leirhnjúkur (0010) but great local deformation of the tilt station makes the comparison of tilt before and after these events unreliable.

The tilt station A, Námaskard (Fig. 10). A slight tilt towards south is observed during inflation periods and corresponding tilt towards north during subsidence events except during the subsidence events of April and September 1977. During the April 1977 event, tilt of about 60 μ-rad towards east is indicated and during the September 1977 event about 80 μ-rad tilt towards southeast is observed. These large and anomalous tilts are associated with rifting and magma intrusions south of the Krafla area (Tryggvason, 1978c).

The tilt station 0020, Mývatn N (Fig. 10). This station shows no significant tilt, except during the subsidence event of April and September, 1977. During the April event tilt of some 45 μ-rad towards west is indicated and during the September event tilt of nearly 50 μ-rad towards WSW is observed. It is rather surprising to find no indication of tilt asso-

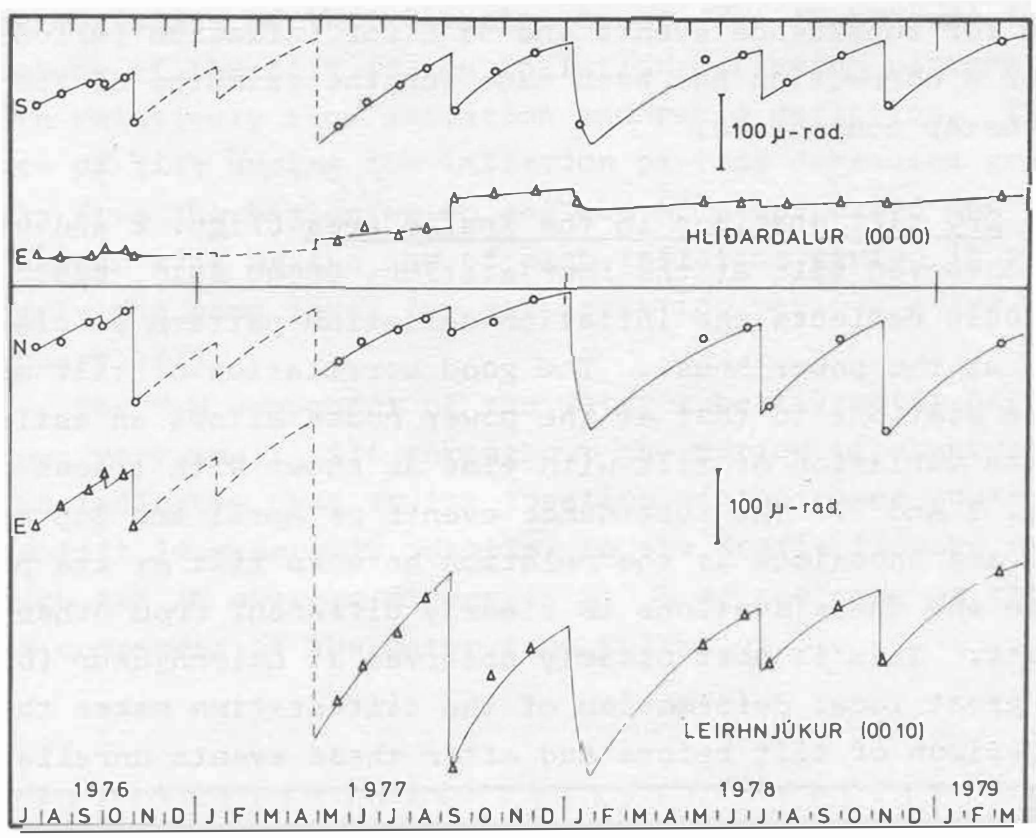

Fig. 8. Observed tilt at the tilt stations Hlídardalur (0000) and Leirhnjúkur (0010) from July 1976 to March 1979. Open circles are the N-S component and triangles are the E-W component. The letter at the beginning of each trace gives the direction of tilt corresponding to upward displacement on the graph. Lines are drawn to show how the tilt has progressed between observations if relation between tilt at these stations and at the Krafla power house is as indicated on Figs. 3 and 4 except during deflation events with southward magma flow.

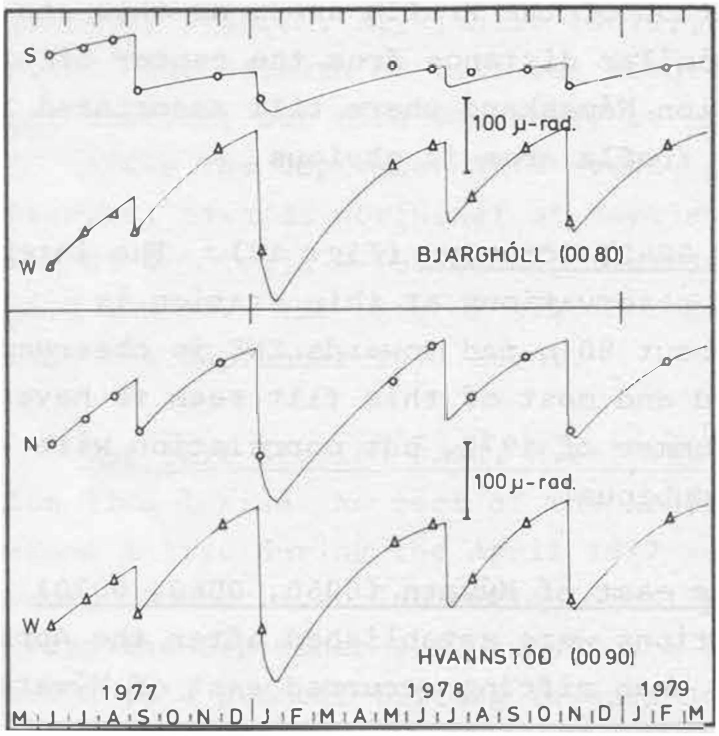

Fig. 9. Observed tilt at the tilt stations Bjarghóll (0080) and Hvannstóð (0090) from June 1977 to March 1979. See Fig. 8 for explanation.

