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OPTICAL LEVELLING TILT STATIONS IN THE VICINITY OF KRAFLA AND THE KRAFLA FISSURE SWARM

OBSERVATIONS 1976 TO 1994

by

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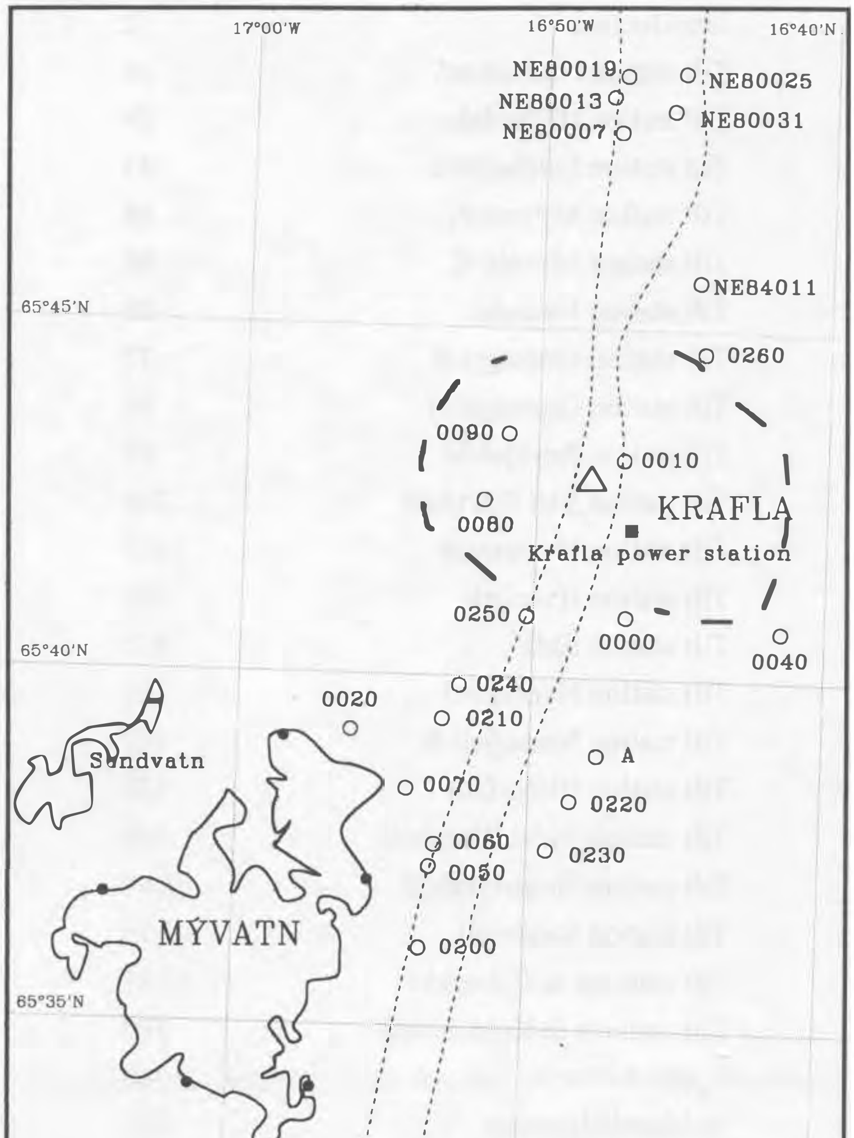


Fig. 1. Map of the Krafla region showing the Krafla caldera (thick dashed line), the most active part of the Krafla fissure swarm (thin dashed lines), optical levelling tilt stations (open circles), center of inflations and deflations at Krafla (triangle), and lake level stations at the shore of lake Mývatn (filled circles).

The volcanic episode of Krafla, North Iceland which lasted from 1975 to 1984 was characterised by large scale ground deformation on the crustal plate boundary in North Iceland (Björnsson et al. 1977). The first sign of this ground deformation was indirect, but frequency of earthquakes increased greatly in the vicinity of Krafla in early 1975. The first direct and obvious sign of ground deformation occurred on 20 December 1975 when a small eruption occurred and numerous ground fissures were displaced, both vertically and horizontally. At the same time an intense earthquake swarm commenced.

The first direct measurement of ground deformation of the December 1975 event was levelling of the foundation of a geothermal power station at Krafla on 18 January 1976, while the power station was under construction (Björnsson et al. 1985). Previous levelling of the power station foundation was made on November 20,1975. The north end of the 70 m long foundation had subsided about 48 mm relative to the south end from November 26, 1975 to January 18, 1976, corresponding to a ground tilt of almost 700 μrad down to an azimuth of due north.

Further measurements at a number of locations (Fig. 1) in 1976 and later, demonstrated that Krafla volcano inflated at a relatively steady rate, but this inflation was interrupted repeatedly by rapid deflations, associated with earthquake swarms, opening of ground fissures and sometimes eruptions of basaltic lava.

A water tube tiltmeter was installed at the Krafla geothermal power station in August 1976. This was a one component tiltmeter, oriented parallel to the long walls of the main building of the power station, in direction N13°E-S13°W. Length of the water tube was about 69.5 m and readings were manual, usually once per day. This tiltmeter was operated for almost 11 years (Figs 2, 3, and 4). A continuously recording, two component, electronic tiltmeter was installed in a cellar, about 20 m west of the water tube tiltmeter in August 1977 (Tryggvason 1982b, Ólafsson 1983). One component, the north component, is parallel to the water tube tiltmeter, another component, the east component, is oriented E13°S-W13°N, perpendicular to the first component. The records of the water tube tiltmeter and the north component of the electronic tiltmeter (Figs. 5, 6, 7, and 8) are very similar, Records of these tiltmeters at the Krafla power station are the best source of information on inflations and deflations of the Krafla volcano during the period of rapid ground deformation, 1976-1987. Several of the very small deflation events (Table 1) were observed only on records of the electronic tiltmeter at the Krafla power station.

Table 1

Subsidence events at Krafla during the 1977-1985 period of volcanic activity. No subsidence events have been recorded 1986-1995.

Date	Subsidence cm	volume 10^6 m^3	Remarks
20 Dec. 1975	280	220	First event, very large, slow, eruption
26 Sep. 1976	22	17	Moderate size, slow
31 Oct. 1976	58	46	Large, fast
20 Jan. 1977	36	28	Moderate size, fast
1 Apr. 1977	2	1.5	Very small, slow
11 Apr. 1977	6	4.7	Small, slow
16 Apr. 1977	6	4.7	Small, slow
27 Apr. 1977	100	79	Large, fast, eruption
8 Sep. 1977	66	52	Large, fast, eruption
2 Nov. 1977	3.5	2.8	Very small, fast
7 Jan. 1978	139	109	Very large, rather slow
10 Jul. 1978	67	53	Large, rather slow
10 Nov. 1978	79	62	Large, rather slow
13 May 1979	82	64	Large, slow
3 Aug. 1979	5.5	4.3	Small, slow
18 Nov. 1979	2.5	2.0	Very small, slow
2 Dec. 1979	4.5	3.5	Very small, slow
1 Feb. 1980	2.0	1.5	Very small, slow
11 Feb. 1980	13	10	Small, rather slow
16 Mar 1980	66	52	Large, fast, eruption
21 Jun. 1980	3.5	2.8	Very small, slow
10 Jul. 1980	68	53	Large, rather fast, eruption
14 Sep. 1980	1	0.8	Very small, fast
1 Oct. 1980	3	2.4	Very small, fast
18 Oct. 1980	38	30	Moderate size, very fast, eruption
23 Dec. 1980	12	9	Small, slow
30 Jan. 1981	45	35	Moderate size, fast, eruption
14 May 1981	1	0.8	Very small
18 Nov. 1981	47	37	Moderate size, fast, eruption
4 Sep. 1984	98	77	Large, fast, eruption
1 Jul. 1985	6	4.7	Small, slow

First column gives the date when each subsidence event started. Second column gives calculated subsidence at the point where subsidence was greatest. Maximum subsidence and volume of magma (third column) which flowed from the shallow Krafla magma chamber, correspond to each other with the estimated volume of magma equal to two times the volume of the subsidence bowl (Tryggvason 1981), assuming Mogi model deformation and depth to the source equal 2.5 km. The calculated subsidence is that expected if the removal of magma occurred instantaneously. The values of columns 2 and 3 are partly derived from recording tiltmeter at the Krafla power station and partly from observed tilt at optical levelling tilt stations. (From: Eysteinn Tryggvason, unpublished manuscript entitled KRÖFLUELDAR).

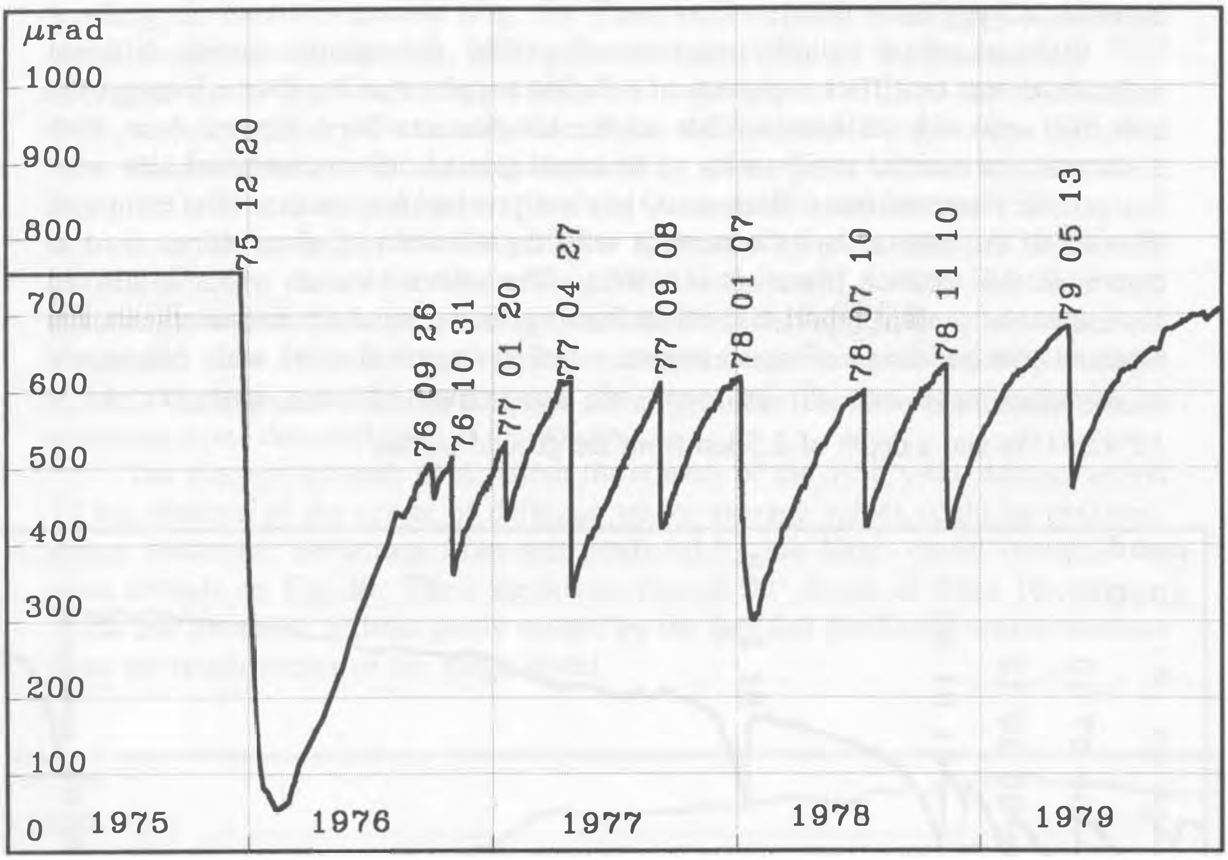


Fig. 2. Record of the water tube tiltmeter at the Krafla power station, August 1976 to December 1979, supplemented by result of levelling of the foundation of Krafla power station before August 1976. It is assumed that no tilt occurred before December 20, 1975. Tilt component in azimuth 13° is recorded, and uplift towards N13°E is considered positive tilt. Given are dates of commencement of major deflation events of Krafla volcano.

It has frequently been stated that ground deformation during each deflation of Krafla resembles strikingly that predicted from a point source of decreased pressure within a perfectly elastic, homogeneous half-space (Mogi model, Mogi 1958). The model theory is correct only if the pressure source is very small compared with the distance of the source from the flat surface of the half-space. Ground deformation during inflation of Krafla also resembles that predicted by the Mogi model with increased pressure at the point source. This model can be criticized with respect to Krafla as the geologic formations are certainly not homogeneous and not perfectly elastic, the topography deviates from the flat surface assumed in the model, and the pressure source can not be expected to be very small, compared to the depth to the source. Thus none of the required criteria of the model is valid in case of Krafla. Still the observed ground deformation resembles that predicted by the Mogi model (Tryggvason 1978), and comparison of the model and observed deformation can be used to estimate the location, both geographic coordinates and the depth from the earth's surface, of the center of a hypothetical magma reservoir. Also the volume change of this reservoir during deflations and inflations of Krafla volcano can be estimated (Tryggvason 1981).

Comparison of various measures of ground deformation during different deflation events or different periods of inflation suggest that the source location has been the same for all events. This source location can be computed from both horizontal and vertical components of observed ground deformation, and also from few precise observations or from many but less precise observations. The computed location of the source varies somewhat with the selection of observations used to determine this location (Ewart et al. 1991). The source location which is adopted for use in the present report is derived from various ground tilt measurements and repeated precise distance measurements. An average value of well determined source locations is obtained, resulting in the accepted source location of 65°42'54"N 16°47'51"W and a depth of 2.5 km from the ground surface.

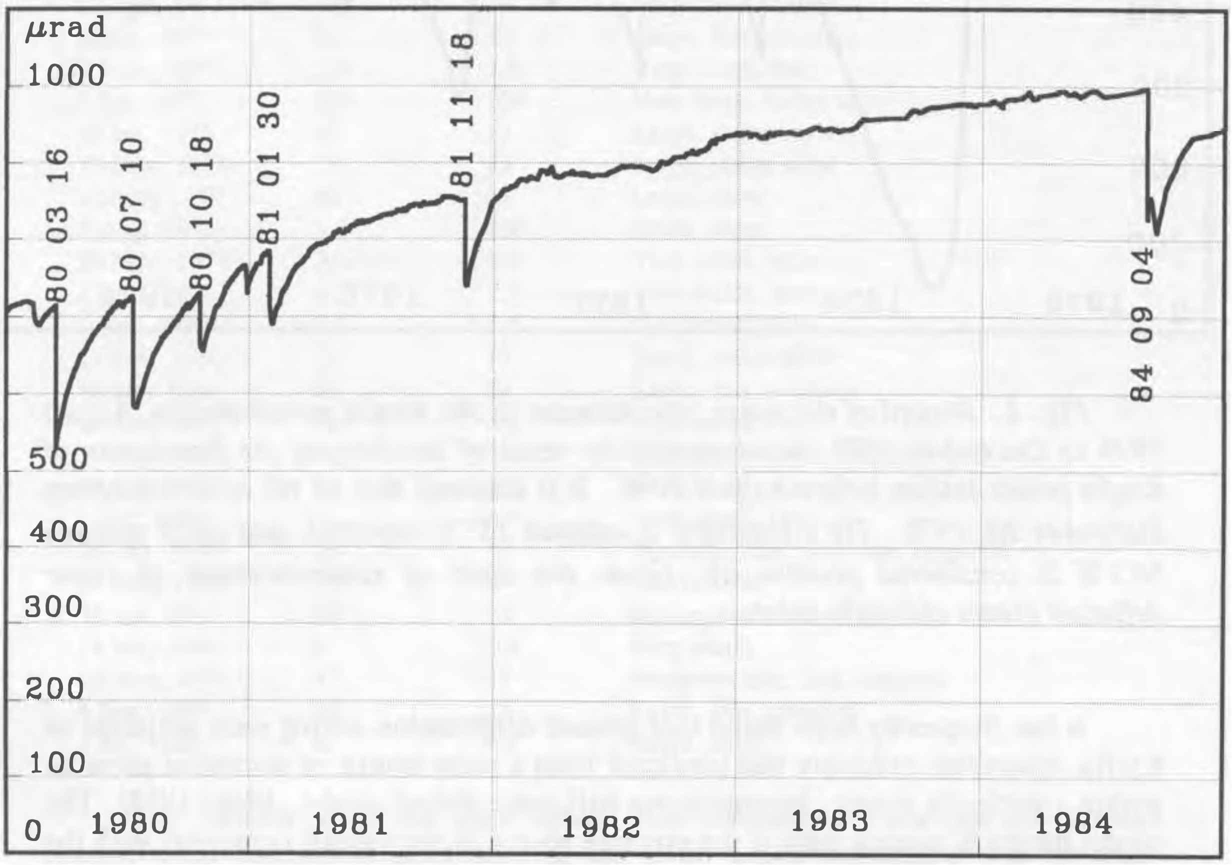


Fig. 3. Records of the water tube tiltmeter at the Krafla power station, January 1980 to December 1984. See Fig. 2 for explanation.

The present report deals primarily with observations of ground tilt at optical levelling tilt (dry-tilt) stations (Fig. 1). These stations were established at different times, the first one in January, 1976, seven in July 1976, six in May and June 1977 (Tryggvason, 1978), five in July 1980, five in October 1981 and two in October 1984, a total of 26 dry-tilt station. One of the stations established in July 1976, has been abandoned because it was considered of no value. Three stations constructed in July, 1980, were destroyed by lava flows in October 1980 and January 1981.

Only tilt station at less than 10 km distance from the center of the Krafla caldera did show clearly the tilt associated with deflation of Krafla. The tilt vectors at these stations do not meet in one point, but for each station, the tilt vectors have almost the same azimuth for all deflation events (Fig. 9), excluding events where rifting occurred near the station and the observed tilt was largely caused by processes other than deflation of the volcano.

The average azimuth of deflation tilt at each of the 10 dry-tilt stations within 10 km distance of the center of deflation where average values could be obtained, shows systematic deviations from that predicted by the Mogi model (towards the open triangle on Fig. 9). These deviations exceed 20° at six of these 10 stations. These deviations are at least partly caused by the fact that the Krafla region deviates from the requirements of the Mogi model.

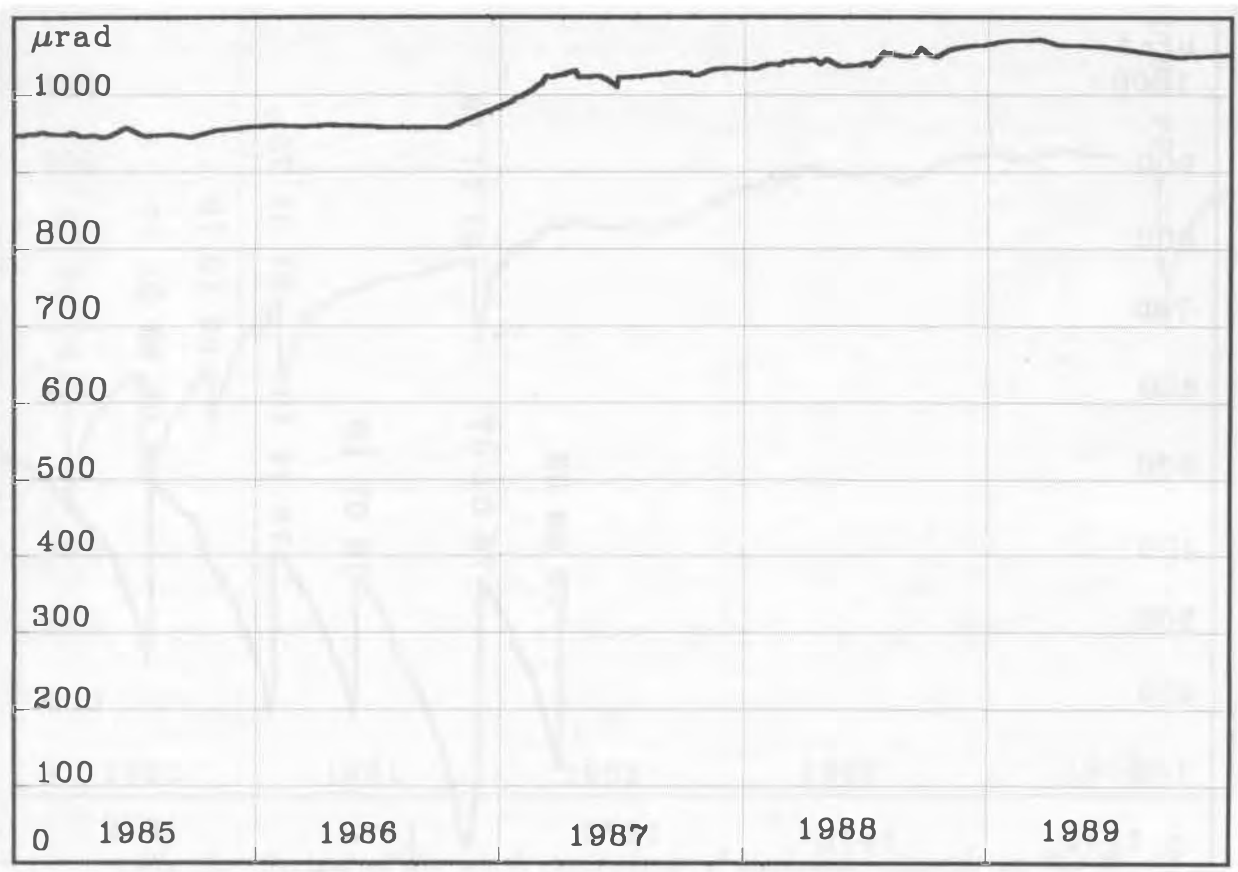


Fig. 4. Record of the water tube tiltmeter at the Krafla power station January 1985 to December 1989. This tiltmeter was not observed after January 17, 1990, and readings were less frequent after 1984 than previously.

Propagation of seismic waves through the source region suggests two separate regions of molten magma (Einarsson 1978). If this is true, it represents a significant deviation from the single point source assumed by the Mogi model.

During the period of most intense activity of Krafla, each deflation event was followed by a period of rapid inflation, until the ground level at the center of deflation/inflation was at similar or higher level than before the deflation (Figs 2, 3, 5, and 6). The tilt between late 1977 and late 1979 is a sum of several deflations and several inflation periods, resulting in net inflation (Figs. 2) The accumulated tilt vectors during this period (Fig. 10) are in direction roughly opposite to the deflation tilt vectors (Fig. 9), except for the station 0010, which lies nearest to the center of deflation/inflation. Four tilt stations near the east shore of Mývatn, at distances of 10 to 13 km from the center of deflation/inflation exhibit tilt up in westerly direction amounting to about 40 μrad. These stations were greatly affected by rifting event of September 8, 1977 and certainly also the event of 27 April 1977 (before these stations were constructed) but these events caused tilt up in easterly direction in the region of these stations (Tryggvason 1980). The 1977-1979 tilt east of Mývatn, but west of the axis of the Krafla fissure swarm (Fig. 1) can be explained as the result of gradual relaxation of the strain produced by the rifting events of April 27 and September 8, 1977.

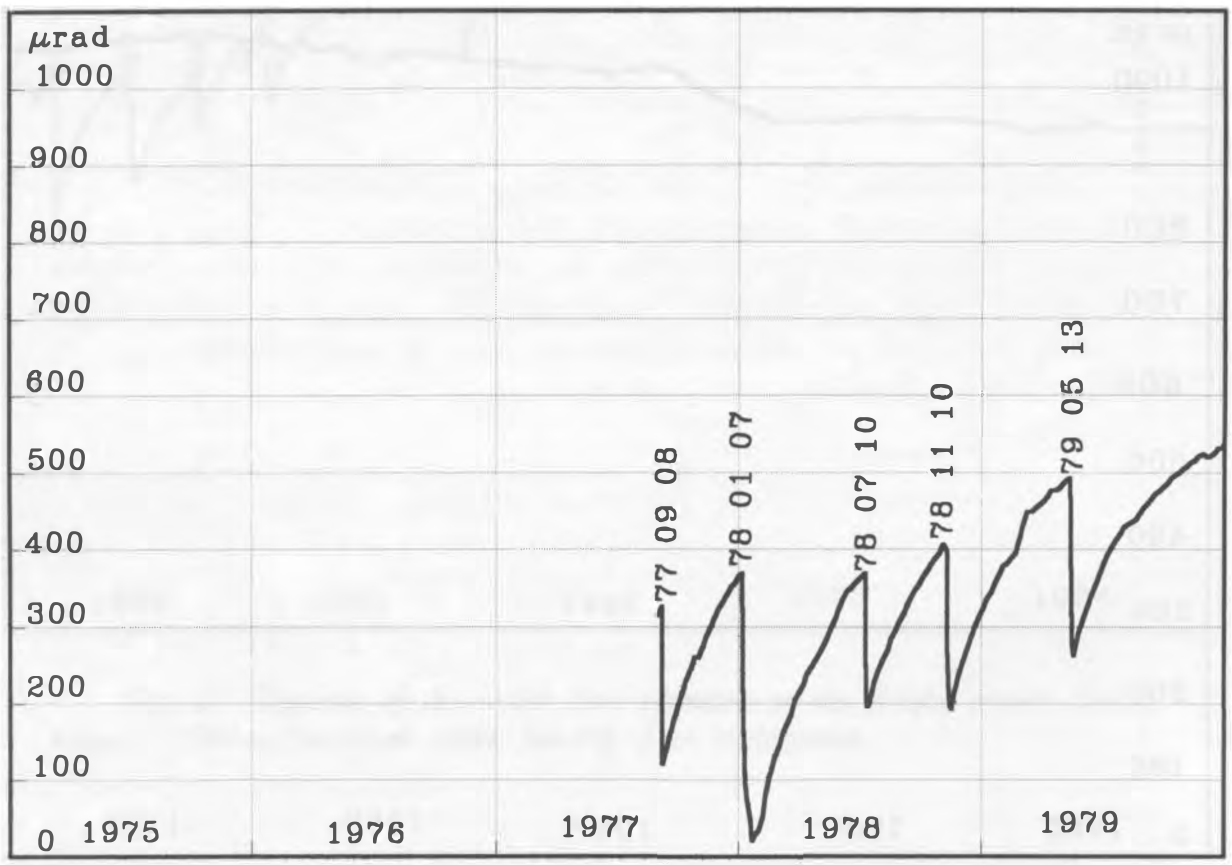


Fig. 5. Record of the north component of electronic tiltmeter in the Krafla power station August 1977 to December 1979. Tilt scale is the same as in Figs 2 to 4, except it has been shifted about 280 μrad.

During the latter part of the period of volcanic and tectonic activity at Krafla, 1981 to 1989, the Krafla volcano inflated at a slower rate than before, but this inflation was interrupted in November 1981 and September 1984 by rapid deflations and subsequent rapid inflations, which disturbed only briefly the general inflation trend (Figs 6 and 7) The accumulated tilt during this period (Fig. 11) deviates greatly from that observed during the two-year period late 1977 to late 1979. Stations west of the axis of the Krafla fissure swarm and south of the center of deflation/inflation all exhibit accumulated tilt up in northerly direction, although the tilt azimuth points west of the center of deflation/inflation. Stations east of the Krafla fissure swarm and south of the center of deflation/inflation exhibit accumulated tilt up in northerly direction (except station 0220), and the tilt vectors point east of the center of deflation/inflation. This is explained by general inflation of the Krafla region, causing the northerly tilt at the southern stations, in addition to continuation of the relaxation of the strain caused by the rifting events of 1977. This relaxation is responsible for the westward tilt component of the western stations and the eastward tilt component of the eastern stations.

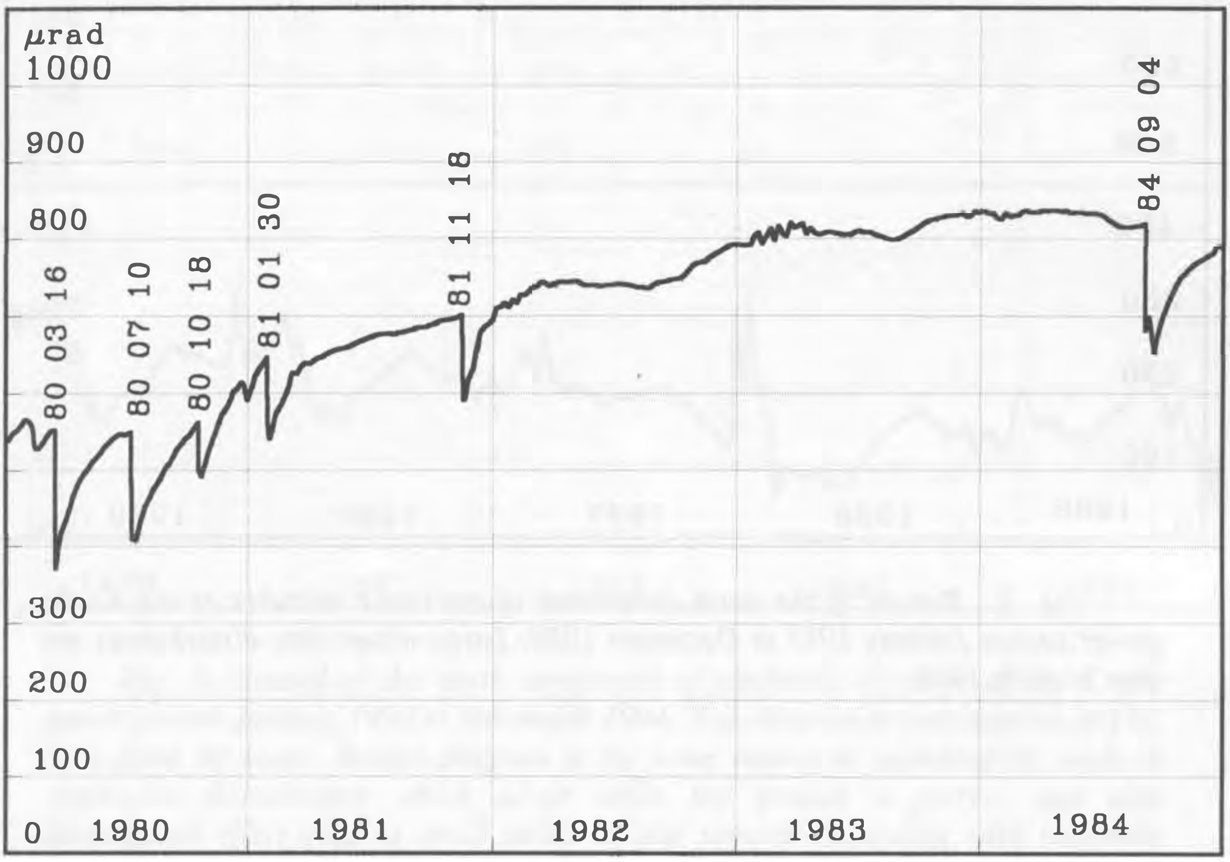


Fig. 6. Record of the north component of electronic tiltmeter at the Krafla power station January 1980 to December 1984. Winter time disturbances, caused by thermal stress in frozen ground, are seen, especially in January to March 1983.

At stations near to the center of deflation/inflation (stations 0010, 0080, and 0090), observed tilt was more northerly in 1979-1989 than before 1979 (Fig. 10 and 11). This is explained as tilt caused by inflation of a region centred about 5 km north of the generally accepted center of deflation/inflation (Tryggvason 1986) This northern inflation apparently commenced at the time of the July 1980 eruption, progressed at rapid rate at the beginning, but inflation rate decreased gradually to zero around 1990. This northern inflation causes large northerly component of tilt at the stations 0000, 0040, and 0250, south of Krafla and simultaneously small southerly tilt at the northern stations 0260 and 84011.

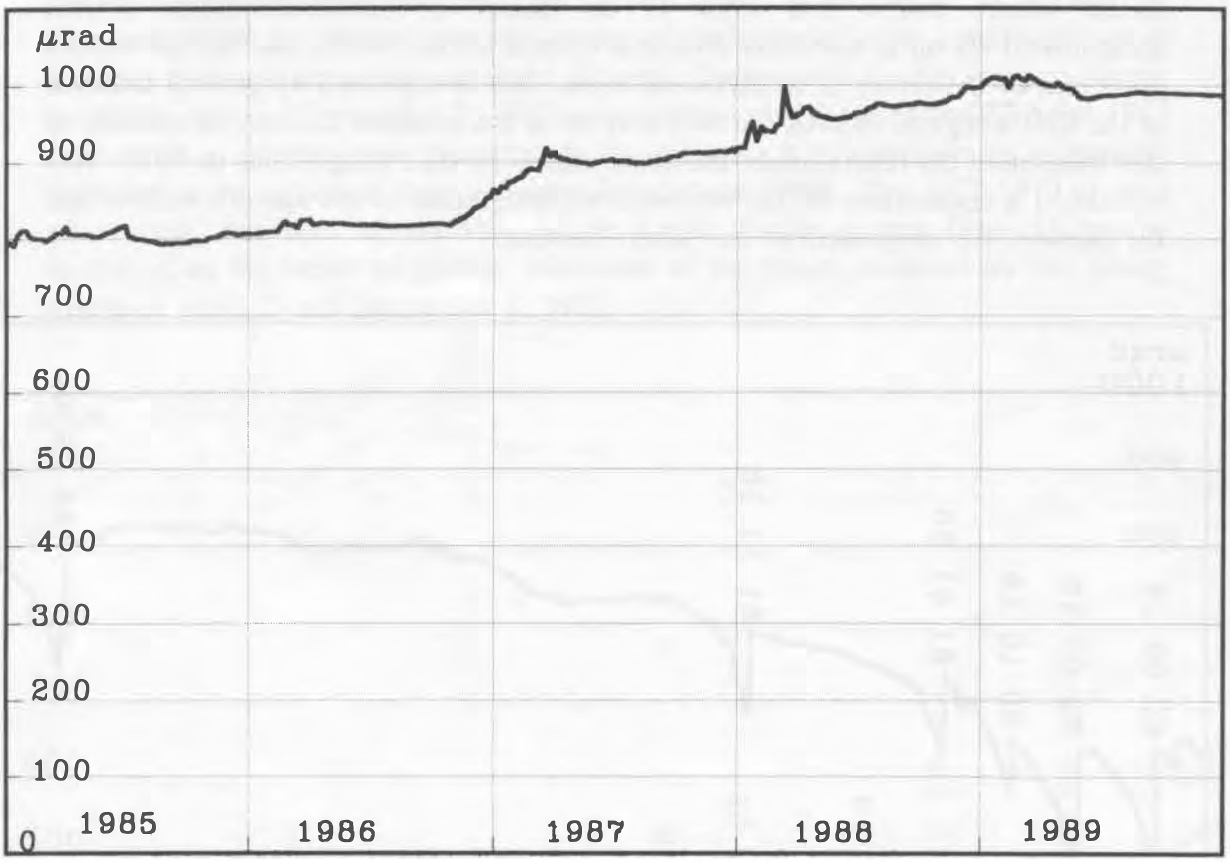


Fig. 7. Record of the north component of electronic tiltmeter at the Krafla power station January 1985 to December 1989. Large winter time disturbances are seen in early 1988.

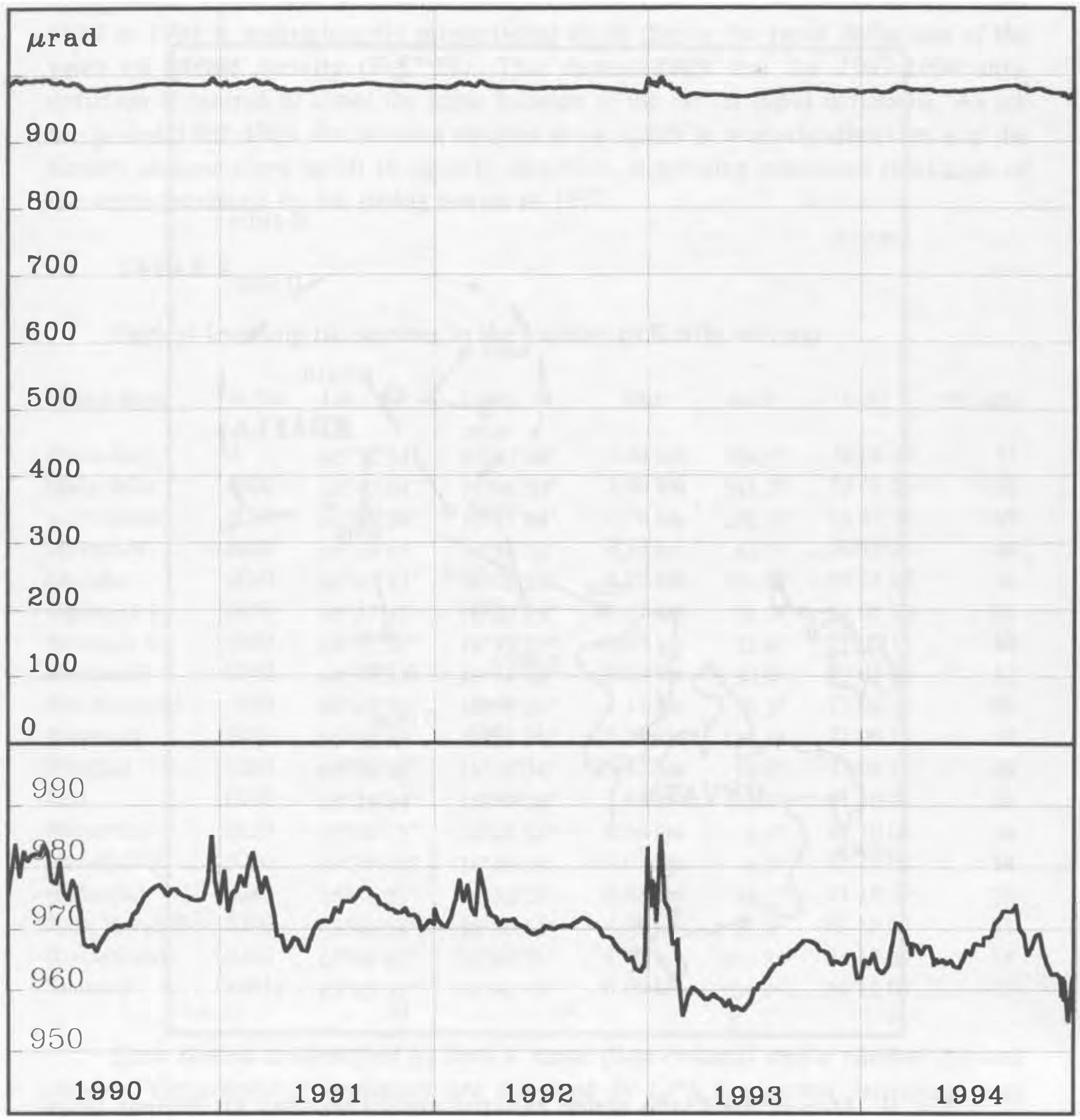


Fig. 8. Record of the north component of electronic tiltmeter at the Krafla power station January 1990 to December 1994. Top diagram is continuation of Fig. 7 in same tilt scale. Bottom diagram is the same record in expanded tilt scale to emphasize disturbances which occur while the ground is frozen, and also temperature effect causing small peaks in late summer coinciding with maximum temperature in the underground cellar where the tiltmeter is located.

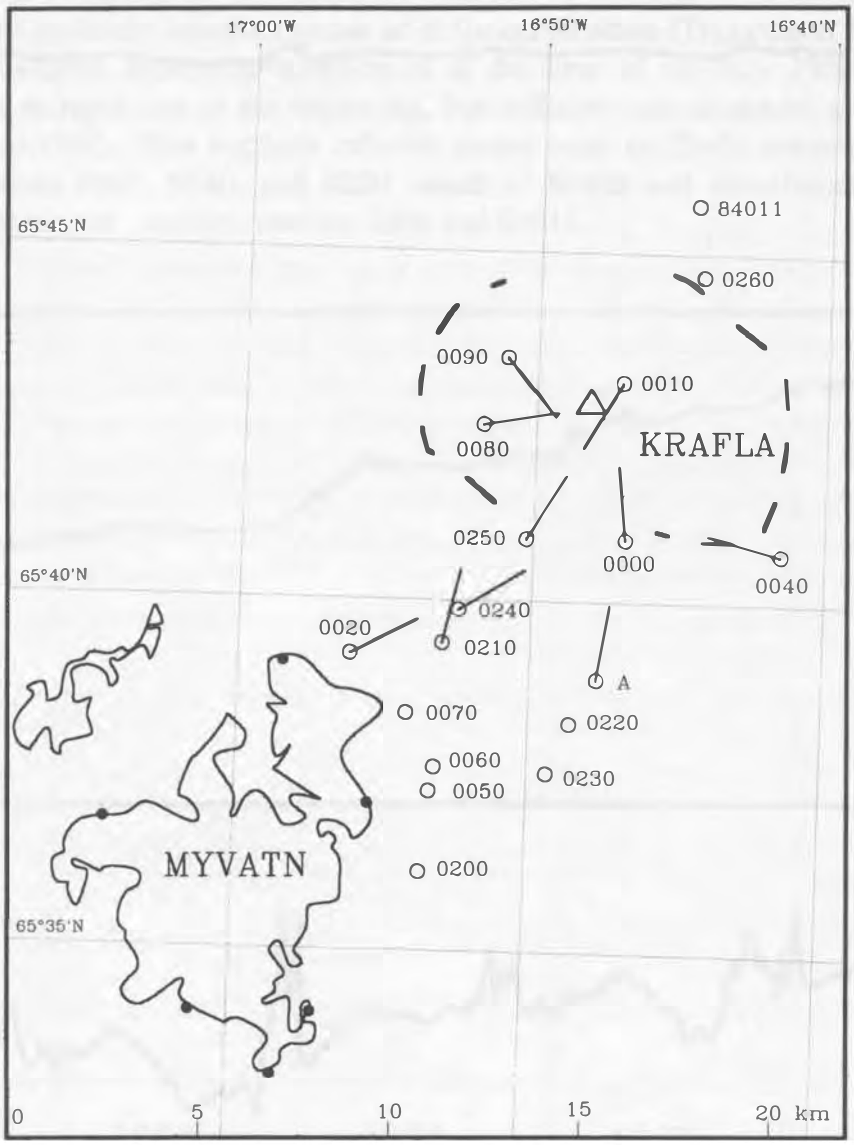


Fig. 9. Map of the Krafla region showing optical levelling tilt stations (open circles) and the average direction of downward tilt during deflation events of the Krafla volcano. Two northern stations were established after the last large deflation of Krafla, and six southern stations experienced too small tilt during the deflation events to determine tilt azimuth.