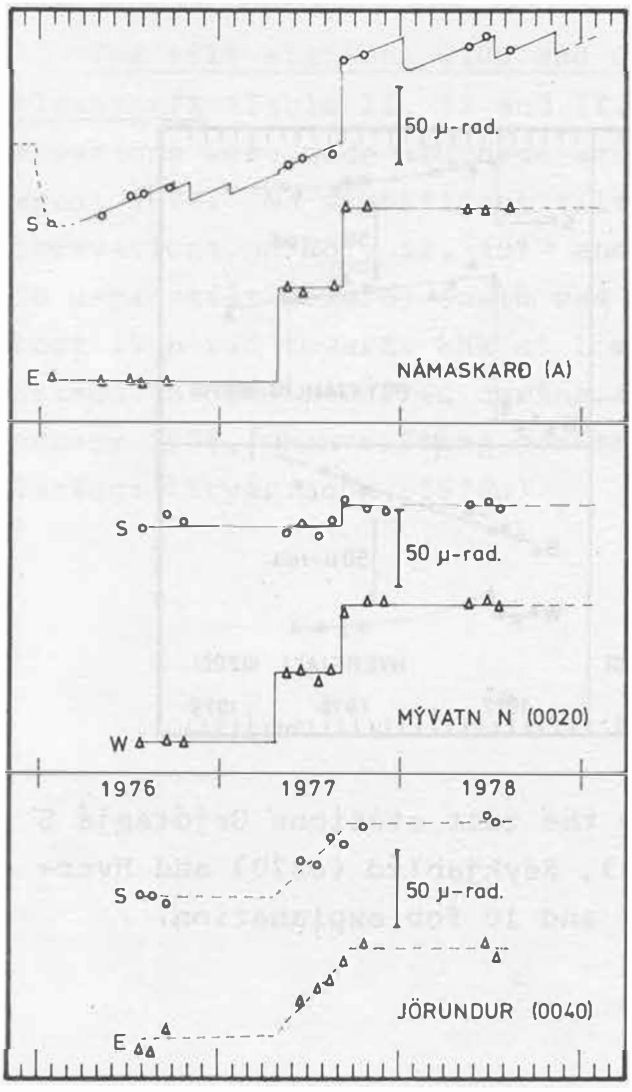

Fig. 10. Observed tilt at the tilt stations Námaskard (A), Mývatn N (0020) and Jörundur (0040) from January 1976 to March 1979. The authors interpretation as how tilt has progressed is shown by solid or dashed lines. See Fig. 8 for explanation.

ciated with the inflation of the Krafla area, as this station lies at rather similar distance from the center of inflation as the station Námaskard where tilt associated with inflation of the Krafla area is obvious.

The tilt station 0040, Jörundur (Fig. 10). The interpretation of the tilt observations at this station is difficult. Tilt of about 80 μ-rad towards ENE is observed over a two year period and most of this tilt seem to have occurred during the summer of 1977, but correlation with subsidence events is dubious.

The tilt stations east of Mývatn (0050, 0060, 0070) (Fig. 11). These stations were established after the April 1977 subsidence event when rifting occurred east of Mývatn. The observed tilt at these stations is dominated by the September 1977 event, when tilt of 65 to 100 μ-rad towards SW to WSW was observed. The tilt was greatest at the most

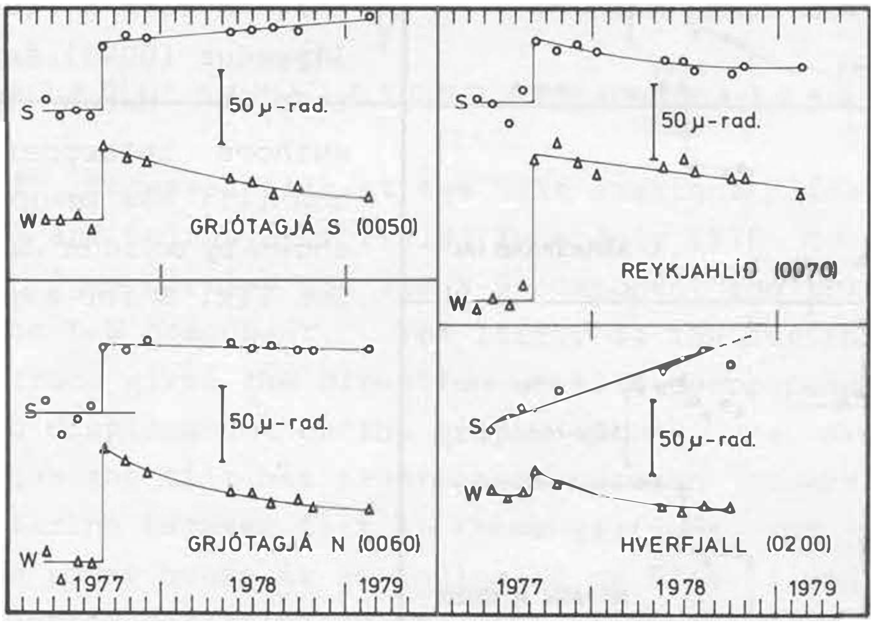

Fig. 11. Observed tilt at the tilt stations Grjótagjá S (0050), Grjótagjá N (0060), Reykjahlíð (0070) and Hverfjall (0200). See Figs. 8 and 10 for explanation.

northerly station, Reykjahlíd (0070), and decreased towards south. The azimuth of tilt was about WSW at the northernmost station, but more southerly at the southern stations.

After the September 1977 event, gradual tilt has been observed, towards northeast at Reykjahlíd (0070), towards east at Grjótagjá N (0060) and towards southeast at Grjótagjá S (0050). The rate of tilt has decreased gradually after the September 1977 event.

The tilt station 0200, Hverfjall (Fig. 11). This station lies inside the part of the Krafla fissure swarm that became active during the April 1977 subsidence and rifting event. There is an indication of slight tilt towards west during the September 1977 subsidence event, but the striking result is a gradual tilting towards south, or possibly slightly east of south throughout the period of observation. This southward tilt has reached about 50 μ-rad in 16 months.

The tilt stations 0100 and 0110 (Hóll and Lón) in Kelduhverfi (Table II, 13 and II, 14 in appendix). Five observations were made at these stations between July 1976 and August 1978. No significant tilt was observed except between observations on July 15, 1977 and May 21, 1978, when about 200 μ-rad tilt towards south was observed at Hóll (0100) and about 15 μ-rad towards WNW at Lón (0110). This tilt is assumed to have occurred during the subsidence event of January 1978, when rifting occurred in the vicinity of these stations (Tryggvason, 1978c).

LOCATION OF THE CENTER OF INFLATION-DEFLATION

The following discussion is based on two assumptions, which both are debatable.

(1) The magnitude of tilt is assumed to depend on the distance from the hypothetical center of inflation-deflation, but not on the azimuth from this center.

(2) The variation of tilt with distance from the center of inflation-deflation is assumed to be the same as is predicted from pressure variations within a small spherical volume inside an elastic half space.

The tilt station at the Krafla power house and the three spirit level tilt stations Hlídardalur (0000), Bjarghóll (0080) and Hvannstód (0090) were used to determine the apparent center of inflation-deflation. These stations were selected because their observed tilt correlates well with each other and because of their rather large tilt. The station Leirhnjúkur (0010) could also have been included in this study but its closeness to the center of inflation-deflation and the rather poor correlation between its tilt and that at the power house made it less fit for this study.

Assumption 2 above requires that for a given depth h to the center of the small spherical volume of varying pressure, the tilt τ at a radial distance r is (Mogi, 1958):

$$\tau = Kr\,(h^2+r^2)^{-5/3} \qquad (1)$$

From Table 3 we get the amount of tilt at the four stations used in this study.

By selecting a location (x, y) and depth h, the expected relative tilt $(r\,(h^2+r^2)^{-5/3})$ is computed for each tilt station and correlated with the observed tilt. The coefficient of correlation between calculated and observed tilt at all stations varies with the selected location of the center of disturbance, and also with the assumed depth. Fig. 12 shows the area where near perfect correlation ($r^2 > 0.99$) was found between observed and calculated tilt if depth (h) was assumed to be 3 km.

If the assumed depth was 2.8 or 3.2 km, the correlation did not change significantly, except that the area of best correlation is shifted about 50 m eastwards if assumed depth is increased by 200 m. The depth of the center of about 3 km is accepted from earlier determinations (Björnsson et al., 1979).

The observed tilt at the station 0010 (Leirhnjúkur) can be used to compute the apparent horizontal distance to the center of inflation-deflation using equation (1). The value of K in that equation, which corresponds to a center near the center of maximum correlation between observed and calculated tilt at the four other stations, is 370 ± 20 for tilt of one unit on the north component of the power house tiltmeter, if distances (h and r) are in km. This gives the calculated distance from tilt station 0010 to the center of inflation-deflation as 600 ± 100 m, which agrees perfectly with the center of the area of maximum correlation of computed and observed tilt as shown on Fig. 12.

Thus the magnitude of observed tilt at the spirit level tilt stations 0000, 0010, 0080 and 0090, and the tilt station in the Krafla power house all agree with a center of the inflation-deflation area being on the west side of the hill Leirhnjúkur, at 65°43.04´N, 16°48.08´W and depth of the center of a spherical volume of increasing and decreasing pressure of about 3.0 km.

The accuracy of this determination is difficult to evaluate, but the correlation between observed and calculated tilt varies very little for 200 m displacements of the center of inflation-deflation.

If, however, the direction of tilt is considered, much less accuracy is indicated. The direction of tilt at the station 0010 indicates that the center of inflation-deflation lies to the southwest of that station, indicating that this

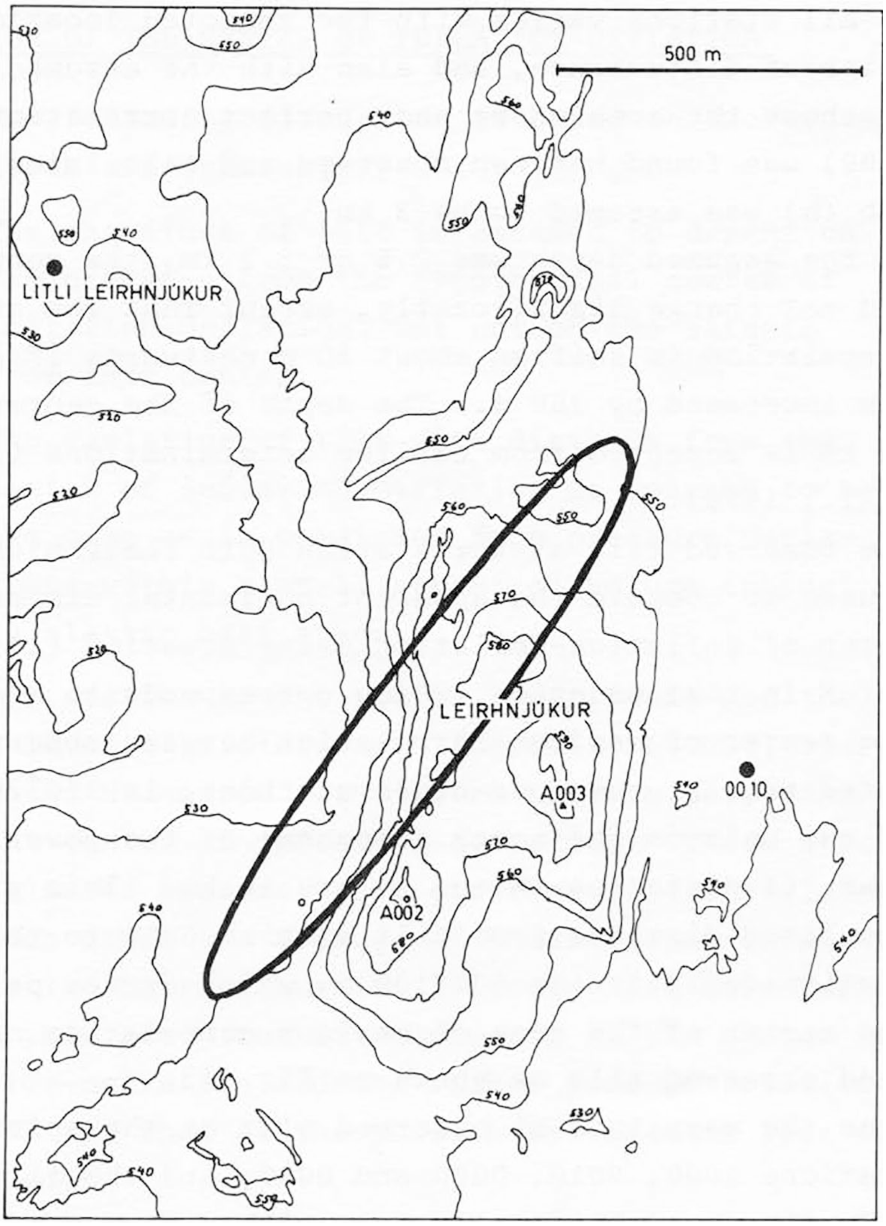

Fig. 12. A map of Leirhnjúkur (see Fig. 1 for location). The correlation between calculated and observed tilt at the stations 0000, 0080, 0090, and the power house is better than 0.99, if center of inflation-deflation lies at 3 km depth below the encircled area, but poorer correlation is found outside this elliptical area.

center is roughly 400 m south of the location given by the maximum correlation between calculated and observed tilt. The direction of tilt at the station 0090 also indicates southerly location for the center of inflation-deflation. This clearly shows that the assumptions which were made above are not exactly true, and that a center of inflation-deflation is difficult to define. It can be expected, that a different location of tilt stations would indicate different location of the inflation-deflation center.

SUMMARY

The tilt observations in the Krafla-Mývatn area have demonstrated that several processes are causing ground deformation in this region.

In the central part of the Krafla area, more precisely inside the Krafla caldera, the tilt is dominated by the inflation-deflation sequences, caused by slow expansions followed by rapid contractions of a magma chamber laying at about 3 km depth below Leirhnjúkur. The exact location of this magma chamber cannot be determined from the tilt observations alone, because of irregularities in the tilt. However, most tilt observations indicate that the magma chamber is centered below the south end of Leirhnjúkur. Tilt in the Mývatn area is characterized by large ground deformation during the two subsidence events in the Krafla region, when magma entered the fissure zone south of Krafla in April and September 1977. The flanks of the fissure zone were uplifted during these events causing tilt of 50 to 100 μ-rad, while the fissure zone subsided and expanded in E-W direction. This is explained by lateral flow of magma from the Krafla magma chamber into a fissure below the central part of the fissure zone to form a dike. At the same time was E-W tensional stress released to cause thickening of the crust on both sides of the dike, thus pro-

ducing the uplift of the flanks of the fissure zone (Björnsson et al., 1979; Tryggvason, 1978c). Gradual relaxation of the tilting of the flanks of the fissure zone in the Mývatn area has been observed since September 1977. This may be caused by slow plastic deformation of the lower boundary of the elastic crust as a result of stress anomalies caused by the sudden deformation and dike injection in September 1977.

Slow gradual tilt towards south at the most southerly tilt stations in the Mývatn area is difficult to explain and further observations will be needed.

REFERENCES

Björnsson, A.; G. Johnsen; S. Sigurdsson; G. Thorbergsson and E. Tryggvason, Rifting of the plate boundary in North Iceland 1975-1978, J. Geophys. Res. 84, 3029-3038, 1979.