The general inflation of the Krafla volcano ceased in 1989 (Figs. 7 and 8, Tryggvason 1994) and a slow deflation commenced. The accumulated tilt from 1989 to 1994 is approximately proportional to tilt during the rapid deflations of the years of intense activity (Fig. 12). This demonstrates that the 1989-1994 slow deflation is centred at about the same location at the earlier rapid deflations. As for the period 1981-1989 the western stations show uplift in westerly direction and the eastern stations show uplift in easterly direction, suggesting continued relaxation of the strain produced by the rifting events of 1977.

TABLE 2

Optical levelling tilt stations in the vicinity of Krafla volcano

Station name	St.No.	Lat., N	Long., W	Dist	Azim	Date	No. obs
Námaskarð	A	65°38'54"	16°47'40"	7.44 km	358.9°	76 01 27	51
Hlíðardalur	0000	65°40'54"	16°46'50"	3.80 km	348.2°	76 07 27	71
Leirhnjúkur	0010	65°43'09"	16°47'04"	0.76 km	232.3°	76 07 27	69
Mývatn-N	0020	65°39'14"	16°56'10"	9.33 km	43.1°	76 07 27	49
Jörundur	0040	65°40'43"	16°41'29"	6.35 km	309.7°	76 07 27	31
Grjótagjá-S	0050	65°37'17"	16°53'19"	11.25 km	21.9°	77 05 19	45
Grjótagjá-N	0060	65°37'37"	16°53'10"	10.63 km	22.6°	77 05 19	48
Reykjahlíð	0070	65°38'23"	16°54'10"	9.69 km	30.0°	77 05 20	52
Ytri Bjarghóll	0080	65°42'34"	16°51'49"	3.11 km	78.5°	77 06 14	54
Hvannstóð	0090	65°43'30"	16°51'04"	2.71 km	114.3°	77 06 14	55
Hverfjall	0200	65°36'08"	16°53'34"	13.32 km	19.2°	77 06 15	46
Eldá	0210	65°39'24"	16°53'00"	7.61 km	31.3°	81 10 04	28
Hverarönd	0220	65°38'15"	16°48'34"	8.66 km	3.6°	81 10 04	26
Námafjall-S	0230	65°37'33"	16°49'19"	10.01 km	6.5°	81 10 04	24
Hlíðarfjall	0240	65°39'53"	16°52'28"	6.63 km	32.3°	81 10 07	29
Syðri Bjarghóll	0250	65°40'54"	16°50'14"	4.14 km	26.2°	81 10 07	31
Hreindýrahóll	0260	65°44'42"	16°44'21"	4.29 km	218.8°	84 10 03	19
Sandmúli	84011	65°45'52"	16°44'35"	6.06 km	204.4°	84 10 03	12

Each station is identified by both a name (first column) and a number (second column. Geographic coordinates are obtained by GPS navigation instrument and refer to the central marker of the arrays, with these exceptions: Coordinates of stations Hreindýrahóll and Sandmúli are from maps in scale 1:50000, and are less reliable than those of other stations, and for Sandmúli, coordinates refer to marker NE84011. Fifth column gives the distance from the tilt station to the center of deflation/inflation of Krafla volcano (65°42'54"N, 16°47'51"W) and sixth column gives the azimuth from the station to the center of deformation. The two last column give the date when each station was first observed and the number of observations made at each station before 1995. See Table T1 for stations in Gjástykki and chapter on tilt stations in Kelduhverfi.

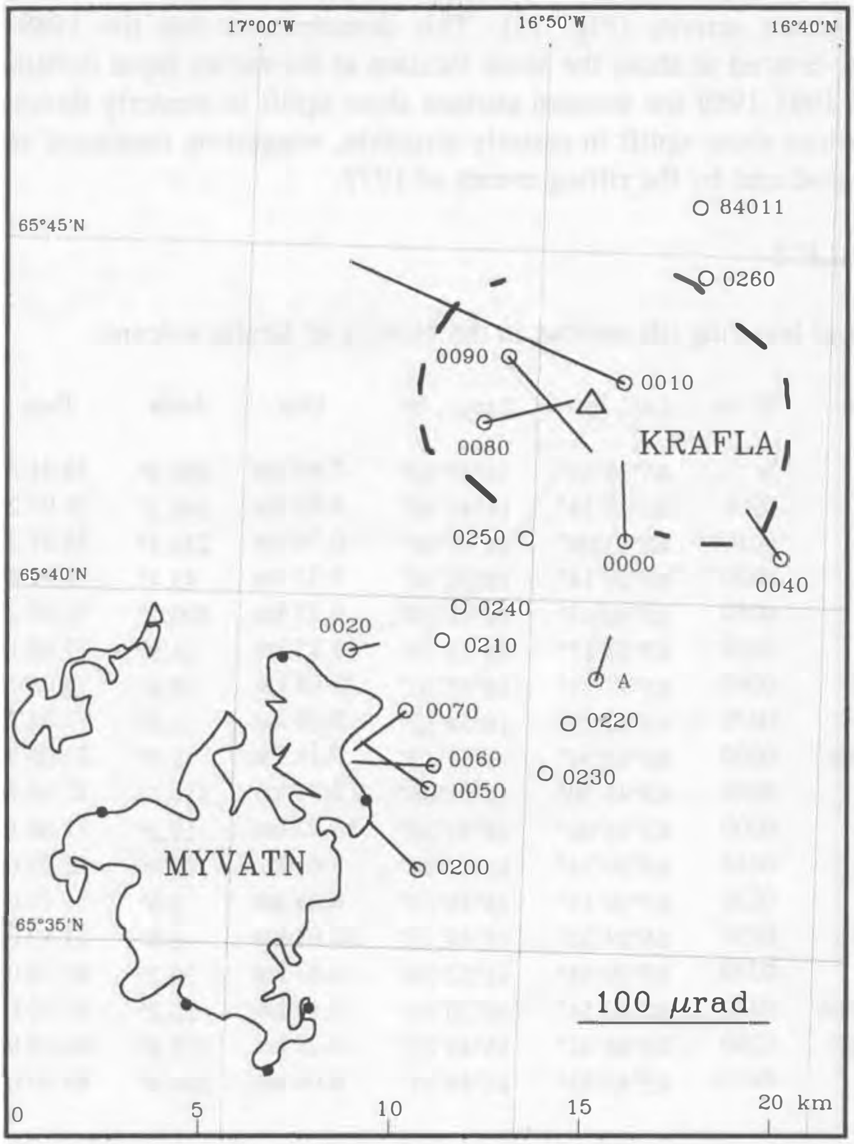


Fig. 10. Observed accumulated tilt from last observation of 1977 to last observation of 1979 at the optical levelling tilt stations in the Krafla region. Length of bar is proportional to observed tilt and bar extends in direction of upward tilt. Tilt at stations east of lake Mývatn reflect strain relaxation after rifting events of April and September 1977. At other stations, uplift towards the Krafla center of deformation (triangle) is observed.

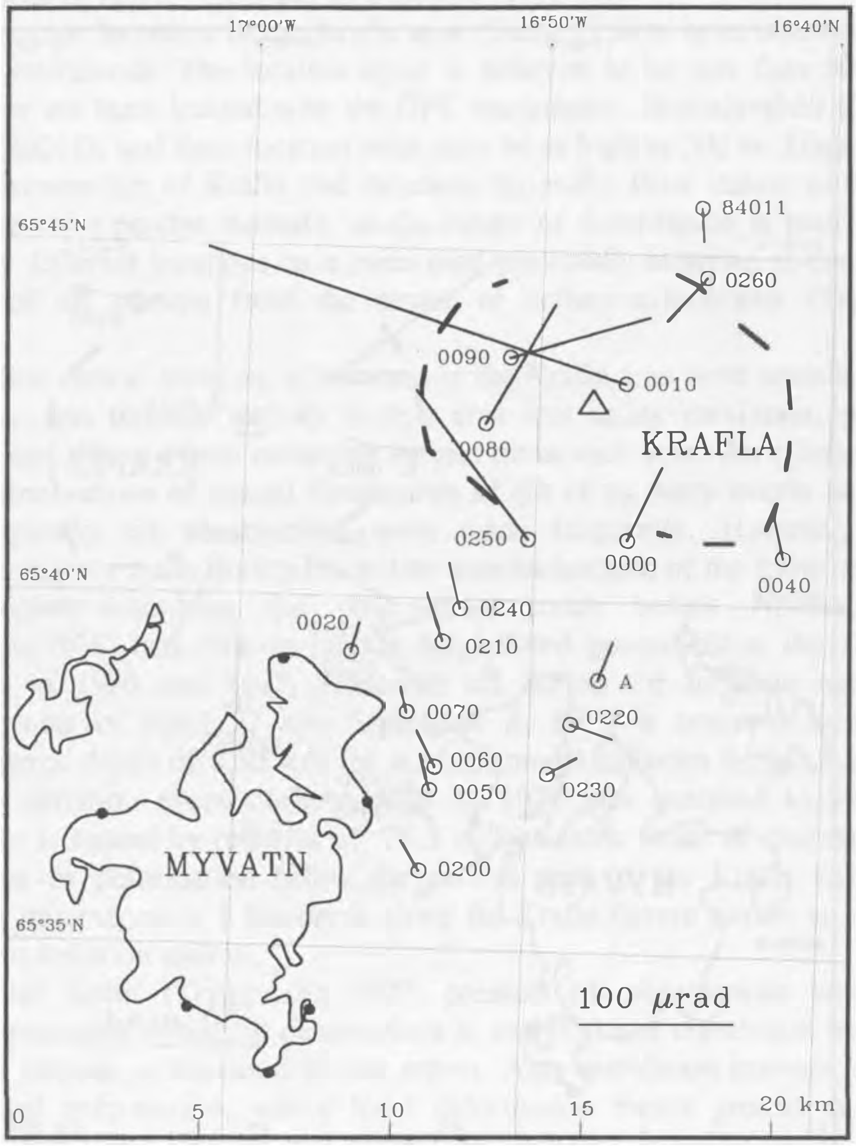


Fig. 11. Observed tilt from October 1981 to June 1989 at optical levelling tilt stations in the Krafla region. At the northern stations 0260 and 84011, tilt from October 1984 to June 1989 is shown. Length of bar is proportional to observed tilt and bar points towards uplift.

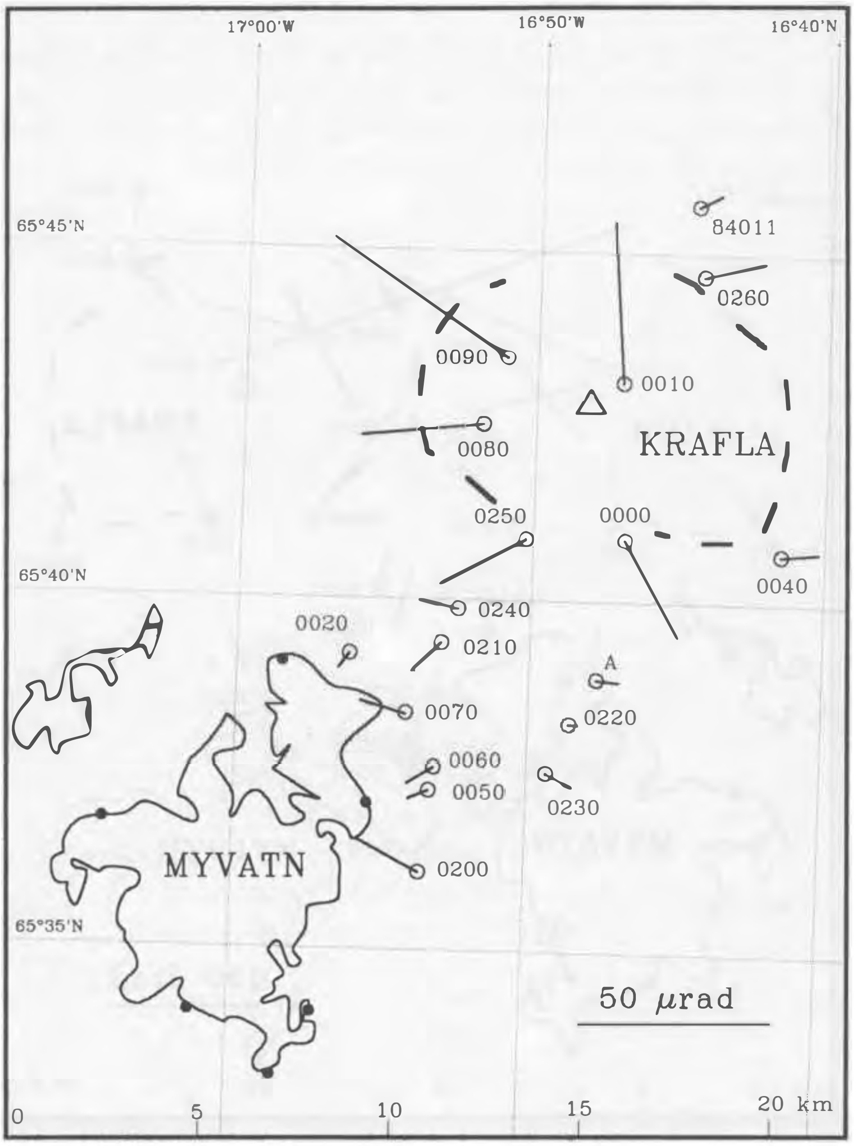


Fig. 12. Observed tilt from June 1989 to July 1994 at optical levelling tilt stations in the Krafla region. Length of bar is proportional to observed tilt and bar extends toward uplift.

This report presents all observations of each optical levelling tilt station in the Krafla area, Gjástykki and Kelduhverfi before 1995. The observational results are presented both in tabular form and as diagrams (Fig. 13).

The station locations in the Krafla area (Table 2) have been obtained by GPS navigation instrument. The location error is believed to be less than 50 m. Two stations have not been located with the GPS instruments, Hreindýrahóll (0260) and Sandmúli (84011), and their location error may be as high as 200 m. Distance to the center of deformation of Krafla and direction (azimuth) from station to this center (Table 2) is not a precise measure, as the center of deformation is poorly known, and slightly different locations have been used previously to arrive at distances and directions of tilt stations from the center of deflations/inflations (Tryggvason, 1994).

The first optical levelling tilt stations in the Krafla area were established while the volcanic and tectonic activity in this area was at its maximum, with large subsidence and rifting events occurring several times each year. An effort was made to obtain observations of spatial distribution of tilt of as many events as possible, and consequently tilt observations were made frequently. However, few tilt measurements were made during the winter seasons because of the snow cover.

A report describing the observations made before November 1977 (Tryggvason 1978) lists relative marker heights and ground tilt at the 12 stations constructed in 1976 and 1977. Observed tilt during the inflation between the deflation events of April 27 and September 8, 1977 is analysed to obtain an apparent source depth of 2.93 km for a Mogi model inflation bulge. Also the tilt during the deflation event of September 8, 1977 was analysed to explain the observed tilt as caused by removal of 28.3 million cubic meter of magma from the usual source of deformation below the central part of the Krafla caldera, and distributing this magma at 3 km depth along the Krafla fissure swarm at 4 to 8 km south of the deflation source.

Another report (Tryggvason 1979) presents tilt observations before April 1979. The precision of the tilt observations is analysed and correlation between tilt at different stations is discussed in that report. Also correlation between calculated tilt and local deformation, where local deformation means ground deformation within the 25 m radius circular area covered by each tilt station.

Models of the Krafla volcanic system, including location of the center of deformation, depth of a magma chamber and volume of displaced magma, have used the dry tilt observation extensively (Björnsson et al. 1979, Tryggvason 1980 and 1994, Ewart et al. 1991].

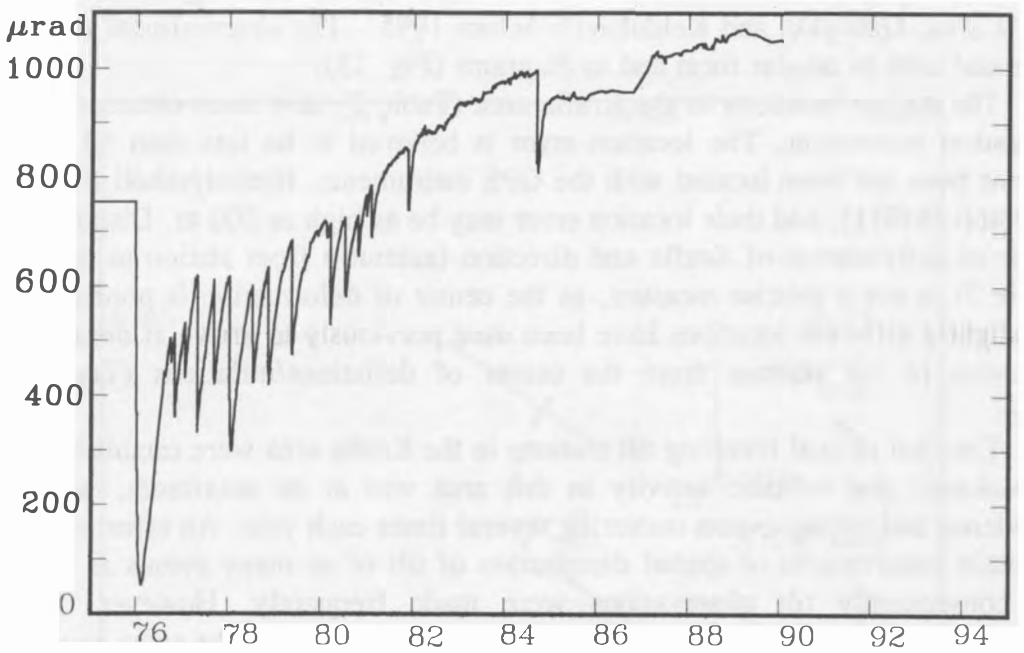


Fig. 13. Observed north component of tilt at the water tube tiltmeter in the Krafla powerhouse. The time scale is the same as in similar graphs of tilt at the optical levelling tilt stations later in this report so that readers can compare the results of the water tube tiltmeter at the Krafla geothermal power station and the results of observations at the optical levelling tilt stations.

TILT STATION A, NÁMASKARÐ

This optical levelling tilt station (dry-tilt station) is the first to be established in the vicinity of Krafla after the initial subsidence and rifting event of December 20, 1975. It was constructed on January 27, 1976, five weeks after the event of December 20 by drilling 5 holes, 15 mm in diameter and about 70 mm deep, into pahoehoe lava of unknown age and hammering specially designed copper alloy marker nails into each hole. No cement was used and no inscription was on the markers. The markers were arranged in an L-shaped array, each leg about 100 m long (Fig. A1). It lies on the road to the Krafla power station, about 200 m north of the junction with highway 1. Three markers are east of the power station road and 2 markers are west of the road. It is about 7.4 km south of the center of the Krafla caldera and one to two km east of the axis of the Krafla fissure swarm, east of the zone where notable fissure displacements were seen during the 1975-1984 activity. This station was observed 51 times from January 1976 to July 1994. The tilt error ellipse, defined by distributions of markers, assuming same weight to all markers, has its long axis in an azimuth of 160° and the short axis in azimuth 70°. The long axis of the error ellipse is 2.76 times greater than the short axis.

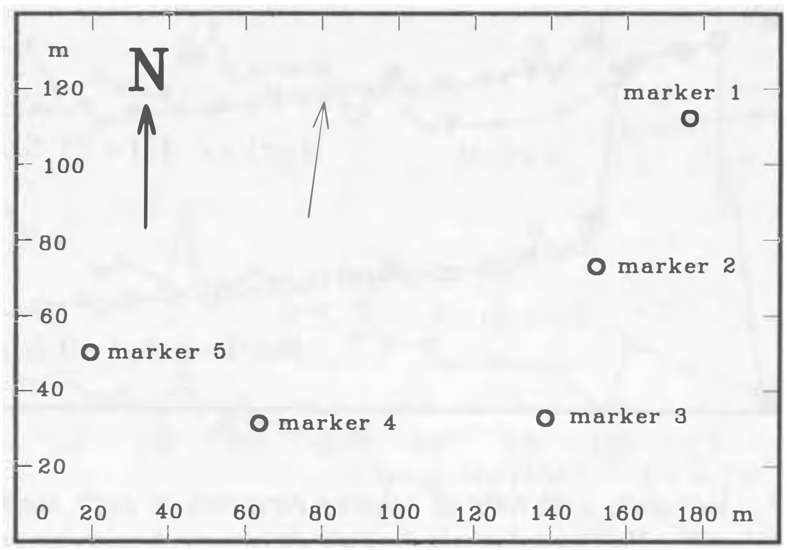


Fig. A1. Map of relative position of markers at the tilt station Námaskarð, sometimes named tilt station A. The markers (open circles) are made of copper alloy nails with 37 mm diameter convex top plate, hammered into 15 mm diameter holes drilled in the lava surface. They carry no inscriptions, but numbers 1 to 5 are assigned to the markers as indicated. Thin arrow gives the average direction of downward tilt during deflations of the Krafla volcano, excluding deflation with ground rifting near this tilt station.

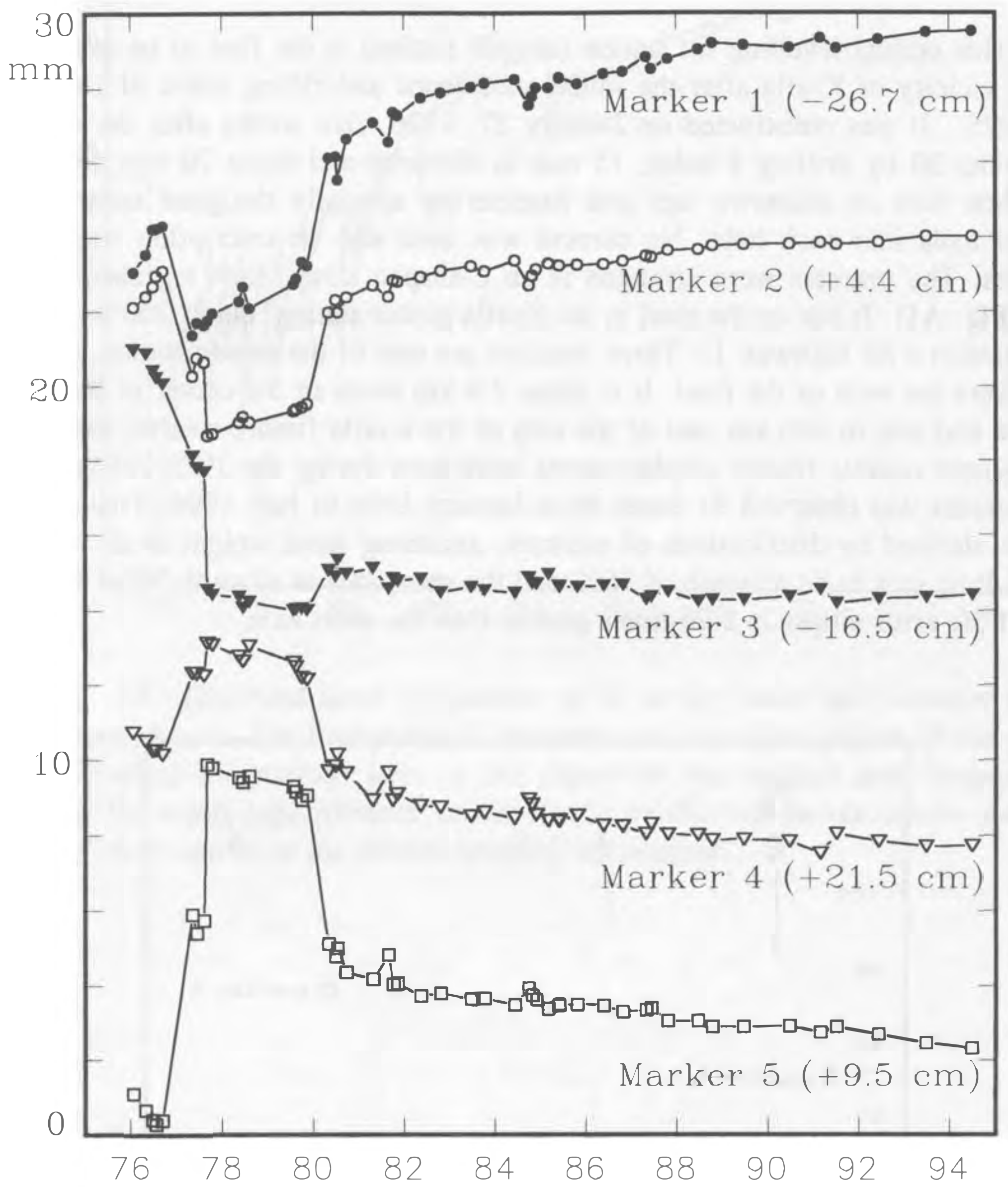


Fig. A2. Variation with time of relative elevation of each marker of the tilt station Námaskarð. Horizontal scale is time in years, beginning at January 1, 1975. Vertical scale is in millimeters. Reference elevation is the average elevation of all five markers of the tilt station. Relative elevation of each marker is found by adding to the left scale values, constants presented in parenthesis besides the marker identification. Large displacements were observed during rifting events of April and September 1977 and March 1980.

Diagrams of relative marker elevation (Fig. A2 and A3) and tilt versus time (Fig. A4) suggest several different modes of deformation of the ground at this station. Permanent vertical displacements of several millimeters did occur three times, between observations of 76 09 19 and 77 05 16, between 77 08 17 and 77 09 12, and between 79 11 18 and 80 05 07 (Table A3). These permanent displacements occurred during rifting events of 27 April 1977, 8 September 1977

1980 (Tryggvason 1980 and 1982), but in these events, rifting did occur in the southern part of the Krafla fissure swarm, near this tilt station. These marker displacements also appear as ground tilt with large component perpendicular to the strike of the Krafla fissure swarm (Figs A4, A5, and A6).

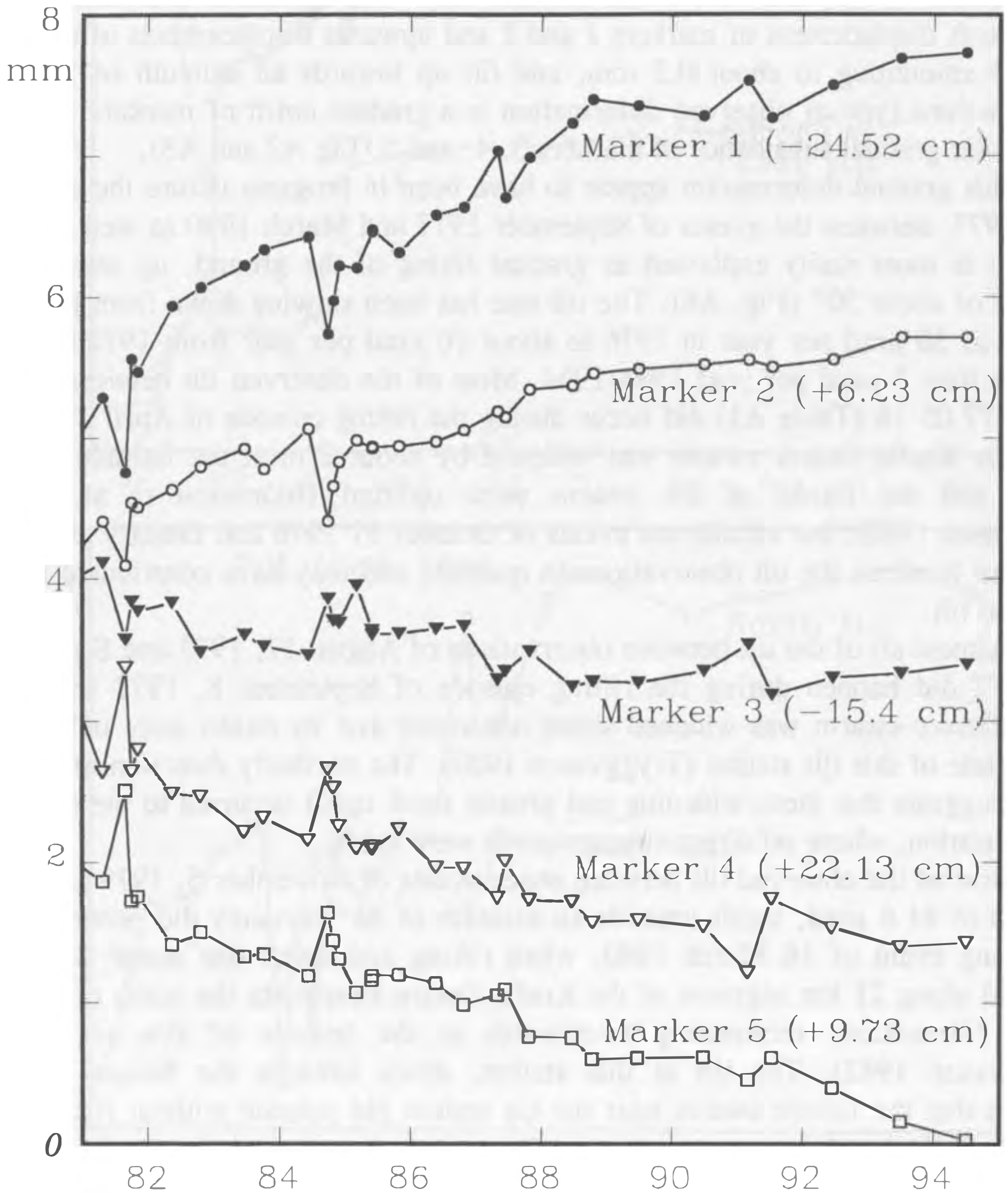


Fig. A3. Variation of relative elevation of markers of tilt station Námaskarð 1981-1994. Same as Fig. A2 except the vertical scale is expanded to clarify elevation variations when activity at Krafla became less violent after 1980. Downward displacements of markers 1 and 2 and upward displacements of markers 4 and 5 are observed during the deflation events and eruptions of November 1981 and September 1984.

Another mode of observed deformation is tilting of the ground surface, down towards north, during deflation of the Krafla volcano, followed by tilt in opposite direction during the rapid inflation which followed the deflation. This type of deformation is seen at the Námaskarð station only if observations were made shortly before and shortly after such event as was the case in July 1980 and September 1984 (Figs. A3, A4, A5, and A6, Table A1 and A2). The deflations are observed as downwards displacement of markers 1 and 2 and upwards displacements of markers 4 and 5 amounting to about 0.2 mm, and tilt up towards an azimuth of 182° to 195°. A third type of observed deformation is a gradual uplift of markers 1 and 2 and similar gradual subsidence of markers 3, 4, and 5 (Fig A2 and A3).

This gradual deformation appear to have been in progress before the event of April 1977, between the events of September 1977 and March 1980 as well as after 1980. It is most easily explained as gradual tilting of the ground, up towards an azimuth of about 30° (Fig. A6). The tilt rate has been slowing down from possibly as high as 20 μrad per year in 1976 to about 10 μrad per year from 1977 to 1984 and less than 3 μrad per year 1984-1994. Most of the observed tilt between 76 09 19 and 77 05 16 (Table A1) did occur during the rifting episode of April 27, 1977 when the Krafla fissure swarm was widened by about 2 m at the latitude of this station and the flanks of the swarm were uplifted (Björnsson et al. 1979, Tryggvason 1980), but subsidence events of October 31 1976 and January 20, 1977 did occur between the tilt observations in question and may have contributed to the observed tilt.

Almost all of the tilt between observations of August 17, 1977 and September 12, 1977 did happen during the rifting episode of September 8, 1977 when the Krafla fissure swarm was widened about one meter and its flanks were uplifted at the latitude of this tilt station (Tryggvason 1980). The northerly direction of the tilt vector suggests that more widening and greater flank uplift occurred to the north of this tilt station, where no direct measurements were made.

Most of the observed tilt between observations of November 5, 1979 and May 7, 1980 of 44.6 μrad, uplift towards an azimuth of 84° certainly did occur during the rifting event of 16 March 1980, when rifting and about one meter widening occurred along 21 km segment of the Krafla fissure swarm, to the north of the tilt station Námaskarð, terminating southwards at the latitude of this tilt station (Tryggvason 1982). The tilt at this station, down towards the fissure swarm, suggests that the fissure swarm near the tilt station did subside without rifting and associated flank uplifts.

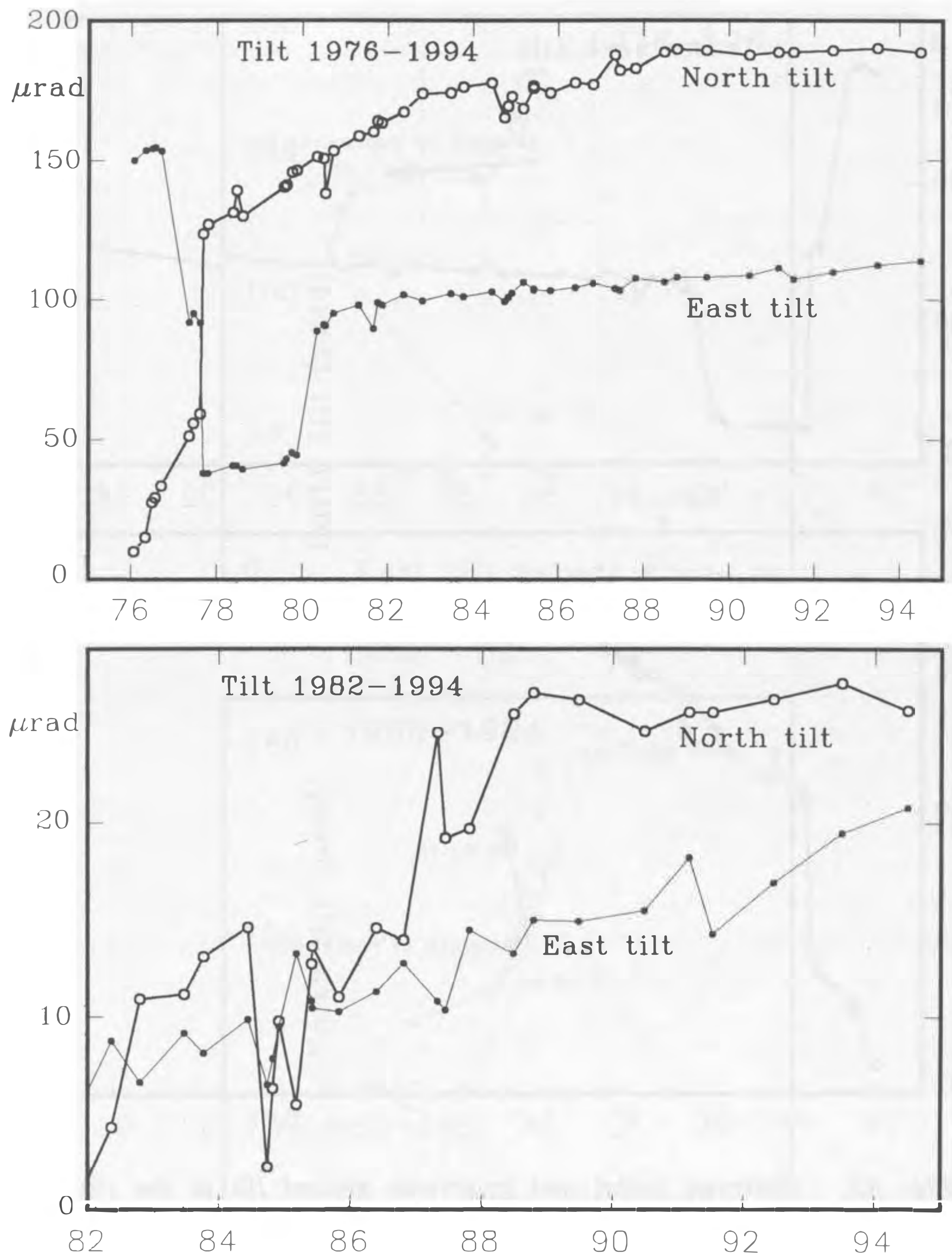


Fig. A4. Observed tilt of the ground at the tilt station Námaskarð since first observation of 27 January 1976. East component of tilt (filled circles) is positive if land is rising at east side of the station relative to its west side. North component of tilt (open circles) is positive if land is rising at north side of the station, relative to its south side. The top diagram presents tilt during the whole period of observations, 1976-1994, showing large tilt variations during the rifting events of April and September 1977 and March 1980. Bottom diagram presents tilt variations after 1981 on an expanded tilt scale, showing tilt variations associated with eruption and subsidence event of September 1984.

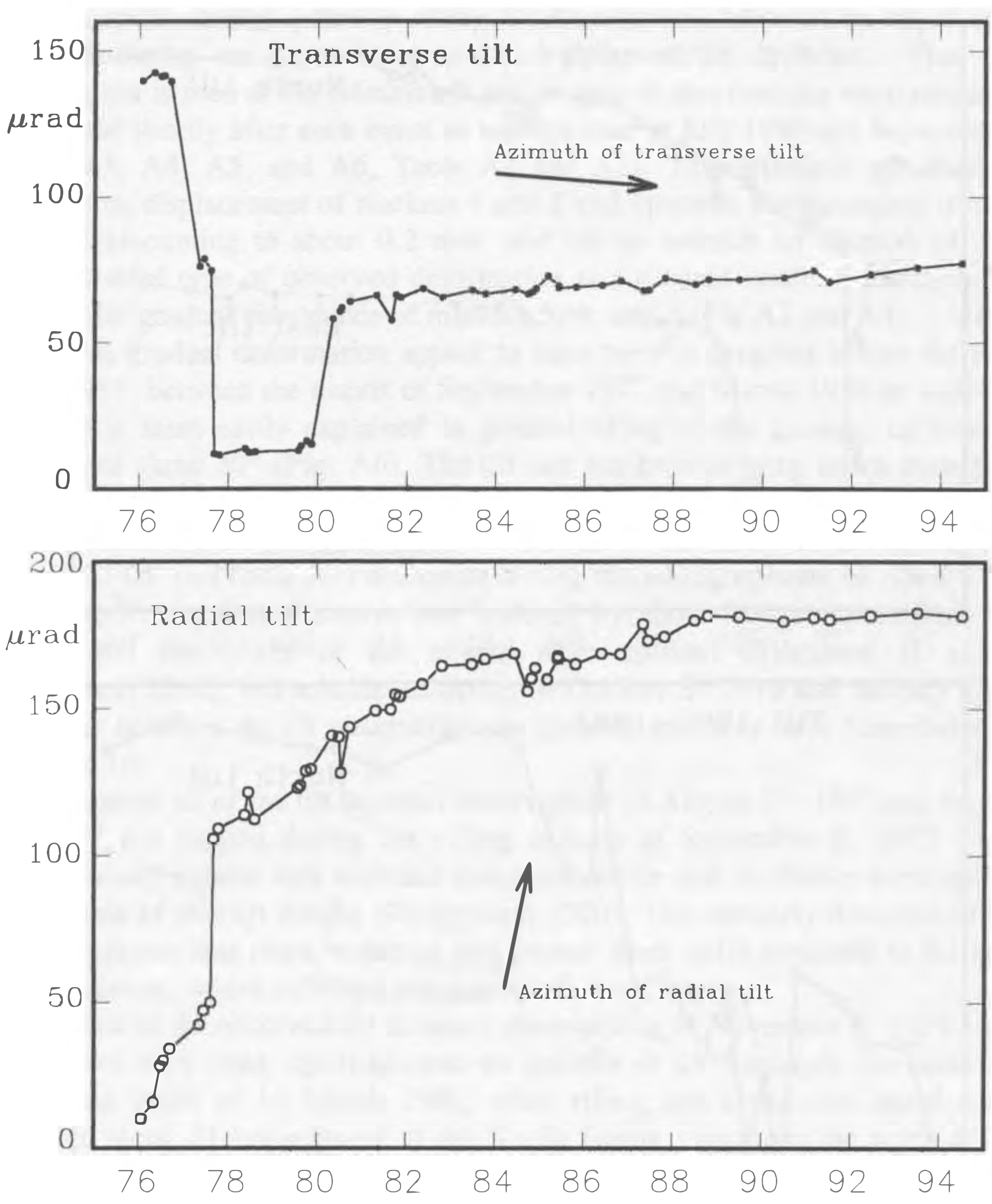


Fig. A5. Observed radial and transverse ground tilt at the tilt station Námaskarð relative to center of deformation at Krafla volcano. Positive transverse tilt is uplift towards an azimuth of 98.6° and positive radial tilt is uplift towards the center of deformation at Krafla at an azimuth of 8.6°. The radial direction is taken as a direction parallel to the average tilt direction during deflation events of Krafla, excluding events of rifting near the Námaskarð tilt station. Large transverse tilt was observed during subsidence events of April and September 1977 and March 1980. Only one of these three events, that of September 1977, shows significant radial tilt. Positive radial tilt (uplift towards the center of deformation) has been observed from 1976 to 1988, but no radial tilt after 1989. Positive transverse tilt (up towards 98.6°) has been going on at a nearly constant rate of about one μrad per year from 1980 to 1994.

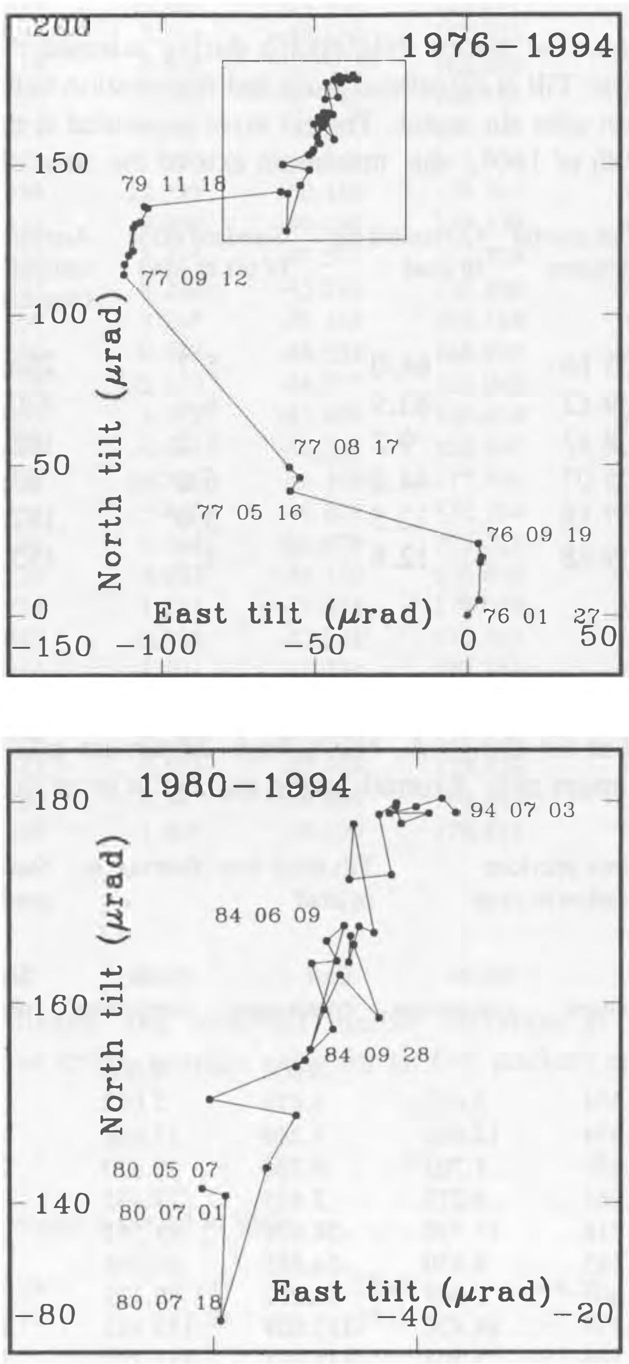


Fig. A6. North component of tilt plotted against east component of tilt at the tilt station Námaskarð. The permanent displacements of April 27, 1977, September 8, 1977 and March 16, 1977 appear as large tilt between observations of 76 09 19 and 77 05 16, between observations of 77 08 17 and 77 09 12 and between observations of 11 09 18 and 80 05 07. Otherwise, uplift towards an azimuth of about 20° appear persistent. The top diagram shows all observations from 1976 to 1994, but the bottom diagram shows observations from 1980 to 1994 (rectangle on top graph) on expanded tilt scale. Note tilt associated with eruptions and subsidence events of 10 July 1980 (between observations of 80 07 01 and 80 07 18) and 4 September 1984 (between observations of 84 06 09 and 84 09 28).

Table A1

Observed tilt at the station Námaskarð during selected rifting events of the Krafla fissure swarm. Tilt is calculated from last observation before the rifting event and first observation after the event. The tilt error presented is the standard error of tilt along the azimuth of 160°, the maximum axis of the error ellipse.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt (degrees)	Date of rifting event
76 09 19	77 05 16	64.0	5.7	286.1	77 04 27
77 08 17	77 09 12	83.9	6.4	320.2	77 09 08
78 06 24	78 08 12	9.2	1.2	188.3	78 07 10
79 11 05	80 05 07	44.6	6.0	83.7	80 03 16
80 07 01	80 07 18	12.5	3.0	182.1	80 07 10
84 06 09	84 09 28	12.8	3.7	195.1	84 09 04

Table A2

Observed tilt at tilt station A, Námaskarð. Minimum axis of the error ellipse is 36% of the maximum axis. Azimuth of the maximum error axis is 160°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	since first observation
76 01 27			0.000	0.000		
76 05 07	3.674	5.012	3.674	5.012	1.445	1.445
76 07 02	0.574	12.656	4.249	17.668	1.692	3.131
76 07 27	0.457	1.702	4.706	19.370	2.812	5.759
76 09 19	-1.261	4.275	3.445	23.645	1.309	6.492
77 05 16	-61.516	17.750	-58.071	41.395	5.663	1.019
77 06 17	3.185	4.450	-54.885	45.844	4.672	5.653
77 08 17	-3.407	3.347	-58.292	49.192	1.357	4.657
77 09 12	-53.737	64.420	-112.029	113.612	6.422	5.570
77 10 21	0.108	3.501	-111.921	117.112	0.761	6.240
78 05 21	2.688	4.325	-109.233	121.437	1.615	5.162
78 06 24	0.028	7.685	-109.205	129.122	1.146	6.110
78 08 12	-1.335	-9.129	-110.540	119.992	1.152	7.193
79 08 01	2.166	10.402	-108.374	130.394	0.857	6.640
79 08 19	1.559	0.704	-106.815	131.098	0.213	6.460
79 10 06	2.322	4.619	-104.493	135.717	1.363	5.734
79 11 18	-0.960	0.750	-105.452	136.467	1.378	4.992
80 05 07	44.337	4.902	-61.116	141.369	5.976	6.414
80 07 01	2.275	-0.688	-58.840	140.681	3.949	10.142
80 07 18	-0.460	-12.528	-59.301	128.153	3.003	8.303
80 09 24	4.493	15.243	-54.807	143.408	1.681	9.480
81 04 26	3.958	5.306	-50.850	148.702	4.346	8.157
81 08 29	-9.521	1.611	-60.371	150.314	4.068	10.535

81 10 04	9.397	3.891	-50.974	154.204	2.087	9.462
81 11 08	-0.894	-0.667	-51.867	153.537	1.117	10.114
82 05 15	3.630	3.766	-48.238	157.303	0.996	9.119
82 10 21	-2.115	6.602	-50.352	163.905	2.016	11.135
83 06 22	2.510	0.246	-47.843	164.152	1.349	10.710
83 10 09	-1.027	1.973	-48.870	166.124	1.692	9.954
84 06 09	1.723	1.530	-47.147	167.654	2.070	11.726
84 09 28	-3.339	-12.387	-50.486	155.267	3.749	8.220
84 10 28	1.334	4.063	-49.151	159.330	1.593	9.801
84 11 30	1.636	3.445	-47.515	162.775	1.213	9.830
85 03 05	3.797	-4.279	-43.718	158.496	1.274	9.894
85 05 30	-2.466	7.268	-46.184	165.764	1.316	9.881
85 06 01	-0.355	0.913	-46.538	166.677	0.198	9.959
85 10 27	-0.199	-2.629	-46.737	164.049	0.907	10.751
86 05 23	1.054	3.565	-45.683	167.614	1.601	9.550
86 10 24	1.462	-0.624	-44.221	166.990	0.622	10.042
87 04 30	-1.948	10.711	-46.169	177.701	0.769	10.796
87 06 11	-0.455	-5.446	-46.624	172.254	1.195	11.728
87 10 24	4.146	0.464	-42.478	172.718	0.837	11.521
88 05 88	-1.232	5.933	-43.710	178.652	1.173	12.010
88 10 14	1.735	1.123	-41.974	179.775	0.373	11.860
89 06 26	-0.067	-0.392	-42.041	179.383	0.417	12.259
90 06 25	0.544	-1.621	-41.497	177.761	0.764	12.254
91 03 01	2.746	0.991	-38.752	178.752	2.316	10.668
91 07 10	-3.938	0.003	-42.690	178.756	4.268	13.313
92 06 14	2.641	0.673	-40.049	179.429	1.047	12.334
93 06 30	2.550	0.817	-37.499	180.246	0.451	12.769
94 07 03	1.300	-1.405	-36.199	178.841	0.627	12.665

Table A3

Marker coordinates and observed marker elevation at the tilt station A (Námaskarð), relative to the average value for all five markers at the tilt station.

Marker	1	2	3	4	5
Marker coordinates in meters, surveyed 81 08 29					
East	66.29	41.97	28.65	-46.38	-90.54
North	52.13	13.32	-27.04	-28.63	-9.76
Y M D	Marker elevation, centimeter				
76 01 27	-24.3940	6.6120	-14.4022	22.5745	9.6097
76 05 07	-24.3462	6.6422	-14.4140	22.5522	9.5659
76 07 02	-24.2786	6.6693	-14.4568	22.5251	9.5411
76 07 27	-24.2770	6.6967	-14.4756	22.5269	9.5291
76 09 19	-24.2697	6.7088	-14.4934	22.5156	9.5386
77 05 16	-24.5640	6.4272	-14.6866	22.7329	10.0904
77 06 17	-24.5301	6.4754	-14.7178	22.7324	10.0402
77 08 17	-24.5370	6.4655	-14.7300	22.7268	10.0746
77 09 12	-24.5251	6.2677	-15.0446	22.8142	10.4877
77 10 21	-24.5052	6.2730	-15.0575	22.8103	10.4795
78 05 21	-24.4729	6.3041	-15.0639	22.7784	10.4544

78 06 24	-24.4336	6.3189	-15.0914	22.7648	10.4415
78 08 12	-24.4901	6.3039	-15.0771	22.8064	10.4569
79 08 01	-24.4254	6.3331	-15.0987	22.7611	10.4301
79 08 19	-24.4111	6.3394	-15.0949	22.7504	10.4161
79 10 06	-24.3673	6.3450	-15.0928	22.7207	10.3944
79 11 18	-24.3765	6.3533	-15.0987	22.7158	10.4060
80 05 07	-24.0869	6.5981	-14.9941	22.4704	10.0124
80 07 01	-24.0839	6.6306	-15.0097	22.4851	9.9778
80 07 18	-24.1464	6.5981	-14.9664	22.5154	9.9994
80 09 24	-24.0359	6.6389	-15.0036	22.4652	9.9354
81 04 26	-23.9916	6.6707	-14.9888	22.3937	9.9162
81 08 29	-24.0446	6.6394	-15.0426	22.4672	9.9807
81 10 04	-23.9646	6.6839	-15.0159	22.3944	9.9024
81 11 08	-23.9734	6.6806	-15.0227	22.4098	9.9055
82 05 15	-23.9263	6.6930	-15.0168	22.3785	9.8715
82 10 21	-23.9131	6.7094	-15.0519	22.3761	9.8796
83 06 22	-23.8979	6.7221	-15.0396	22.3519	9.8634
83 10 09	-23.8865	6.7075	-15.0478	22.3612	9.8654
84 06 09	-23.8772	6.7363	-15.0540	22.3458	9.8493
84 09 28	-23.9467	6.6709	-15.0139	22.3959	9.8936
84 10 28	-23.9227	6.6953	-15.0297	22.3826	9.8743
84 11 30	-23.8982	6.7126	-15.0314	22.3554	9.8616
85 03 05	-23.8994	6.7279	-15.0052	22.3394	9.8374
85 05 30	-23.8739	6.7224	-15.0361	22.3411	9.8463
85 06 01	-23.8723	6.7236	-15.0394	22.3389	9.8494
85 10 27	-23.8889	6.7241	-15.0384	22.3532	9.8501
86 05 23	-23.8620	6.7271	-15.0355	22.3262	9.8443
86 10 24	-23.8564	6.7353	-15.0334	22.3255	9.8290
87 04 30	-23.8169	6.7485	-15.0714	22.3044	9.8356
87 06 11	-23.8496	6.7443	-15.0652	22.3307	9.8397
87 10 24	-23.8215	6.7637	-15.0511	22.3028	9.8059
88 06 21	-23.7971	6.7664	-15.0763	22.3018	9.8054
88 10 14	-23.7804	6.7753	-15.0727	22.2872	9.7904
89 06 26	-23.7848	6.7784	-15.0736	22.2887	9.7912
90 06 25	-23.7920	6.7814	-15.0653	22.2844	9.7915
91 03 01	-23.7665	6.7849	-15.0463	22.2518	9.7760
91 07 10	-23.7932	6.7796	-15.0820	22.3042	9,7912
92 06 14	-23.7699	6.7852	-15.0699	22.2839	9.7705
93 06 30	-23.7507	6.8012	-15.0668	22.2701	9.7463
94 07 03	-23.7469	6.8011	-15.0603	22.2728	9.7333

TILT STATION 0000, HLÍÐARDALUR

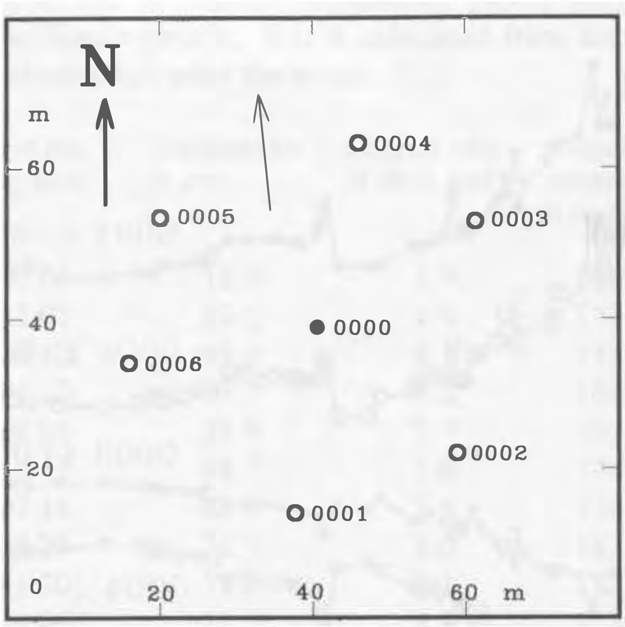


Fig. B1. Map of relative position of markers at the tilt station Hlíðardalur, also named tilt station 0000. Solid circle is a marker at the center of a 25.0 m radius circle defined by six markers (open circles). The markers consist of copper alloy nails with 37 mm diameter convex top plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Thin arrow gives the average direction of downward tilt during subsidence events of the Krafla volcano, excluding events of ground rifting near this tilt station.

This tilt station was constructed on 27 July, 1976 and was the second optical levelling tilt station to be established in the vicinity of Krafla after the initial rifting event of 20 December 1975. It consists of 7 permanent markers, where six markers form a circle of 25.0 m radius and the seventh marker is located at the center of this circle (Fig. B1). The only purpose of the center marker is to guide the observer where to place the tripod during observation of the tilt station. Only the six markers that form the circle are used to determine ground tilt at the location of the station. This station lies on pahoehoe lava from 1728, about 3.8 km south of the center of the Krafla caldera. It was observed 71 times from July 1976 to July 1994. The tilt error ellipse is almost circular and the computed standard error of ground tilt between observations is generally less than 3 μrad if observed tilt is small. The average standard error of tilt of 10 observations from 1988 to 1993 is 1.67 ± 0.64 μrad. The observed deformation is dominated by the deflations and subsequent inflations of the Krafla volcano (Tables B1 and B2). Effort was made to make observations soon after each deflation event, but during the deflation events, markers 0001 and 0002 were uplifted, frequently about 2 mm but marker 0004 and to lesser degree 0003 and 0005 subsided 1 to 2 mm (Fig. B2).

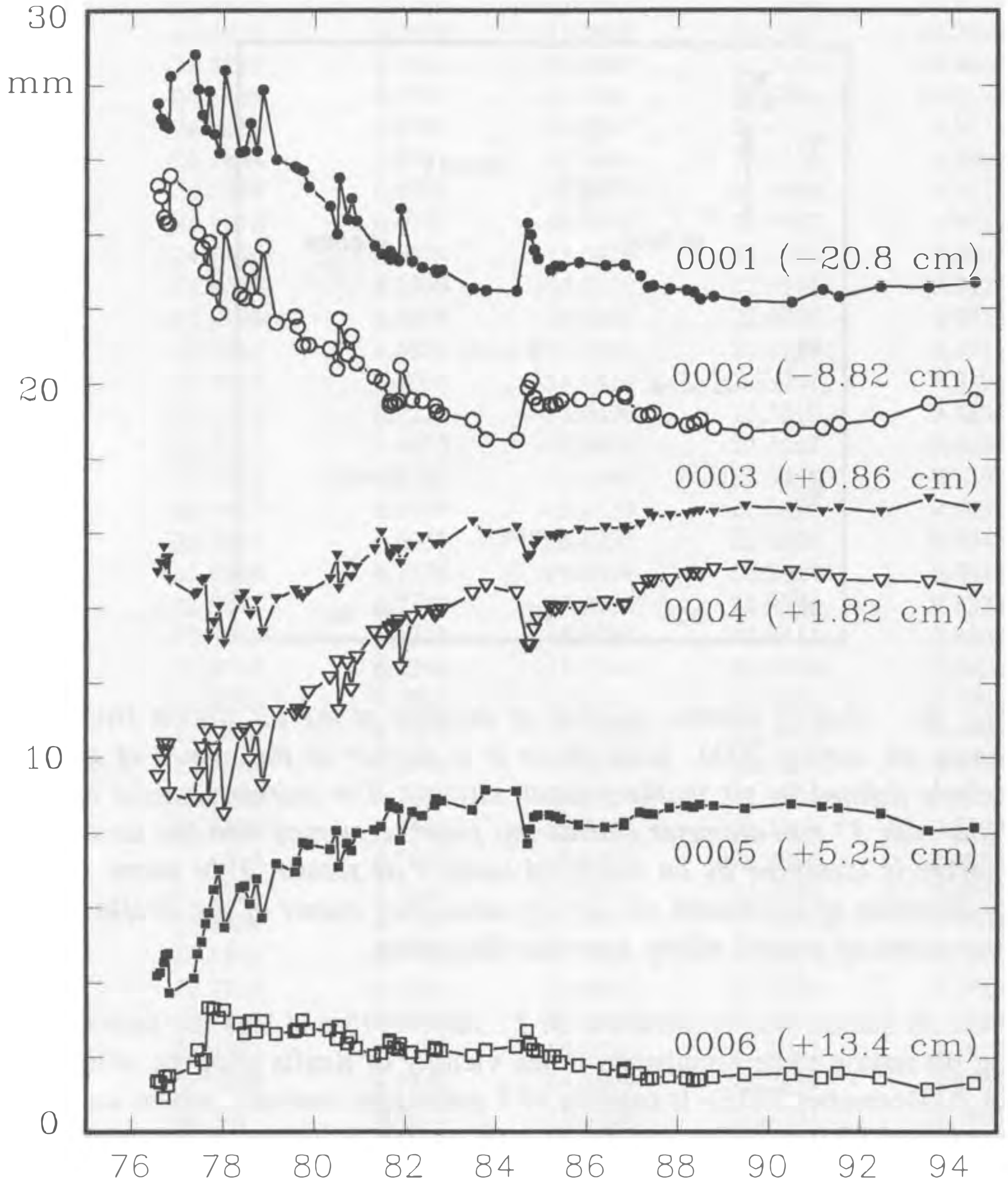


Fig. B2. Change of relative elevation of each marker of the Hlíðardalur tilt station (tilt station 0000) plotted against time. The reference is the average elevation of all six markers of the station. Horizontal scale is in years, beginning on January 1, 1975. Vertical scale is in mm. The relative elevation of each marker is found by adding the values of the left scale to constants given in parenthesis besides the marker identification.

Table B1

Observed tilt at the tilt station Hlíðardalur (0000) during selected rifting events of the Krafla fissure swarm. Tilt is calculated from last observation before the event and first observation after the event.

Date of first observation	Date of last observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of rifting event
76 09 18	76 10 02	18.0	1.9	253.8	76 09 26
76 10 23	76 11 01	59.5	1.9	171.6	76 10 31
77 08 15	77 09 10	69.2	8.1	214.6	77 09 08
77 12 01	78 01 13	97.7	3.5	168.8	78 01 07
78 06 22	78 08 05	35.9	2.7	180.9	78 07 10
78 09 30	78 11 13	68.7	1.8	174.7	78 11 10
80 06 30	80 07 14	62.6	2.6	176.6	80 07 10
80 09 21	80 10 25	24.7	2.0	182.9	80 10 18
81 11 07	81 11 20	51.8	2.1	172.3	81 11 18
84 06 08	84 09 06	71.3	3.9	173.9	84 09 04

Table B2

Observed tilt at the tilt station Hlíðardalur (0000) during periods of inflation of the Krafla volcano. Tilt is calculated from two subsequent observations made during periods of continuos inflations, usually soon after rifting events.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of previous rifting event
76 07 20	76 09 18	25.0	4.7	6.5	75 12 20
77 09 10	77 10 21	51.8	3.7	350.9	77 09 08
78 01 13	78 05 19	89.1	2.8	358.3	78 01 07
78 08 05	78 09 30	37.0	3.0	352.5	78 07 10
78 11 13	79 03 04	87.3	4.2	350.8	78 11 10
80 05 07	80 09 30	28.9	3.5	2.9	80 03 16
80 07 14	80 09 21	49.4	2.5	1.6	80 07 10
80 10 25	80 12 06	31.3	3.3	355.7	80 10 18
81 11 20	82 02 22	53.1	2.2	356.1	81 11 18
84 09 30	84 10 27	19.2	1.3	356.6	84 09 04
86 10 24	87 02 25	17.4	2.3	350.8	84 09 04

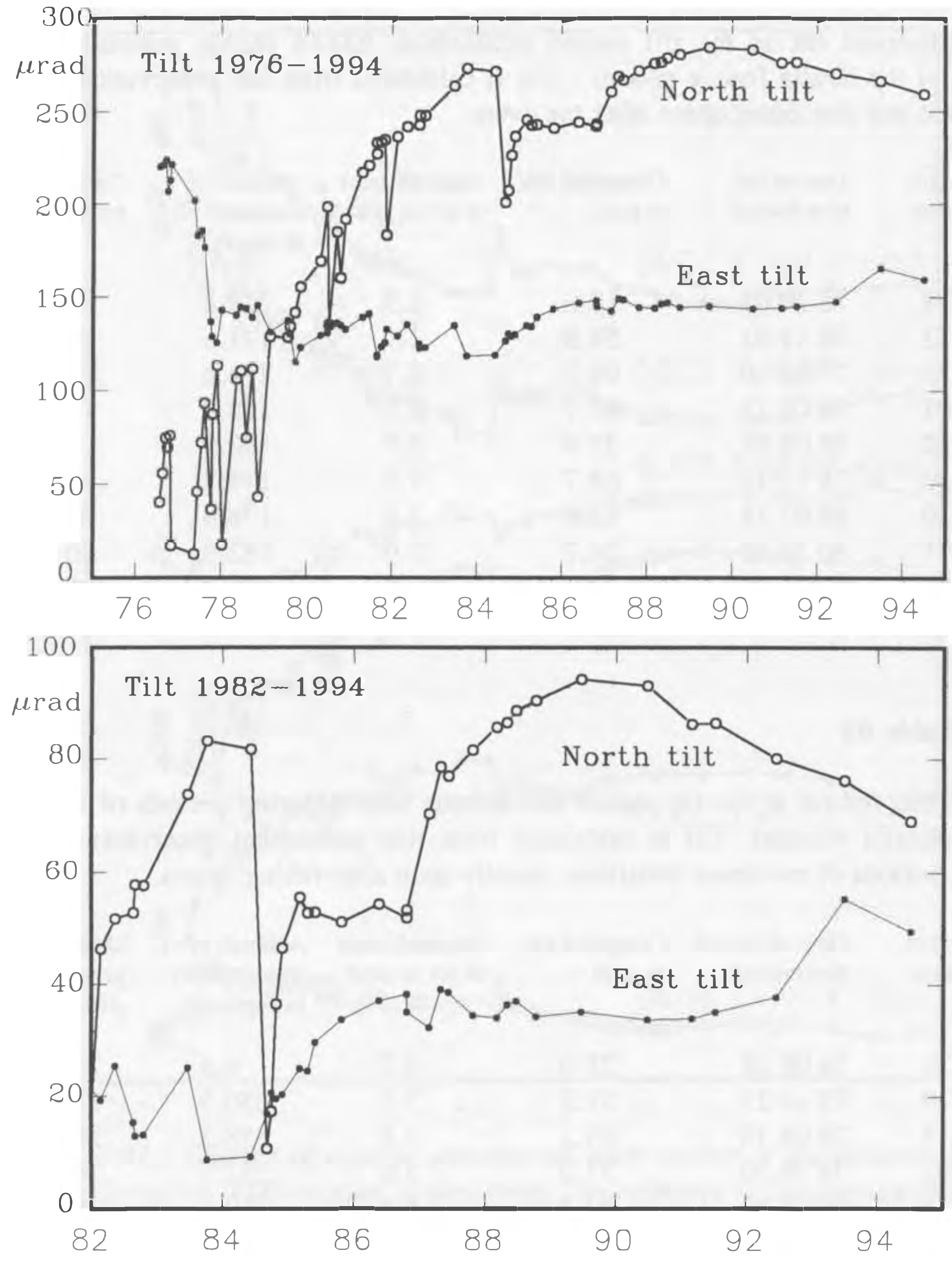


Fig. B3. Observed ground tilt at the Hlíðardalur tilt station (tilt station 0000) since it was first observed on July 27, 1976. North component of tilt (open circles) shows subsidence events of the Krafla volcano as downward tilt (down toward north), and secular upward tilt from 1979 (or earlier) to 1989, followed by tilt down toward north from 1989 to 1994. East component of tilt (solid circles) remains relatively stable from 1977 to 1994. Top graph presents all tilt observations at this station and the bottom graph shows tilt from 1982 to 1994 on expanded tilt scale.

This corresponds to ground tilt of 50 to 100 μrad, up towards south during each deflation event, and tilt up towards north during inflation of Krafla volcano (Figs. B3 and B4).

In addition to the marker displacements and ground tilt associated with inflations and deflations of Krafla, continuous uplift towards north was observed from 1976 to 1989, but slow subsidence towards north in 1989 to 1993. The northerly uplift in 1976 to 1989 amounts to 200 to 250 μrad while 1989-1993 subsidence towards north is observed as 18 μrad of tilt (Figs B3 and B4).

Some permanent displacements were observed at this tilt station during the rifting events of April 27, 1977 and September 8, 1977, and possibly to lesser degree during other rifting events. The event of April 27 1977 is not well observed as last observation before the event was on November 1, 1976, immediately after the rifting event of October 31, 1976, and another rifting event occurred on January 20, 1977. However, tilt up towards west of about 20 μrad is observed between November 1 1976 and May 18, 1977, which is believed to have occurred during the April 27 event, as the event of January 20, 1977 caused rifting far away from this tilt station. (Fig. B6, Tryggvason 1980).

During the event of September 8, 1977 tilt of 69 μrad up towards an azimuth of 215° was observed between observations of August 15 and September 10 1977. Part of this tilt is caused by deflation of Krafla, but the westerly component of about 40 μrad is permanent deformation caused by rifting to the west of the tilt station. The possible north or south component of this permanent tilt is uncertain.

No permanent deformation was observed at this tilt station during the rifting event of March 16, 1980 although rifting is suggested at the latitude of the station (Tryggvason 1980), and permanent deformation was observed at other tilt stations, both those close to the center deformation and also at stations farther south than the Hlíðardalur station.

The inflation progress after the 1984 eruption is well observed at this tilt station (Tryggvason 1994). The rapid inflation which started at the end of the last eruption of Krafla, on September 18, 1984, came to a halt in early 1985 and a very slow deflation is indicated for about 18 month, March 1985 to October 1986 (Fig. B4). Rapid inflation of about 25 μrad occurred between end of October 1986 and end of April 1987, followed by much slower inflation which lasted until 1989, but slow deflation, observed as tilt up towards south started in 1989 or early 1990 and is still continuing in 1994 (Figs B3, B4, and B8). This 1989-1994 deflation tilt amounts to about 25 μrad in 5 years, corresponding to a tilt rate of 5 μrad per year. It has been shown that north component of tilt at the tilt station 0000 is 42 ± 5 per cent of that observed at the Krafla power station (Tryggvason 1979), and 1 μrad at the power station corresponds to about 3.5 mm vertical displacement at center of uplift/subsidence. If these relations hold true in 1989 to 1994, then the tilt at station 0000 suggests subsidence of 208 mm in five years at the center of subsidence of Krafla volcano.

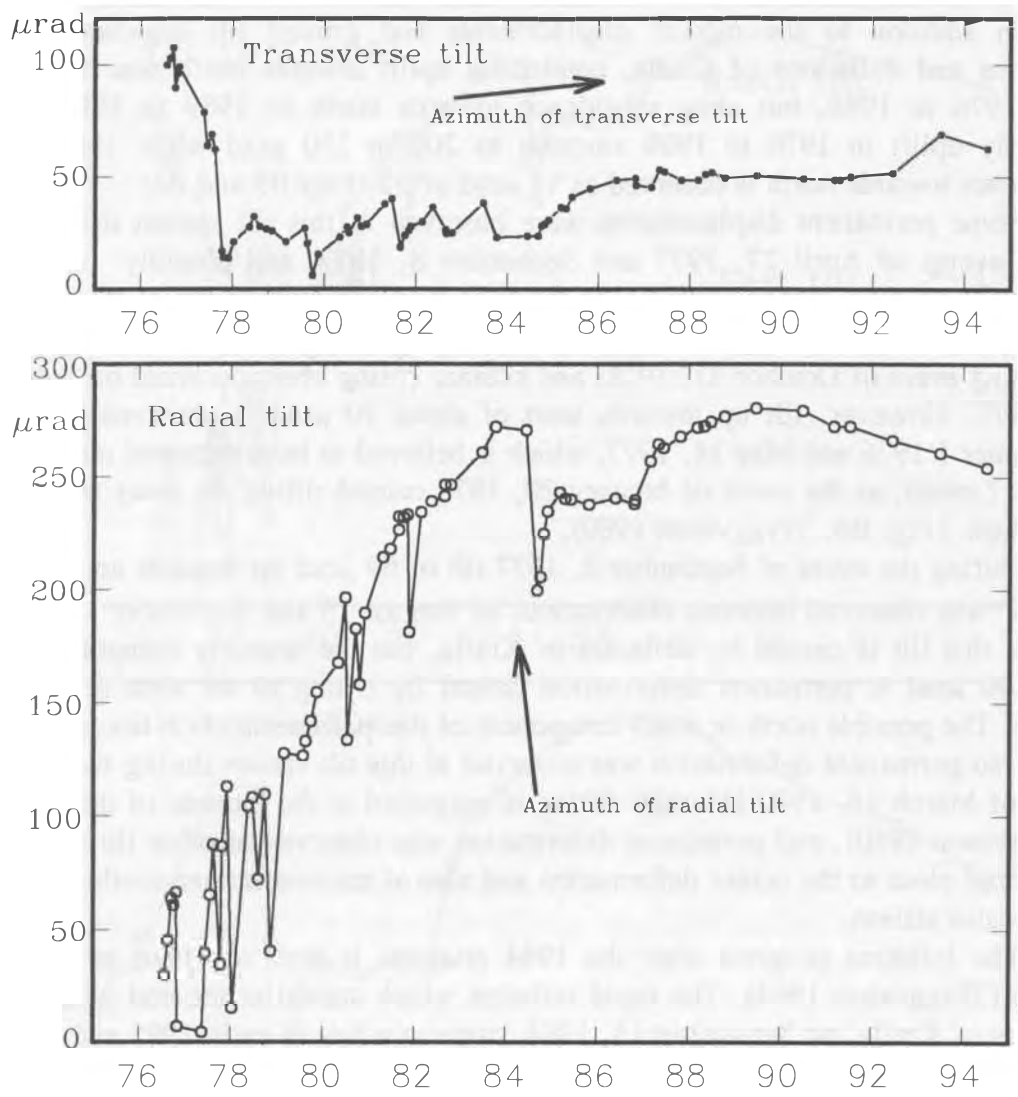


Fig. B4. Transverse tilt (top) and radial tilt (bottom) at the tilt station Hlíðardalur. Radial tilt is taken as tilt in azimuth 354°, a direction opposite to average tilt direction during deflation events of Krafla excluding those events when rifting occurred near this tilt station. Transverse tilt is dominated by downward tilt (down towards 84°) during two rifting events of 1977 and gradual upward tilt of about 2.5 μrad per year after these events. Radial tilt is dominated by deflations and subsequent inflations of Krafla volcano and also uplift towards the volcano from 1976 to 1989 followed by slow subsidence of the volcano after 1989.

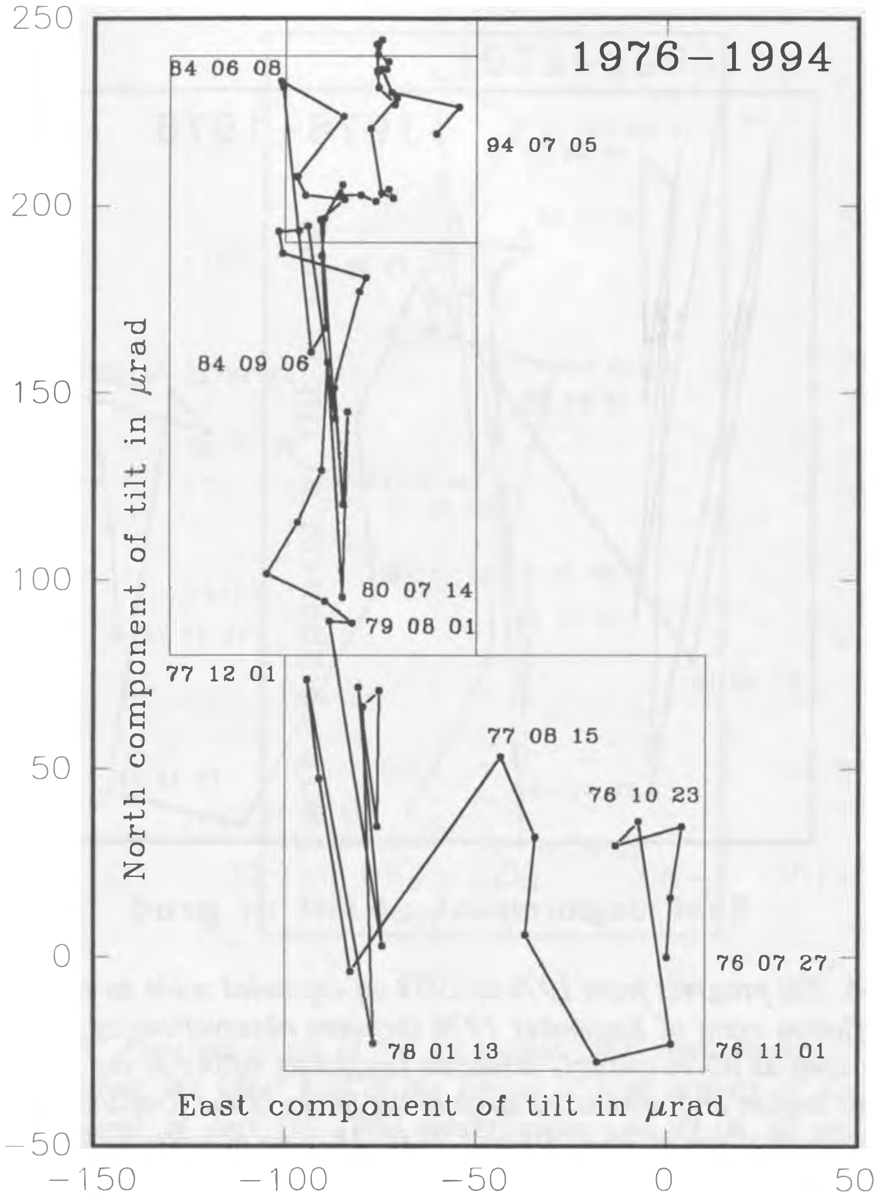


Fig. B5. North component of tilt plotted against east component of tilt at the Hlíðardalur tilt station, showing progress of the tilt vector at the tilt station 0000 from July 27, 1976 July 5, 1994. The tilt is dominated by deflation tilt in azimuth about 174° followed by inflation tilt in azimuth about 354°. In addition is westward tilt during rifting events of 1977. Rectangles define areas of north versus east tilt presented in Figures B6, B7, and B8. They are plotted on expanded tilt scale for easier view.

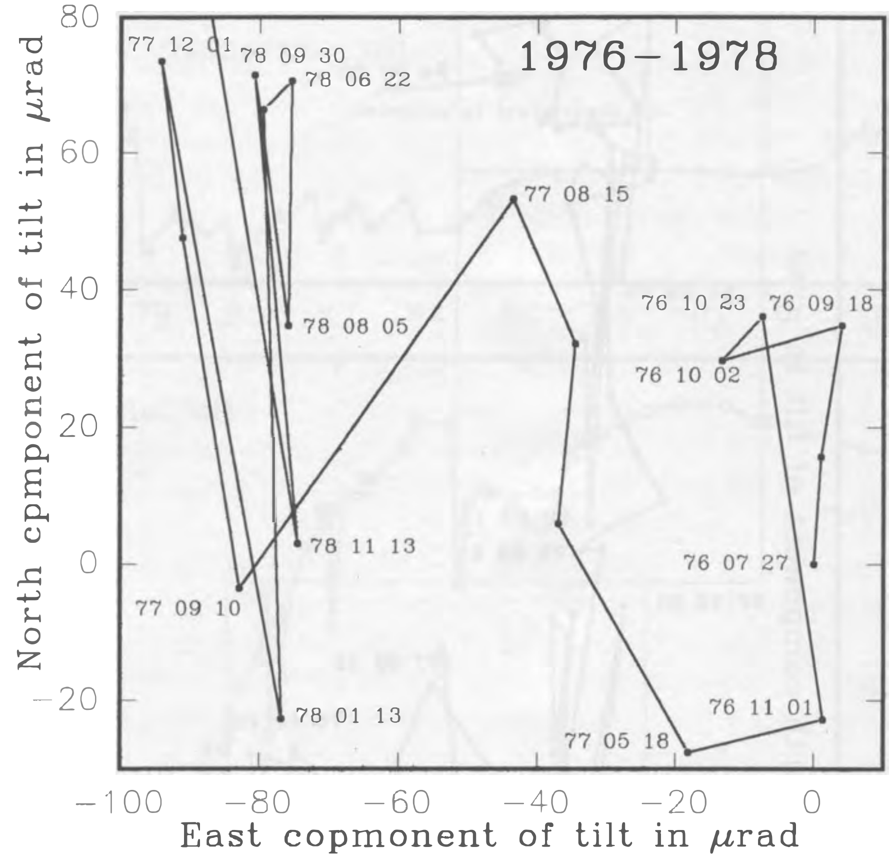


Fig. B6. Tilt progress from 1976 to 1978 on expanded scale as compared with Fig. B5. Deflation event of September 1976 (between observations of 76 09 18 and 76 10 02) is seen as tilt in westerly direction suggesting rifting of the ground in the vicinity of this station and associated uplift of the flanks of the Krafla fissure swarm. Tilt between observations of 76 11 01 and 77 05 18 is up in westerly direction. This westerly tilt is believed to have occurred during the rifting event of April 27, 1977, but the subsidence event of January 20, 1977 was associated with rifting about 10 km north of this station and is not expected to have caused permanent tilt at this station. Most of the south-westerly tilt between 77 08 15 and 77 09 10 occurred during rifting event of September 8, 1977. Subsidence events of October 31, 1966 (between 76 10 23 and 76 11 01), January 8, 1978 (between 77 12 01 and 78 01 13), July 10, 1978 (between 78 06 22 and 78 08 05), and November 10, 1988 (between 78 09 30 and 78 11 13) all show tilt towards an azimuth of about 174°.

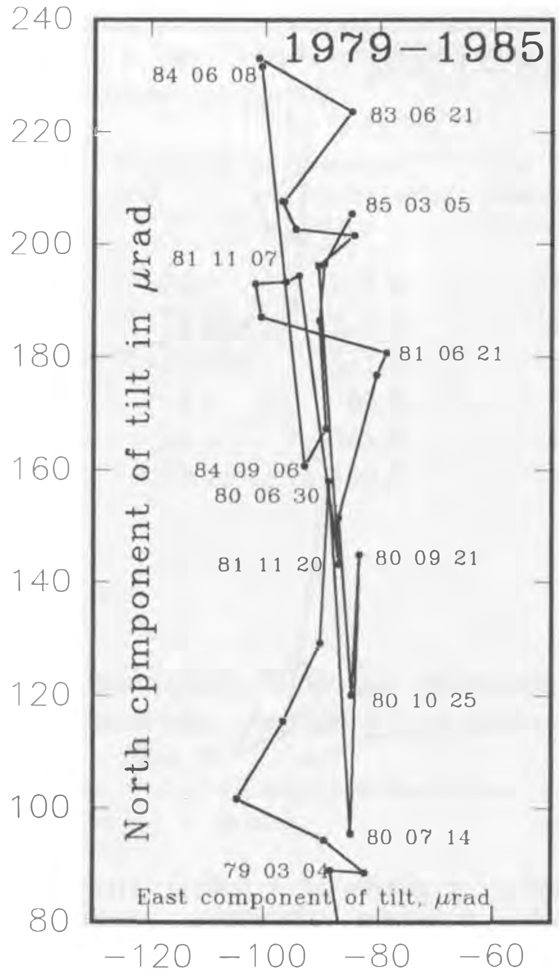


Fig. B7. Progress of tilt at the tilt station 0000 from March 1979 to March 1985. This covers the latter half of the period of high activity of Krafla volcano. Subsidence events of July 10, 1980 (observations of 80 06 30 and 80 07 14), October 18, 1980 (observations 80 09 21 and 80 10 25), November 18, 1981 (observations 81 11 07 and 81 11 20), and September 4, 1984 (observations 84 06 08 and 84 09 06) are all observed with tilt up toward an azimuth of about 174°. North-westerly tilt of 17 to 23 μrad, possibly of seasonal origin, was observed between observations of 79 08 19 and 79 10 01 (near the bottom of diagram), between 81 06 23 and 81 08 29 (upper center of the graph), and between 83 06 21 and 83 10 08. This tilt exceeds greatly the expected observational error and is not correlated with observations at other tilt stations.

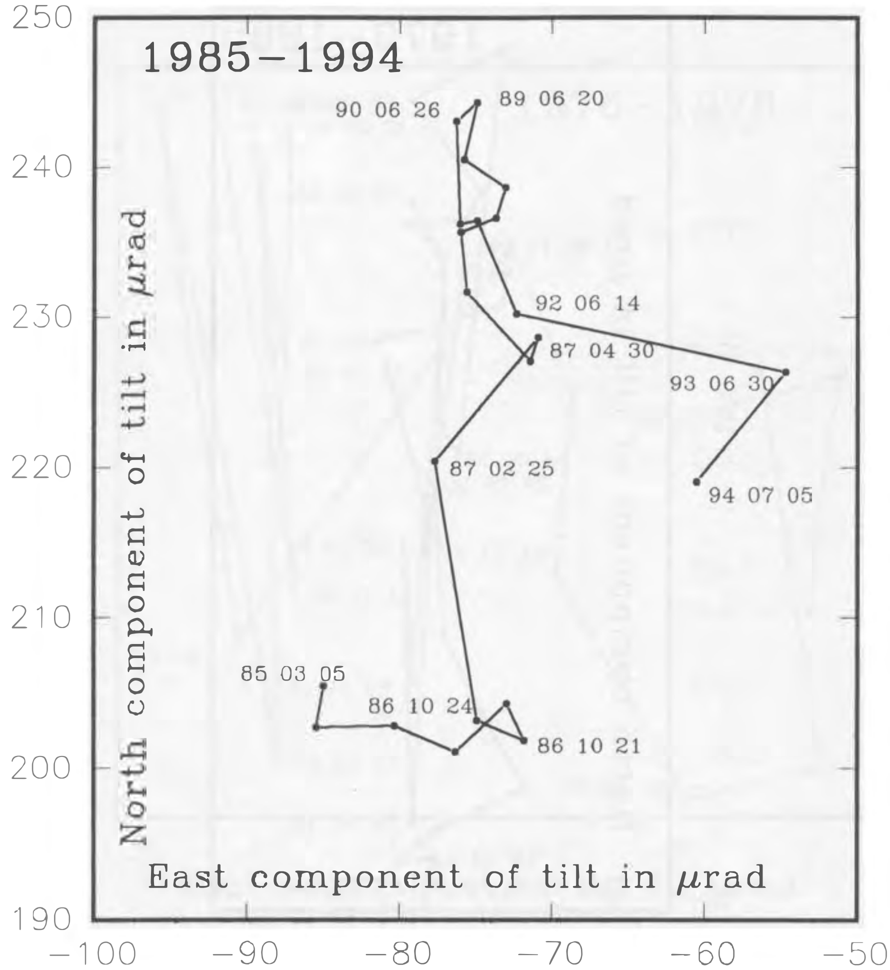


Fig. B8. Progress of tilt at tilt station 0000 from March 1985 to July 1994, a period following the high activity of Krafla during the Krafla fires. The period of no inflation nor deflation, from March 1985 to October 1986 shows tilt up towards east of about 15 μrad, but only 5 μrad tilt was observed between May 30, 1985 and October 24, 1986. Inflation from October 1986 to June 1989 is observed with tilt of about 43 μrad up towards north, normal inflation azimuth. After June 1989, tilt in southerly or south-easterly direction is observed. Apparent tilt of about 18 μrad between 92 06 14 and 93 06 30 is unexplained and not in agreement with observations at other tilt stations and therefore suspected to be the result of observational errors.