Brandsdóttir, B. and P. Einarsson, Seismic activity associated with the September 1977 deflation of the Krafla central volcano in NE-Iceland, J. Volcanol. Geothermal Res., in press, 1979.

Einarsson, P. and B. Brandsdóttir, Seismological evidence for lateral magma intrusion during the July 1978 deflation of the Krafla volcano in NE-Iceland, Science Institute, University of Iceland, RH-79-9, 1-14, 1979.

Gerke, K.; D. Möller and B. Ritter, Geodätische Lagemessungen zur bestimmung horizontaler krustenbewegungen in Nordost-Island, Festschrift für Walter Höpcke, 23-33, Hannover 1978.

Johnsen, G.V., Hæðar- og þyngdarmælingar á Kröflu-Námafjalls-svæðinu (Ground elevation and gravity observations in the Krafla-Námafjall region), National Energy Authority OS 79010, 1-98, 1979.

Mogi, K., Relations between the eruptions of various volcanoes and the deformation of the ground surfaces around them, Bull. Earthquake Res. Inst. 36, 99-134, 1958.

Sindrason, S. and H. Ólafsson, A magnetoresistor geotiltmeter for monitoring ground movement, Nordic Volcanological Institute 7806, 1-7, 1978.

Tryggvason, E., Tilt observations in the Krafla-Mývatn area 1976-1977, Nordic Volcanological Institute 7802, 1-45, 1978a.

Tryggvason, E., Distance measurements in 1977 in the Krafla-Mývatn area and observed ground movements, Nordic Volcanological Institute 7810, 1-47, 1978b.

Tryggvason, E., Subsidence events in the Krafla area, preliminary report based on tilt and distance measurements, Nordic Volcanological Institute 7814, 1-65, 1978c.

APPENDIX I

Coordinates and elevation of bench marks of the spirit level tilt stations in the Mývatn-Krafla-Kelduhverfi area, North Iceland. The horizontal coordinates are measured from the center of gravity of all bench marks at each tilt station. The elevation of the bench marks is measured from the average elevation of each tilt station. The change in elevation since first measurement at each tilt station is found by subtracting bench mark elevation as found in the first measurement from that found in current measurement. The table contains data of measurements from December 1977 through March 1979 in the Krafla Mývatn area, and all measurements in the Kelduhverfi area. Earlier measurements in the Krafla-Mývatn area were reported by Tryggvason (1978a).

TABLE I, 1 Tilt station A, Námaskard

Bench marks		1	2	3	4	5
Coordinates of bench marks (meter)						
X (east)		63	40	30	-45	-90
Y (north)		52	13	-27	-29	-10
Relative elevation of bench marks (centimeter)						
21/5	1978	-24.473	6.304	-15.064	22.778	10.454
24/6	1978	-24.434	6.319	-15.091	22.765	10.442
12/8	1978	-24.490	6.304	-15.077	22.806	10.457
Change in relative elevation since 27/1 (millimeter)						
21/5	1978	-0.79	-3.08	-6.62	2.04	8.45
24/6	1978	-0.40	-2.93	-6.89	1.90	8.32
12/8	1978	-0.96	-3.08	-6.75	2.32	8.47

TABLE I, 2 Tilt station 0000, Hlídardalur

Bench marks		0001	0002	0003	0004	0005	0006
Coordinates of bench marks (meter)							
X (east)		-2.8	18.7	21.6	6.5	-19.6	-24.1
Y (north)		-25.9	-18.3	12.4	23.2	13.7	-5.2
Relative elevation of bench marks (centimeter)							
1/12	1977	-18.182	-6.632	2.264	2.886	5.355	13.708
13/1	1978	-17.960	-6.402	2.166	2.670	5.799	13.727
19/5	1978	-18.181	-6.582	2.283	2.882	5.905	13.693
22/6	1978	-18.178	-6.592	2.299	2.895	5.910	13.666
5/8	1978	-18.103	-6.512	2.242	2.813	5.860	13.698
30/9	1978	-18.177	-6.598	2.279	2.898	5.930	13.669
13/11	1978	-18.012	-6.453	2.196	2.746	5.823	13.699
4/3	1979	-18.201	-6.558	2.284	2.942	5.970	13.699
Change in relative elevation since 27/7 1976 (millimeter)							
1/12	1977	-1.34	-3.43	-0.91	1.15	2.85	1.68
13/1	1978	0.88	-1.14	-1.90	-1.01	1.29	1.88
19/5	1978	-1.34	-2.94	-0.72	1.11	2.35	1.53
22/6	1978	-1.30	-3.03	-0.57	1.25	2.40	1.26
5/8	1978	-0.56	-2.23	-1.13	0.42	1.90	1.59
30/9	1978	-1.30	-3.09	-0.76	1.27	2.59	1.30
13/11	1978	0.35	-1.64	-1.59	-0.25	1.53	1.60
4/3	1979	-1.54	-3.70	-0.72	1.72	3.00	1.24

TABLE I, 3 Tilt station 0010, Leirhnjúkur

Bench marks		0011	0012	0013	0014	0015
Coordinates of bench marks (meter)						
X (east)		3.7	-23.6	-17.4	15.1	22.4
Y (north)		23.4	11.1	-20.5	-19.5	5.5
Relative elevation of bench marks (centimeter)						
1/12	1977	11.092	-5.837	-2.119	2.898	-6.034
19/5	1978	11.263	-5.834	-2.164	2.759	-6.024
28/6	1978	11.287	-5.810	-2.032	2.726	-6.173
19/7	1978	11.557	-5.839	-2.378	2.624	-5.965
30/9	1978	11.355	-5.791	-2.022	2.664	-6.205
13/11	1978	11.680	-5.839	-2.399	2.538	-5.979
4/3	1979	11.413	-5.750	-1.907	2.567	-6.323
Change in relative elevation since 27/7 1976 (millimeter)						
1/12	1977	6.84	-12.70	4.72	1.03	0.11
19/5	1978	8.55	-12.66	4.27	-0.36	0.21
28/6	1978	8.80	-12.43	5.60	-0.69	-1.27
19/7	1978	11.50	-12.72	2.14	-1.71	0.79
30/9	1978	9.47	-12.24	5.69	-1.32	-1.60
13/11	1978	12.73	-12.72	1.92	-2.58	0.65
4/3	1979	10.06	-11.83	6.84	-2.28	-2.78

TABLE I, 4 Tilt station 0020, Mývatn N

Bench marks	0021	0022	0023	0024	0025
Coordinates of bench marks (meter)					
X (east)	-26.5	3.2	21.6	19.1	-17.5
Y (north)	-3.1	-23.7	-8.0	14.5	20.2
Relative elevation of bench marks (centimeter)					
2/12 1977	-20.884	7.731	18.128	2.497	-7.472
20/5 1978	-20.886	7.725	18.129	2.488	-7.456
29/6 1978	-20.892	7.713	18.152	2.483	-7.455
19/7 1978	-20.876	7.729	18.131	2.476	-7.461
Change in relative elevation since 27/7 1976 (millimeter)					
2/12 1977	-2.51	-0.41	2.57	1.45	-1.10
20/5 1978	-2.53	-0.47	2.58	1.36	-0.94
29/6 1978	-2.59	-0.59	2.80	1.31	-0.93
19/7 1978	-2.42	-0.43	2.60	1.24	-0.99