Table B3

Observed ground tilt at the Hlíðardalur (0000) tilt station during extended periods of relatively slow ground deformation

Date of first observation	Date of last observation	Observed tilt in μrad	Azimuth of observed tilt in degrees	East component of tilt in μrad	North component of tilt in μrad
79 08 01	79 11 18	30.4	332.0	-14.3	25.8
81 04 26	81 11 07	22.2	322.5	-13.5	17.6
82 05 15	84 06 08	34.2	331.8	-16.1	30.1
85 05 30	86 10 24	5.4	86.3	5.4	0.3
87 04 30	89 06 20	16.2	345.8	-4.0	15.7
89 06 20	94 07 05	29.1	150.3	14.4	-25.2

Table B4

Observed tilt at tilt station 0000, Hlíðardalur. Minimum axis of the error ellipse is 98% of the maximum axis. Azimuth of the maximum error axis is 97°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observati on	East component	North component	East component	North component	Since prev observation	Since first observation
76 07 27			0.000	0.000		
76 08 20	0.999	15.655	0.999	15.655	1.238	1.238
76 09 18	2.970	19.086	3.969	34.741	4.675	4.546
76 10 02	-17.293	-5.031	-13.324	29.711	1.879	3.165
76 10 23	5.857	6.354	-7.468	36.064	0.898	3.523
76 11 01	8.738	-58.868	1.270	-22.804	1.882	2.724
77 05 18	-19.444	-4.687	-18.174	-27.490	5.617	7.605
77 06 13	-18.819	33.312	-36.993	5.821	2.843	6.784
77 07 17	2.465	26.302	-34.528	32.123	1.042	6.608
77 08 15	-8.963	21.186	-43.491	53.309	1.650	8.044
77 09 10	-39.347	-56.936	-82.838	-3.626	8.143	1.016
77 10 21	-8.194	51.187	-91.032	47.561	3.704	3.174
77 12 01	-3.102	25.913	-94.134	73.474	3.546	4.935
78 01 13	17.292	-96.144	-76.842	-22.670	3.486	1.741
78 05 19	-2.693	89.078	-79.535	66.407	2.793	3.382
78 06 22	4.175	4.236	-75.360	70.643	2.327	4.996
78 08 05	-0.542	-35.916	-75.902	34.727	2.746	2.466
78 09 30	-4.865	36.712	-80.767	71.439	3.021	4.925
78 11 13	6.328	-68.443	-74.439	2.996	1.773	3.607
79 03 04	-14.016	86.138	-88.455	89.134	4.225	7.690
79 08 01	6.035	-0.423	-82.420	88.711	3.231	5.495
79 08 19	-7.224	5.715	-89.644	94.425	1.317	6.408
79 10 01	-15.083	7.325	-104.727	101.750	2.497	8.020
79 11 18	8.056	13.810	-96.671	115.560	2.623	6.733
80 05 07	6.263	13.711	-90.408	129.271	3.052	5.302
80 06 30	1.473	28.829	-88.936	158.100	3.493	6.042

80 07 14	3.995	-62.512	-84.940	95.588	2.562	3.834
80 09 21	1.384	49.344	-83.556	144.932	2.471	5.705
80 10 25	-1.264	-24.690	-84.820	120.242	1.990	4.712
80 12 06	-2.357	31.250	-87.177	151.492	3.346	7.529
81 04 26	6.612	25.459	-80.565	176.951	1.624	7.303
81 06 21	1.731	3.798	-78.835	180.748	5.385	7.760
81 08 29	-21.861	6.372	-100.696	187.120	4.822	8.530
81 08 31	-0.989	5.952	-101.685	193.073	1.356	7.616
81 10 04	5.342	0.252	-96.343	193.325	1.086	8.571
81 11 07	2.247	1.207	-94.096	194.532	1.065	7.903
81 11 20	6.973	-51.281	-87.123	143.251	2.086	9.324
82 02 22	-3.581	52.962	-90.703	196.213	2.234	8.300
82 05 15	6.166	5.427	-84.537	201.640	1.169	8.346
82 08 24	-10.116	1.100	-94.653	202.740	1.190	7.401
82 09 30	-2.381	5.010	-97.034	207.749	0.997	7.945
82 10 19	0.268	-0..096	-96.765	207.654	1.176	8.990
83 06 21	11.869	16.082	-84.896	223.736	3.422	9.333
83 10 08	-16.225	9.486	-101.121	233.222	2.668	10.593
84 06 08	0.460	-1.467	-100.660	231.755	2.515	10.542
84 09 06	7.549	-70.920	-93.111	160.835	3.877	11.582
84 09 30	3.777	6.499	-89.334	167.334	5.085	8.236
84 10 27	-1.152	19.130	-90.485	186.464	1.342	9.422
84 11 30	0.802	10.012	-89.683	196.476	0.892	9.600
85 03 05	4.705	8.984	-84.978	205.460	1.359	8.753
85 04 18	-0.468	-2.720	-85.445	202.739	0.435	9.171
85 05 30	5.128	0.133	-80.317	202.872	0.536	9.275
85 10 23	3.985	-1.727	-76.332	201.145	1.295	10.391
86 05 22	3.391	3.142	-72.941	204.287	0.830	10.350
86 10 21	1.164	-2.385	-71.777	201.902	1.544	9.515
86 10 24	-3.110	1.318	-74.887	203.220	0.571	9.660
87 02 25	-2.779	17.199	-77.666	220.418	2.267	11.909
87 04 30	6.766	8.208	-70.900	228.627	1.174	10.974
87 06 11	-0.498	-1.584	-71.397	227.043	0.760	11.001
87 10 23	-4.202	4.623	-75.600	231.666	0.912	11.279
88 03 06	-0.382	3.980	-75.982	235.646	0.802	12.014
88 05 02	2.332	0.920	-73.650	236.566	0.313	11.758
88 06 21	0.627	2.058	-73.022	238.624	1.877	9.947
88 10 11	-2.753	1.856	-75.775	240.481	2.097	11.686
89 06 20	0.891	3.853	-74.885	244.333	1.841	11.806
90 06 26	-1.363	-1.261	-76.248	243.072	1.704	10.581
91 03 01	0.228	-6.860	-76.020	236.212	2.300	12.555
91 07 09	1.134	0.209	-74.886	236.421	2.521	10.668
92 06 14	2.577	-6.232	-72.309	230.190	1.872	11.818
93 06 30	17.637	-3.863	-54.672	226.327	1.364	11.149
94 07 05	-5.843	-7.237	-60.504	219.083	1.288	10.011

Table B5

Marker coordinates and observed marker elevation at the tilt station 0000 (Hlíðardalur), relative to the average value for all six markers at the tilt station

Marker	0001	0002	0003	0004	0005	0006
Marker coordinates in meters, surveyed 81 08 29						
East	-2.35	18.98	21.34	6.00	-19.93	-24.03
North	-25.85	-17.90	12.86	23.39	13.34	-5.84
Y M D	Marker elevation, centimeter					
76 07 27	-18.0473	-6.2887	2.3555	2.7708	5.6704	13.5394
76 08 20	-18.0885	-6.3180	2.3798	2.8111	5.6801	13.5356
76 09 18	-18.1068	-6.3738	2.4217	2.8559	5.7073	13.4957
76 10 02	-18.1008	-6.3895	2.3747	2.8367	5.7277	13.5513
76 10 23	-18.1144	-6.3914	2.3951	2.8541	5.7296	13.5271
76 11 01	-17.9745	-6.2638	2.3370	2.7237	5.6244	13.5532
77 05 18	-17.9177	-6.3235	2.2947	2.7080	5.6635	13.5750
77 06 13	-18.0111	-6.4161	2.3004	2.7771	5.7283	13.6216
77 07 17	-18.0784	-6.4554	2.3324	2.8448	5.7614	13.5951
77 08 15	-18.1193	-6.5182	2.3388	2.8945	5.8082	13.5962
77 09 10	-18.0168	-6.4403	2.1773	2.7070	5.8373	13.7357
77 10 21	-18.1309	-6.5646	2.2224	2.8424	5.8999	13.7309
77 12 01	-18.1816	-6.6319	2.2645	2.8862	5.9552	13.7077
78 01 13	-17.9597	-6.4023	2.1658	2.6698	5.7990	13.7275
78 05 19	-18.1809	-6.5824	2.2833	2.8821	5.9053	13.6928
78 06 22	-18.1776	-6.5921	2.2986	2.8954	5.9099	13.6659
78 08 05	-18.1029	-6.5115	2.2425	2.8130	5.8605	13.6985
78 09 30	-18.1774	-6.5981	2.2792	2.8975	5.9297	13.6692
78 11 13	-18.0120	-6.4527	2.1963	2.7458	5.8233	13.6993
79 03 04	-18.2013	-6.6582	2.2835	2.9425	5.9703	13.6633
79 08 01	-18.2191	-6.6411	2.3077	2.9339	5.9480	13.6704
79 08 19	-18.2244	-6.6682	2.2967	2.9459	5.9747	13.6754
79 10 01	-18.2325	-6.7195	2.2880	2.9397	6.0240	13.7002
79 11 18	-18.2747	-6.7187	2.3051	2.9933	6.0203	13.6746
80 05 07	-18.3247	-6.7272	2.3375	3.0330	6.0078	13.6735
80 06 30	-18.4007	-6.7814	2.3992	3.0757	6.0569	13.6504
80 07 14	-18.2500	-6.6482	2.3115	2.9438	5.9610	13.6818
80 09 21	-18.3616	-6.7436	2.3714	3.0721	6.0229	13.6386
80 10 25	-18.3058	-6.6945	2.3417	3.0007	6.0035	13.6545
80 12 06	-18.3639	-6.7675	2.3681	2.0876	6.0504	13.6254
81 04 26	-18.4331	-6.8032	2.4163	3.1558	6.0591	13.6051
81 06 21	-18.4546	-6.8136	2.4614	3.1275	6.0672	13.6119
81 08 29	-18.4460	-6.8683	2.3950	3.1600	6.1195	13.6400
81 08 31	-18.4692	-6.8773	2.4058	3.1661	6.1291	13.6456
81 10 04	-18.4635	-6.8727	2.4160	3.1738	6.1190	13.6273
81 11 07	-18.4710	-6.8650	2.4157	3.1832	6.1142	13.6230
81 11 20	-18.3323	-6.7726	2.3784	3.0592	3.0312	13.6362
82 02 22	-18.4732	-6.8637	2.4230	3.1935	6.1068	13.6135
82 05 15	-18.4898	-6.8655	2.4495	3.2075	6.0957	13.6027
82 08 24	-18.4966	-6.8799	2.4289	3.1986	6.1236	13.6254
82 09 03	-18.5045	-6.8945	2.4285	3.2090	6.1405	13.6208
82 10 19	-18.4968	-6.9015	2.4307	3.2127	6.1355	13.6195
83 06 21	-18.5463	-6.9161	2.4896	3.2566	6.1114	13.6049

83 10 08	-18.5522	-6.9685	2.4575	3.2787	6.1637	13.6210
84 06 08	-18.5540	-6.9691	2.4739	3.2589	6.1609	13.6292
84 09 06	-18.3724	-6.8322	2.3916	3.1188	6.1233	13.6711
84 09 30	-18.4017	-6.8138	2.3997	3.1192	6.0607	13.6357
84 10 27	-18.4422	-6.8574	2.4253	3.1618	6.0920	13.6206
84 11 30	-18.4673	-6.8757	2.4385	3.1907	6.0973	13.6166
85 03 05	-18.4972	-6.8757	2.4520	3.2207	6.0970	13.6030
85 04 18	-18.4869	-6.8742	2.4476	3.2152	6.0942	13.6039
85 05 30	-18.4868	-6.8639	2.4562	3.2200	6.0868	13.5879
85 10 23	-18.4764	-6.8624	2.4680	3.2188	6.0719	13.5803
86 05 22	-18.4860	-6.8599	2.4745	3.2339	6.0656	13.5720
86 10 21	-18.4843	-6.8476	2.4748	3.2209	6.0709	13.5654
86 10 24	-18.4858	-6.8554	2.4661	3.2263	6.0776	13.5711
87 02 25	-18.5131	-6.9048	2.4835	3.2705	6.1052	13.5588
87 04 30	-18.5434	-6.9030	2.5115	3.2897	6.1004	13.5449
87 06 11	-18.5388	-6.8990	2.5029	3.2908	6.0986	13.5456
87 10 23	-18.5476	-6.9189	2.5057	3.2936	6.1158	13.5515
88 03 06	-18.5523	-6.9304	2.5085	3.3061	6.1215	13.5465
88 05 02	-18.5571	-6.9257	2.5134	3.3103	6.1176	13.5415
88 06 21	-18.5753	-6.9168	2.5169	3.3082	6.1245	13.5423
88 10 11	-18.5683	-6.9374	2.5144	3.3202	6.1214	13.5496
89 06 20	-18.5813	-6.9476	2.5304	3.3265	6.1147	13.5572
90 06 26	-18.5845	-6.9402	2.5268	3.3136	6.1265	13.5576
91 03 01	-18.5507	-6.9379	2.5158	3.3045	6.1197	13.5485
91 07 09	-18.5678	-6.9274	2.5258	3.2944	6.1160	13.5590
92 06 14	-18.5419	-6.9156	2.5151	3.2924	6.1019	13.5481
93 06 30	-18.5432	-6.8734	2.5524	3.2901	6.0566	13.5174
94 07 05	-18.5297	-6.8630	2.5270	3.2668	6.0650	13.5338

TILT STATION 0010, LEIRHNJÚKUR

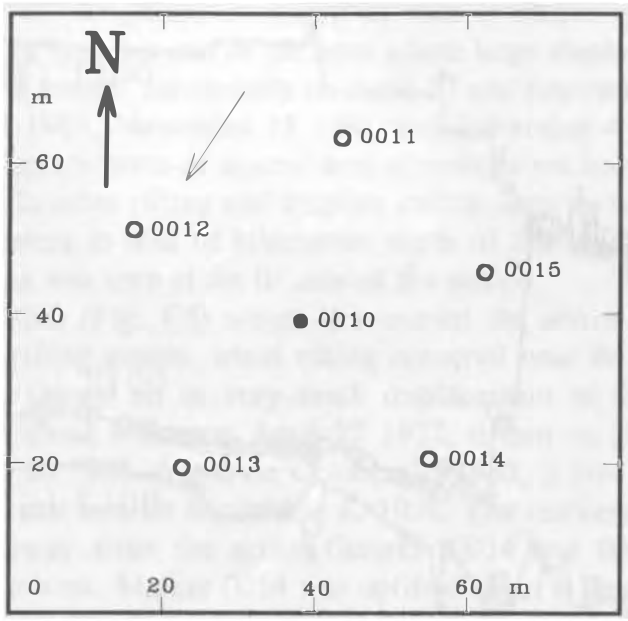


Fig. C1. Map of relative position of markers at the tilt station Leirhnjúkur, also named tilt station 0010. Solid circle is a marker at the center of a 25.0 m radius circle defined by five markers (open circles). The markers consist of copper alloy nails with 37 mm diameter convex surface plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Thin arrow gives the average direction of downward tilt during subsidence events of the Krafla volcano, excluding events of ground rifting near this tilt station.

This station was established on July 27, 1976 on flat pahoehoe lava of the 1724-1729 Mývatn fires, about 200 m east of the small ridge Leirhnjúkur which is known for extensive fumaroles. The 1724-1729 eruption fissure follows the western side of Leirhnjúkur and the small eruption of 20 December, 1975 came from a fissure immediately to the north of Leirhnjúkur. The eruptions of October 1980, November 1981 and September 1984 came from fissures which crossed the Leirhnjúkur ridge and lava flowed down the slopes of the ridge, although the main lava flow of these eruptions came to the surface several km north of Leirhnjúkur. Fissures opened across Leirhnjúkur in December 1975, April 1977, September 1977, and March 1980 in addition to the eruptions of October 1980, November 1981 and September 1984.

This station lies about one km north-east of the center of deformation, the site of greatest vertical displacement during inflations and deflations of the Krafla volcano (Tryggvason 1994). Five bench marks form a circle of 25.0 m radius and a central marker identifies the spot where tripods are placed during observations (Fig C1). It was observed 69 times from July 1976 to July 1994.

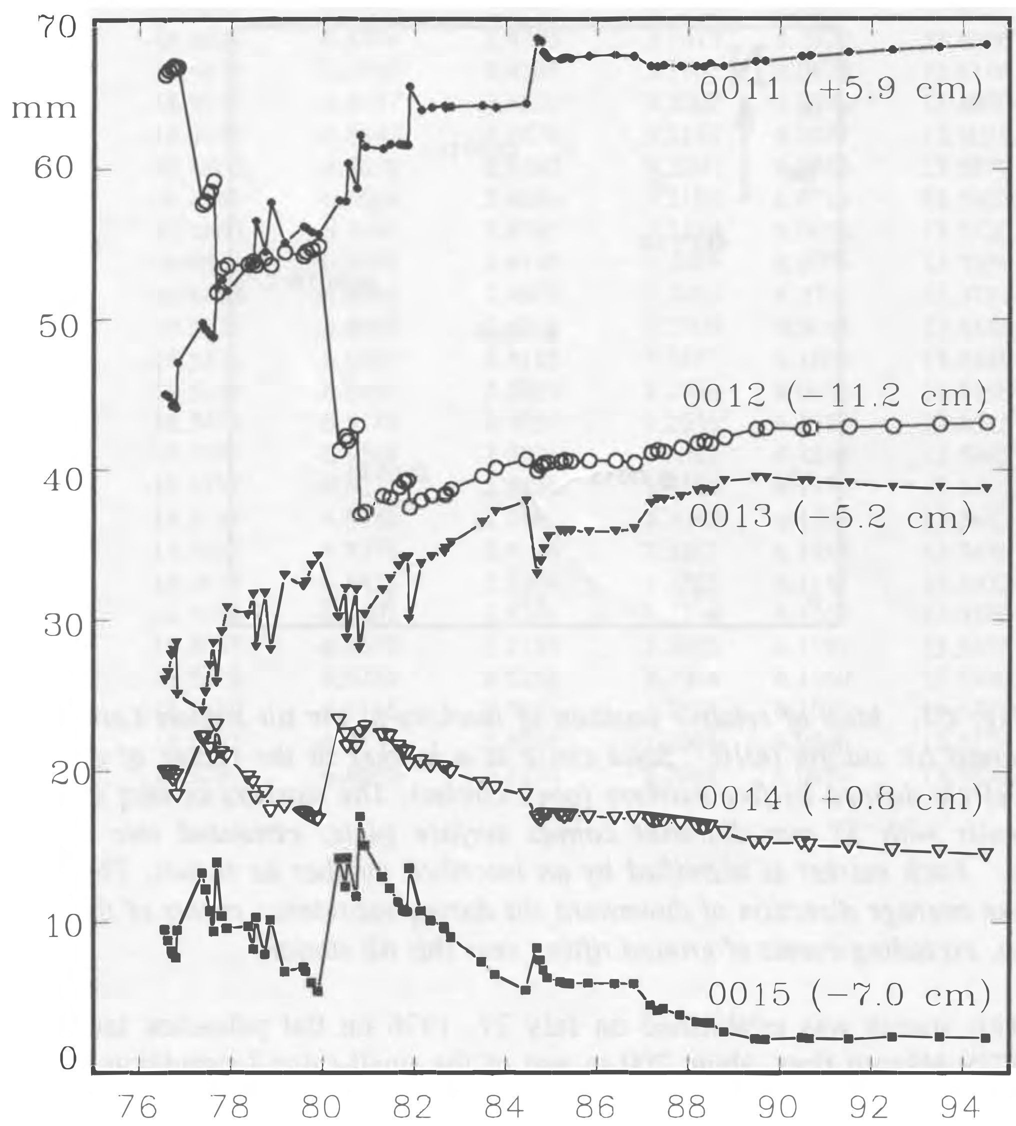


Fig. C2. Variation with time of the relative elevation of each of five markers forming the 25 m radius circle of the Leirhnjúkur tilt station. Note that marker 0012 has been displaced downwards during the rifting events when fissure displacements were seen near this station (April and September 1977, March October 1980, and November 1981). Marker 0013 shows up and down displacements which correlate with inflations and deflations of Krafla volcano. Marker 0011 was uplifted about 22 mm from 1977 to 1984. Marker 0014 has subsided continuously, except for the events of April 1977 and March 1980, when it was uplifted.

The tilt error ellipse is near circular and standard error of tilt is very variable, indicating that the area of the station has been subject to irregular deformation (Table C1 and C4). The observed ground deformation is very complicated (Fig. C2 and C3) but it can be recognised as caused by several distinct processes. The tilt station is located very near but east of the zone where large displacements were seen during several rifting events, particularly on April 27 and September 8 1977, March 16 and October 18 1980, November 18 1981 and September 4 1984. In most of these events fault displacements of several tens of centimeters occurred about 200 m west of the station. In other rifting and eruptive events, activity was concentrated in areas several kilometers to tens of kilometers north of the Leirhnjúkur tilt station and no surface rifting was seen at the latitude of the station.

The marker 0012 (Fig. C2) which lies nearest the active fissures, subsided during each of the rifting events, when rifting occurred near the tilt station, while other rifting events caused no or very small displacement of this marker. These displacements were about 9 mm on April 27 1977, 6 mm on September 8 1977, 13.5 mm on March 16 1980, 6 mm on October 18 1980, 2 mm on November 18, 1981, and less than one mm on September 4, 1994. The markers at this tilt station which lie farthest away from the active fissures (0014 and 0015) were uplifted during these rifting events. Marker 0014 was uplifted about 6 mm on March 6 1980 but uplift was not clearly defined during most other events. Marker 0015 was uplifted about 8 mm on March 16 1980 and about 5 mm on October 18 1980 and probably about 3 mm in each event of November 18 1981 and September 4, 1984. The computed tilt during these events of rifting very near the station is subject to large error because of irregular distribution of marker displacements within the tilt station array (Table C1).

Table C1

Computed ground tilt at the Leirhnjúkur (0010) tilt station during selected rift events of the Krafla fissure swarm. Tilt is calculated from last observation before the rifting event and first observation after the event.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of rifting event
76 10 23	76 11 01	129.9	1.6	25.1	76 10 31
76 11 01	77 05 18	248.2	56.2	101.5	77 04 28
77 08 15	77 09 10	229.6	42.6	85.1	77 09 08
78 06 28	78 07 19	126.6	1.8	31.7	78 07 10
78 09 30	78 11 13	143.7	1.9	31.1	78 11 10
79 11 24	80 05 08	438.9	48.2	98.5	80 03 16
80 06 30	80 07 14	118.9	3.0	32.9	80 07 10
80 09 24	80 10 24	232.1	28.8	72.9	80 10 18
81 11 07	81 11 20	168.5	11.0	42.5	81 11 18
84 06 08	84 09 06	185.5	5.2	31.9	84 09 04

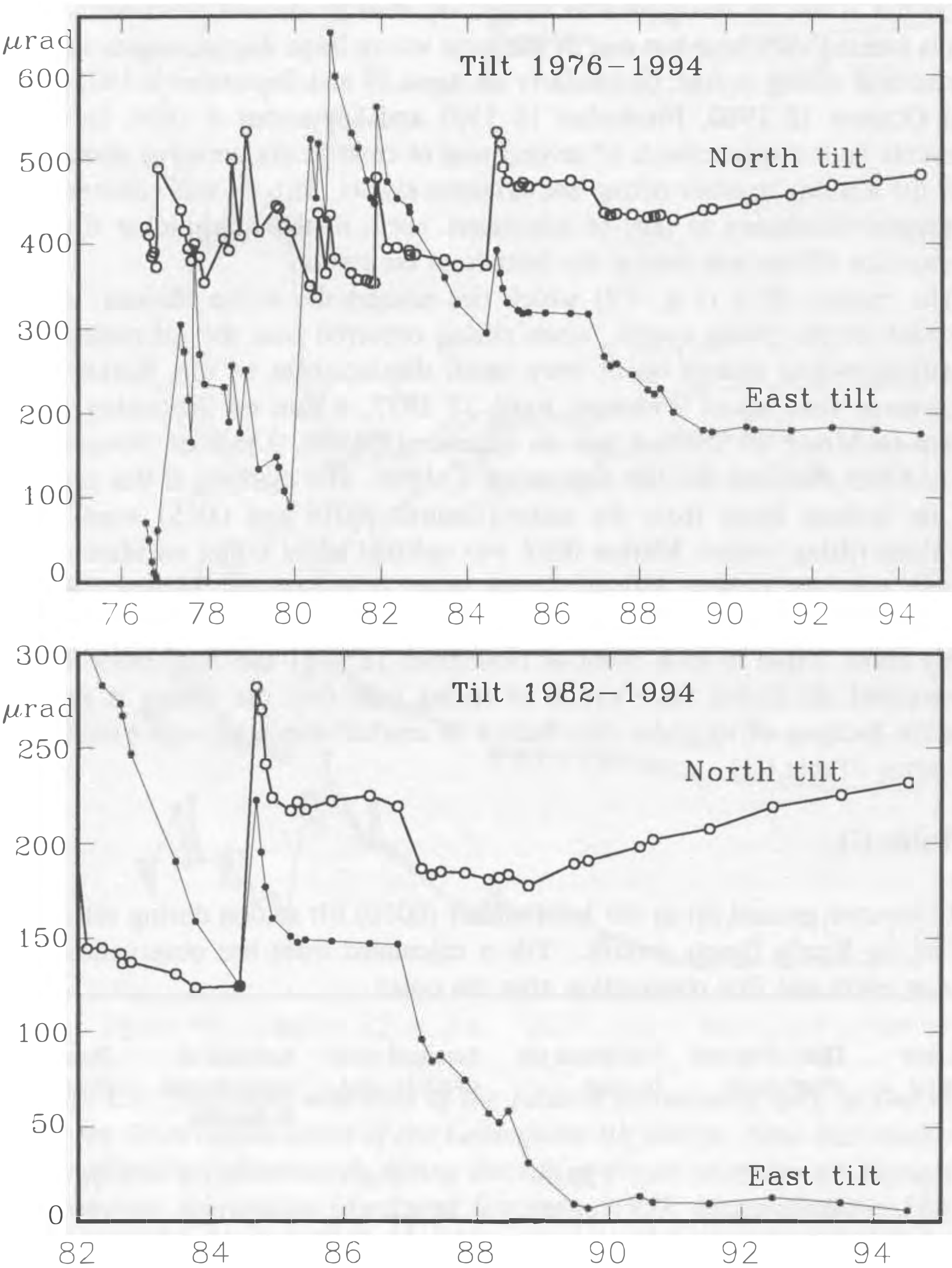


Fig. C3. Observed tilt of the ground at the tilt station Leirhnjúkur since first observation of July 27, 1976. East component of tilt is marked with solid dots connected by a thin line and north component of tilt is shown with open circles connected by a thick line. Lower graph presents the tilt after 1981 on expanded tilt scale to emphasise the relatively gentle tilt variations after the activity of Krafla volcano subsided. The large tilt variations from 1977 to 1984 are not well defined as irregular marker displacements cause very large errors of the computed tilt.

Last observation before the event of April 28, 1977 was made on November 1 1976 and a deflation event occurred on January 20, 1977. Rifting during this January 1977 event occurred between 5 and 15 km north of the Leirhnjúkur tilt station, suggesting that only minor permanent displacements occurred at this tilt station during the January 1977 event. However, the observation of November 1 1976 was made immediately after a rather large deflation event of October 31, 1976. Therefore, the observed tilt between November 1 1976 and May 18, 1977 (Table C1) is partly inflation tilt after the October 31, 1976 deflation event, and also inflation tilt for 19 days after the April 28 rifting event. Computed tilt during subsidence events when rifting occurred in the immediate vicinity of the Leirhnjúkur station, are uncertain as seen by the very large standard errors (Table C1), while subsidence events of no rifting in the vicinity of the station are computed with standard errors of less than 3 μrad. The azimuth of tilt during events of rifting near the Leirhnjúkur station is up in easterly direction, but variable from one event to another. Those events when no rifting occurred near the station show tilt up towards an azimuth of about 30 degrees. Similar tilt azimuth is also observed during the event of 84 09 04, suggesting that the rifting near the station has caused only minor effect on the ground tilt of this event.

Table C2

Observed tilt at the tilt station Leirhnjúkur (0010) during selected periods of continuous inflation of the Krafla volcano. Tilt is calculated from two observations, usually soon after a deflation event.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of previous rifting event
76 07 27	76 09 08	58.0	3.4	232.7	75 12 20
77 05 18	77 06 13	41.0	5.7	231.6	77 04 28
77 09 10	77 10 21	126.1	23.5	263.0	77 09 08
78 07 19	78 09 30	120.2	7.7	221.3	78 07 10
78 11 13	79 03 04	166.3	11.0	224.7	78 11 10
80 05 08	80 06 30	70.3	10.8	258.6	80 03 16
80 07 14	80 09 24	114.8	6.2	231.8	80 07 10
80 10 24	80 12 03	73.1	11.4	225.1	80 10 18
81 11 20	82 02 21	121.8	13.4	226.5	81 11 18
84 10 03	84 10 27	33.7	1.8	212.4	84 09 04
86 10 21	87 03 03	60.4	4.1	237.2	84 09 04

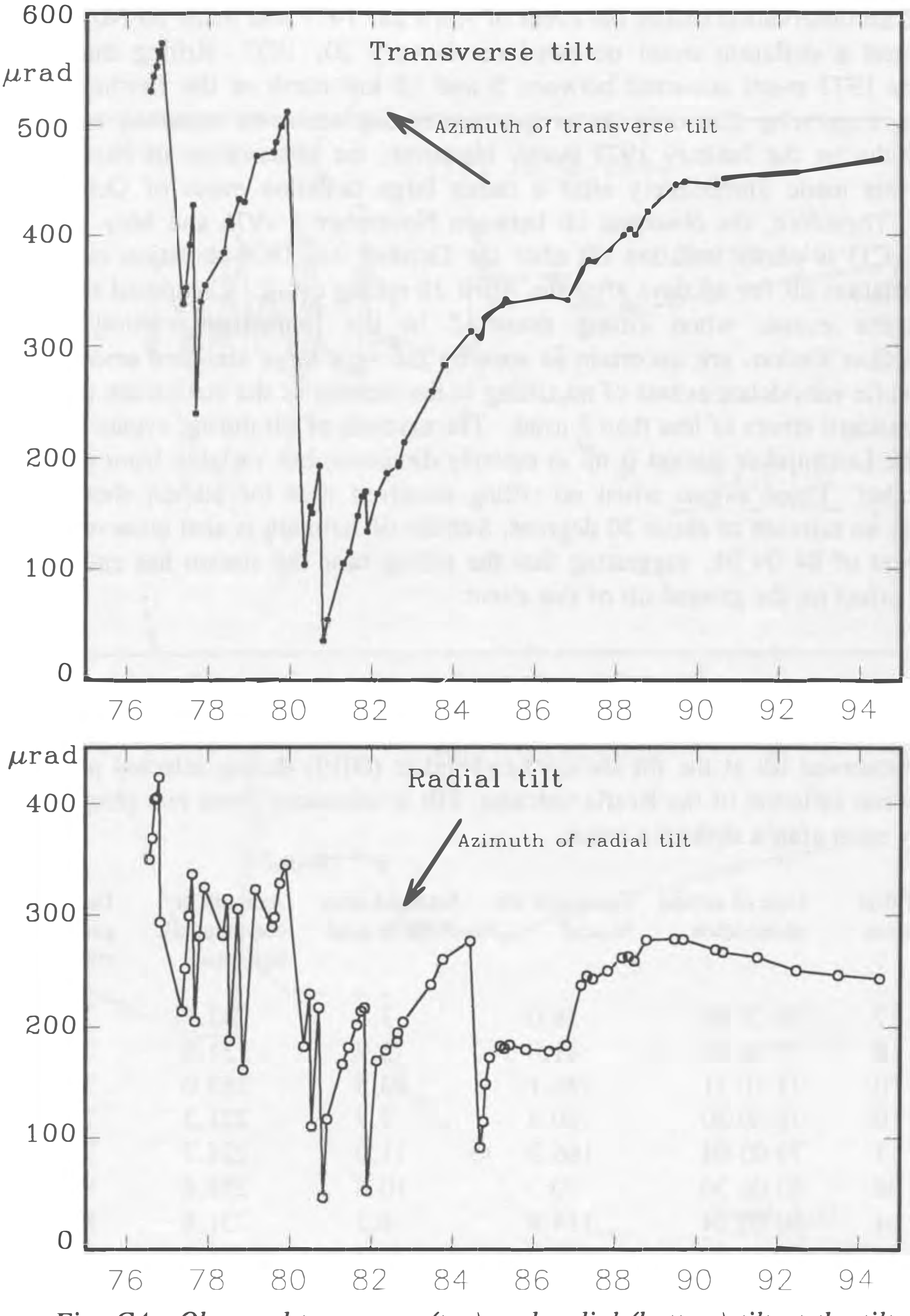


Fig. C4. Observed transverse (top) and radial (bottom) tilt at the tilt station Leirhnjúkur, relative to the center of inflations and deflations of the Krafla volcano. Azimuth of radial tilt is taken as 210°, the average direction of downward tilt during deflations of Krafla volcano, ignoring events of rifting near this tilt station. Transverse tilt is positive in azimuth 300°. Principal features in transverse component of tilt is downwards tilt during main events of rifting near this station (April and September 1977, March and October 1980 and November 1981) and upward tilt after these events at gradually decreasing rate. Radial tilt is dominated by deflations and following inflations of Krafla volcano.

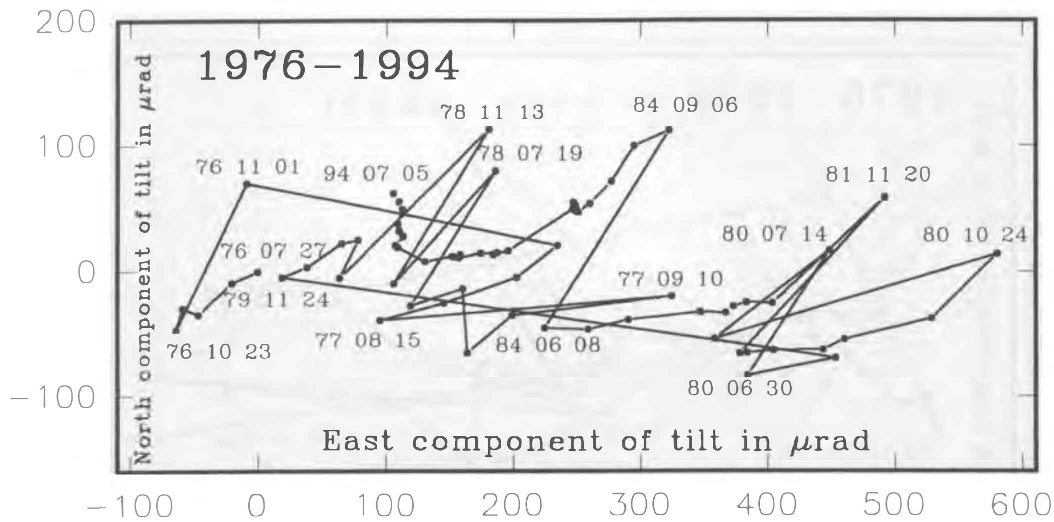


Fig. C5. North component of tilt plotted against east component of tilt at the tilt station Leirhnjúkur, showing progress of the tilt vector through time. Deflation events without rifting near the station appear as tilt up towards an azimuth of about 30° while certain events of rifting near the station show tilt up towards an azimuth of about 100°.

It becomes evident when data of Table C1 and Table C2 are compared, that tilt during inflations of Krafla volcano is not opposite in direction to tilt during deflations. Tilt during deflations, without rifting near the Leirhnjúkur tilt station, is up towards average azimuth of about 30°. During inflation (Table C2), excluding inflations after the events of 77 09 08 and 80 03 16, the average tilt azimuth is about 227°, or 47° west of south. This comparison also shows that the standard error of computed tilt is generally less than 3 μrad for deflation tilt when no rifting occurred near the tilt station, usually greater than 3 μrad and frequently greater than 10 μrad for rapid inflation tilt soon after deflations and may exceed 40 μrad for deflation tilt when rifting of the ground occurred near the Leirhnjúkur tilt station (Tables C1 and C2). These errors of the computed tilt are the results of irregular ground deformation within the 50 m diameter area of the tilt station

The tilt observations at the Leirhnjúkur tilt station show some secular deformation which is not well defined. Marker 0014 shows almost no displacements during deflation and rifting events (except the events of April 28, 1977 and March 16, 1980), but this marker has been subsiding continuously relative to average elevation of all five markers of the tilt station.(Fig. C2). The subsidence rate of this marker was about 1.2 mm per year from 1980 to 1984 and somewhat higher from 1977 to 1980, and about 0.4 mm per year from 1984 to 1994.

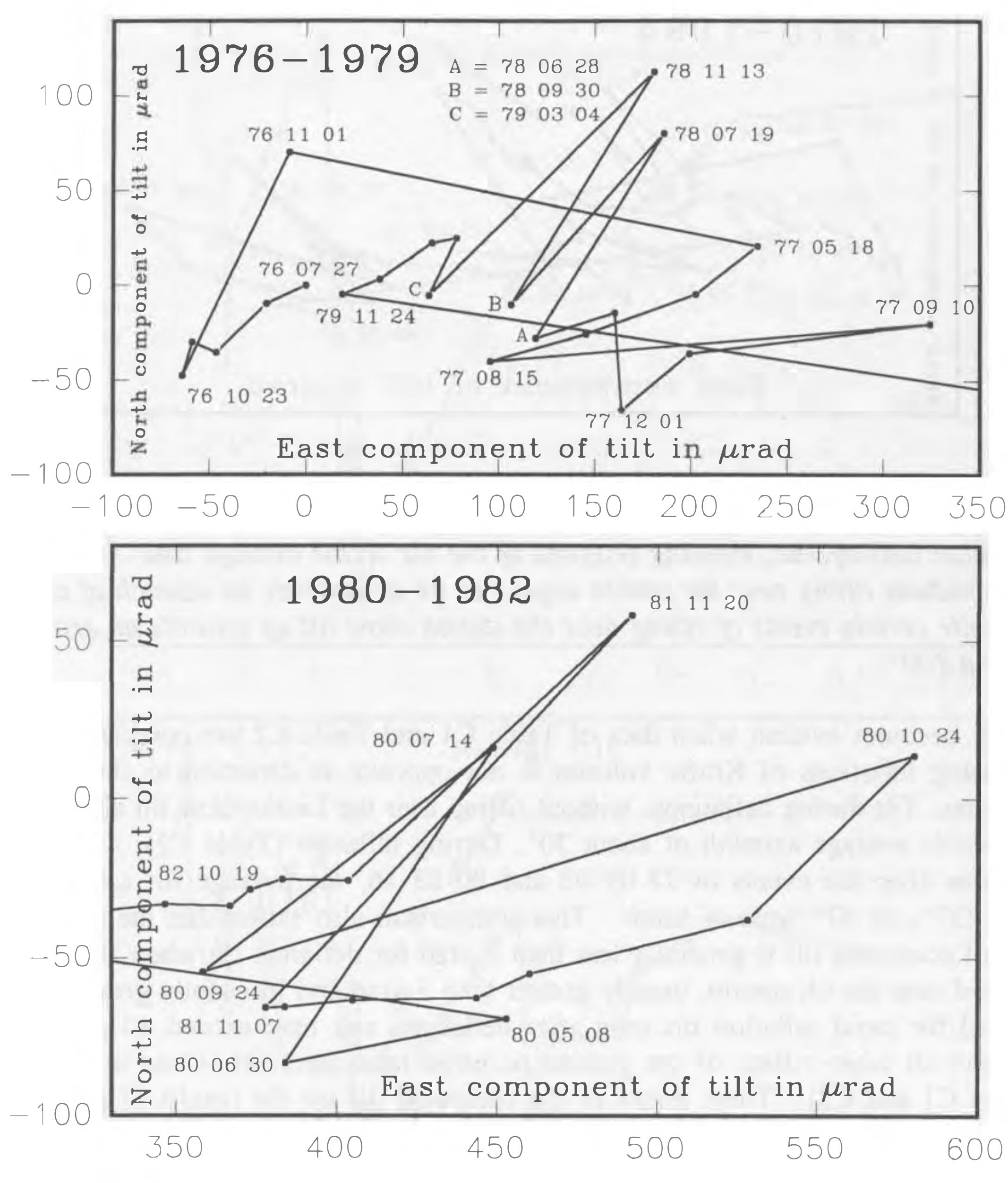


Fig. C6. Sections of Fig. C5 in expanded scale for easier comprehension of the tilt progress at the Leirhnjúkur tilt station.

When tilt is split into transverse component and radial component with respect to the center of deformation of Krafla volcano (Fig C4), it is evident that the transverse component (azimuth N 60° W) shows almost no response to the deflation events if no rifting occurred near Leirhnjúkur, but rifting events of April 27, 1977, September 8, 1977, March 16 1980, October 18, 1980 and November 18, 1981 show distinct downward transverse tilt (down towards an azimuth of 300°). However, the secular tilt has very large transverse component, up towards an azimuth of 300°. This transverse secular tilt came to a halt for about 18 months from April 1985 to October 1986, and in 1989 its rate became very slow.

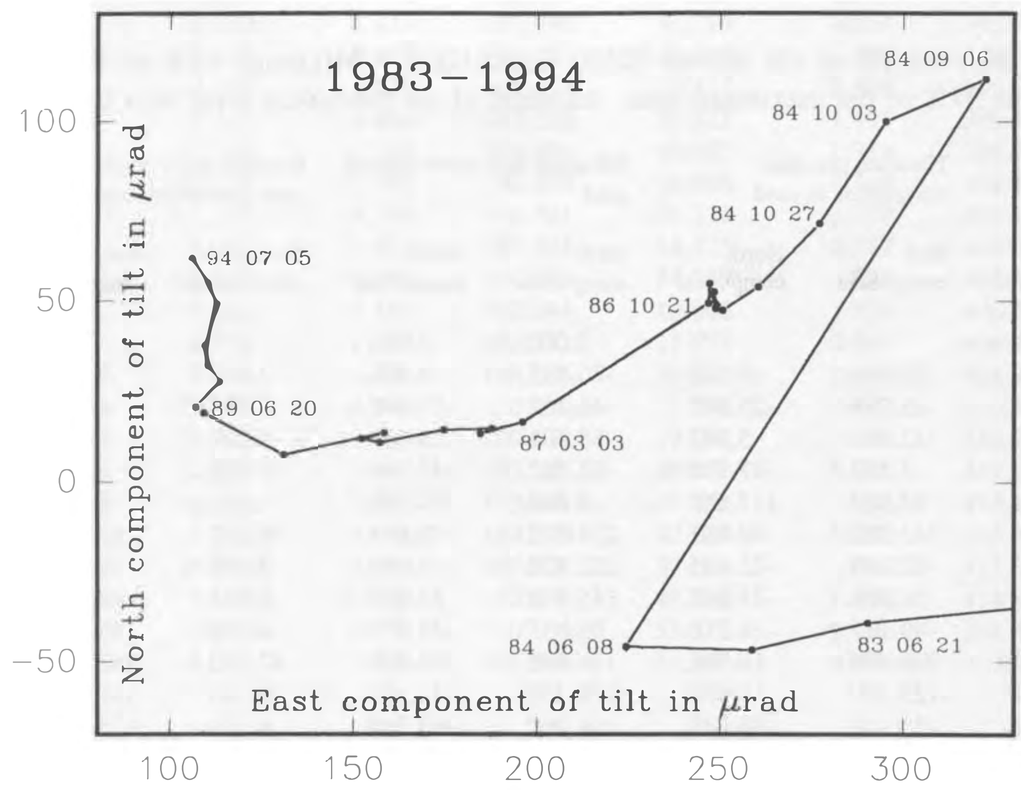


Fig. C7. Progress of tilt at the Leirhnjúkur tilt station 1983-1994, during the end of the 1975-1984 period of rifting and eruptions of Krafla volcano and following years. The deflation of September 4, 1984 is seen as uplift towards an azimuth of about 31° followed by tilt up towards south-west, veering towards west in about 1987. In 1989 the tilt azimuth turns abruptly towards north and this uplift-azimuth remains constant during the 5 years 1989-1994

Table C3

Observed ground tilt at the Leirhnjúkur (0010) tilt station during extended periods of relatively slow ground deformation.

Date of first observation	Date of last observation	Observed tilt in μrad	Azimuth of observed tilt in degrees	East component of tilt in μrad	North component of tilt in μrad
79 08 01	79 11 24	66.1	243.4	-59.1	-29.6
81 04 20	81 11 07	83.0	262.5	-82.3	-10.9
82 05 14	84 06 08	158.8	262.6	-158.2	-20.5
85 06 01	86 10 21	2.5	305.5	-2.0	1.5
87 04 28	89 06 20	75.6	274.7	-75.4	5.8
89 06 20	94 07 05	42.8	355.8	-3.1	42.6

Table C4

Observed tilt at tilt station 0010, Leirhnjúkur. Minimum axis of the error ellipse is 97% of the maximum axis. Azimuth of the maximum error axis is 175°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
76 07 27			0.000	0.000		
76 08 20	-20.438	-9.536	-20.438	-9.536	3.707	3.707
76 09 08	-25.714	-25.562	-46.152	-35.097	3.407	4.800
76 10 02	-12.449	5.443	-58.601	-29.654	4.337	8.239
76 10 23	-5.107	-17.710	-63.707	-47.364	1.356	9.468
76 11 01	55.067	117.650	-8.640	70.286	1.613	8.840
77 05 18	243.210	-49.461	234.570	20.825	56.192	65.026
77 06 13	-32.149	-25.445	202.420	-4.620	5.709	70.526
77 07 17	-56.871	-21.043	145.550	-25.663	8.547	78.653
77 08 15	-49.917	-14.116	95.633	-39.779	6.775	85.405
77 09 10	228.799	19.539	324.432	-20.240	42.629	127.718
77 10 21	-125.199	-15.456	199.233	-35.696	23.540	151.078
77 12 01	-35.168	-30.049	164.065	-65.745	6.504	155.710
78 05 19	-3.716	51.496	160.349	-14.249	11.989	167.444
78 06 28	-40.961	-13.520	119.389	-27.769	12.647	179.278
78 07 19	66.489	107.751	185.878	79.982	1.841	177.625
78 09 30	-79.379	-90.200	106.498	-10.218	7.745	185.349
78 11 13	74.304	122.992	180.803	112.774	1.888	187.113
79 03 04	-116.984	-118.186	63.818	-5.413	10.951	198.017
79 08 01	14.240	30.182	78.058	24.770	5.165	203.071
79 08 19	-12.482	-2.604	65.576	22.166	0.576	203.640
79 10 03	-27.300	-18.995	38.277	3.170	5.208	208.752
79 11 24	-19.320	-7.992	18.956	-4.821	2.653	211.396
80 05 08	434.096	-64.675	453.052	-69.496	48.233	259.142
80 06 30	-68.860	-13.940	384.192	-83.436	10.796	269.922
80 07 14	64.515	99.851	448.707	16.415	3.002	267.675
80 09 24	-90.261	-70.906	358.446	-54.491	6.210	273.790
80 10 24	221.792	68.315	580.238	13.823	28.773	301.096
80 12 03	-51.801	-51.615	528.438	-37.792	11.428	311.154
81 04 20	-68.114	-17.276	460.324	-55.068	9.064	318.447
81 06 19	-16.715	-7.793	443.609	-62.861	9.512	327.521
81 08 27	-38.732	-0.761	404.877	-63.621	3.695	331.176
81 10 03	-20.931	-2.071	383.946	-65.693	1.797	332.971
81 11 07	-5.910	-0.234	378.036	-65.927	0.627	333.437
81 11 20	113.929	124.149	491.965	58.223	11.003	344.231
82 02 21	-88.299	-83.833	403.667	-25.611	13.413	357.512
82 05 14	-20.600	0.464	383.067	-25.147	4.280	361.544
82 08 24	-9.808	-3.230	373.259	-28.377	3.923	364.964
82 09 03	-6.460	-5.208	366.799	-33.585	0.997	364.744
82 10 19	-19.947	0.590	346.852	-32.995	2.885	367.269
83 06 21	-56.391	-6.176	290.461	-39.170	8.074	375.020
83 10 08	-31.580	-7.290	258.881	-46.461	2.838	377.696
84 06 08	-34.346	0.832	224.535	-45.628	6.289	383.309
84 09 06	97.973	157.549	322.508	111.920	5.181	387.461
84 10 03	-27.298	-11.910	295.210	100.010	3.367	390.802

84 10 27	-18.065	-28.467	277.145	71.543	1.793	390.395
84 12 02	-16.757	-17.742	260.388	53.801	2.879	393.273
85 03 13	-9.577	-6.442	250.811	47.359	2.509	395.580
85 04 18	-3.120	4.415	247.691	51.774	0.661	395.159
85 06 01	1.159	-3.928	248.849	47.845	0.909	395.844
85 10 23	-0.357	4.571	248.493	52.417	0.301	396.086
86 05 22	-1.342	2.406	247.150	54.822	1.195	396.991
86 10 21	-0.344	-5.519	246.806	49.303	1.315	398.306
87 03 03	-50.728	-32.706	196.078	16.598	4.140	402.439
87 04 28	-11.557	-3.226	184.521	13.372	1.676	404.045
87 06 14	3.003	1.453	187.524	14.825	0.917	404.494
87 10 26	-12.888	-0.506	174.636	14.319	1.824	405.126
88 03 05	-17.552	-3.518	157.084	10.800	1.933	406.986
88 05 02	-4.772	1.173	152.312	11.974	0.967	406.761
88 06 21	5.974	1.591	158.286	13.565	2.610	408.432
88 10 11	-27.327	-5.816	130.959	7.748	2.449	410.499
89 06 20	-21.841	11.415	109.118	19.163	2.106	412.604
89 09 08	-2.031	1.690	107.086	20.853	0.671	412.055
90 06 26	6.358	7.081	113.445	27.934	1.211	413.127
90 08 28	-3.286	4.133	110.159	32.067	0.270	413.181
91 07 07	-0.632	5.573	109.527	37.640	1.044	413.906
92 06 18	3.129	11.577	112.656	49.216	1.244	414.375
93 06 30	-2.467	6.154	110.189	55.370	0.732	414.451
94 07 05	-4.227	6.438	105.963	61.808	0.767	415.183

Table C5

Marker coordinates and observed marker elevation at the tilt station 0010 (Leirhnjúkur), relative to the average values of all five markers at the tilt station

Marker	0011	0012	0013	0014	0015
Marker coordinates in meters, surveyed 81 08 27					
East	3.62	-23.72	-17.32	15.08	22.32
North	23.42	11.10	-20.60	-19.39	5.47
Y M D	Marker elevation, centimeter				
76 07 27	10.4075	-4.5671	-2.5912	2.7953	-6.0446
76 08 20	10.3950	-4.5358	-2.5393	2.7972	-6.1173
76 09 18	10.3353	-4.5193	-2.4251	2.7934	-6.1843
76 10 02	10.3552	-4.5041	-2.3931	2.7452	-6.2031
76 10 23	10.3195	-4.5179	-2.3441	2.7721	-6.2294
76 11 01	10.6155	-4.5135	-2.6890	2.6358	-6.0490
77 05 18	10.8791	-5.4331	-2.7971	3.0221	-5.6709
77 06 13	10.8399	-5.4114	-2.6738	3.0242	-5.7788
77 07 17	10.8063	-5.3444	-2.4929	2.9544	-5.9234
77 08 15	10.7886	-5.2769	-2.3499	2.8939	-6.0556
77 09 10	11.1194	-6.0208	-2.6055	3.1067	-5.5998
77 10 21	11.1631	-5.8596	-2.2741	2.9247	-5.9543
77 12 01	11.0915	-5.8370	-2.1190	2.8982	-6.0338
78 05 19	11.2626	-5.8335	-2.1642	2.7590	-6.0237
78 06 28	11.2870	-5.8098	-2.0316	2.7259	-6.1716
78 07 19	11.5573	-5.8387	-2.3777	2.6243	-5.9652
78 09 30	11.3546	-5.7910	-2.0222	2.6635	-6.2050
78 11 13	11.6803	-5.8393	-2.3993	2.5377	-5.9793
79 03 04	11.4132	-5.7503	-1.9071	2.5667	-6.3226
79 08 01	11.5173	-5.7759	-1.9772	2.5268	-6.2909
79 08 19	11.5093	-5.7522	-1.9477	2.5116	-6.3209
79 10 03	11.4780	-5.7358	-1.8381	2.4934	-6.3976
79 11 24	11.4661	-5.7124	-1.7784	2.4764	-6.4519
80 05 08	11.6922	-7.0661	-2.1854	3.1364	-5.5769
80 06 30	11.6895	-6.9740	-1.9957	3.0428	-5.7627
80 07 14	11.9411	-7.0032	-2.3280	2.9610	-5.5707
80 09 24	11.7756	-6.8989	-2.0044	2.9571	-5.8294
80 10 24	12.1261	-7.4964	-2.3921	3.0614	-5.2989
80 12 03	12.0511	-7.4802	-2.1709	3.0925	-5.4924
81 04 20	12.0367	-7.3723	-2.0041	3.0382	-5.6986
81 06 19	12.0654	-7.3863	-1.9316	3.0274	-5.7748
81 08 27	12.0665	-7.3146	-1.8468	2.9614	-5.8663
81 10 03	12.0633	-7.2765	-1.7995	2.9313	-5.9185
81 11 07	12.0618	-7.2655	-1.7857	2.9198	-5.9305
81 11 20	12.4537	-7.4523	-2.2025	2.8437	-5.6428
82 02 21	12.2971	-7.4032	-1.8302	2.8608	-5.9244
82 05 14	12.3147	-7.3736	-1.7841	2.8297	-5.9868
82 08 24	12.3258	-7.3700	-1.7530	2.8258	-6.0285
82 09 03	12.3077	-7.3601	-1.7289	2.8214	-6.0399
82 10 19	12.3181	-7.3241	-1.6901	2.7934	-6.0974
83 06 21	12.3282	-7.2353	-1.5566	2.7200	-6.2563
83 10 08	12.3156	-7.1815	-1.4795	2.6873	-6.3420

84 06 08	12.3407	-7.1255	-1.4090	2.6403	-6.4465
84 09 06	12.7740	-7.2015	-1.8972	2.4928	-6.1682
84 10 03	12.7544	-7.1667	-1.8139	2.4721	-6.2457
84 10 27	12.6832	-7.1517	-1.7312	2.5099	-6.3102
84 12 02	12.6505	-7.1464	-1.6549	2.5152	-6.3645
85 03 13	12.6415	-7.1436	-1.6130	2.5047	-6.3894
85 04 18	12.6497	-7.1287	-1.6200	2.4947	-6.3958
85 06 01	12.6459	-7.1387	-1.6132	2.5063	-6.4002
85 10 23	12.6573	-7.1342	-1.6205	2.4956	-6.3981
86 05 22	12.6652	-7.1338	-1.6172	2.4834	-6.3977
86 10 21	12.6590	-7.1458	-1.6002	2.4918	-6.4046
87 03 03	12.5858	-7.0828	-1.4300	2.4740	-6.5468
87 04 28	12.5834	-7.0668	-1.3988	2.4630	-6.5808
87 06 14	12.5883	-7.0754	-1.4027	2.4598	-6.5700
87 10 26	12.5897	-7.0470	-1.3825	2.4495	-6.6099
88 03 05	12.5859	-7.0183	-1.3395	2.4300	-6.6583
88 05 02	12.5836	-7.0054	-1.3314	2.4159	-6.6626
88 06 21	12.6028	-7.0244	-1.3452	2.4301	-6.6633
88 10 11	12.5868	-6.9780	-1.2738	2.3902	-6.7253
89 06 20	12.6163	-6.9244	-1.2513	2.3318	-6.7725
89 09 08	12.6176	-6.9145	-1.2546	2.3283	-6.7769
90 06 26	12.6434	-6.9266	-1.2779	2.3257	-6.7644
90 08 28	12.6515	-6.9148	-1.2797	2.3112	-6.7682
91 07 07	12.6698	-6.9101	-1.2898	2.3024	-6.7724
92 06 18	12.6978	-6.9082	-1.3135	2.2779	-6.7539
93 06 30	12.7134	-6.8952	-1.3240	2.2660	-6.7602
94 07 05	12.7302	-6.8820	-1.3264	2.2449	-6.7666

TILT STATION 0020, MÝVATN-N

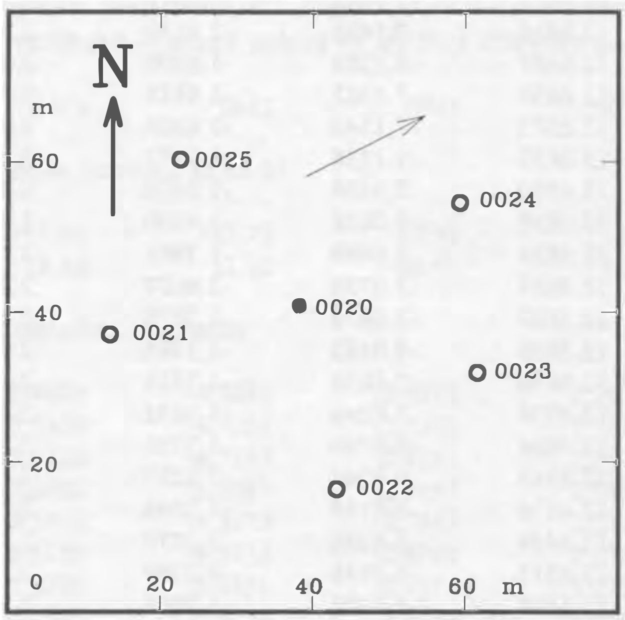


Fig. D1. Map of relative position of markers at the tilt station Mývatn-N, also named tilt station 0020. Solid circle is a marker at the center of a 25.0 m radius circle defined by 5 markers (open circles). The markers consist of copper alloy nails with 37 mm diameter convex top plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Thin arrow gives the average direction of downward tilt during subsidence events of Krafla volcano, excluding events of ground rifting near this tilt station.

This tilt station was constructed on 27 July 1976. It lies on pahoehoe lava of 1729, about 0.5 km from the north shore of lake Mývatn and about 0.1 km north of the Húsavík-Mývatn road, some 2 km west of Reykjahlíð. Five bench marks form a circle of 25.0 m radius and a sixth marker is located at the center of the circle, marking the location of the tripod during observations (Fig D1). It was observed 49 times from July 1976 to July 1994. The standard error of computed tilt between successive observations was usually less than 2 μrad, except if large tilt was observed or observations were made during adverse weather condition (Table D2).

During three rifting events, large ground tilt and marker displacements occurred at this station. These were the events of April 27, 1977, September 8, 1977, and March 16, 1980. In April 1977 rifting was observed farther south than in any other event of the 1977-1984 Krafla fires. Widening of the Krafla fissure swarm in the vicinity of this tilt station was about 2 m (Björnsson et al. 1979) In September 1977, a small amount of pumice was erupted in Bjarnarflag, about 5 km east of this tilt station and the Krafla fissure swarm was widened about 1.1 m at the latitude of the station (Tryggvason 1980). In March 16, 1980, the third event of large tilt and displacements at this station, more than 20 km segment of the Krafla fissure swarm was widened about, or more than, one meter. This widening terminated southwards at the latitude of the Mývatn-N station (Tryggvason 1982).

Markers 0021 and 0025 were displaced downward in each of these events, but markers 0023 and 0024 were displaced upward (fig. D2). Marker 0022 appear to be unaffected by these rifting events. This means that ground tilt at this tilt station was up towards east in each of these three rifting events (Fig. D4 and D6), the result of uplift of the west flank of the Krafla fissure swarm.

It is worth noticing that the Námaskarð tilt station showed tilt up towards west during the rift events of April 27 and September 8, 1977, caused by uplift of the east flank of the Krafla fissure zone, but during the event of March 16, 1980, tilt at the Námaskarð station was up towards east (Figs. A4 and A6), suggesting that the east flank of the Krafla fissure swarm was not uplifted nearest to the Námaskarð station, although the west flank was uplifted nearest to the Mývatn-N station, but these stations are at nearly the same latitude.

Ground displacements at other times are small. Markers 0021 and 0022 have subsided slowly after the rifting events (Fig. D3), and markers 0024 and 0025 have been displaced upwards at the same time. These displacements correspond to tilting of the ground up towards north (Fig. D4 bottom) at a rate of about 3 μrad per year until 1990, and near zero tilt after 1990. Tilt during deflation events, other than those when rifting occurred south of Krafla, were rarely observed because the periods between observations included tilt before and after the subsidence events, so the deformation during the events could not be estimated. Three events (Table D1) occurred shortly after observation at this tilt station, and observations were also made shortly after these events. These observations show tilt up towards an azimuth of about 240° which is in fair agreement with the direction to the center of subsidence during the Krafla subsidence events.

Table D1

Observed tilt at the tilt station Mývatn-N (0020) during selected rift events of the Krafla fissure swarm. Tilt is calculated from last observation before the event and the first observation after the event. The computed tilt includes tilt both before and after the rifting event, in addition to tilt during the event. Events of 77 04 27, 77 09 08 and 80 03 16 were associated with ground rifting near the tilt station, while during the other events, rifting occurred 10 to 40 km north of the station.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of rifting event
76 10 23	77 05 16	45.6	8.9	99.4	77 04 27
77 08 15	77 09 11	39.0	5.9	70.9	77 09 08
78 06 28	78 07 19	7.3	2.4	277.5	78 07 10
80 02 14	80 05 07	27.0	2.8	93.4	80 03 16
80 07 01	80 07 15	11.8	3.6	240.6	80 07 10
84 06 09	84 09 28	10.2	1.4	243.5	84 09 04

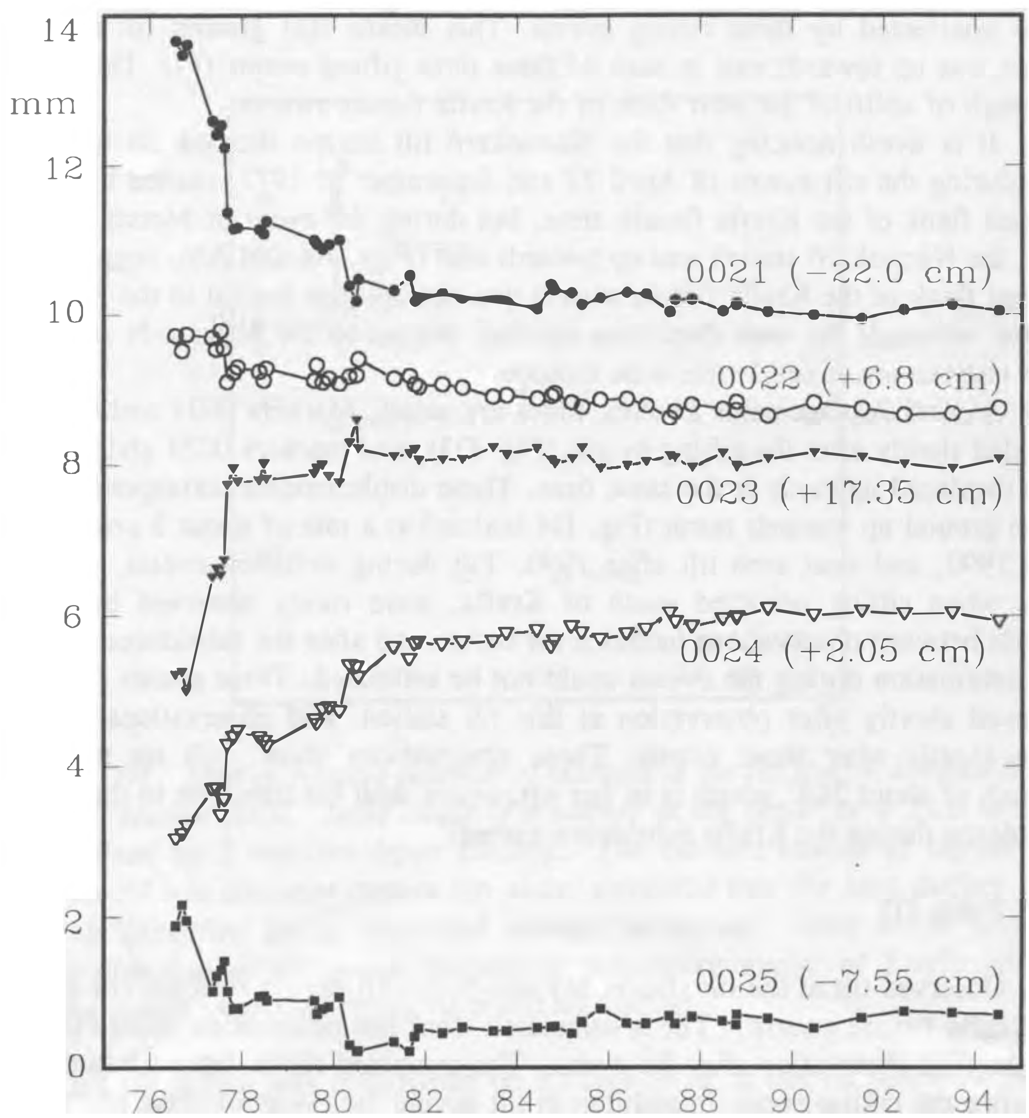


Fig. D2. Variation of relative marker elevation with time at the tilt station Mývatn-N (0020). Horizontal scale is in years, beginning at 1975. Vertical scale is in millimeters. Reference elevation is the average elevation of all five markers of the tilt station. Relative elevation is found by adding to the left scale values the constants given in parenthesis besides the marker identifications.

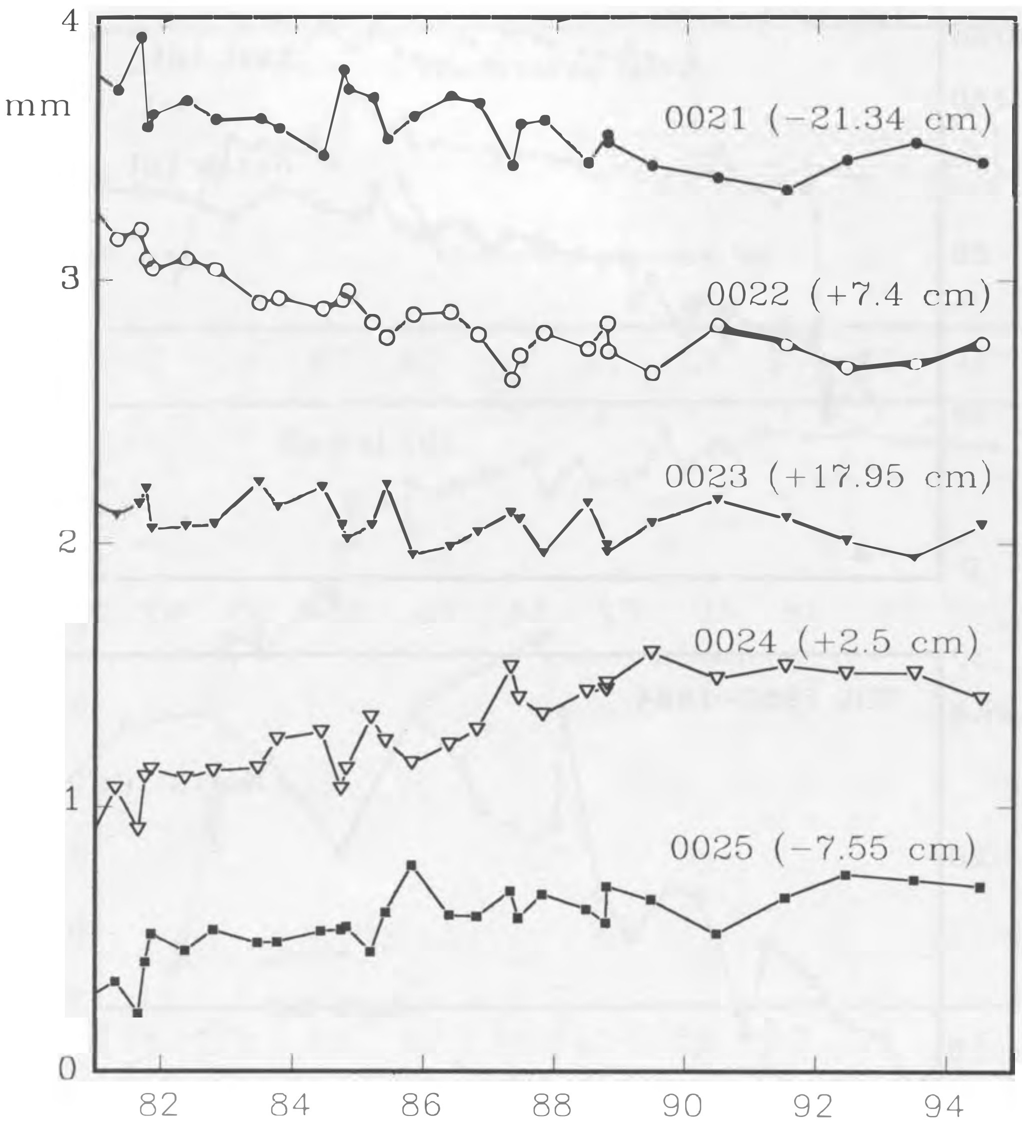


Fig. D3. Variation of relative elevation of markers at the tilt station Mývatn-N (0020) from 1981 to 1994. Same as Fig. D2 except the vertical scale is expanded to clarify elevation variations when the activity of Krafla became less violent after 1980. Random elevation variations suggest observational errors or random marker movements, possibly caused by thermal strain in the lava on which the station is located.

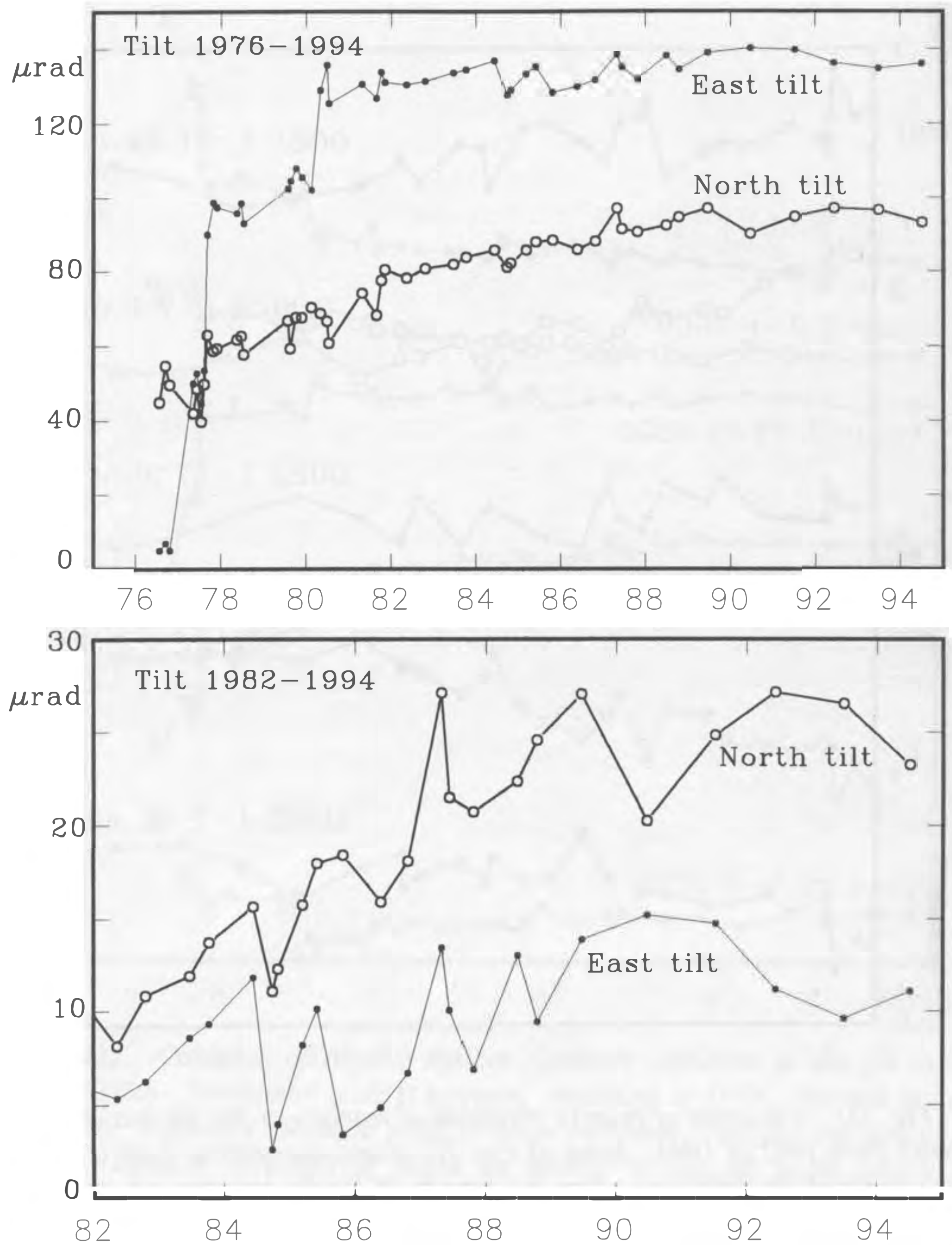


Fig. D4. Observed tilt of the ground at the tilt station Mývatn-N (0020) since first observation of 27 July 1976. The top diagram presents tilt during the whole period of observations, 1976-1994, showing large tilt variations during rifting events of April and September 1977 and March 1980. Bottom diagram shows observed tilt variations after 1981 on expanded tilt scale showing tilt variation during the September 1984 eruption and gradual uplift towards north from 1982 to 1990. Random tilt variations, especially on the east component, suggest observational errors or minor irregular marker displacement

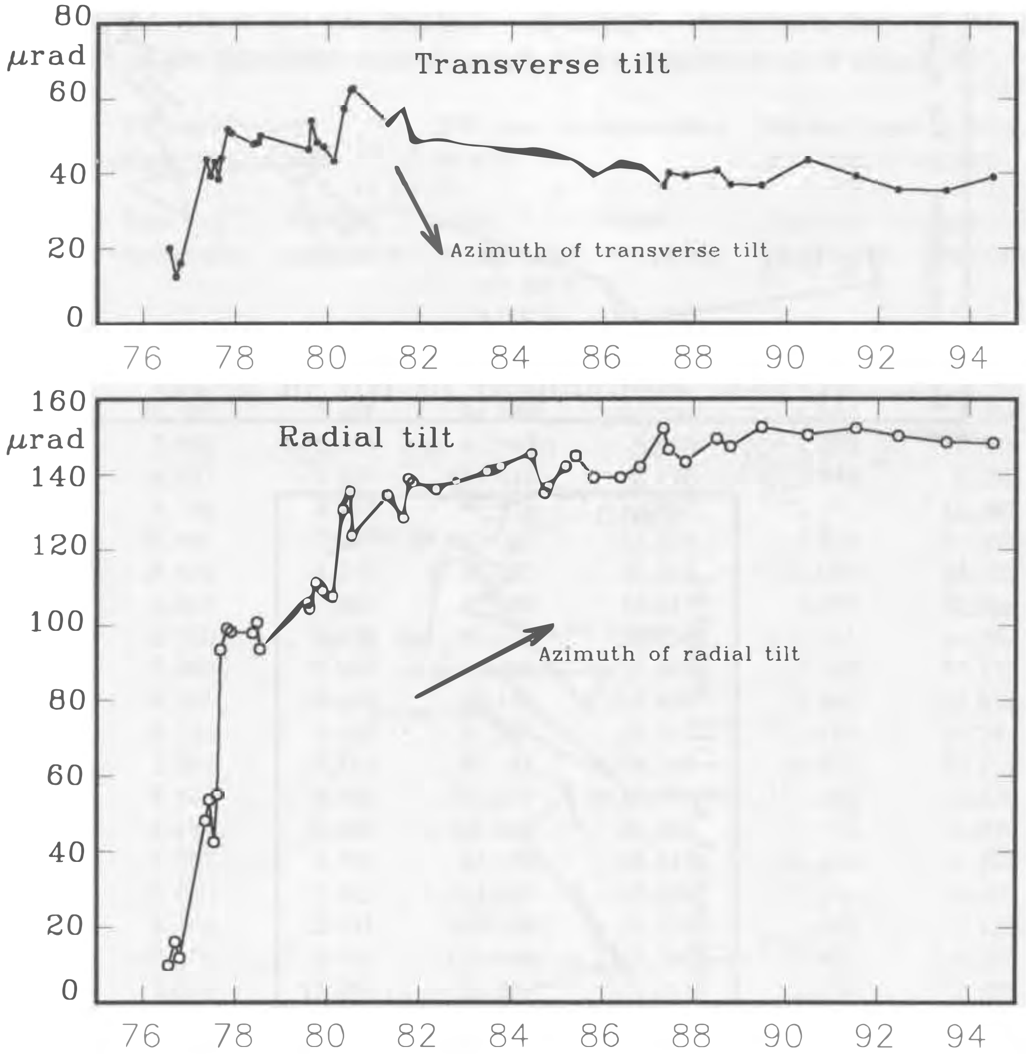


Fig. D5. Observed radial and transverse ground tilt at the tilt station Mývatn-N (0020). The radial azimuth is taken as 62.0°, the average azimuth of downward tilt during the two events of July 1980 and September 1984 (Table D1). Azimuth to the accepted center of subsidence at Krafla is about 48°, suggesting that azimuth of ground tilt deviates about 14° from theoretical tilt as predicted by the Mogi model. Downward transverse tilt from 1980 to 1994 suggest subsidence towards the Krafla fissure swarm. This reduces the tilt caused by uplift of the west flank of the fissure swarm during three rifting events of 1977 to 1980.

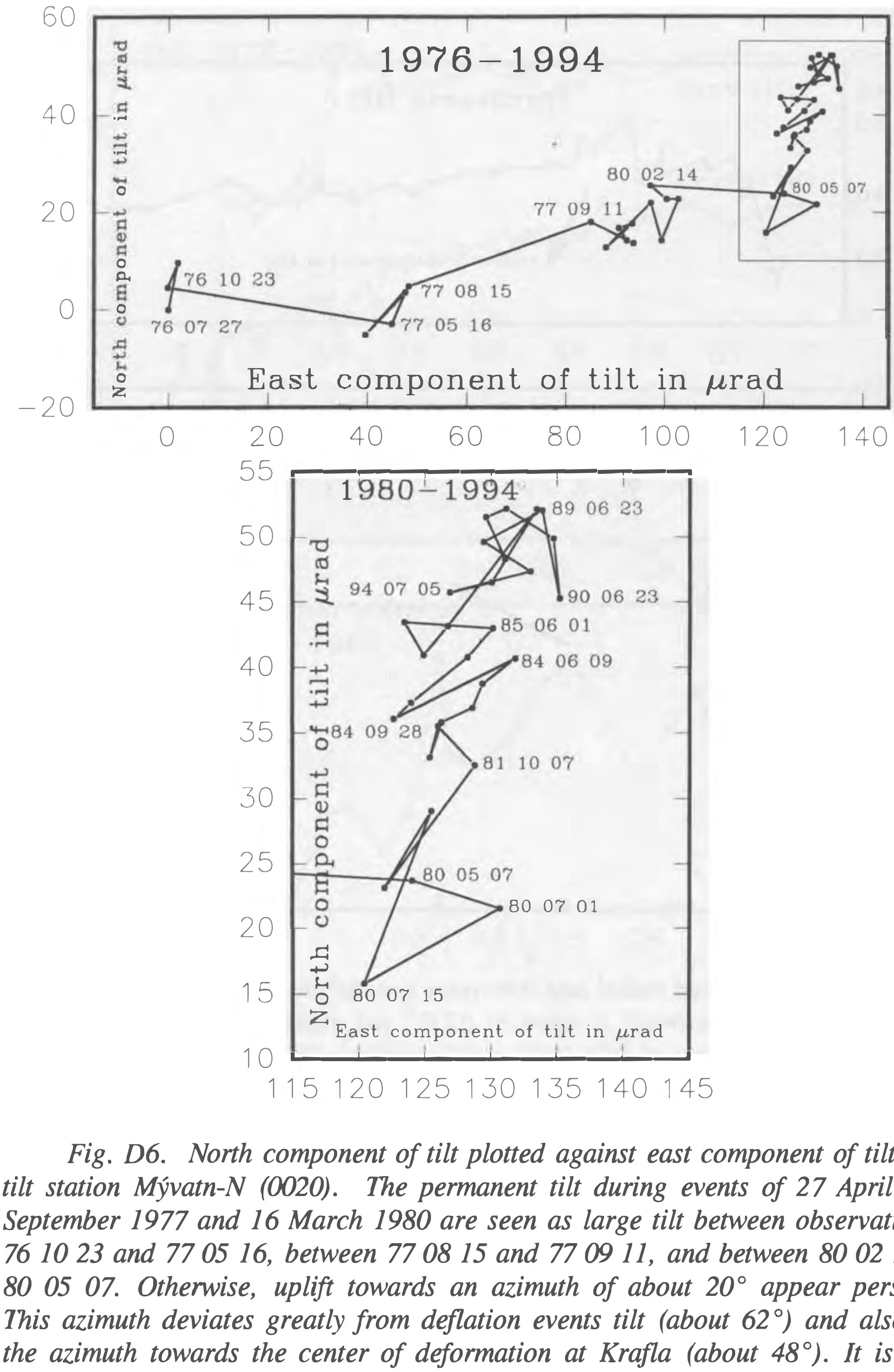


Fig. D6. North component of tilt plotted against east component of tilt at the tilt station Mývatn-N (0020). The permanent tilt during events of 27 April 1977, September 1977 and 16 March 1980 are seen as large tilt between observations of 76 10 23 and 77 05 16, between 77 08 15 and 77 09 11, and between 80 02 14 and 80 05 07. Otherwise, uplift towards an azimuth of about 20° appear persistent. This azimuth deviates greatly from deflation events tilt (about 62°) and also from the azimuth towards the center of deformation at Krafla (about 48°). It is worth noting that this persistent tilt has the same azimuth at the two stations, Námaskarð (Fig. A6) and Mývatn-N, although the tilt azimuth during subsidence events differ by about 53° at these two stations.