TABLE I, 5 Tilt station 0040, Jörundur

Bench marks	0041	0042	0043	0044	0045
Coordinates of bench marks (meter)					
X (east)	23.0	0.9	-24.6	-14.6	15.1
Y (north)	2.6	25.3	10.9	-21.0	-17.9
Relative elevation of bench marks (centimeter)					
28/6 1978	31.084	13.246	-2.518	-13.844	-27.968
11/8 1978	31.000	13.249	-2.554	-13.845	-27.949
Change in relative elevation since 27/7 1976 (millimeter)					
28/6 1978	-1.63	1.30	2.33	-0.15	-1.86
11/8 1978	-1.47	1.33	1.97	-0.16	-1.67

TABLE I, 6 Tilt station 0050, Grjótagjá S

Bench marks	0051	0052	0053	0054	0055
Coordinates of bench marks (meter)					
X (east)	1.5	-20.7	-18.5	15.2	22.6
Y (north)	22.4	12.2	-19.8	-21.9	7.1
Relative elevation of bench marks (centimeter)					
3/12 1977	-49.793	-11.928	31.521	9.723	20.477
20/5 1978	-49.762	-11.928	31.538	9.700	20.451
29/6 1978	-49.770	-11.912	31.542	9.690	20.450
12/8 1978	-49.766	-11.888	31.549	9.686	20.419
29/9 1978	-49.771	-11.909	31.556	9.680	20.444
17/2 1979	-49.740	-11.899	31.565	9.636	20.438
Changes in relative elevation since 19/5 1977 (millimeter)					
3/12 1977	0.90	-0.26	-1.49	-0.35	1.21
20/5 1978	1.22	-0.26	-1.32	-0.59	0.95
29/6 1978	1.13	-0.10	-1.28	-0.68	0.93
12/8 1978	1.18	0.14	-1.21	-0.73	0.63
29/9 1978	1.12	-0.07	-1.14	-0.78	0.88
17/2 1979	1.43	0.03	-1.05	-1.22	0.81

TABLE I, 7 Tilt station 0060, Grjótagjá N

Bench marks	0061	0062	0063	0064	0065
Coordinates of bench marks (meter)					
X (east)	4.6	-24.8	-17.5	16.3	21.5
Y (north)	22.9	10.9	-21.2	-17.2	4.7
Relative elevation of bench marks (centimeter)					
6/12 1977	-2.942	53.702	31.143	-37.765	-44.138
20/5 1978	-2.958	53.734	31.163	-37.782	-44.157
29/6 1978	-2.972	53.729	31.174	-37.782	-44.149
6/8 1978	-2.963	53.750	31.179	-37.787	-44.180
29/9 1978	-2.960	53.735	31.186	-37.780	-44.180
28/10 1978	-2.974	53.757	31.183	-37.777	-44.189
17/2 1979	-2.964	53.756	31.190	-37.780	-44.202
Change in relative elevation since 19/5 1977 (millimeter)					
6/12 1977	0.66	-0.53	-1.87	0.00	1.73
20/5 1978	0.50	-0.21	-1.67	-0.16	1.54
29/6 1978	0.36	-0.25	-1.56	-0.17	1.62
6/8 1978	0.45	-0.04	-1.51	-0.21	1.31
29/9 1978	0.48	-0.19	-1.44	-0.15	1.30
28/10 1978	0.35	0.03	-1.47	-0.12	1.21
17/2 1979	0.44	0.02	-1.41	-0.15	1.09

TABLE I, 8 Tilt station 0070, Reykjahlíd

Bench marks		0071	0072	0073	0074	0075
Coordinates of bench marks (meter)						
X (east)		-20.1	-15.2	9.7	22.4	3.0
Y (north)		16.1	-22.0	-23.1	5.5	23.6
Relative elevation of bench marks (centimeter)						
1/12	1977	42.271	-47.761	0.894	1.932	2.664
13/1	1978	42.274	-47.729	0.890	1.912	2.654
20/5	1978	42.276	-47.759	0.942	1.906	2.634
29/6	1978	42.273	-47.790	0.979	1.897	2.641
19/7	1978	42.282	-47.749	0.970	1.886	2.611
2/10	1978	42þ287	-47.743	0.975	1.871	2.610
28/10	1978	42.297	-47.766	0.979	1.861	2.629
17/2	1979	42.313	-47.736	0.959	1.842	2.622
Change in relative elevation since 20/5 1977 (millimeter)						
1/12	1977	-1.45	-2.28	0.17	2.28	1.28
13/1	1978	-1.42	-1.96	0.12	2.09	1.18
20/5	1978	-1.40	-2.26	0.65	2.03	0.98
29/6	1978	-1.42	-2.57	1.01	1.94	1.04
19/7	1978	-1.34	-2.16	0.93	1.82	0.75
2/10	1978	-1.29	-2.10	0.98	1.67	0.74
28/10	1978	-1.18	-2.33	1.01	1.58	0.93
17/2	1979	-1.02	-2.03	0.81	1.39	0.85

TABLE I, 9 Tilt station 0080, Bjarghóll

Bench marks	0081	0082	0083	0084	0085
Coordinates of bench marks (meter)					
X (east)	14.6	-9.8	-24.2	-4.2	23.5
Y (north)	19.5	21.6	-3.9	-25.7	-11.3
Relative elevation of bench marks (centimeter)					
2/12 1977	12.111	34.510	-19.826	-9.753	-17.043
11/1 1978	11.870	34.555	-19.464	-9.630	-17.332
19/5 1978	12.094	34.559	-19.754	-9.793	-17.106
28/6 1978	12.126	34.530	-19.836	-9.770	-17.051
5/8 1978	12.027	34.574	-19.658	-9.732	-17.212
30/9 1978	12.117	34.533	-19.825	-9.766	-17.059
12/11 1978	11.946	34.567	-19.575	-9.660	-17.278
16/2 1979[x)]	(12.127)	(34.520)	(-19.847)	(-9.776)	(-17.023)
Change in relative elevation since 14/6 1977 (millimeter)					
2/12 1977	2.02	-2.65	-3.20	-0.14	3.98
11/1 1978	-0.39	-2.21	0.42	1.08	1.09
19/5 1978	1.85	-2.17	-2.49	-0.55	3.36
28/6 1978	2.17	-2.45	-3.31	-0.32	3.90
5/8 1978	1.18	-2.02	-1.53	0.06	2.30
30/9 1978	2.08	-2.43	-3.20	-0.28	3.82
12/11 1978	0.37	-2.08	-0.70	0.78	1.63
16/2 1979[x)]	(2.18)	(-2.56)	(-3.42)	(-0.38)	(4.18)

[x)] Bench mark 0085 was not found because of snow cover. Its elevation was estimated from tilt at the Krafla power house.