Table D2

Observed tilt at tilt station 0020, Mývatn-N. Minimum axis of the error ellipse is 78 of the maximum axis. Azimuth of the maximum error axis is 20°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since pre observation	Since first observation
76 07 27			0.000	0.000		
76 09 17	2.034	9.628	2.034	9.628	2.686	2.686
76 10 23	-2.065	-5.111	-0.030	4.517	4.978	3.352
77 05 16	44.929	-7.468	44.899	-2.951	8.905	5.594
77 06 16	2.750	6.451	47.649	3.499	3.059	7.385
77 07 20	-8.037	-8.655	39.612	-5.156	2.544	8.252
77 08 15	8.758	9.957	48.371	4.801	2.171	10.387
77 09 11	36.697	13.085	85.067	17.886	5.919	15.241
77 10 29	8.630	-4.270	93.697	13.616	0.061	15.281
77 12 02	-1.317	0..601	92.380	14.217	2.625	12.688
78 05 20	-1.580	2.438	90.800	16.656	1.951	14.264
78 06 28	2.680	0.909	93.480	17.565	3.119	17.321
78 07 19	-5.361	-4.909	88.118	12.656	2.444	14.878
79 08 01	9.152	9.109	97.271	21.764	1.119	13.791
79 08 22	2.047	-7.517	99.318	14.248	0.563	13.412
79 10 03	3.513	8.286	102.831	22.534	1.089	13.695
79 11 24	-2.490	0.068	100.341	22.602	1.736	11.979
80 02 14	-3.283	2.709	97.059	25.311	0.450	12.277
80 05 07	26.987	-1.612	124.045	23.699	2.814	10.679
80 07 01	6.653	-2.141	130.698	21.558	2.685	13.188
80 07 15	-10.255	-5.768	120.444	15.790	3.605	9.587
81 04 25	5.058	13.260	125.501	29.051	2.208	7.588
81 08 29	-3.536	-5.899	121.965	23.152	2.084	9.048
81 10 07	6.810	9.397	128.774	32.548	2.787	8.699
81 11 09	-2.767	2.995	126.008	35.543	1.167	7.567
82 05 16	-0.649	-2.379	125.358	33.164	0.563	7.567
82 10 20	0.925	2.677	126.284	35.841	0.843	7.791
83 06 24	2.330	1.082	128.613	36.923	2.373	9.792
83 10 08	0.741	1.825	129.355	38.748	1.736	8.058
84 06 09	2.473	1.927	131.828	40.676	1.079	8.802
84 09 28	-9.162	-4.574	122.666	36.102	1.415	9.040
84 10 28	1.324	1.195	123.990	37.296	1.349	7.775
85 03 12	4.249	3.449	128.239	40.745	1.980	7.734
85 06 01	1.907	2.237	130.146	42.982	3.492	9.934
85 10 26	-6.697	0.442	123.450	43.424	2.629	8.090
86 05 23	1.443	-2.516	124.893	40.909	2.394	7.361
86 10 24	1.847	2.214	126.740	43.122	0.856	8.057
87 04 30	6.711	8.981	133.451	52.104	0.682	8.045
87 06 12	-3.387	-5.601	130.064	46.503	1.038	8.130
87 10 24	-3.166	-0.772	126.898	45.731	1.776	6.887
88 06 27	6.100	1.630	132.998	47.361	1.319	8.205
88 10 14	-3.005	-2.375	129.992	44.986	2.240	6.103
88 10 17	-0.546	4.613	129.447	49.599	0.753	6.517
89 06 23	4.437	2.440	133.883	52.039	0.855	7.115
90 06 23	1.310	-6.774	135.193	45.265	0.702	7.239

91 07 11	-0.462	4.576	134.731	49.841	0.963	6.945
92 06 13	-3.560	2.304	131.171	52.145	0.540	7.030
93 06 30	-1.533	-0.625	129.638	51.519	0.879	6.389
94 07 05	1.423	-3.253	131.061	48.266	1.667	7.640

Table D3

Marker coordinates and observed marker elevation at tilt station 0020 (Mývatn-N), relative to the average value of all five markers at the tilt station.

Marker	0021	0022	0023	0024	0025
Marker coordinates in meters, surveyed 81 08 29					
East	-26.48	3.14	21.59	19.21	-17.44
North	-2.99	-23.68	-8.07	14.43	20.31
Y M D	Marker elevation, centimeter				
76 07 27	-20.6331	7.7719	17.8713	2.3520	-7.3619
76 09 17	-20.6518	7.7525	17.8742	2.3588	-7.3339
76 10 23	-20.6386	7.7737	17.8490	2.3700	-7.3543
77 05 16	-20.7393	7.7695	18.0003	2.4183	-7.4489
77 06 16	-20.7577	7.7548	18.0120	2.4192	-7.4282
77 07 20	-20.7455	7.7792	18.0028	2.3835	-7.4200
77 08 15	-20.7760	7.7557	18.0235	2.4047	-7.4078
77 09 11	-20.8641	7.7112	18.1234	2.4779	-7.4486
77 10 29	-20.8854	7.7238	18.1458	2.4883	-7.4724
77 12 02	-20.8839	7.7309	18.1279	2.4966	-7.4716
78 05 20	-20.8864	7.7246	18.1294	2.4884	-7.4559
78 06 29	-20.8922	7.7130	18.1517	2.4827	-7.4550
78 07 19	-20.8755	7.7293	18.1310	2.4758	-7.4607
79 08 01	-20.9009	7.7126	18.1379	2.5116	-7.4614
79 08 22	-20.9059	7.7336	18.1458	2.5056	-7.4792
79 10 03	-20.9127	7.7106	18.1496	2.5251	-7.4724
79 11 24	-20.9073	7.7155	18.1345	2.5270	-7.4698
80 02 14	-20.9011	7.7084	18.1264	2.5227	-7.4566
80 05 07	-20.9614	7.7180	18.1790	2.5838	-7.5195
80 07 01	-20.9816	7.7199	18.2086	2.5814	-7.5281
80 07 15	-20.9533	7.7413	18.1713	2.5680	-7.5275
81 04 25	-20.9674	7.7155	18.1608	2.6070	-7.5157
81 08 29	-20.9476	7.7191	18.1651	2.5913	-7.5279
81 10 07	-20.9816	7.7078	18.1708	2.6113	-7.5082
81 11 09	-20.9767	7.7043	18.1560	2.6143	-7.4977
82 05 16	-20.9716	7.7079	18.1569	2.6109	-7.5039
82 10 20	-20.9787	7.7038	18.1573	2.6138	-7.4962
83 06 24	-20.9785	7.6915	18.1733	2.6148	-7.5010
83 10 09	-20.9819	7.6931	18.1638	2.6256	-7.5007
84 06 09	-20.9924	7.6893	18.1713	2.6283	-7.4967
84 09 28	-20.9600	7.6923	18.1570	2.6068	-7.4960
84 10 28	-20.9671	7.6957	18.1519	2.6145	-7.4948
85 03 12	-20.9704	7.6841	18.1570	2.6339	-7.5044
85 06 01	-20.9862	7.6783	18.1723	2.6249	-7.4895
85 10 26	-20.9774	7.6871	18.1456	2.6166	-7.4718

86 05 23	-20.9698	7.6881	18.1486	2.6236	-7.4906
86 10 24	-20.9723	7.6796	18.1546	2.6293	-7.4911
87 04 30	-20.9960	7.6623	18.1618	2.6532	-7.4815
87 06 12	-20.9804	7.6715	18.1593	2.6414	-7.4916
87 10 24	-20.9789	7.6803	18.1464	2.6351	-7.4827
88 06 27	-20.9951	7.6741	18.1655	2.6439	-7.4883
88 10 14	-20.9845	7.6838	18.1493	2.6446	-7.4934
88 10 17	-20.9870	7.6731	18.1467	2.6470	-7.4798
89 06 23	-20.9961	7.6649	18.1577	2.6585	-7.4848
90 06 23	-21.0007	7.6829	18.1666	2.6489	-7.4976
91 07 11	-21.0053	7.6758	18.1596	2.6537	-7.4839
92 06 13	-20.9940	7.6672	18.1510	2.6510	-7.4752
93 06 30	-20.9873	7.6685	18.1449	2.6511	-7.4772
94 07 05	-20.9949	7.6762	18.1568	2.6416	-7.4797

TILT STATION 0030, MÝVATN-E

This station was established and measured for the first time on 27 July 1976. It consists of 5 bench marks in a T-shaped array (Fig. E1) on pahoehoe lava of unknown age, immediately west of Grjótagjá, the principal fault on the west side of the Krafla fissure swarm, and immediately south of the highway from Reykjahlíð towards east. The relative elevation of all five markers of this station was obtained only once, on 27 July 1976, but relative elevation of four of the markers was obtained during 5 additional measurements in 1976 and 1977 (Table E1).

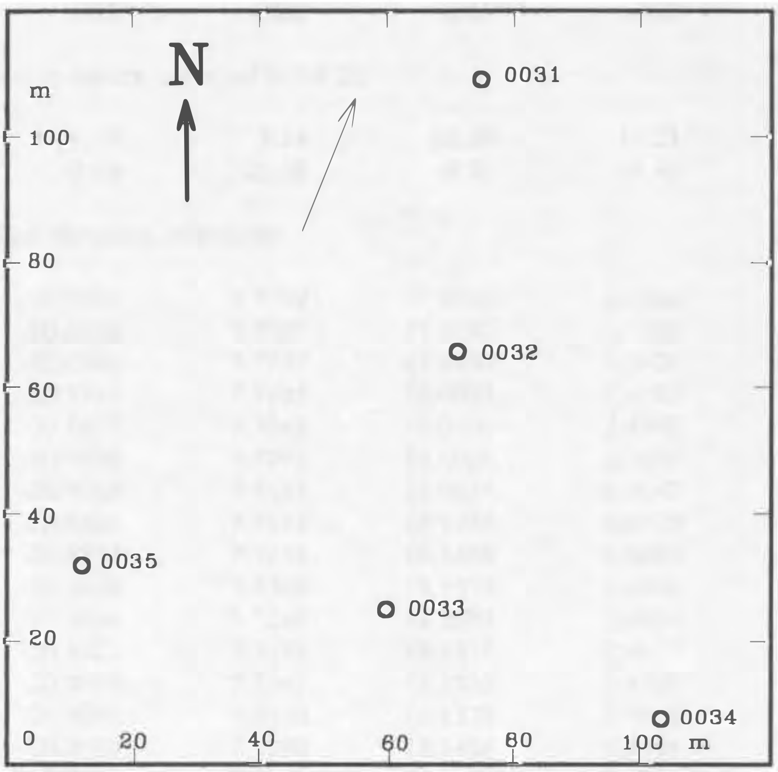


Fig. E1. Map of relative position of markers at the tilt station Mývatn-E, also named tilt station 0030. The markers (open circles) consist of copper alloy nails with 37 mm diameter convex top plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Thin arrow gives the approximate direction to the center of deformation of Krafla volcano.

Levelling from 0033 to 0035 required a temporary marker (frog) resulting in lower accuracy of the relative elevation of 0035. Therefore, and also because of the time it took to make the levelling, marker 0035 was not measured after the initial levelling. Levelling of 23 October 1976 was aborted because of adverse weather condition. Observed elevation of marker 0034 on 17 August 1977 appear to be in error.

Table E1

Marker coordinates relative to marker 0033 and observed marker elevation relative to marker 0031 at the tilt station 0030 (Mývatn-N).

Marker	0031	0032	0033	0034	0035
Marker coordinates in meters surveyed 76 07 27					
East	14.96	11.22	0.00	43.31	-47.69
North	84.10	40.69	0.00	-17.63	6.97
Y M D	Marker elevation, centimeter				
76 07 27	0.0000	53.8720	117.0040	277.0128	-240.0910
76 09 19	0.0000	53.8408	116.9448	276.9430	
76 10 23	0.0000	53.8530			
77 05 20	0.0000	53.9905	117.4065	277.6325	
77 06 17	0.0000	53.9512	117.3520	277.5567	
77 08 17	0.0000	53.8875	117.2723	277.9598	
77 09 12	0.0000	53.6290	116.6260	277.3868	

Table E2

Observed ground tilt at tilt station 0030, Mývatn-E, based on levelling of the four markers 0031, 0032, 0033, and 0034. Azimuth of the maximum axis of the error ellipse is about 80°. The minimum error ellipse axis is 37% of the maximum axis.

	Tilt since previous observation in µrad		Tilt since first observation in µrad		Standard error of tilt in µrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
76 07 27			0.000	0.000		
76 09 19	0.427	6.957	0.427	6.957	0.114	0.114
77 05 20	32.840	-61.483	33.267	-54.525	14.223	14.337
77 06 17	-1.647	6.697	31.620	-47.829	1.470	15.807
77 08 17	110.579	-10.679	142.199	-58.508	9.314	25.121
77 09 12	42.298	69.750	184.497	11.242	8.148	16.973

The rifting events of April 27 and September 8, 1977 caused great fault displacements east of this station. The Grjótagjá fault, 10 to 50 m east of this tilt station was displaced in both these events, its east side subsided relative to its west side. The tilt of 70 μrad, up towards an azimuth of 152° (SSE) between observations of 76 09 19 and 77 05 20 (Table E2) is believed to have occurred during the event of April 27, 1977. The rifting event of 8 September 1977 also caused large tilt at this station, but last observation before that event is not trustworthy. Ground tilt from 77 06 17 to 77 09 12 of 164 μrad up towards an azimuth of 69° may be taken as the tilt caused by the rifting event of September 8 1977.

The dubious observation of 77 08 17 and the difficulty of making good tilt observations at this station, caused it to be abandoned after the observation of 12 September 1977. At that time another station (Tilt station 0060, Grjótagjá N) had been constructed a short distance to the south of station 0030. Station 0060 was considered much more reliable than station 0030, and also tilt observations at station 0060 were easier and less time consuming than observations at station 0030.

TILT STATION 0040, JÖRUNDUR

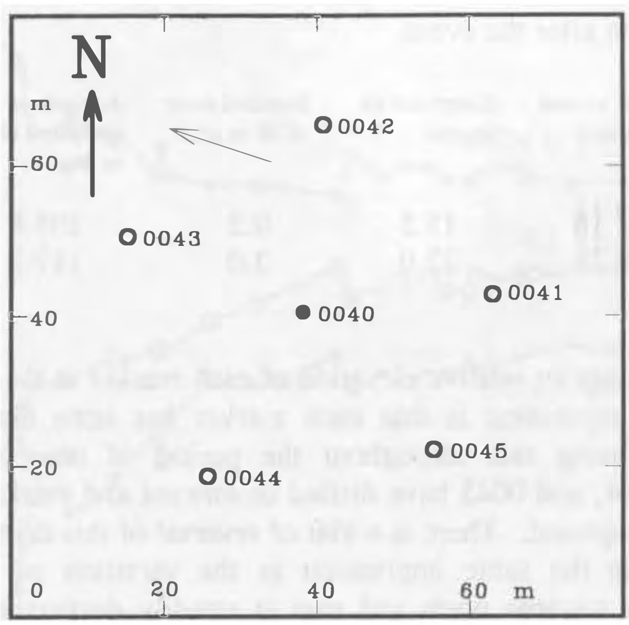


Fig. F1. Map of relative position of markers at the tilt station Jörundur, also named tilt station 0040. Solid circle is a marker at the center of a 25.0 m diameter circle defined by 5 markers (open circles). The markers consist of copper alloy nails with 37 mm diameter convex top plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Thin arrow gives the average direction of downward tilt during two well recorded deflations of the Krafla volcano, taken as the direction to the center of deformation.

This station lies on a pahoehoe lava of unknown age, pre-historic but post-glacial. It was constructed on July 27, 1976 immediately to the west of an old track from highway 1 about 4 km east of Námaskarð towards Hrafntinnuhryggur. The station location is on Jörundargrjót, about 4 km north of highway 1 and about 0.5 km south-west of the mountain Jörundur. It was observed 34 times from July 1976 to July 1994. The inflation-deflation cycle of Krafla volcano is not well observed at this station, partly because of few observation, but the remoteness of the station caused it to be observed less frequently than the more accessible stations.

Observation was made few days before the subsidence event of July 10, 1980, and also immediately after that event. In 1984 observation was made in early June, and again in late September, immediately after the eruption of September 1984. Recording tiltmeters suggested almost no deformation between the June observation and the eruption, therefore the tilt between early June and late September 1984 is taken as the tilt caused by deflation of Krafla volcano during that eruption. These are the only observations which determine the tilt at the Jörundur station during deflations of Krafla (Table F1).

Table F1

Observed tilt at the tilt station Jörundur during two rifting and subsidence events of Krafla volcano. Tilt is computed from last observation before the events and first observation after the event.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of rifting event
80 07 01	80 07 18	18.5	0.5	103.8	80 07 10
84 06 09	84 09 28	22.0	3.0	117.2	84 09 04

When the change in relative elevation of each marker at the tilt station 0040 is viewed, the first impression is that each marker has been drifting in the same direction at decreasing rate throughout the period of observations (Fig. F2). Markers 0041, 0044, and 0045 have drifted downward and markers 0042 and 0043 have been drifting upward. There is a hint of reversal of this drift after 1989.

The tilt gives the same impression as the variation of marker elevation. Progressing tilt up towards north and east at steadily decreasing rate is apparent (Fig. F3). The east component of tilt shows reversal in tilt direction after 1989 Fig. F3 bottom). It is of interest to note that both transverse and radial tilt (Fig. F4) give similar impression. The transverse tilt suggest uplift at decreasing rate in northerly direction, possibly because of inflation of the area of main lava production 5 to 10 km north of the center of deformation at Krafla. This component shows no reversal after 1989. The radial tilt shows uplift at decreasing rate in direction to the center of deformation with clear reversal (subsidence) after 1989. In general, the observed tilt was up towards north-west at decreasing rate from 1976 to 1989 (Fig. F5). It amounts to about 160 μrad. After 1989 a very slow tilt up towards east is observed (Fig. F5 bottom), amounting to about 10 μrad in 5 years.

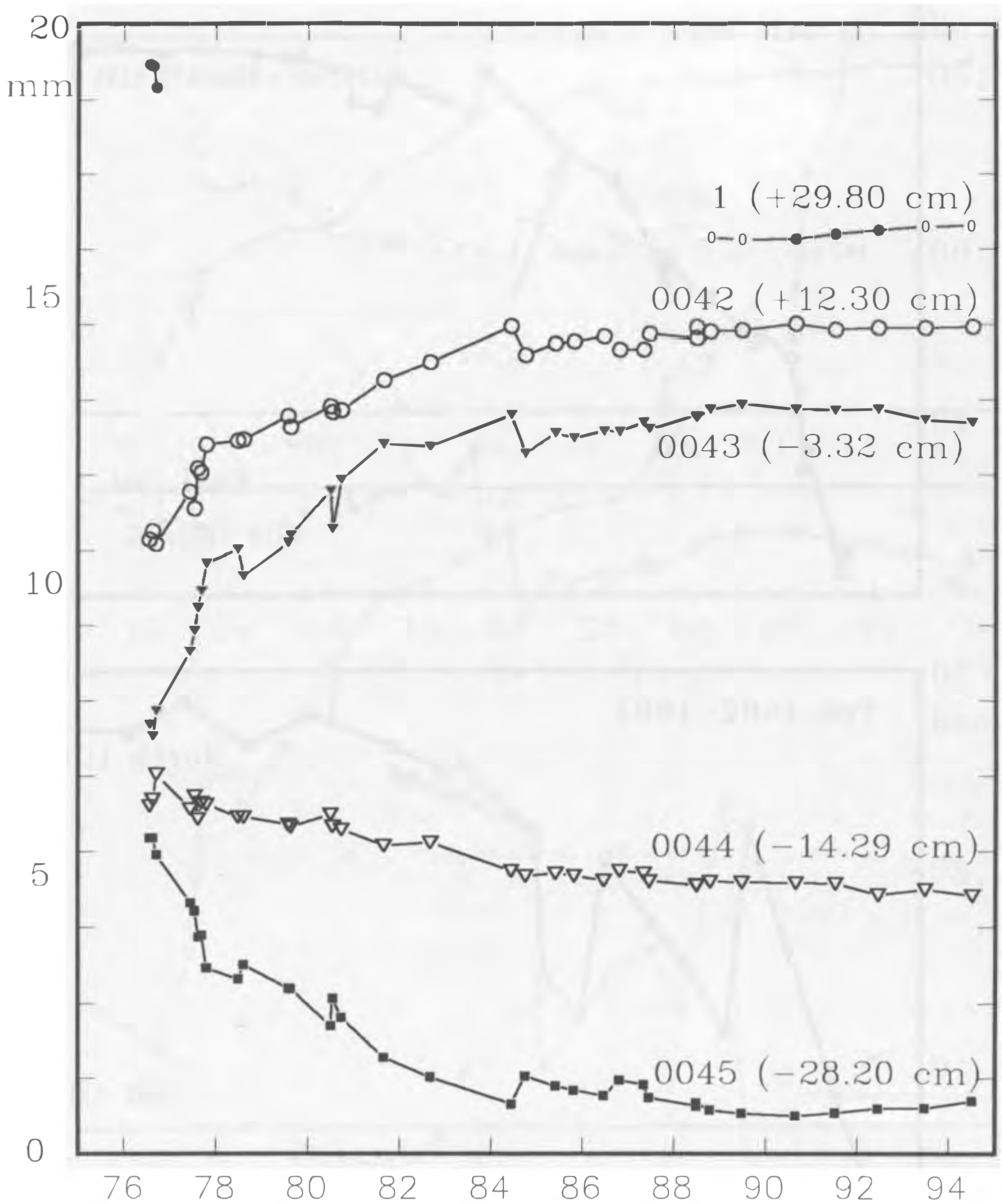


Fig. F2. Variation with time of relative elevation of each marker of the tilt station Jörundur. Horizontal scale is time in years. Vertical scale is in millimeter. Reference elevation is the average elevation of all five markers of the tilt station. Relative elevation of each marker is found by adding to the left scale values, constants presented in parenthesis besides the marker identification.

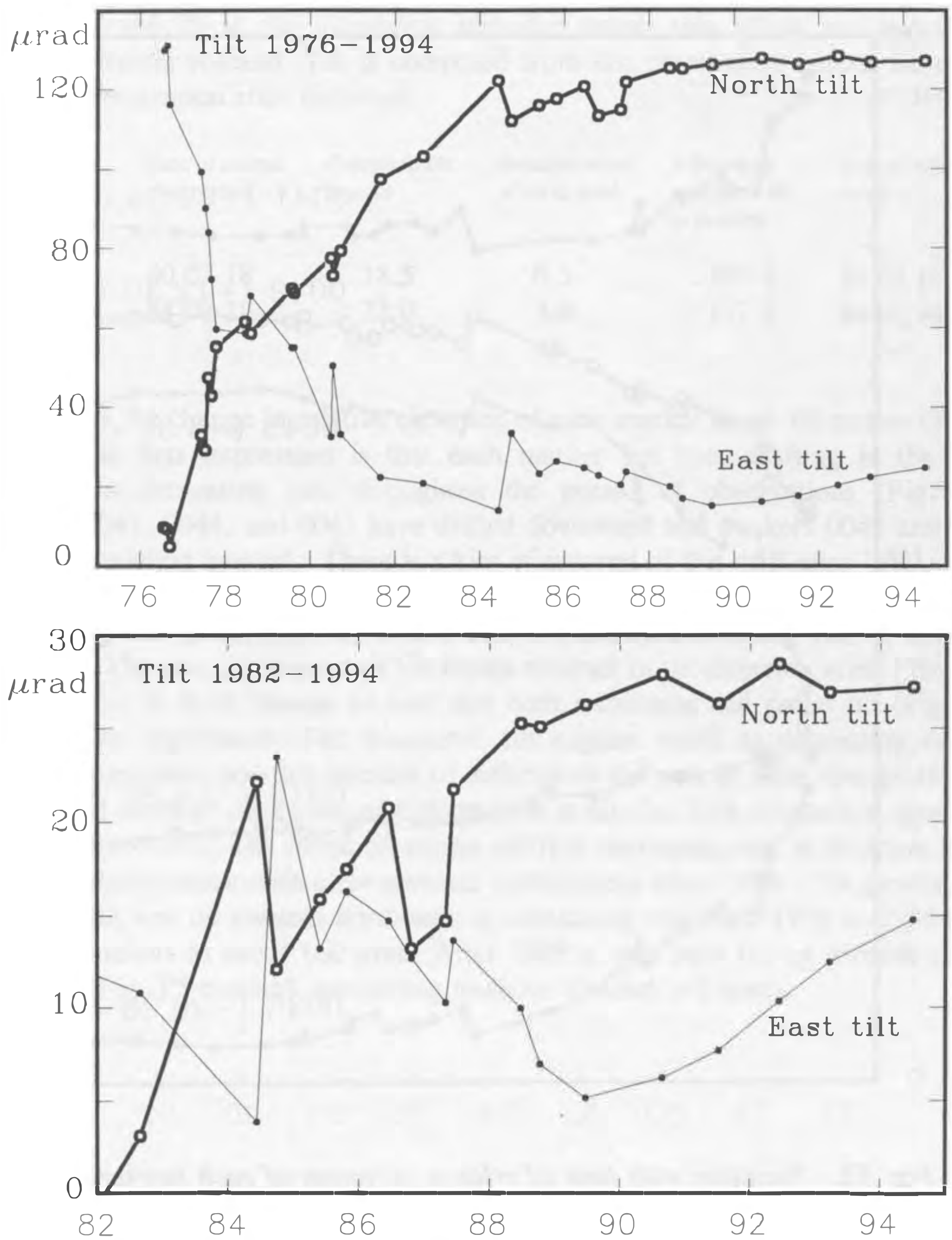


Fig. F3. Observed tilt of the ground at the tilt station Jörundur from date of first observation of 27 July 1976 to 1994. East component of tilt (filled circles) is positive if the east side of the tilt station is rising relative to its west side. North component of tilt (open circles) is positive if north side of the tilt station is rising relative to the south side. The top diagram presents tilt during the whole period of observation, 1976-1994, showing relatively large tilt up towards north-west during the years 1976 to 1981. Bottom diagram shows tilt variations from 1982 to 1994, during period of relatively gentle tilt. Unexplained tilt variations occurred in 1986-1987 (bottom graph) with southward tilt of 7 µrad between June and October 1986 followed by similar northward tilt between May and June 1987.

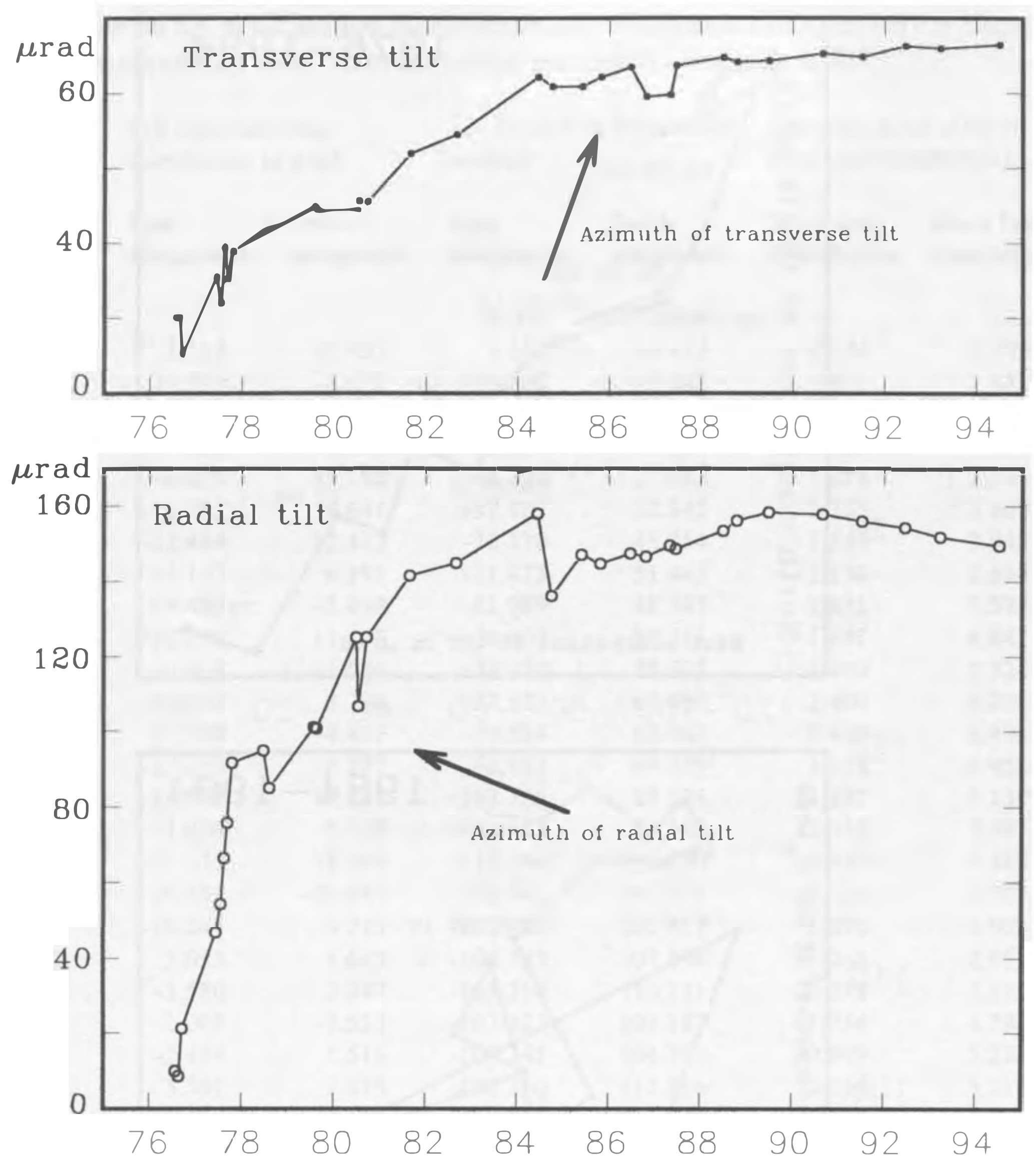


Fig. F4. Observed transverse tilt (top) and radial tilt (bottom) at the tilt station Jörundur, relative to the center of deformation of Krafla volcano. The azimuth of radial tilt is taken as 290.5, the average azimuth of downward tilt during the subsidence events of July 1980 and September 1984. Positive transverse tilt is up toward an azimuth of 20.5 and positive radial tilt is up toward an azimuth of 290.5. The unexplained tilt variations in 1986-1987 (Fig. F3) is purely transverse. Reversal of tilt after 1989 is only seen on the radial component.

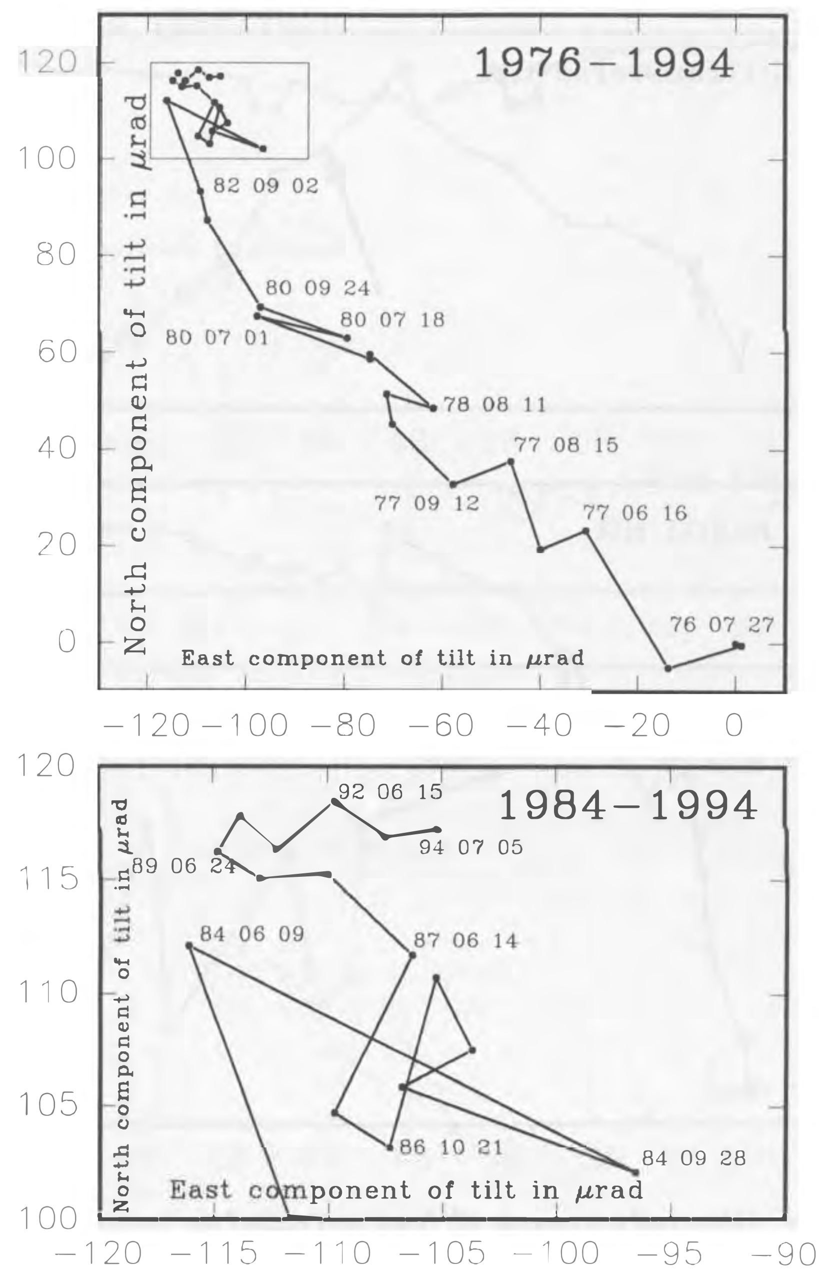


Fig. F5. North component of tilt plotted against east component at the tilt station Jörundur. Upper diagram presents all tilt observations from 1976 to 1994 and the lower graph shows observations of 1984 to 1994 (rectangle in upper graph) in expanded tilt scale. From 1976 to 1980 the general azimuth of tilt is about 311° changing to about 335° from 1980 to 1984, and to about 85° from 1989 to 1994.

Table F2

Observed tilt at tilt station 0040, Jörundur. Minimum axis of the error ellipse is 91% of the maximum axis. Azimuth of the maximum error axis is 40°.

	Tilt since previous observation in µrad		Tilt since first observation in µrad		Standard error of tilt in µrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
76 07 27			0.000	0.000		
76 08 20	1.187	-0.457	1.187	-0.457	2.399	2.399
76 09 19	-14.990	-4.551	-13.803	-5.008	1.425	2.435
77 06 16	-16.900	28.189	-30.704	23.181	2.383	1.218
77 07 19	-9.329	-3.889	-40.033	19.291	2.238	1.066
77 08 15	-6.070	18.192	-46.103	37.483	1.811	1.241
77 09 12	-11.783	-4.641	-57.887	32.842	2.255	3.467
77 10 21	-12.484	12.412	-70.370	45.254	1.540	3.948
78 06 28	-1.103	6.191	-71.473	51.445	2.136	2.634
78 08 11	9.485	-2.898	-61.989	48.547	1.851	3.377
79 08 01	-12.918	11.165	-74.907	59.711	1.641	4.841
79 08 19	-0.064	-1.036	-74.970	58.675	2.410	3.524
80 07 01	-22.553	8.794	-97.523	67.469	1.400	4.083
80 07 18	17.940	-4.407	-79.584	63.062	0.469	4.496
80 09 24	-17.299	6.277	-96.883	69.339	3.418	5.952
81 08 27	-10.842	17.887	-107.725	87.226	1.192	5.139
82 09 02	-1.459	5.938	-109.183	93.164	3.019	2.895
84 06 09	-6.911	18.966	-116.094	112.130	1.529	4.288
84 09 28	19.552	-10.055	-96.542	102.075	3.021	3.057
85 05 29	-10.247	3.775	-106.789	105.851	1.890	4.065
85 10 23	3.055	1.643	-103.733	107.494	1.266	2.953
86 06 18	-1.580	3.247	-105.314	110.741	0.274	3.175
86 10 21	-2.008	-7.553	-107.322	103.187	1.754	4.794
87 05 02	-2.419	1.516	-109.741	104.703	0.849	5.224
87 06 14	3.391	7.013	-106.350	111.716	2.016	3.215
88 06 26	-2.454	2.131	-108.804	113.847	2.127	4.099
88 06 27	-1.229	1.396	-110.034	115.242	2.390	4.116
88 10 13	-3.057	-0.211	-113.090	115.031	1.242	3.789
89 06 24	-1.773	1.197	-114.864	116.228	0.341	4.052
90 08 28	1.076	1.597	-113.788	117.825	1.044	3.178
91 07 10	1.469	-1.503	-112.318	116.322	0.859	3.568
92 06 15	2.641	2.133	-109.678	118.455	1.185	4.746
93 06 24	2.162	-1.538	-107.516	116.917	1.350	3.396
94 07 05	2.302	0.294	-105.214	117.211	1.089	4.299

Table F3

Marker coordinates and observed marker elevation at the tilt station 0040 (Jörundur), relative to the average value of all five markers at the tilt station.

Marker	0041	0042	0043	0044	0045
Marker coordinates in meters, surveyed 81 08 27					
East	23.00	0.71	-24.73	-14.29	15.32
North	2.92	25.35	10.62	-21.22	-17.67
Y M D	Marker elevation, centimeter				
76 07 27	31.2467	13.1158	-2.7511	-13.8294	-27.7821
76 08 20	31.2437	13.1262	-2.7666	-13.8208	-27.7824
76 09 19	31.2158	13.1092	-2.7331	-13.7872	-27.8046
77 06 16	31.1768	13.1784	-2.6549	-13.8332	-27.8669
77 07 19	31.1642	13.1565	-2.6265	-13.8162	-27.8778
77 08 15	31.1454	13.2096	-2.5964	-13.8469	-27.9119
77 09 12	31.1046	13.2036	-2.5736	-13.8246	-27.9099
77 10 21	31.0760	13.2414	-2.5374	-13.8271	-27.9531
78 06 28	31.0839	13.2461	-2.5184	-13.8441	-27.9676
78 08 11	31.0996	13.2486	-2.5541	-13.8449	-27.9491
79 08 01	31.0647	13.2791	-2.5096	-13.8549	-27.9794
79 08 19	31.0744	13.2642	-2.4998	-13.8583	-27.9803
80 07 01	31.0196	13.2920	-2.4412	-13.8410	-28.0295
80 07 18	31.0571	13.2843	-2.4917	-13.8570	-27.9927
80 09 24	31.0196	13.2866	-2.4257	-13.8617	-28.0187
81 08 27	31.0066	13.3268	-2.3779	-13.8829	-28.0724
82 09 02	31.0077	13.3505	-2.3815	-13.8788	-28.0978
84 06 09	30.9920	13.3974	-2.3401	-13.9158	-28.1333
84 09 30	31.0505	13.3599	-2.3908	-13.9228	-28.0966
85 05 29	31.0174	13.3751	-2.3639	-13.9189	-28.1098
85 10 23	31.0313	13.3773	-2.3705	-13.9229	-28.1152
86 06 18	31.0288	13.3843	-2.3618	-13.9288	-28.1226
86 10 21	31.0139	13.3667	-2.3624	-13.9162	-28.1022
87 05 02	31.0110	13.3663	-2.3505	-13.9191	-28.1077
87 06 14	31.0255	13.3877	-2.3589	-13.9293	-28.1252
88 06 26	31.0298	13.3821	-2.3414	-13.9349	-28.1357
88 06 27	31.0145	13.3964	-2.3439	-13.9353	-28.1318
88 10 13	31.0143	13.3904	-2.3335	-13.9302	-28.1410
89 06 24	31.0114	13.3917	-2.3261	-13.9315	-28.1454
90 08 28	31.0127	13.4004	-2.3324	-13.9320	-28.1488
91 07 10	31.0192	13.3923	-2.3338	-13.9330	-28.1448
92 06 15	31.0241	13.3951	-2.3331	-13.9470	-28.1390
93 06 24	31.0299	13.3952	-2.3461	-13.9403	-28.1387
94 07 05	31.0306	13.3967	-2.3495	-13.9484	-28.1294

TILT STATION 0050, GRJÓTAGJÁ-S

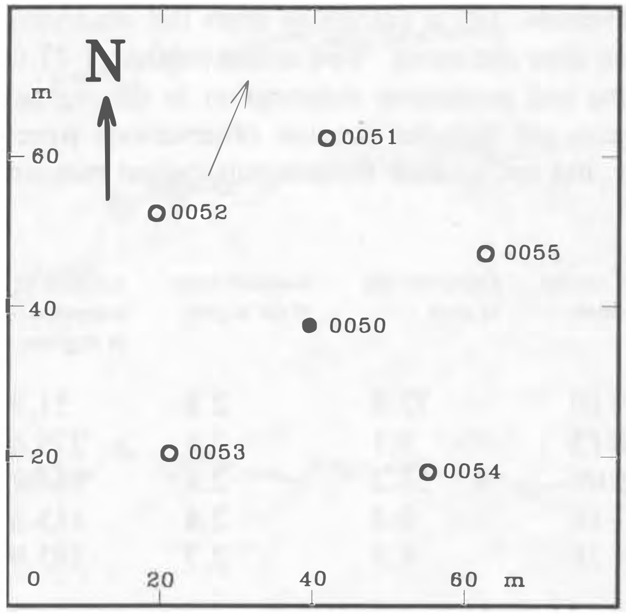


Fig. G1. Map of relative position of markers at the tilt station Grjótagjá-S, also named tilt station 0050. Solid circle is a marker at the center of a 25.0 m radius circle defined by 5 markers (open circles). The markers consist of copper alloy nails with 37 mm diameter convex top plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Trace of the Grjótagjá fault lies about 10 m east of the markers 0054 and 0055. Thin arrow gives the approximate direction to the center of deformation at Krafla.

This station, together with stations 0060, 0070, and 0200 was established shortly after the rifting event of 28 April 1977 in the area greatly affected by that event. It is located on rough pahoehoe lava on the uplifted west flank of the Grjótagjá fault, less than 50 m from the fault trace and about two km south of the main highway from Mývatn toward east Iceland. Two markers of the station (0054 and 0055) are within 10 meters of the exposed Grjótagjá fault trace (Fig. G1). The station was observed 47 times from May 1977 to July 1994. The observed ground deformation is dominated by two events, those of 8 August 1977 and 16 March 1980. The ground rifting of the event of September 8, 1977 terminated southwards near this station, possibly somewhat farther south. Markers 0051 and 0055 were uplifted more than one mm relative to average elevation of all markers of the station (Fig. G2), and marker 0053 subsided, demonstrating that the west flank of Grjótagjá fault was uplifted, also demonstrating that rifting and fault displacements extended beyond this station to the south. The event of March 16, 1980 is primarily seen as uplift of marker 0052 and subsidence of marker 0055 (Fig. G2), showing no uplift of the west flank of Grjótagjá fault, in agreement with southward termination of rifting some two km north of this station (Tryggvason 1982a).