TABLE I, 10 Tilt station 0090, Hvannstód

Bench marks	0091	0092	0093	0094	0095
Coordinates of bench marks (meter)					
X (east)	18.1	-4.8	-25.0	-9.5	21.2
Y (north)	10.4	21.2	7.3	-27.7	-11.4
Relative elevation of bench marks (centimeter)					
2/12 1977	-44.318	36.131	24.023	-37.334	21.498
11/1 1978	-44.380	36.451	24.447	-37.517	20.999
19/5 1978	-44.324	36.178	24.124	-37.393	21.414
28/6 1978	-44.331	36.098	24.001	-37.258	21.491
5/8 1978	-44.350	36.255	24.236	-37.378	21.237
30/9 1978	-44.306	36.121	24.010	-37.311	21.486
12/11 1978 x)	(-44.355)	(36.339)	(24.355)	(-37.467)	(21.127)
16/2 1979	-44.290	36.127	24.004	-37.327	21.487
Change in relative elevation since 14/5 1977 (millimeter)					
2/12 1977	0.68	-2.99	-3.78	1.33	4.77
11/1 1978	0.04	0.19	0.49	-0.51	-0.23
19/5 1978	0.62	-2.53	-2.77	0.74	3.94
28/6 1978	0.55	-3.33	-4.00	2.08	4.70
5/8 1978	0.35	-1.76	-1.64	0.88	2.16
30/9 1978	0.80	-3.10	-3.91	1.56	4.65
12/11 1978	(0.31)	(-0.92)	(-0.46)	(0.00)	(1.06)
16/2 1979	0.95	-3.04	-3.97	1.39	4.66

x) Bench mark 0094 was not found because of ice cover. Its elevation was estimated from tilt at the Krafla power house.

TABLE I, 11 Tilt station 0200, Hverfjall

Bench marks	0201	0202	0203	0204	0205
Coordinates of bench marks (meter)					
X (east)	4.3	-24.7	-10.0	9.7	20.5
Y (north)	24.1	13.4	-23.8	-21.0	7.5
Relative elevation of bench marks (centimeter)					
21/5 1978	-28.576	10.480	45.510	7.193	-34.608
29/6 1978	-28.551	10.497	45.501	7.167	-34.612
12/8 1978	-28.535	10.494	45.478	7.176	-34.613
2/10 1978	-28.574	10.491	45.498	7.188	-34.602
Change in relative elevation since 15/6 1977 (millimeter)					
21/5 1978	1.15	0.53	-0.51	-1.19	0.02
29/6 1978	1.40	0.70	-0.60	-1.46	-0.03
12/8 1978	1.56	0.67	-0.83	-1.36	-0.04
2/10 1978	1.17	0.64	-0.63	-1.25	0.07

TABLE I, 12 Tilt station 0100, Hóll

Bench marks	0101	0102	0103	0104
Coordinates of bench marks (meter)				
X (east)	-29.6	-6.0	15.8	19.7
Y (north)	3.2	-17.3	-9.4	23.6
Relative elevation of bench marks (centimeter)				
28/7 1976	77.269	12.022	-43.961	-45.330
17/5 1977	77.304	12.001	-43.974	-45.331
15/7 1977	77.278	12.055	-43.990	-45.342
21/5 1978	77.331	11.698	-44.191	-44.838
11/8 1978	77.343	11.678	-44.178	-44.843
Change in relative elevation since 28/7 1976 (millimeter)				
28/7 1976	0.00	0.00	0.00	0.00
17/5 1977	0.35	-0.21	-0.13	-0.01
15/7 1977	0.08	0.33	-0.29	-0.12
21/5 1978	0.62	-3.24	-2.30	4.92
11/8 1978	0.74	-3.44	-2.17	4.86

TABLE I, 13 Tilt station 0110, Lón

Bench marks	0110	0112	0113	0114	0115
Coordinates of bench marks (meter)					
X (east)	28.2	7.6	-17.2	-18.6	0.0
Y (north)	5.3	22.8	10.7	-12.1	-26.6
Relative elevation of bench marks (centimeter)					
28/7 1976	-13.192	4.188	-18.657	32.995	-5.333
17/5 1977	-13.184	4.171	-18.610	32.979	-5.356
15/7 1977	-13.196	4.189	-18.659	33.000	-5.333
21/5 1978	-13.162	4.194	-18.683	32.968	-5.317
11/8 1978	-13.143	4.194	-18.686	32.951	-5.316
Change in relative elevation sunce 28/7 1976					
28/7 1976	0.00	0.00	0.00	0.00	0.00
17/5 1977	0.08	-0.17	0.47	-0.16	0.22
15/7 1977	-0.05	0.01	-0.02	0.05	0.00
21/5 1978	0.30	0.06	-0.26	-0.26	0.16
11/8 1978	0.49	0.07	-0.29	-0.44	0.17

APPENDIX II

Observed ground tilt at the spirit level tilt stations in the Mývatn-Krafla-Kelduhverfi area from time of first measurement at each station to the time of any subsequent observation. The tilt components are given in microradians and positive values denote tilt towards north and east or subsidence north and east of the station.

TABLE II, 1 Tilt station A, Námaskard

Date		N-component of tilt	E-component of tilt
27/1	1976	0.0	0.0
7/5	1976	-5.2	-3.7
2/7	1976	-19.1	-2.8
27/7	1976	-19.4	-4.8
19/9	1976	-23.9	-3.4
16/5	1977	-38.1	58.3
17/6	1977	-42.8	55.2
17/8	1977	-45.2	58.6
12/9	1977	-107.3	112.6
21/10	1977	-110.8	112.5
21/5	1978	-115.3	109.8
24/6	1978	-123.0	109.8
12/8	1978	-113.8	111.1

TABLE II, 2 Tilt station 0000, Hlídardalur

Date		N-component of tilt	E-component of tilt
27/7	1976	0.0	0.0
20/8	1976	-16.8	1.1
18/9	1976	-30.6	3.0
2/10	1976	-30.2	12.7
23/10	1976	-37.2	10.2
1/11	1976	21.8	2.7
18/5	1977	26.2	22.3
13/6	1977	-7.5	40.3
17/7	1977	-29.5	33.8
15/8	1977	-54.1	42.3
10/9	1977	2.0	82.9
21/10	1977	-49.3	90.0
1/12	1977	-75.2	92.5
13/1	1978	21.2	77.4
19/5	1978	-67.9	78.1
22/6	1978	-72.0	73.8
5/8	1978	-36.2	75.1
30/9	1978	-72.9	79.2
13/11	1978	-4.4	74.4
4/3	1979	-90.7	86.5

TABLE II, 3 Tilt station 0010, Leirhnjúkur

Date		N-component of tilt	E-component of tilt
27/7	1976	0.0	0.0
20/8	1976	5.4	27.7
18/9	1976	33.8	49.2
2/10	1976	29.0	71.0
23/10	1976	47.5	73.2
1/11	1976	-74.5	-1.0
18/5	1977	-19.5	-233.4
13/6	1977	9.3	-187.3
17/7	1977	25.9	-145.0
15/8	1977	39.9	-95.1
10/9	1977	20.9	-323.6
21/10	1977	35.9	-198.3
1/12	1977	65.8	-163.1
19/5	1978	14.2	-159.4
28/6	1978	27.6	-118.4
19/7	1978	-79.9	-185.0
30/9	1978	10.0	-105.5
13/11	1978	-112.7	-180.0
4/3	1979	5.1	-62.8