Table G1

Observed tilt at the station Grjótagjá-S (0050) during selected rifting events of the Krafla fissure swarm. Tilt is calculated from last observation before the event and first observation after the event. Two events, those of 77 09 08 and 80 03 16 caused ground rifting and permanent deformation in the region of this tilt station, while the other events are included because observations were made short before and after the events, but not because those events caused measurable deformation at this station.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of rifting event
77 08 16	77 09 10	72.8	2.8	51.8	77 09 08
78 06 29	78 08 12	9.1	2.1	275.6	78 07 10
79 11 18	80 05 07	34.2	2.4	284.1	80 03 16
80 06 29	80 07 18	9.4	2.4	155.3	80 07 10
84 06 09	84 09 28	4.4	2.7	193.9	84 09 04

The tilt at the Grjótagjá-S tilt station is dominated by the two events of permanent deformation, those of September 8 1977 and March 16 1980 (Fig. G3 top). Additional secular tilt up towards north and west has been progressing at decreasing rate throughout the period of observation. There is indication that this progressing tilt has terminated in 1992, but a tilt reversal in 1989, as observed at all stations within about 10 km distance from the center of deformation at Krafla, is not observed at this station (Fig. G3 bottom). This secular tilt can be explained partly as caused by relaxation of the stress which was stored in the flanks of the Krafla fissure swarm during rifting and widening events, in case of this locality the events of 27 April 1977, before this station was established, and the event of September 8, 1977, and possibly the event of March 16, 1980, although no rifting occurred at the latitude of this station during this last event (Fig. G4 top). A portion of this secular tilt, the radial component (fig. G4 bottom), can be explained as caused by increased pressure at great depth below the Krafla region. Increased pressure in the 3-km depth magma chamber below Krafla can not produce as much tilt at 11 km horizontal distance, as observed at tilt station 0050, without causing tilt at stations closer to Krafla far in excess of that observed.

The plot of north versus east component of tilt (Fig. G5) shows that between the events of April 1977 and March 1980, tilt was progressing up towards an azimuth of about 300° at an average rate of 10 to 15 μrad per year and after 1980 the tilt has been progressing up towards an azimuth of about 340° at an average rate of 3 to 4 μrad per year. The tilt azimuth in 1980 - 1994 deviates about 40° anticlockwise from the direction towards the center of deformation at Krafla.

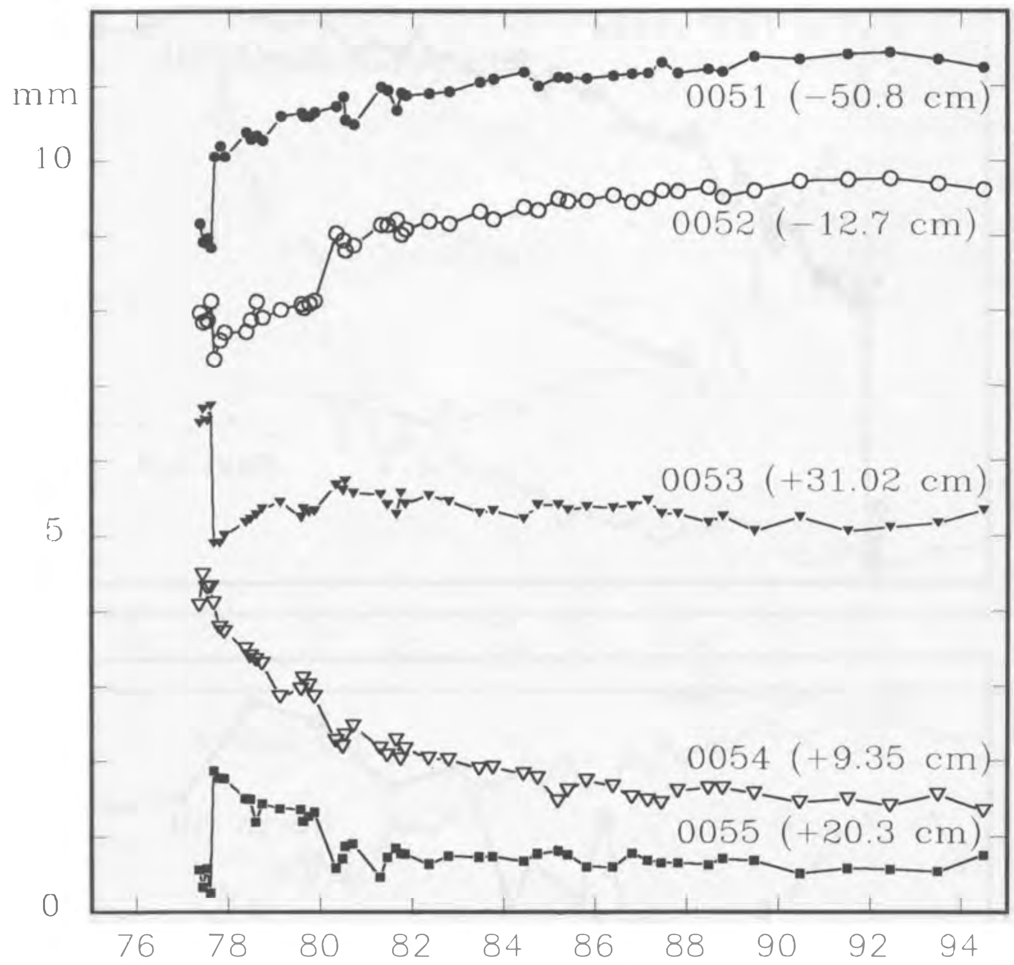


Fig. G2. Variation with time of relative elevation of each marker at tilt station Grjótagjá-S. Horizontal scale is in years and vertical scale in mm. Reference elevation is the average elevation of all five markers forming the circular array of the tilt station. Relative elevation of each marker is found by adding the left scale values to constants given in parenthesis beside the marker identification.

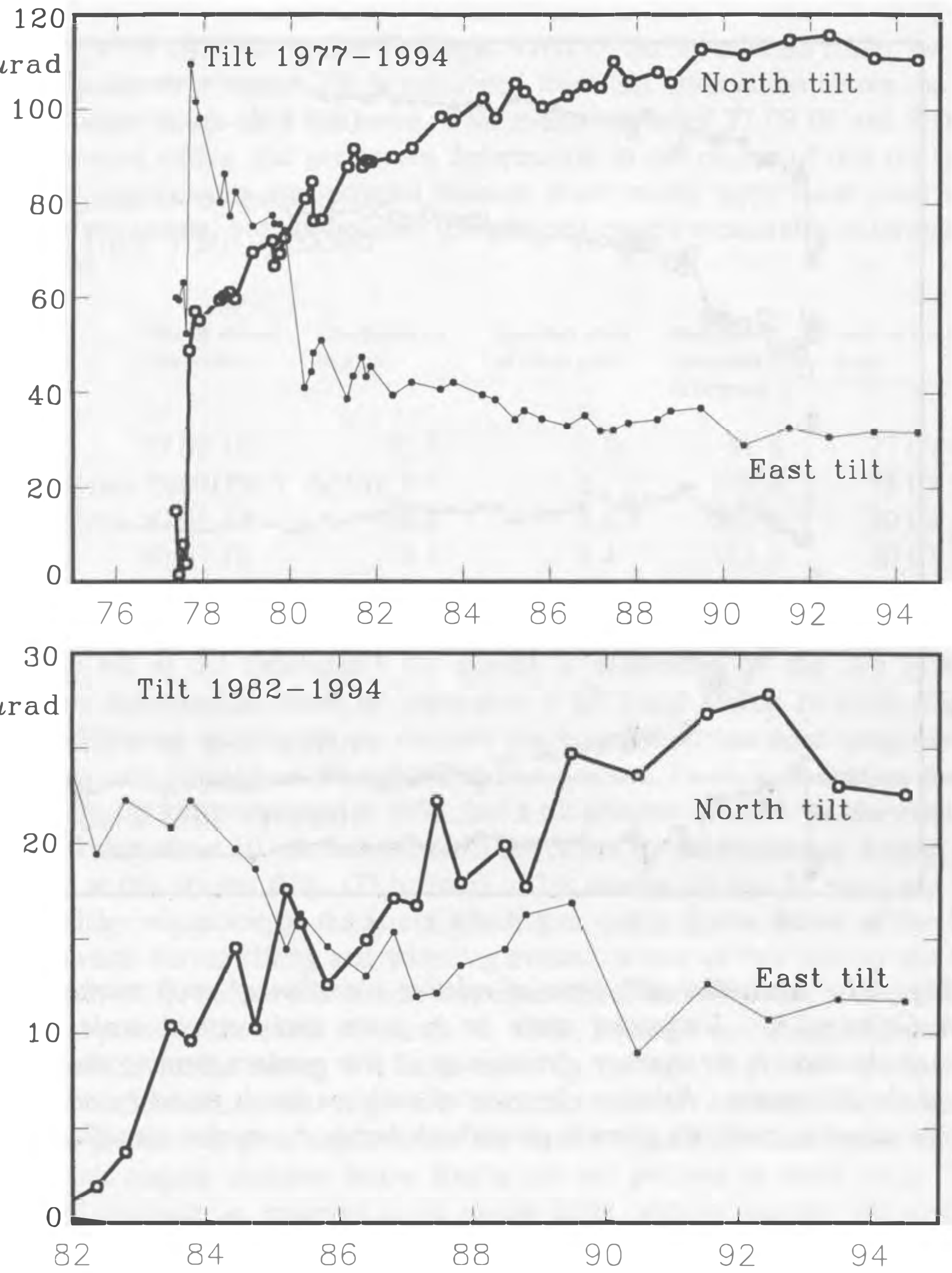
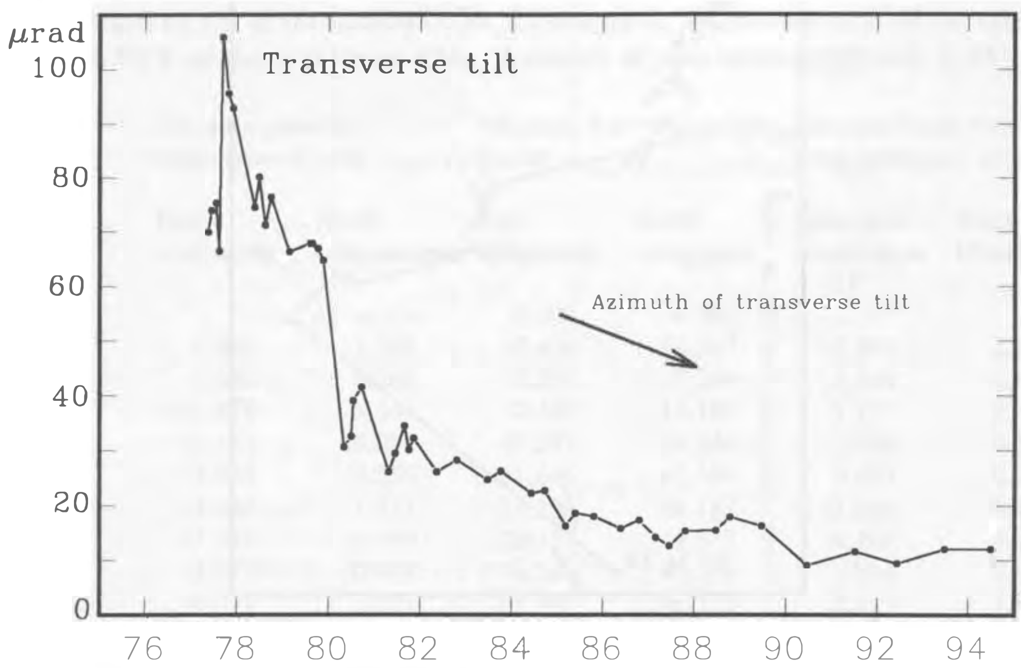


Fig. G3. Observed north and east component of tilt at the tilt station Grjótagjá-S since the first observation of 19 May, 1977. The east component (solid circles) is positive if land is rising toward east and north component (open circles) is positive if land is rising toward north. Rifting event of April 1977 is seen as large tilt up towards north and east and the rifting event of March 1980 is seen as large tilt down towards east. Bottom graph shows tilt after 1981 on expanded tilt scale, suggesting that tilt up in northerly direction continued after 1989, but a reversal is indicated in 1992. Events of July 1978, July 1980 and September 1984 (Table G!) are all hidden in noise caused by observational errors or random unexplained marker displacements.



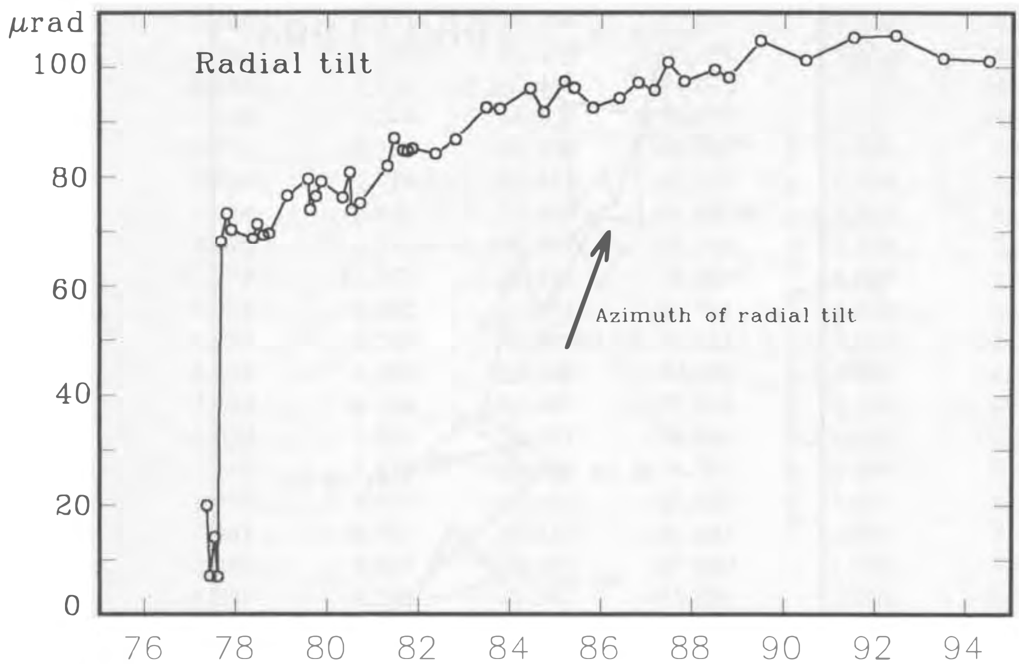
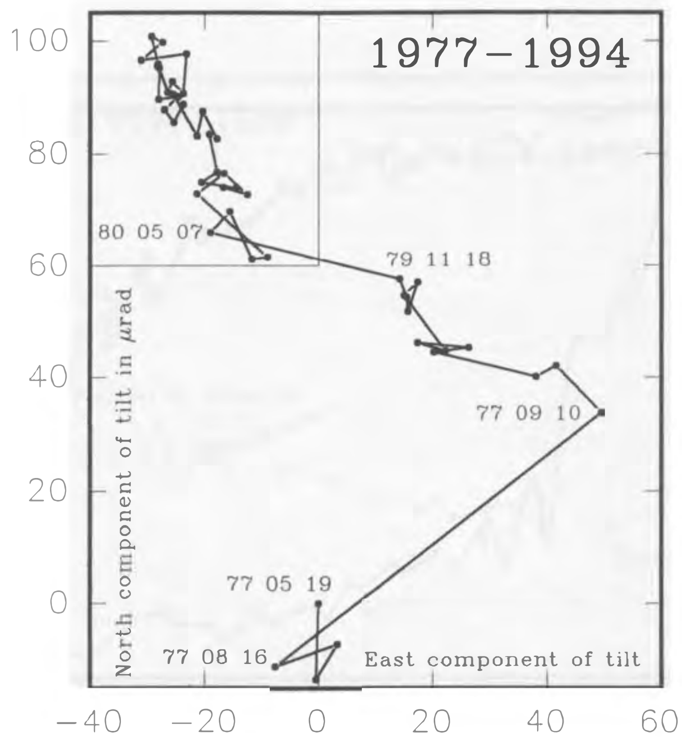


Fig. G4. Observed radial and transverse components of ground tilt at the tilt station Grjótagjá-S (0050). Positive transverse tilt is taken as tilt up toward an azimuth of 111°, and radial tilt is taken at tilt up towards 21°, the approximate direction toward the center of deformation at Krafla.



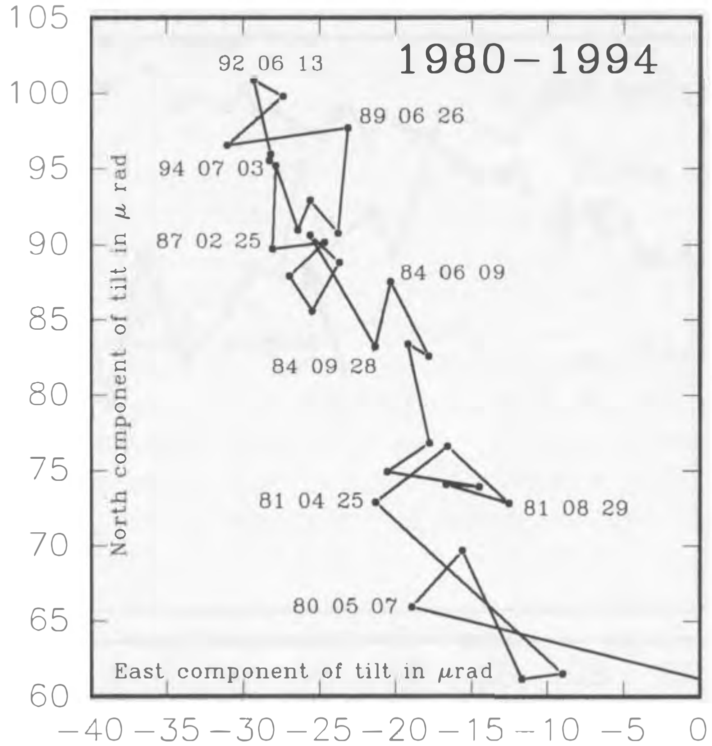


Fig. G5. North component of tilt plotted against east component of tilt at the station Grjótagjá-S (0050). Permanent displacements of September 8, 1977 and March 16 1980 are seen as large tilt between 77 08 16 and 77 09 10, and between 79 11 18 and 80 05 07 (upper graph). Progressing tilt between 77 09 10 and 79 11 18 is clearly seen on the top graph. The bottom graph shows the north versus east component of tilt from 1980 to 1994 on an expanded tilt scale (rectangle on top graph), demonstrating progressive tilt up towards an azimuth of approximately 340°.

Table G2

Observed tilt at tilt station 0050, Grjótagjá-S. Minimum axis of the error ellipse is 98% of the maximum axis. Azimuth of maximum error axis is 68°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
77 05 19			0.000	0.000		
77 06 16	-0.426	-13.507	-0.426	-13.507	2.296	2.296
77 07 18	3.680	6.263	3.253	-7.244	2.140	1.033
77 08 16	-10.819	-3.944	-7.565	-11.188	1.777	2.690
77 09 10	57.163	45.034	49.597	33.846	2.830	0.869
77 10 28	-7.952	8.255	41.646	42.100	0.605	0.495
77 12 03	-3.542	-1.917	38.104	40.183	1.640	1.278
78 05 20	-7.947	4.389	30.157	44.572	4.103	3.352
78 06 29	-3.817	0.781	26.340	45.353	1.610	2.229
78 08 12	-9.033	0.883	17.307	46.236	2.119	1.870
78 09 29	4.986	-1.413	22.294	44.823	3.116	3.209
79 02 17	-7.262	9.863	15.032	54.686	3.152	6.341
79 08 02	2.365	2.371	17.396	57.057	2.310	4.287
79 08 20	-1.763	-5.278	15.633	51.779	1.514	4.690
79 10 04	-0.186	2.597	15.448	54.376	1.050	4.190
79 11 18	-1.216	3.244	14.232	57.620	1.219	4.968
80 05 07	-33.132	8.350	-18.900	65.970	2.360	2.699
80 06 29	3.319	3.716	-15.581	69.686	1.306	3.970
80 07 18	3.914	-8.493	-11.668	61.193	2.377	4.336
80 09 21	2.670	0.353	-8.997	61.546	2.248	2.505
81 04 25	-12.275	11.353	-21.272	72.899	4.628	3.623
81 06 20	4.721	3.682	-16.551	76.581	2.421	2.280
81 08 29	4.037	-3.769	-12.514	72.812	3.613	1.655
81 10 05	-4.131	1.286	-16.646	74.098	5.281	4.285
81 11 08	2.147	-0.184	-14.499	73.914	2.260	2.072
82 05 16	-6.032	1.033	-20.531	74.947	0.437	2.508
82 10 20	2.769	1.838	-17.761	76.785	0.481	2.661
83 06 22	-1.393	6.637	-19.154	83.422	1.071	1.594
83 10 08	1.341	-0.781	-17.813	82.641	1.209	2.692
84 06 09	-2.480	4.869	-20.293	87.510	1.288	1.725
84 09 28	-1.049	-4.249	-21.342	83.261	2.744	3.007
85 03 12	-4.215	7.360	-25.557	90.621	1.626	4.570
85 05 29	1.873	-1.807	-23.684	88.814	1.623	2.990
85 10 26	-1.754	-3.226	-25.438	85.587	1.753	1.800
86 05 23	-1.516	2.327	-26.954	87.914	0.264	1.797
86 10 23	2.313	2.226	-24.641	90.141	2.542	4.189
87 02 25	-3.402	-0.404	-28.044	89.737	0.255	4.178
87 06 14	0.204	5.477	-27.840	95.214	1.610	2.760
87 10 24	1.467	-4.256	-26.373	90.957	1.304	1.584
88 06 23	0.804	1.952	-25.568	92.910	1.293	0.388
88 10 17	1.823	-2.141	-23.746	90.769	1.546	1.875
89 06 26	0.624	6.949	-23.121	97.718	1.563	1.373
90 06 23	-7.908	-1.146	-31.029	96.572	0.401	1.599
91 07 10	3.654	3.234	-27.375	99.806	1.149	1.145
92 06 13	-1.887	1.042	-29.263	100.849	0.738	1.351
93 06 28	1.099	-4.857	-28.164	95.992	0.433	1.380

94 07 03	-0.111	-0.423	-28.275	95.569	4.253	4.016

Table G3

Marker coordinates and observed marker elevation at the tilt station 0050 (Grjótagjá-S) relative to the average value of all five markers at the tilt station.

Marker	0051	0052	0053	0054	0055
Marker coordinates in meters, surveyed 81 08 29					
East	1.69	-20.59	-18.80	15.10	22.60
North	22.36	12.39	-19.62	-22.04	6.92
Y M D	Marker elevation, centimeter				
77 05 19	-49.8830	-11.9021	31.6704	9.7585	20.3564
77 06 16	-49.9076	-11.9146	31.6891	9.7991	20.3339
77 07 18	-49.9030	-11.9120	31.6740	9.7822	20.3587
77 08 16	-49.9153	-11.8870	31.6935	9.7830	20.3258
77 09 10	-49.7941	-11.9647	31.5103	9.7613	20.4873
77 10 28	-49.7791	-11.9384	31.5109	9.7282	20.4784
77 12 03	-49.7935	-11.9282	31.5213	9.7230	20.4773
78 05 20	-49.7615	-11.9280	31.5385	9.6998	20.4510
78 06 29	-49.7700	-11.9120	31.5423	9.6903	20.4498
78 08 12	-49.7655	-11.8882	31.5490	9.6855	20.4193
78 09 29	49.7713	-11.9088	31.5560	9.6802	20.4440
79 02 17	-49.7402	-11.8987	31.5650	9.6363	20.4378
79 08 02	-49.7360	-11.8912	31.5448	9.6458	20.4368
79 08 20	-49.7406	-11.8966	31.5561	9.6604	20.4206
79 10 04	-49.7406	-11.8904	31.5521	9.6511	20.4276
79 11 18	-49.7348	-11.8873	31.5534	9.6359	20.4327
80 05 07	-49.7273	-11.7968	31.5879	9.5772	20.3589
80 06 29	-49.7146	-11.8059	31.5806	9.5691	20.3709
80 07 18	-49.7451	-11.8202	31.5931	9.5851	20.3871
80 09 21	-49.7511	-11.8131	31.5769	9.5964	20.3909
81 04 25	-49.7022	-11.7859	31.5748	9.5668	20.3463
81 06 20	-49.7059	-11.7859	31.5614	9.5576	20.3729
81 08 29	-49.7323	-11.7786	31.5484	9.5776	20.3849
81 10 05	-49.7092	-11.7982	31.5768	9.5528	20.3776
81 11 08	-49.7132	-11.7920	31.5622	9.5665	20.3767
82 05 16	-49.7103	-11.7808	31.5734	9.5537	20.3639
82 10 20	-49.7076	-11.7841	31.5659	9.5517	20.3742
83 06 22	-49.6953	-11.7677	31.5503	9.5395	20.3733
83 10 08	-49.6905	-11.7782	31.5535	9.5415	20.3738
84 06 09	-49.6815	-11.7615	31.5432	9.5330	20.3675
84 09 28	-49.7005	-11.7660	31.5612	9.5277	20.3775
85 03 12	-49.6880	-11.7513	31.5612	9.4969	20.3814
85 05 29	-49.6888	-11.7539	31.5546	9.5120	20.3763
85 10 26	-49.6904	-11.7534	31.5587	9.5248	20.3603
86 05 23	-49.6869	-11.7468	31.5572	9.5165	20.3599
86 10 23	-49.6837	-11.7564	31.5598	9.5021	20.3780
87 02 25	-49.6836	-11.7508	31.5672	9.4984	20.3689
87 06 14	-49.6689	-11.7405	31.5493	9.4949	20.3654
87 10 24	-49.6832	-11.7415	31.5491	9.5105	20.3653
88 06 23	-49.6781	-11.7366	31.5378	9.5139	20.3629

88 10 17	-49.6816	-11.7493	31.5460	9.5139	20.3709
89 06 26	-49.6608	-11.7409	31.5262	9.5071	20.3685
90 06 23	-49.6645	-11.7277	31.5452	9.4957	20.3512
91 07 10	-49.6578	-11.7263	31.5264	9.4995	20.3580
92 06 13	-49.6550	-11.7243	31.5315	9.4909	20.3568
93 06 28	-49.6649	-11.7316	31.5372	9.5055	20.3538
94 07 03	-49.6759	-11.7388	31.5544	9.4848	20.3755

TILT STATION 0060, GRJÓTAGJÁ-N

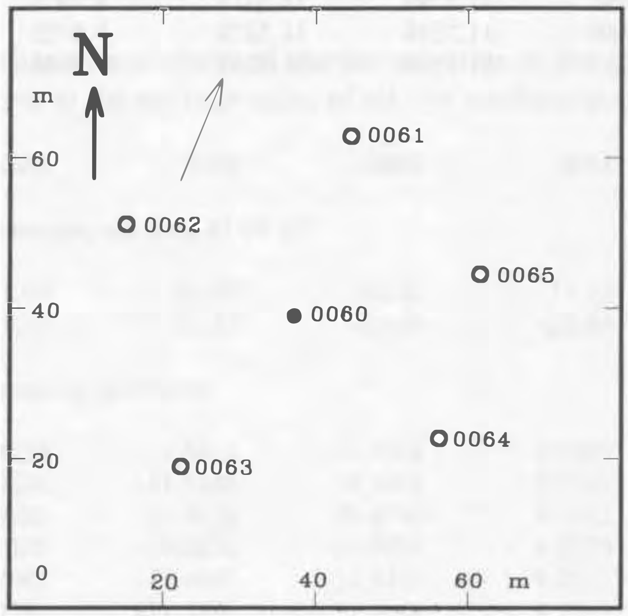


Fig. H1 Map of the relative position of markers at the tilt station Grjótagjá-N, also named tilt station 0060. Solid circle is a marker at the center of a 25.0 m radius circle defined by five markers (open circles). The markers consist of copper alloy nails with 37 mm diameter convex top plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Thin arrow shows the approximate direction to the center of deformation at Krafla.

This station lies on flat pahoehoe lava of pre-historic, but Holocene age about 100 m west of the surface trace of the Grjótagjá fault which marks the west side of the zone that widened during the rifting events of 1977. It was established and observed for the first time on May 19, 1977 about three weeks after the rifting event of 27 April, 1977, which caused large vertical displacements of the Grjótagjá fault near this station. The station consists of 5 markers in a circular pattern of 25.0 m radius around a sixth marker which serves the only purpose to mark the place where tripod should be placed during observation (Fig. H1). It was observed 48 times from May 1977 to July 1994. Relative displacement of the markers is dominated by displacements during and first after the rifting event of September 8, 1977 (Fig. H2) Marker 0063 moved downward about 2.3 mm during this event, and was uplifted about one mm during the following year. Marker 0062 was also displaced downward and markers 0061 and 0065 were displaced upward during this event. The event of March 16, 1980 is seen as upward displacement of marker 0062 and downward displacement of markers 0064 and 0065. Observation on 25 February 1977 indicated that marker 0061 had been uplifted about 0.65 mm since previous observation on 23 October 1986. This displacement was verified by measurement on February 26, 1987, but following observations showed that this marker had moved back to former position (Fig. H2). The observed tilt shows similar pattern as at station 0050 (Fig. H3). Gradual tilt following the rift event of

September 1977 is mainly down toward east, but after the March 1980 event, gradual tilt up toward north is observed in addition to tilt down toward east. Tilt event seen on the north component in early 1987 (Fig. H3 bottom) is caused by vertical displacement of one marker (Fig. H2), and not representing tilting of the ground at the site of this station.

Table H3

Observed tilt at the station Grjótagjá-N (0060) during selected rifting events of the Krafla Volcano. Tilt is calculated from last observation before the event and first observation after the event.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of rifting event
77 08 16	77 09 10	86.1	6.8	63.2	77 09 08
78 06 29	78 08 06	8.2	2.5	283.9	78 07 10
79 11 18	80 05 07	28.4	2.1	303.3	80 03 16
80 06 29	80 07 18	7.7	2.4	183.1	80 07 10
84 06 09	84 09 28	5.9	3.4	163.9	84 09 04

Transverse tilt, toward an azimuth of 111°, (Fig. H4 top) is downward throughout the whole period of observations, except for the upward tilt during the rifting event of September 1977. This downward tilt amounted to 30 to 40 μrad during the first year after the September 1977 rifting event. From 1980 to 1987 the rate of this downward transverse tilt was about 4 μrad per year, and about 2 μrad per year from 1988 to 1994. The radial tilt, up towards an azimuth of 21°, (Fig. H4 bottom) was positive from 1979 to 1990 and slightly negative after 1990. The direction of progressing tilt is clearly seen on Fig. H5 as up towards due west from September 1977 to November 1989, up towards north-west after May 1980 (Fig. H5 bottom), gradually veering in more northerly direction until 1989 when the tilt direction apparently becomes up toward west.

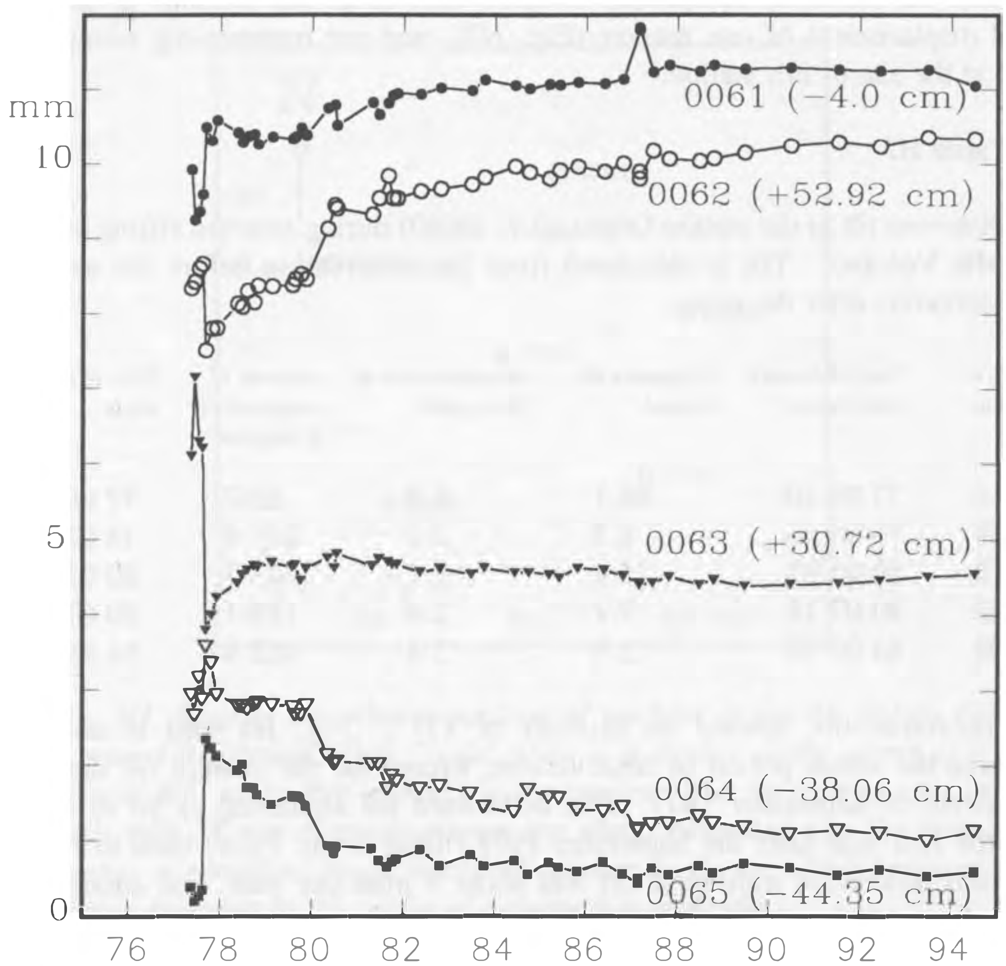


Fig. H2. Variation with time of relative elevation of markers of the tilt station Grjótagjá-N (0060). Horizontal scale is in years beginning 1975 although observations began in 1977. Vertical scale is in millimeters. Reference elevation is the average elevation of all five markers of the circular array. Relative elevation is found by adding to the left scale values, constants presented in parenthesis besides the marker identification.

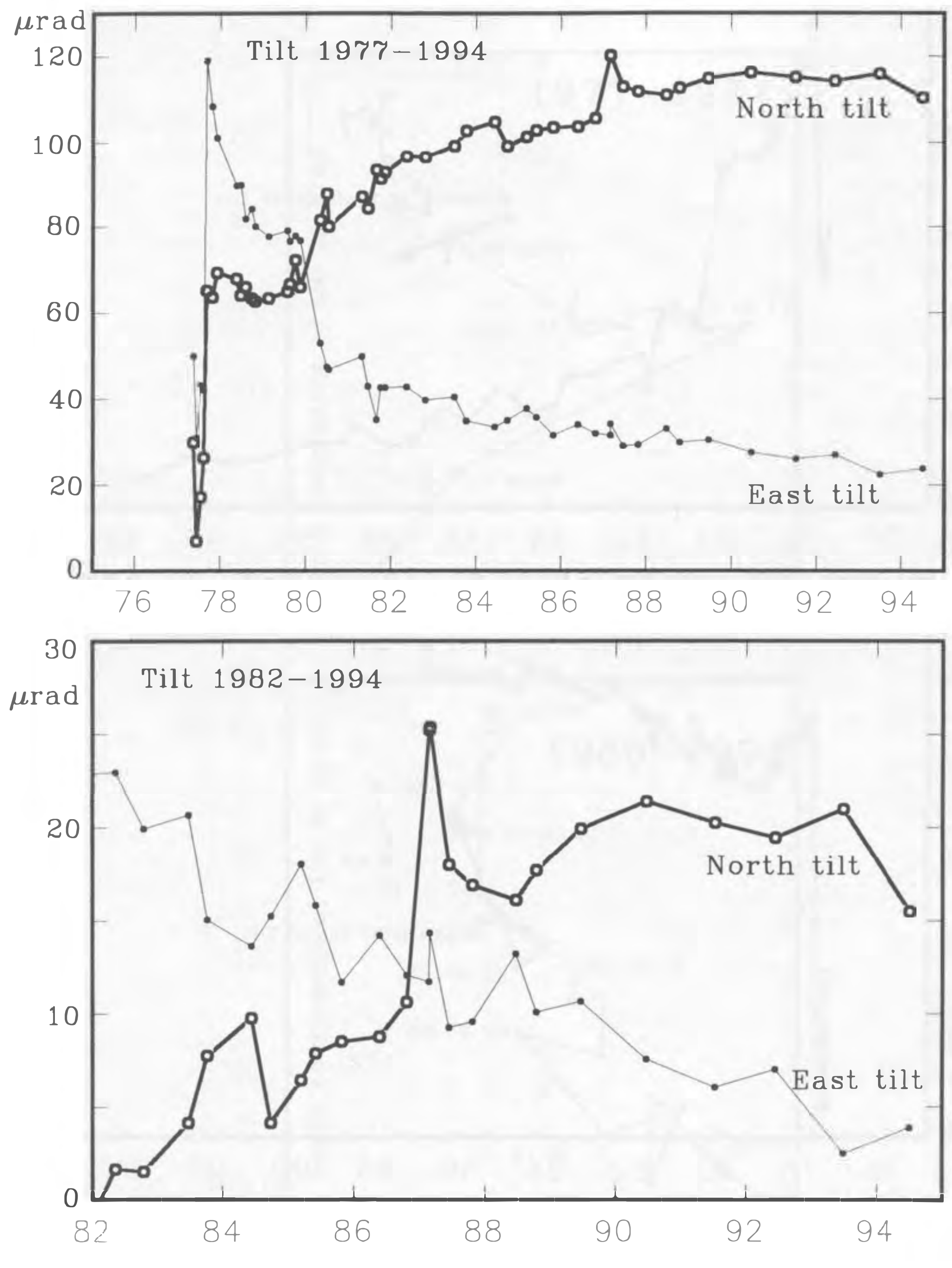


Fig. H3. Observed north and east component of tilt at the tilt station Grjótagjá-N (0060) since it was first observed on May 19, 1977. East component (filled circles) is positive if land is rising at the east side of the station relative to its west side. Similarly is north tilt (open circles) positive if the north side of the tilt station is rising relative to its south side. The top graph shows tilt during the whole period of observations 1977-1994 and the bottom graph shows tilt after 1981 in expanded tilt scale.

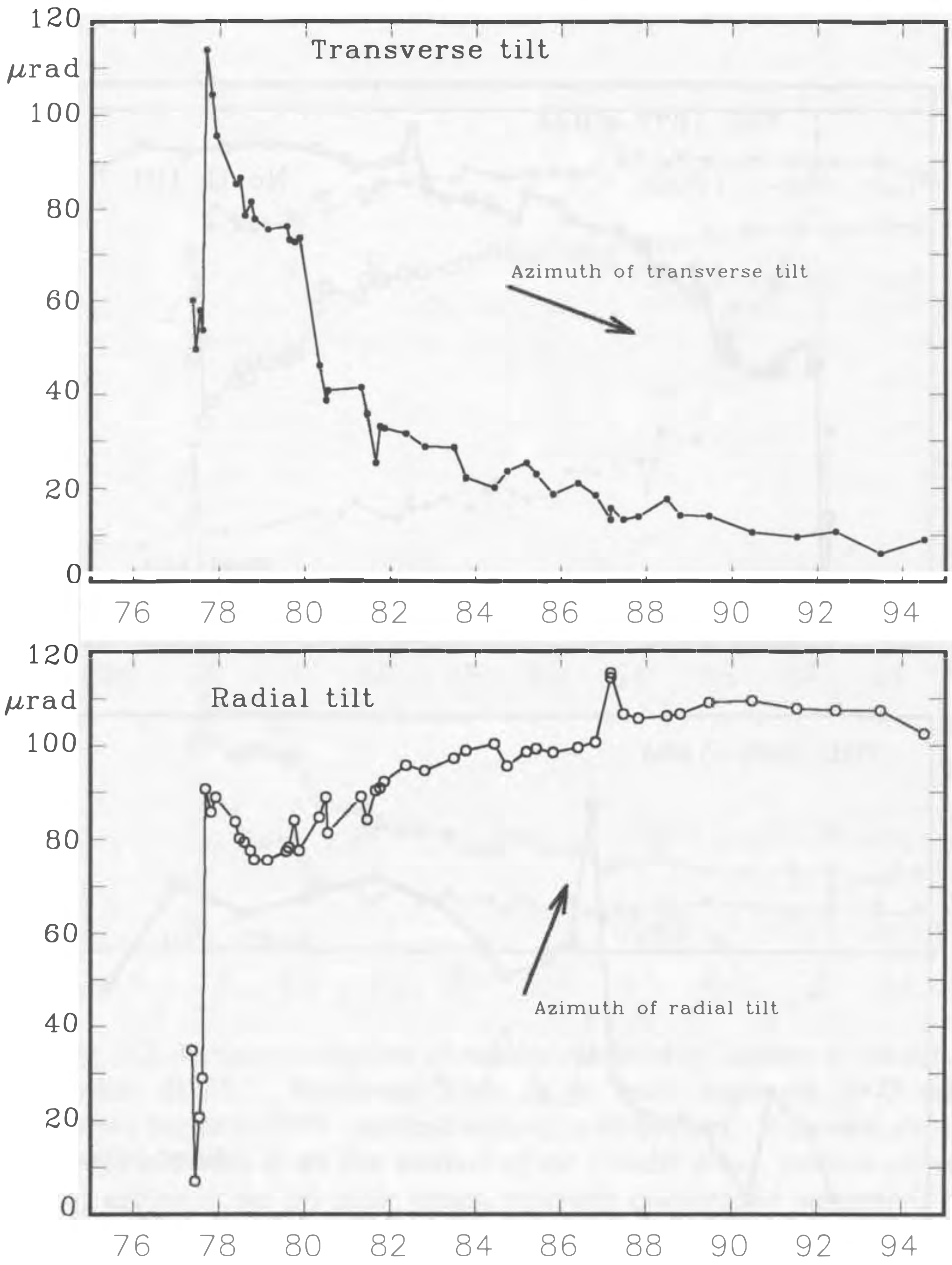


Fig. H4. Observed radial and transverse tilt at the tilt station Grjótagjá-N (0060) with respect to the center of deformation at Krafla. Positive transverse tilt is tilt up toward an azimuth of 111° and positive radial tilt is up towards the center of deformation at Krafla at azimuth 21°.