TABLE II, 4 Tilt station 0020, Mývatn N

Date		N-component of tilt	E-component of tilt
27/7	1976	0.0	0.0
17/9	1976	-9.6	-2.0
23/10	1976	-4.5	0.1
16/5	1977	2.8	-44.9
16/6	1977	-3.7	-47.7
20/7	1977	5.0	-39.7
15/8	1977	-5.0	-48.4
11/9	1977	-18.2	-85.1
29/10	1977	-13.9	-93.7
2/12	1977	-14.5	-92.4
20/5	1978	-17.0	-90.8
29/6	1978	-17.9	-93.5
19/7	1978	-13.0	-88.2

TABLE II, 5 Tilt station 0030, Mývatn E

Date		N-component of tilt	E-component of tilt
27/7	1976	0.0	0.0
19/9	1976	-7.5	-1.7
20/5	1977	57.4	-30.7
17/6	1977	49.7	-29.8
17/8	1977	64.3	-139.0
12/9	1977	-4.3	-185.1

TABLE II, 6 Tilt station 0040, Jörundur

Date		N-component of tilt	E-component of tilt
27/7	1976	0.0	0.0
20/8	1976	0.5	-1.2
19/9	1976	4.9	13.9
16/6	1977	-23.5	30.4
19/7	1977	-19.7	39.8
15/8	1977	-38.0	45.6
12/9	1977	-33.5	57.5
21/10	1977	-46.1	69.8
28/6	1978	-52.3	70.8
11/8	1978	-49.3	61.4

TABLE II, 7 Tilt station 0050, Grjótagjá S

Date		N-component of tilt	E-component of tilt
19/5	1977	0.0	0.0
16/6	1977	11.8	0.3
18/7	1977	7.2	-3.3
16/8	1977	11.2	7.5
10/9	1977	-34.3	-49.4
28/10	1977	-42.4	-41.3
3/12	1977	-40.5	-37.8
20/5	1978	-44.8	-29.8
29/6	1978	-45.6	-26.0
12/8	1978	-46.4	-16.9
29/9	1978	-45.0	-22.0
17/2	1979	-54.8	-14.6

TABLE II, 8 Tilt station 0060, Grjótagjá N

Date		N-component of tilt	E-component of tilt
19/5	1977	0.0	0.0
16/6	1977	23.1	18.9
20/7	1977	12.9	6.6
16/8	1977	3.7	7.8
10/9	1977	-35.4	-68.8
24/10	1977	-33.9	-58.3
6/12	1977	-39.6	-50.9
20/5	1978	-38.0	-39.6
29/6	1978	-34.2	-39.7
6/8	1978	-36.1	-31.8
29/9	1978	-33.5	-34.0
28/10	1978	-32.8	-29.9
17/2	1979	-33.4	-27.6

TABLE II, 9 Tilt station 0070, Reykjahlíd

Date		N-component of tilt	E-component of tilt
20/5	1977	0.0	0.0
16/6	1977	2.9	-7.0
20/7	1977	13.3	-2.9
16/8	1977	-6.4	-15.9
11/9	1977	-38.6	-99.2
24/10	1977	-32.0	-110.9
1/12	1977	-36.2	-97.6
13/1	1978	-31.4	-89.1
20/5	1978	-25.9	-94.9
29/6	1978	-25.5	-100.3
19/7	1978	-18.2	-90.5
2/10	1978	-16.8	-86.6
28/10	1978	-22.1	-86.7
17/2	1978	-20.7	-75.3

TABLE II, 10 Tilt station 0080, Bjarghóll

Date		N-component of tilt	E-component of tilt
14/6	1977	0.0	0.0
18/7	1977	-8.3	-44.1
16/8	1977	-18.1	-69.0
11/9	1977	48.8	-44.2
2/12	1977	29.2	-155.3
11/1	1978	58.9	-18.9
19/5	1978	15.8	-129.6
28/6	1978	21.3	-156.3
5/8	1978	26.0	-87.4
30/9	1978	22.4	-152.0
12/11	1978	44.9	-53.3
17/2	1979	19.2	-154.1

TABLE II, 11 Tilt station 0090, Hvannstód

Date		N-component of tilt	E-component of tilt
14/6	1977	0.0	0.0
18/7	1977	34.4	-34.9
16/8	1977	64.6	-59.2
11/9	1977	16.9	-14.1
2/12	1977	109.6	-133.0
11/1	1978	-16.1	7.5
19/5	1978	82.8	-107.4
28/6	1978	129.8	-129.4
5/8	1978	59.9	-58.7
30/9	1978	114.2	-133.5
12/11	1978	14.8	-29.9
17/2	1979	109.4	-137.6

TABLE II, 12 Tilt station 0200, Hverfjall

Date		N-component of tilt	E-component of tilt
15/6	1977	0.0	0.0
19/7	1977	-8.4	6.3
15/8	1977	-15.2	1.3
11/9	1977	-13.7	-13.0
29/10	1977	-26.6	-4.2
21/5	1978	-39.3	10.3
29/6	1978	-47.8	14.6
12/8	1978	-52.7	11.0
2/10	1978	-42.8	10.9

TABLE II, 13 Tilt station 0100, Hóll

Date		N-component of tilt	E-component of tilt
28/7	1976	0.0	0.0
17/5	1977	-9.1	9.2
15/7	1977	3.6	6.7
21/5	1978	-206.1	3.5
11/8	1978	-207.9	4.8

TABLE II, 14 Tilt station 0110, Lón

Date		N-component of tilt	E-component of tilt
28/7	1976	0.0	0.0
17/5	1977	-7.3	4.6
15/7	1977	0.3	1.1
21/5	1978	3.8	-12.7
11/8	1978	3.4	-19.1

APPENDIX III

Local deformation of tilt stations

Most of the spirit level tilt stations consist of 5 markers permanently placed in pahoehoe lava surface, on the circumference of a circle of 25 m radius. Tilt is computed by fitting a tilted plane to the elevation changes of the markers by the least squares method.

Comparison of the elevation change of a marker with the calculated elevation change, using the least squares tilted plane shows, that the discrepancy between these, frequently exceeds the observational error by significant amount. This relative vertical movement of the markers is the result of what is here called "local deformation". Site investigation has shown no displacement of the markers relative to the lava surface in which they are placed.

To clarify the nature of the local deformation of the spirit level stations, a special study was made on one of the stations, Mývatn N or 0020 (Fig. III,1), which is located a short distance north of Mývatn on the eighteenth century lava. This station is located near the center of the lava field at the north end of Mývatn and at least

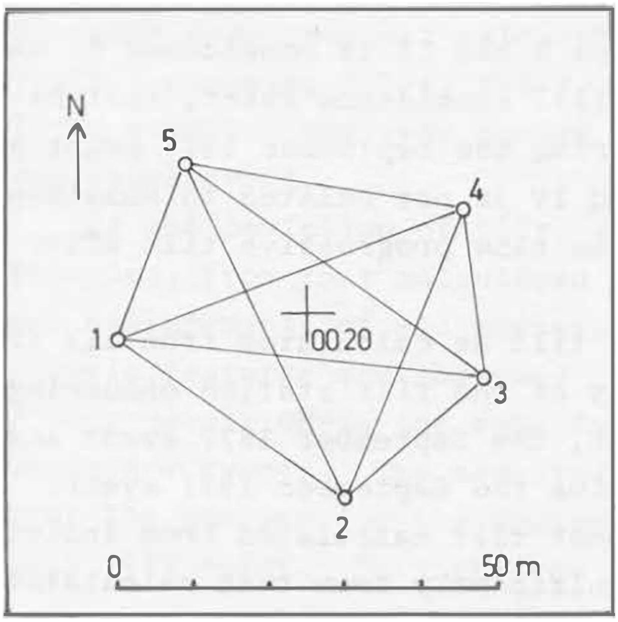

Fig. III,1. The bench mark array of tilt station 0020, Mývatn N.

500 m from its edge in any direction. Its elevation is about 15 m above the lake level of Mývatn. It is very probable that prior to the 1724-1729 eruption, the lake Mývatn extended as far north as this tilt station, which gives a probable thickness of the lava as about 15 m. The lava is a typical pahoehoe lava with rather low porosity and practically no loose rocks on its surface. Large fissures, obviously formed during solidification of the lava, encircle the station but do not enter the area of the station.

A total of 16 measurements have been made at this station from July 1976 to October 1979. Small and irregular tilt has been observed, except during the subsidence events of April 1977 and September 1977, when large tilt occurred. There are indications of slow progressive tilt during the two-year period after the September 1977 event.

To reduce the effect of observational errors, averages of three or four observations during times of no significant tilt are compared. These groups of observations are:

I: July 27, 1976, Sept. 17, 1976 and Oct. 23, 1976.

II: May 16, 1977, June 16, 1977, July 20, 1977 and Aug. 15, 1977.

III: Sept. 11, 1977, Oct. 29, 1977 and Dec. 2, 1977.

IV: Aug. 1, 1979, Aug. 22, 1979 and Oct. 3, 1979.

Observed tilt between groups I and II is considered to have occurred during the April 1977 subsidence event, that between groups II and III during the September 1977 event and that between groups III and IV is not related to subsidence events, but is considered as slow progressive tilt after the September 1977 event.

Table III-1 shows the tilt as calculated from all triangles in the 5 point array of the tilt station occurring during the April 1977 event, the September 1977 event and the two year period following the September 1977 event. This table shows clearly that tilt calculated from individual triangles differs significantly from that calculated

TABLE III-1

Calculated tilt of individual triangles of the 5 marker tilt station Mývatn N (0020) during the April 1977 event, the September 1977 event, and during a 2-year period following the September 1977 event.

Triangles	April 1977 event		Sept. 1977 event		Late 1977 to late 1979	
	Tilt µ-rad	Azim. degrees	Tilt µ-rad	Azim. degrees	Tilt µ-rad	Azim. degrees
1-2-3	62.5	244.5	68.6	233.6	8.45	271.9
2-3-4	111.4	286.7	96.9	274.6	7.14	200.5
3-4-5	49.1	326.2	33.6	296.8	12.75	233.6
4-5-1	34.0	265.1	42.6	237.9	11.40	240.9
5-1-2	38.6	268.4	46.2	243.5	12.88	248.2
1-2-4	36.1	274.1	41.8	246.8	11.35	253.7
2-3-5	68.4	257.8	70.8	244.0	6.72	251.4
3-4-1	57.9	306.1	51.4	284.6	11.86	231.1
4-5-2	33.2	272.4	39.5	243.3	10.35	249.1
5-1-3	53.4	274.9	55.2	253.0	10.83	237.0
Least squares	44.8	275.8	47.7	251.3	10.38	245.5

by the least squares method using measurements of all markers of the tilt station. It is also noteworthy, that the same triangles show greatest calculated tilt for both subsidence events (triangles 2-3-4, 2-3-5, and 1-2-3), but the least tilt during the two year period following the September 1977 subsidence event.

If the deviation of tilt, as calculated from individual triangles, from that calculated by the least squares method from measurements of all markers is considered, more characteristic features are observed (Table III-2). The azimuth of this devaition is the same for every triangle for the two subsidence events. The magnitude of this deviation is always about 19% smaller for the September 1977 event than for the April 1977 event. Further, the deviation of calculated tilt

TABLE III-2

Deviation of tilt as calculated from individual triangles from that calculated by the least squares method from all five markers at tilt station Mývatn N (0020) during the April 1977 event, the September 1977 event, and a 2-year period following the September 1977 event.

Triangles	April 1977 event		Sept. 1977 event		Late 1977 to late 1979	
	Amount μ-rad	Azim. degrees	Amount μ-rad	Azim. degrees	Amount μ-rad	Azim. degrees
1-2-3	33.6	200.8	27.2	201.6	4.69	12.3
2-3-4	68.0	293.9	56.3	294.2	7.35	109.0
3-4-5	40.2	25.4	34.1	26.6	3.36	194.1
4-5-1	13.0	124.8	11.7	128.6	1.34	202.4
5-1-2	8.2	133.3	6.5	143.5	2.56	259.2
1-2-4	8.8	102.8	6.8	99.4	1.82	307.6
2-3-5	29.4	229.6	24.2	229.5	3.76	55.1
3-4-1	32.4	350.3	28.6	350.8	3.15	176.0
4-5-2	11.7	105.3	10.2	103.8	0.64	339.9
5-1-3	8.7	270.4	7.6	263.7	1.64	167.0

for the two-year period following the September 1977 event is in opposite direction from that during the subsidence events and its magnitude roughly 11% of that during the April 1977 event. All deviations from these rules can be explained as the result of observational errors.

Maximum observational errors causing 1.5 μ-rad error in calculated tilt will explain all differences between the April 1977 and September 1977 results, providing the deviations of triangle tilt from least squares tilt is identical in both cases, except for magnitude which is 19% greater for the April event than the September event. The same maximum error will explain almost all differences between observed tilt from late 1977 to late 1979 and tilt during the subsidence events of April 1977 and September 1977 if the deviations of triangle tilt from least square tilt is in opposite directions for every triangle and the magnitude of these deviations is 9 times greater for the April 1977 event than for the late 1977 to late 1979 period.

The cause of this discrepancy between tilt of individual triangles within one tilt station is here named "local ground deformation". The identical pattern of this deformation during the two subsidence events, which greatly affected the Mývatn area, and the opposite pattern during the following two years excludes any systematic observational error as the cause of this effect. The principal reason for the local ground deformation at the station 0020 is certainly related to the large scale ground deformation which took place in the Mývatn area during the subsidence events of April 1977 and September 1977 (Björnsson et al., 1979; Tryggvason, 1978c). During these events, an east-west contraction of roughly 10^{-4} took place in the area of the tilt station. This contraction has supposedly caused wrinkels of the lava on which the tilt station is located. These wrinkels are gradually being evened out after these events, but the amplitude of these wrinkels has decreased by only about 5% in two years.

The observed local deformation show, that tilt observations from a triangle of markers of 50 m side length or smaller may not be representative for the region of the tilt stations. Tilt station consisting of 5 markers within 25 m from a central point is certainly more representative than a triangle, but the observed tilt may deviate significantly and systematically from that of a larger area.