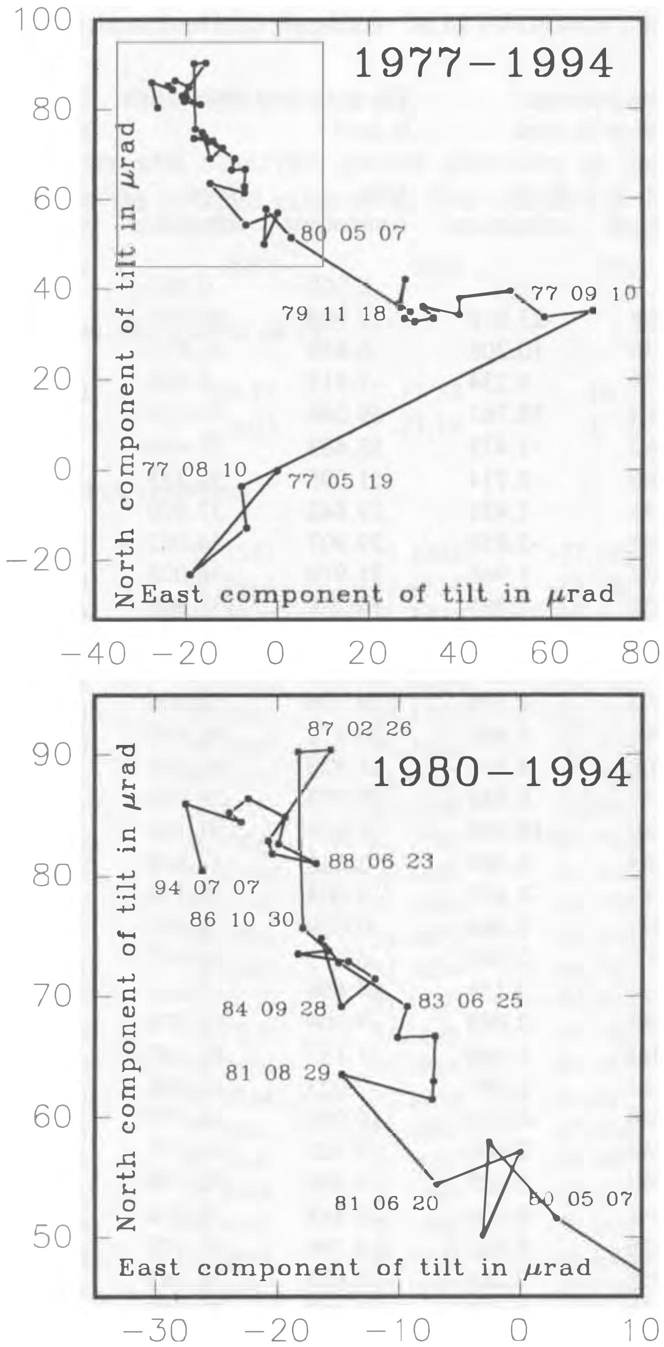


Fig. H5. North component of tilt plotted against east component of tilt at the tilt station Grjótagjá-N (0060). The permanent deformation of September 8, 1977 is seen as large tilt between 77 08 10 and 77 09 10, and that of March 1980 is seen as rather large tilt between 79 11 18 and 80 05 07 (top graph). Bottom graph shows tilt after May 1980 on expanded scale (rectangle on top graph) showing details of the progressing tilt. Random tilt variations around a smooth progressing tilt suggest that observational errors are usually less than 5 µrad.

Table H2

Observed tilt at tilt station 0060, Grjótagjá-N. Minimum axis of the error ellipse is 92% of the maximum axis. Azimuth of maximum axis is 175°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
77 05 19			0.000	0.000		
77 06 16	-18.984	-23.078	-18.984	-23.078	6.524	6.524
77 07 20	12.326	10.208	-6.659	-12.870	9.490	4.895
77 08 16	-1.159	9.234	-7.817	-3.636	2.130	3.885
77 09 10	76.864	38.767	69.046	35.132	6.756	10.539
77 10 24	-10.563	-1.475	58.483	33.656	2.047	12.112
77 12 06	-7.388	5.714	51.095	39.371	5.033	8.876
78 05 20	-11.253	-1.451	39.842	37.920	1.415	10.267
78 06 29	0.065	-3.858	39.907	34.062	1.565	11.439
78 08 06	-7.937	1.966	31.970	36.028	2.474	9.590
78 09 29	2.238	-2.585	34.208	33.443	1.414	8.320
78 10 28	-4.159	-0.707	30.049	32.736	2.472	9.944
79 02 17	-2.247	0.653	27.803	33.389	1.720	8.234
79 08 01	1.303	1.576	29.106	34.964	1.346	9.430
79 08 20	-2.494	1.688	26.612	36.652	0.562	9.624
79 10 04	1.308	5.591	27.920	42.243	1.396	9.790
79 11 18	-1.141	-6.241	26.779	36.002	1.188	8.786
80 05 07	-23.740	15.578	3.039	51.580	2.052	6.744
80 06 29	-5.585	6.307	-2.546	57.888	2.153	8.478
80 07 18	-0.419	-7.659	-3.003	50.136	2,400	10.010
81 04 25	3.032	6.966	0.029	57.102	2.610	7.551
81 06 20	-6.909	-2.743	-6.873	54.407	1.792	9.083
81 08 29	-7.821	9.156	-14.694	63.563	0.705	9.257
81 10 05	7.485	-2.083	-7.209	61.479	2.160	7.180
81 11 08	0.074	1.468	-7.135	62.947	0.794	7.125
82 05 16	0.112	3.761	-7.023	66.708	1.919	8.827
82 10 20	-3.049	-0.135	-10.072	66.573	2.400	7.192
83 06 25	0.744	2.600	-9.327	69.172	2.005	8.707
83 10 09	-5.597	3.627	-14.925	72.799	1.692	7.069
84 06 09	-1.444	2.000	-16.368	74.800	2.098	9.161
84 09 28	1.628	-5.623	-14.740	67.177	3.353	8.557
85 03 12	2.755	2.284	-11.985	71.461	1.933	8.103
85 06 01	-2.175	1.438	-14.160	72.899	1.096	8.840
85 10 26	-4.149	0.659	-18.309	73.558	1.533	7.877
86 05 23	2.534	0.245	-15.775	73.803	1.105	8.285
86 10 23	-2.125	1.851	-17.900	75.654	2.262	8.222
87 02 25	-0.371	14.557	-18.271	90.211	6.109	2.138
87 02 26	2.622	0.172	-15.649	90.383	0.534	1.652
87 06 14	-5.077	-7.401	-20.727	82.982	7.536	9.157
87 10 24	0.307	-1.078	-20.402	81.904	2.187	6.972
88 06 23	3.646	-0.807	-16.774	81.097	1.594	8.555
88 10 17	-3.104	1.596	-19.878	82.693	1.217	7.346
89 06 22	0.552	2.238	-19.326	84.932	1.966	9.149
90 06 23	-3.077	1.458	-22.403	86.390	0.022	9.134
91 07 10	-1.509	-1.147	-23.912	85.243	1.139	9.199

92 06 13	0.953	-0.778	-22.959	84.465	1.249	9.184
93 06 28	-4.531	1.515	-27.490	85.980	0.140	9.114
94 07 07	1.376	-5.430	-26.122	80.502	1.810	10.913

Table H3

Marker coordinates and observed marker elevation at the tilt station 0060 (Grjótagjá N) relative to the average value of all five markers at the tilt station.

Marker	0061	0062	0063	0064	0065
Marker coordinates in meters, surveyed 81 08 29					
East	4.62	-24.77	-17.58	16.17	21.54
North	22.87	11.02	-21.18	-17.23	4.53
Y M D	Marker elevation, centimeter				
77 05 19	-3.0083	53.7542	31.3302	-37.7654	-44.3106
77 06 16	-3.0753	53.7624	31.4354	-37.7921	-44.3306
77 07 20	-3.0638	53.7804	31.3491	-37.7426	-44.3233
77 08 16	-3.0412	53.7864	31.3408	-37.7716	-44.3142
77 09 10	-2.9510	53.6712	31.0984	-37.7033	-44.1151
77 10 24	-2.9692	53.7006	31.1193	-37.7239	-44.1269
77 12 06	-2.9418	53.7015	31.1432	-37.7650	-44.1380
78 05 20	-2.9580	53.7335	31.1627	-37.7815	-44.1568
78 06 29	-2.9717	53.7293	31.1736	-37.7822	-44.1492
78 08 06	-2.9628	53.7505	31.1792	-37.7868	-44.1800
78 09 29	-2.9604	53.7354	31.1856	-37.7804	-44.1804
78 10 28	-2.9735	53.7569	31.1834	-37.7773	-44.1893
79 02 17	-2.9638	53.7565	31.1895	-37.7805	-44.2018
79 08 01	-2.9661	53.7582	31.1834	-37.7851	-44.1906
79 08 20	-2.9642	53.7655	31.1860	-37.7950	-44.1922
79 10 04	-2.9519	53.7729	31.1659	-37.7951	-44.1919
79 11 18	-2.9610	53.7660	31.1815	-37.7827	-44.2040
80 05 07	-2.9252	53.8334	31.1955	-37.8473	-44.2565
80 06 29	-2.9209	53.8643	31.1821	-37.8589	-44.2667
80 07 18	-2.9488	53.8605	31.2007	-37.8555	-44.2568
81 04 25	-2.9176	53.8514	31.1849	-37.8588	-44.2601
81 06 20	-2.9339	53.8741	31.1948	-37.8589	-44.2762
81 08 29	-2.9185	53.9034	31.1907	-37.8908	-44.2848
81 10 05	-2.9081	53.8737	31.1872	-37.8741	-44.2788
81 11 08	-2.9055	53.8737	31.1867	-37.8808	-44.2740
82 05 16	-2.9067	53.8833	31.1766	-37.8914	-44.2617
82 10 20	-2.8978	53.8865	31.1815	-37.8875	-44.2825
83 06 25	-2.9012	53.8922	31.1740	-37.8968	-44.2683
83 10 09	-2.8869	53.9020	31.1825	-37.9147	-44.2827
84 06 09	-2.8944	53.9164	31.1756	-37.9214	-44.2761
84 09 28	-2.8987	53.9085	31.1762	-37.8918	-44.2940
85 03 12	-2.8933	53.8998	31.1736	-37.9019	-44.2781
85 06 01	-2.8937	53.9114	31.1693	-37.9028	-44.2842
85 10 26	-2.8907	53.9160	31.1822	-37.9180	-44.2897
86 05 23	-2.8918	53.9095	31.1798	-37.9199	-44.2778
86 10 23	-2.8859	53.9208	31.1721	-37.9142	-44.2929
87 02 25	-2.8209	53.9092	31.1628	-37.9462	-44.3050

87 02 26	-2.8173	53.9004	31.1603	-37.9442	-44.2991
87 06 14	-2.8772	53.9379	31.1630	-37.9382	-44.2856
87 10 24	-2.8677	53.9264	31.1711	-37.9362	-44.2935
88 06 23	-2.8761	53.9240	31.1608	-37.9270	-44.2816
88 10 17	-2.8676	53.9277	31.1671	-37.9362	-44.2910
89 06 22	-2.8725	53.9351	31.1589	-37.9430	-44.2785
90 06 23	-2.8705	53.9443	31.1612	-37.9504	-44.2846
91 07 10	-2.8732	53.9494	31.1621	-37.9446	-44.2936
92 06 13	-2.8755	53.9435	31.1665	-37.9486	-44.2860
93 06 28	-2.8738	53.9558	31.1719	-37.9592	-14.2948
94 07 07	-2.8950	53.9549	31.1748	-37.9457	-44.2890

TILT STATION 0070, REYKJAHLÍÐ

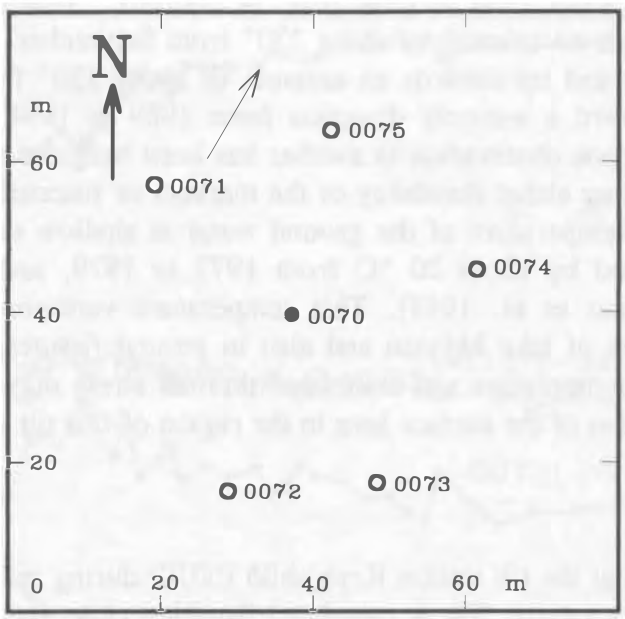


Fig. I1. Map of relative position of markers at the tilt station Reykjahlíð, also named tilt station 0070. Solid circle is a marker at the center of a 25.0 m radius circle defined by 5 markers (open circles). The markers consist of copper alloy nails with convex 37 mm diameter convex top plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Thin arrow gives the approximate direction to the center of deformation at Krafla volcano.

This station lies on pahoehoe lava of Holocene but pre-historic age about 1.5 km west of the fault Grjótagjá and immediately south of the highway towards east from Mývatn. It consists of 6 permanent markers, one at the center of a 25.0 m radius circle defined by the remaining 5 markers (Fig. I1). It was observed 52 times from May 1977 to July 1994. Four of these observations were made on four days in early February 1980. A graph of relative marker elevation as function of time (Fig. I2) shows large downward displacement of markers 0071 and 0072 and large upward displacement of markers 0074 and 0075 during the rifting event of September 1977. Smaller displacements are seen during the rifting event of March 1980, upward at marker 0071 and downward at marker 0074 but no noticeable displacement at the other three markers. Gradual downward movement of marker 0074 is observed from September 1977 to late 1979. Smaller movements, downward at marker 0075 and upward at markers 0071 and 0073 is also seen during this period. After 1980, only small marker displacements are observed, but gradual downward drift is suggested at markers 0072 and 0073 and gradual upward drift of markers 0071 and 0075. Observed tilt (Fig. I3) shows similar pattern as at stations 0050 and 0060, but tilt variations from one observations to another are rather large (Fig. I3 bottom), suggesting that the tilt observations are less accurate than at other stations in this vicinity. The transverse tilt, positive up toward an azimuth of 119°, is downward during the whole period of observation, except for the rifting event of September 1980 (Fig. I4 top). Radial tilt, positive if up toward an azimuth of 29°, is downward from late 1977 to 1980, then upward to 1989 and slightly downward from 1989 to 1994 (Fig. I4 bottom). This means that tilt was generally up towards an azimuth of about 230° from September 1977 to November 1979 (Fig. I5 top) and up towards an azimuth of about 330° from 1980 to 1989, and finally up toward a westerly direction from 1989 to 1994 (Fig. I5 bottom). Observed tilt from one observation to another has been irregular at this station (Figs I3 and I5), suggesting either instability of the markers or inaccurate observations. It is known that the temperature of the ground water at shallow depth in the area of the station increased by about 20 °C from 1977 to 1979, and decreased slowly thereafter (Björnsson et al. 1984). This temperature variation was observed in springs at the shore of lake Mývatn and also in ground fissures as "Stóragjá" and "Grjótagjá". This temperature and associated thermal stress may have caused some irregular deformation of the surface lava in the region of this tilt station.

Table I1

Observed tilt at the tilt station Reykjahlíð (0070) during selected rifting events of the Krafla fissure swarm. Tilt is calculated from last observation before the event and first observation after the event. (Event of 80 03 16 is exception as additional tilt data is included based on observation on 79 11 24, because that was the date of last observation for the event at most stations).

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of rifting event
77 08 16	77 09 11	95.9	2.6	68.9	77 09 08
77 12 13	78 01 13	10.1	2.1	239.1	78 01 07
78 06 29	78 07 19	12.5	3.7	232.2	78 07 10
79 11 24	80 05 07	31.6		277.1	80 03 16
80 02 13	80 05 07	27.3	1.2	262.1	80 03 16
80 06 29	80 07 15	7.4	3.9	183.7	80 07 10
84 06 09	84 09 28	8.1	2.7	209.9	84 09 04

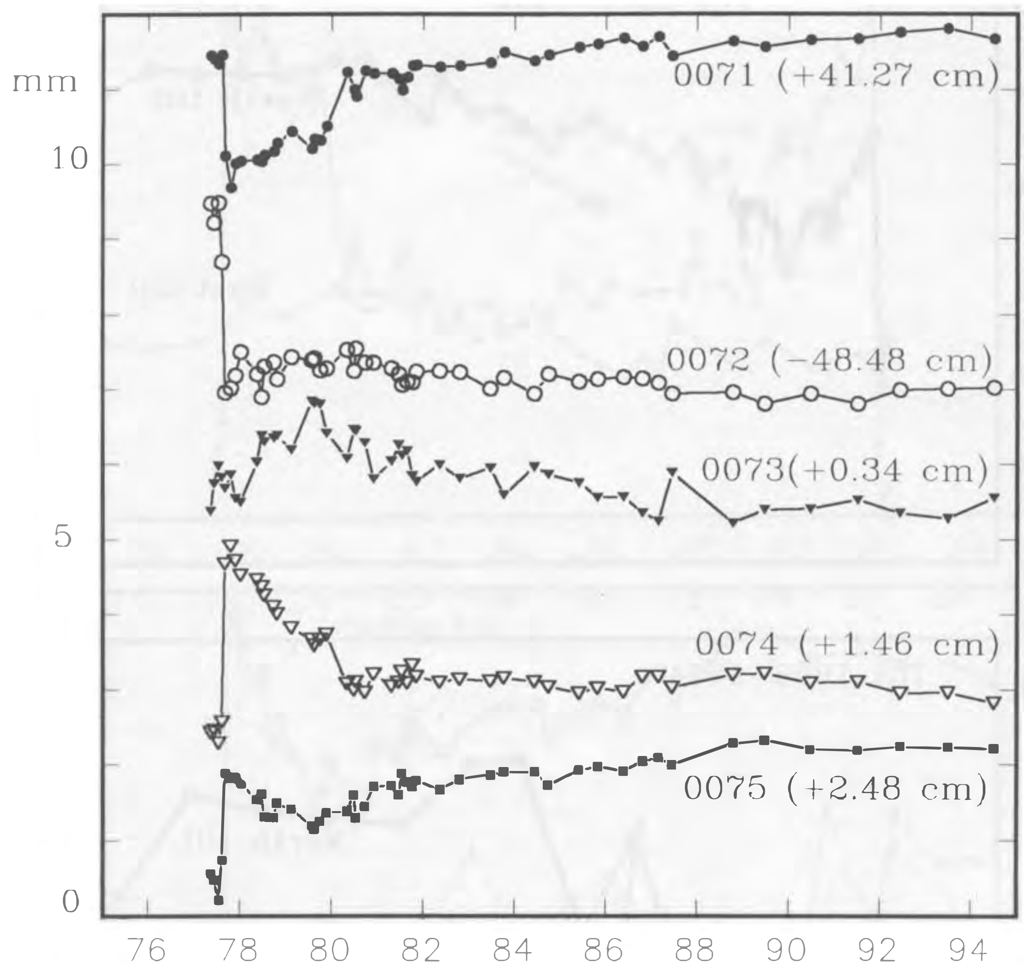


Fig. 12. Variation with time of relative marker elevation at the tilt station Reykjahlíð (0070). Horizontal scale is in years beginning at 1975, but first observations were made in May, 1977, and vertical scale is in mm. Reference elevation is the average elevation of all five markers of the circular array. Relative elevation of each marker is found by adding to the left scale value, constants given inside parenthesis besides the marker identification. Four observations of February 10 to 13, 1980 are not included.

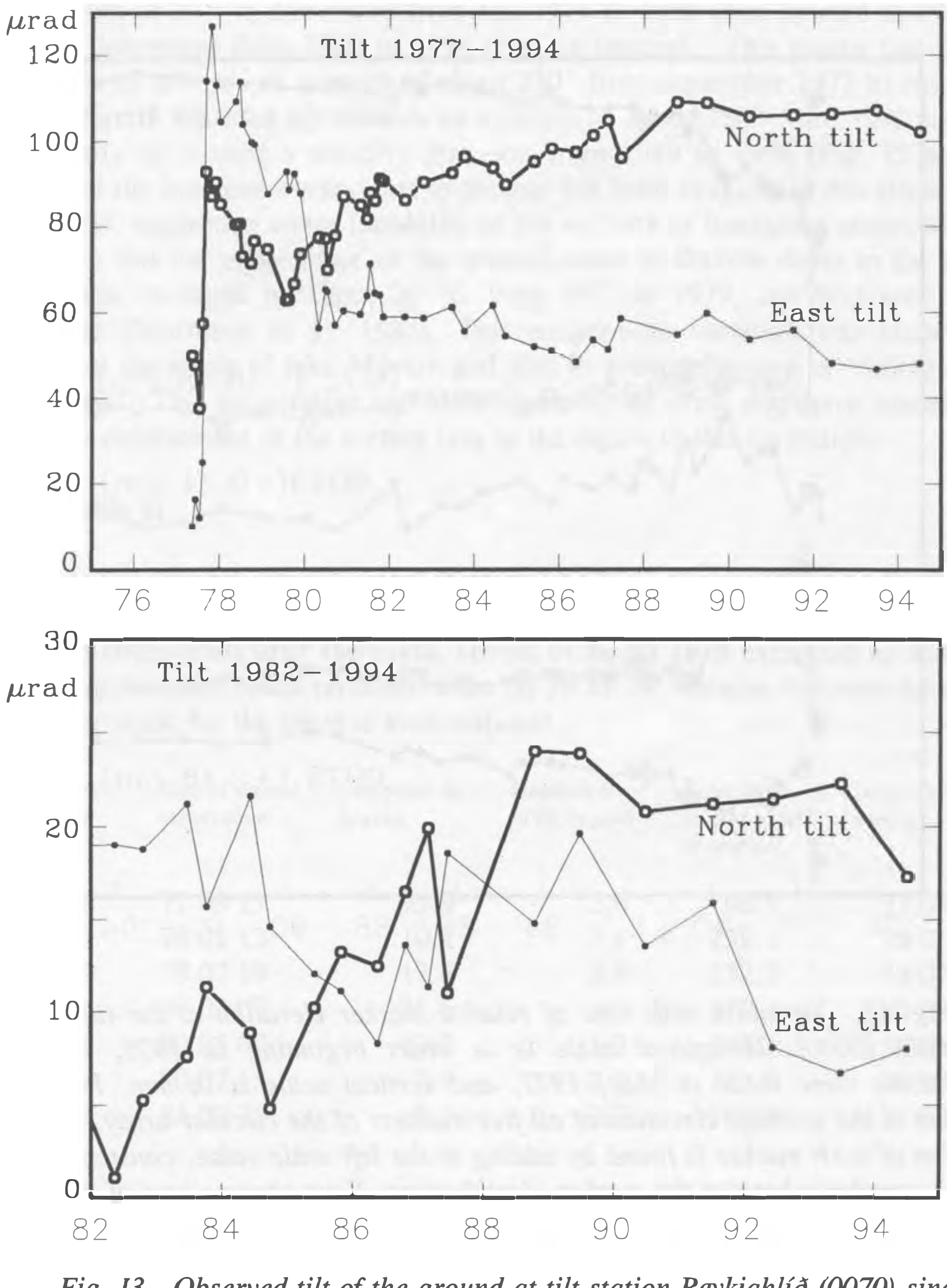


Fig. 13. Observed tilt of the ground at tilt station Reykjahlíð (0070) since first observation of 20 May, 1977. East component (filled circles) is positive if east side of the tilt station is rising relative to the west side. North component of tilt (open circles) is positive if the north side of the tilt station is rising relative to its south side. The top diagram shows the whole period of observation and the bottom graph shows tilt after 1981 on expanded tilt scale. Four observations of February 10 to 13 are not included.

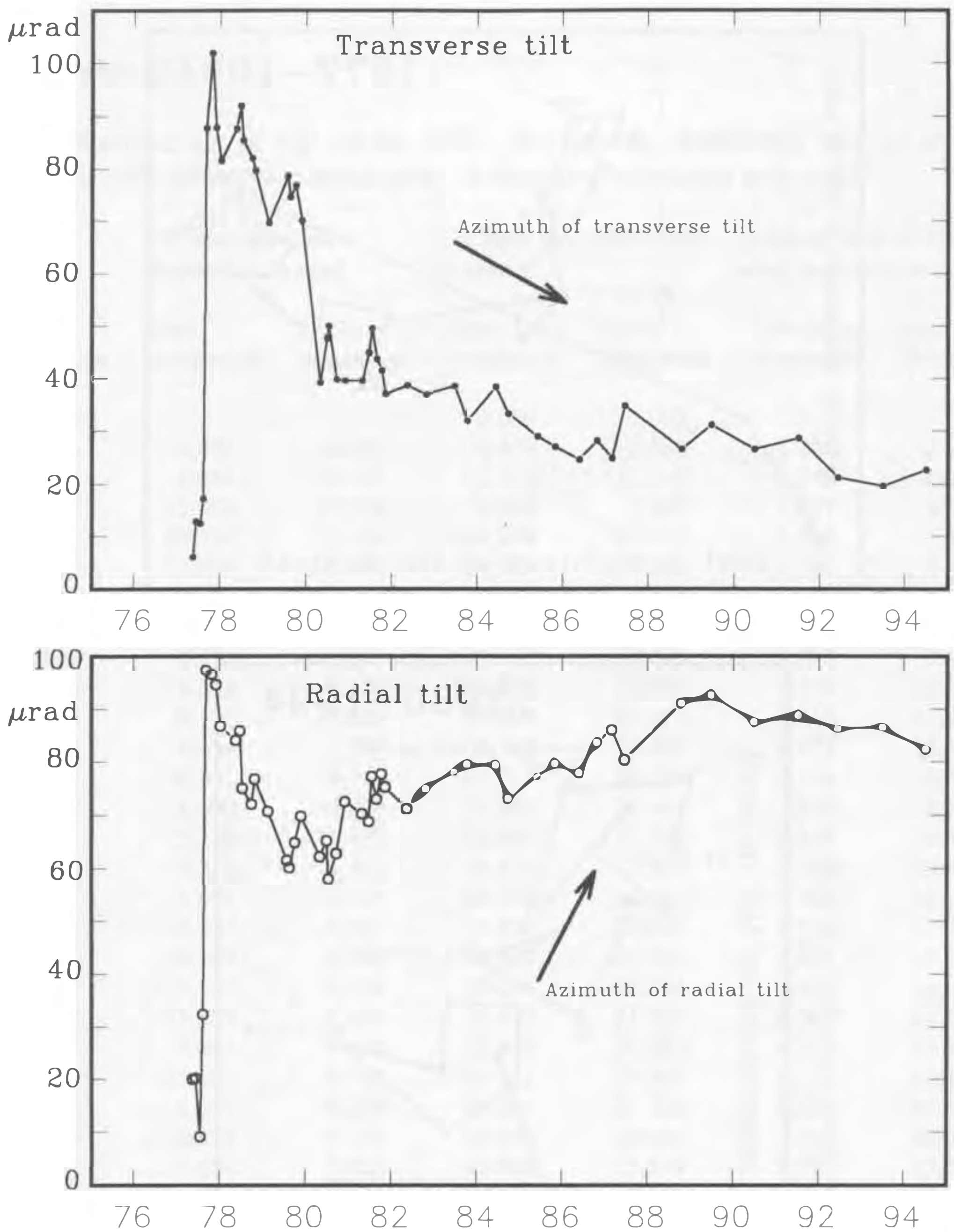


Fig. I4. Observed transverse and radial tilt at the tilt station Reykjahlíð (0070), relative to the center of deformation at Krafla volcano. Positive transverse tilt is up towards an azimuth of 119° and positive radial tilt is up towards an azimuth of 29°. The radial direction is taken as the direction to the average (accepted) center of inflations and deflations of the Krafla volcano.

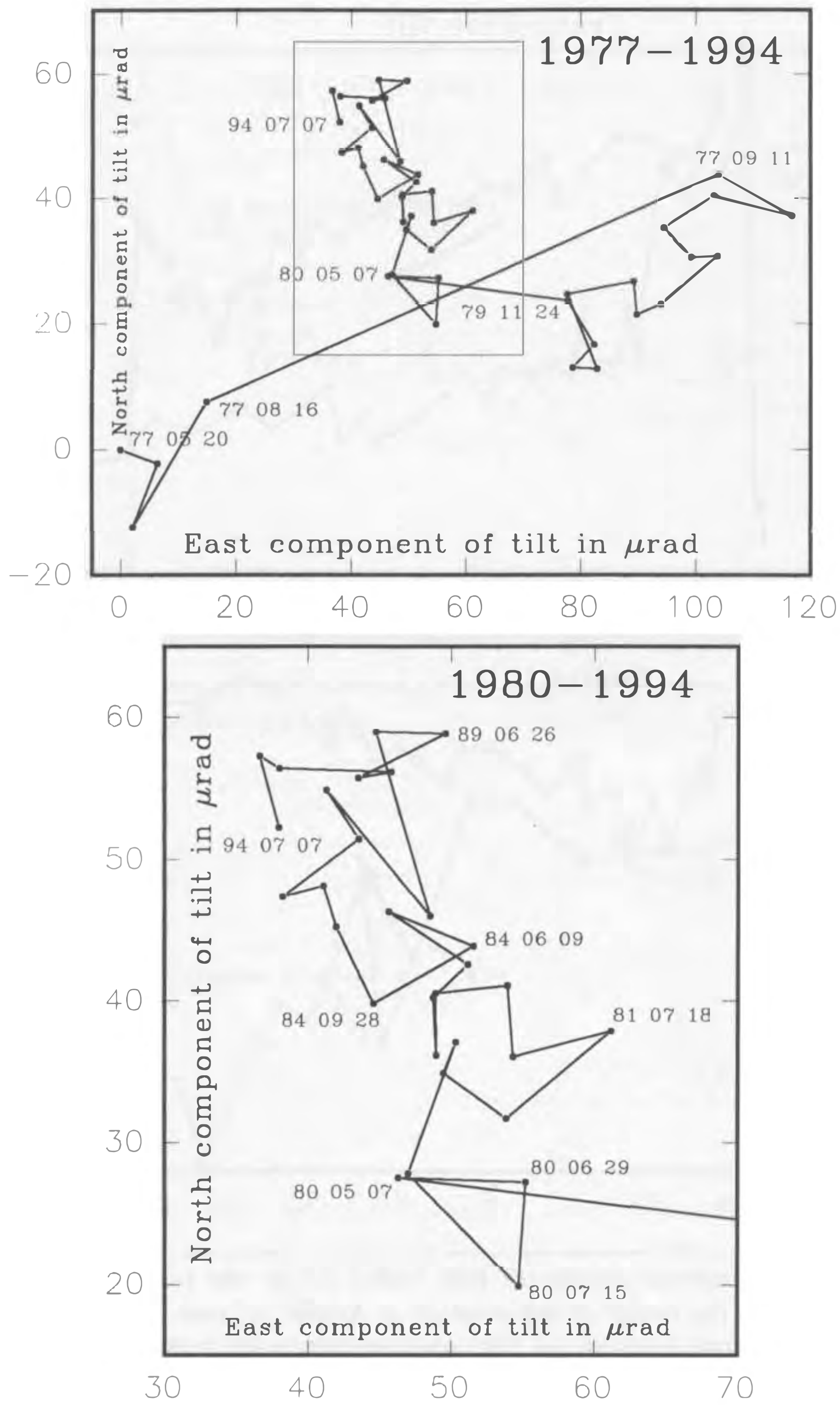


Fig. 15. North component of tilt plotted against east component of tilt at the tilt station Reykjahlíð. Permanent displacements of September 8, 1977 and March 16, 1980 are seen as large tilt towards ENE and W respectively (top). Irregular near random tilt variations suggest that the error limits are rather large, based on the assumption that the gradual tilt variations should be represented by a smooth curve on this type of diagram.

Table I2

Observed tilt at tilt station 0070, Reykjahlíð. Minimum axis of the error ellipse is 74% of the maximum axis. Azimuth of maximum axis is 84°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	since first observation
77 05 20			0.000	0.000		
77 06 16	6.407	-2.193	6.407	-2.193	5.296	5.296
77 07 20	-4.288	-10.187	2.119	-12.379	0.736	6.032
77 08 16	12.806	19.878	14.924	7.499	3.837	9.772
77 09 11	89.174	35.414	104.098	43.913	2.560	7.898
77 10 24	12.898	-5.783	116.997	37.130	1.590	6.843
77 12 01	-13.815	3.244	103.182	40.374	2.438	4.409
78 01 13	-8.630	-5.166	94.552	35.208	2.110	3.184
78 05 20	4.711	-4.668	99.263	30.540	7.883	9.952
78 06 29	4.615	0.130	103.878	30.670	6.358	16.280
78 07 19	-9.870	-7.659	94.009	23.011	3.660	13.017
78 10 02	-4.294	-1.566	89.715	21.445	1.179	13.888
78 10 28	-0.512	5.249	89.213	26.694	3.134	16.858
79 02 17	-11.600	-2.029	77.603	24.665	2.810	14.063
79 08 01	5.258	-11.883	82.861	12.782	6.639	20.701
79 08 20	-4.287	0.195	78.574	12.977	0.750	20.868
79 10 03	3.698	3.635	82.272	16.612	0.766	21.625
79 11 24	-4.537	7.027	77.735	23.639	3.718	17.961
80 02 10	20.199	4.245	97.934	27.884	1.881	19.828
80 02 12	-35.140	-0.324	62.794	27.561	3.735	16.156
80 02 13	13.679	-5.856	76.473	21.705	1.002	15.156
80 02 13	-3.061	9.578	73.412	31.283	4.263	19.403
80 05 07	-27.062	-3.740	46.351	27.543	1.224	18.182
80 06 29	8.871	-0.295	55.221	27.248	6.626	24.140
80 07 15	-0.476	-7.364	54.745	19.884	3.899	20.548
80 09 24	-7.696	7.965	47.048	27.849	1.727	22.151
80 12 06	3.318	9.226	50.366	37.075	5.908	16.398
81 04 25	-0.870	-2.160	49.496	34.915	3.813	20.176
81 06 21	4.366	-3.178	53.862	31.736	2.478	22.261
81 07 18	7.335	6.159	61.197	37.895	2.646	21.291
81 08 29	-6.872	-1.843	54.325	36.052	1.857	22.547
81 10 07	-0.350	5.058	53.975	41.110	5.071	18.501
81 11 09	-5.041	-0.546	48.935	40.564	2.313	17.546
82 05 16	0.060	-4.443	48.995	36.121	2.345	19.811
82 10 21	-0.228	4.139	48.767	40.260	1.878	18.201
83 06 24	2.421	2.340	51.188	42.601	3.332	21.503
83 10 09	-5.535	3.708	45.653	46.309	4.424	17.082
84 06 09	5.942	-2.446	51.595	43.863	5.135	22.215
84 09 28	-7.007	-4.032	44.589	39.831	2.713	19.659
85 06 01	-2.567	5.391	42.022	45.222	1.594	20.384
85 10 28	-0.917	2.972	41.105	48.193	2.321	18.064
86 05 22	-2.826	-0.768	38.279	47.425	0.754	18.284
86 10 23	5.315	4.038	43.594	51.463	3.290	15.126

87 02 26	-2.271	3.439	41.323	54.902	0.648	14.866
87 06 14	7.219	-8.907	48.542	45.996	7.432	22.259
88 10 17	-3.785	12.980	44.757	58.976	6.602	15.762
89 06 26	4.870	-0.109	49.627	58.867	2.548	18.309
90 06 27	-6.088	-3.117	43.538	55.750	0.604	18.088
91 07 10	2.312	0.415	45.851	56.165	2.280	20.181
92 06 13	-7.796	0.283	38.055	56.448	2.451	18.323
93 06 30	-1.351	0.827	36.703	57.275	0.890	17.487
94 07 07	1.302	-4.998	38.005	52.278	3.308	20.595

Table I3

Marker coordinates and observed marker elevation at the tilt station 0070 (Reykjahlíð) relative to the average values of all five markers at the tilt station.

Marker	0071	0072	0073	0074	0075
Marker coordinates in meters, surveyed 81 08 29					
East	-20.89	-11.14	8.35	21.41	2.25
North	16.91	-23.96	-22.74	5.70	24.10
Y M D	Marker elevation, centimeter				
77 05 20	42.4155	-47.5330	0.8777	1.7032	2.5364
77 06 16	42.4108	-47.5584	0.9143	1.7058	2.5276
77 07 20	42.4043	-47.5325	0.9375	1.6895	2.5013
77 08 16	42.4163	-47.6102	0.9228	1.7171	2.5541
77 09 11	42.2806	-47.7839	0.9079	1.9271	2.6684
77 10 24	42.2383	-47.7777	0.9258	1.9513	2.6623
77 12 01	42.2707	-47.7608	0.8944	1.9317	2.6639
78 01 13	42.2736	-47.7294	0.8896	1.9121	2.6541
78 05 20	42.2756	-47.7587	0.9425	1.9065	2.6343
78 06 29	42.2733	-47.7897	0.9788	1.8968	2.6408
78 07 19	42.2817	-47.7490	0.9705	1.8857	2.6110
78 10 02	42.2867	-47.7431	0.9754	1.8706	2.6104
78 10 28	42.2974	-47.7659	0.9786	1.8609	2.6291
79 02 17	42.3134	-47.7361	0.9591	1.8421	2.6216
79 08 01	42.2904	-47.7404	1.0248	1.8266	2.5988
79 08 20	42.3026	-47.7381	1.0216	1.8194	2.5946
79 10 03	42.3016	-47.7539	1.0203	1.8268	2.6051
79 11 24	42.3200	-47.7515	0.9815	1.8335	2.6163
80 02 10	42.2869	-47.7916	0.9984	1.8732	2.6329
80 02 12	42.3567	-47.7373	0.9507	1.8102	2.6197
80 02 13	42.3164	-47.7342	0.9703	1.8386	2.6088
80 02 13	42.3442	-47.7710	0.9680	1.8247	2.6342
80 05 07	42.3929	-47.7269	0.9476	1.7683	2.6183
80 06 29	42.3704	-47.7549	0.9861	1.7601	2.6384
80 07 15	42.3606	-47.7254	0.9843	1.7706	2.6098
80 09 24	42.3947	-47.7436	0.9681	1.7561	2.6249
80 12 06	42.3911	-47.7435	0.9200	1.7813	2.6510
81 04 25	42.3913	-47.7512	0.9435	1.7648	2.6518
81 06 21	42.3842	-47.7595	0.9655	1.7700	2.6400
81 07 18	42.3689	-47.7734	0.9516	1.7849	2.6681
81 08 29	42.3865	-47.7693	0.9572	1.7690	2.6565

81 10 07	42.4019	-47.7699	0.9246	1.7929	2.6506
81 11 09	42.4024	-47.7554	0.9169	1.7776	2.6586
82 05 16	42.3998	-47.7552	0.9388	1.7703	2.6463
82 10 21	42.4017	-47.7565	0.9207	1.7740	2.6600
83 06 24	42.4061	-47.7789	0.9346	1.7718	2.6666
83 10 09	42.4192	-47.7641	0.8987	1.7759	2.6702
84 06 09	42.4082	-47.7853	0.9357	1.7712	2.6702
84 09 28	42.4162	-47.7591	0.9259	1.7644	2.6526
85 06 01	42.4262	-47.7694	0.9150	1.7553	2.6728
85 10 28	42.4309	-47.7663	0.8956	1.7625	2.6775
86 05 22	42.4384	-47.7637	0.8962	1.7575	2.6714
86 10 23	42.4271	-47.7647	0.8750	1.7781	2.6846
87 02 26	42.4396	-47.7706	0.8641	1.7778	2.6891
87 06 14	42.4146	-47.7853	0.9282	1.7628	2.6795
88 10 17	42.4341	-47.7842	0.8616	1.7799	2.7088
89 06 26	42.4261	-47.7993	0.8790	1.7820	2.7124
90 06 27	42.4355	-47.7855	0.8802	1.7695	2.7004
91 07 10	42.4369	-47.7993	0.8923	1.7707	2.6993
92 06 13	42.4458	-47.7805	0.8748	1.7555	2.7044
93 06 30	42.4505	-47.7785	0.8677	1.7567	2.7035
94 07 07	42.4372	-47.7770	0.8951	1.7430	2.7016

TILT STATION 0080, YTRI BJARGHÓLL

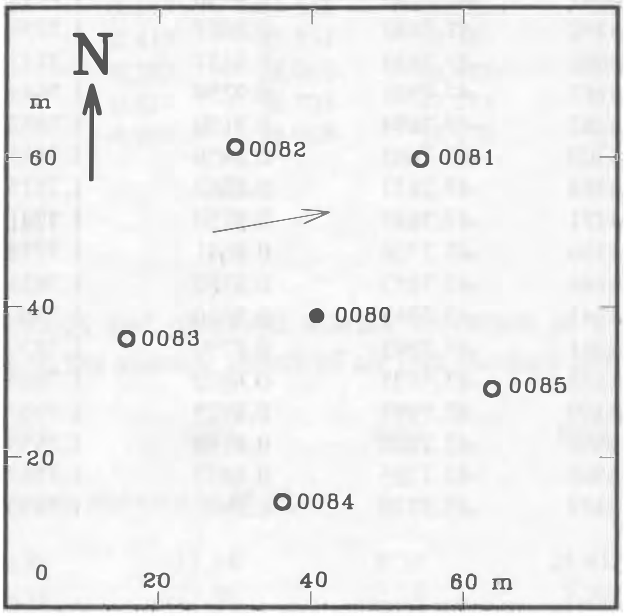


Fig. J1. Map of relative position of markers at the tilt station Ytri Bjarghóll, also named tilt station 0080. Solid circle is a marker at the center of a 25.0 m radius circle defined by five markers (open circles). The markers consist of copper alloy nails with 37 mm diameter convex surface plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Thin arrow points toward the average direction of downward tilt during subsidence events of the Krafla volcano.

This station was constructed on June 14, 1977 at a location about 3 km west of Leirhnjúkur. It lies on a flat pahoehoe lava of the 1724-1729 Mývatn fires, on the west flank of the Krafla fissure swarm, about 400 m south-west of the prominent 565 m palagonite peak Ytri Bjarghóll. It consists of 5 markers on the periphery of a circle of 25.0 m radius, and a sixth marker at the center of this circle (Fig. J1).

Observations were made 53 times from June 1977 to July 1994. Variations of marker elevation with time (Fig. J2) is greatly affected by inflations and deflations of the Krafla volcano, with markers 0081 and 0085 subsiding about 2 mm during each deflation and marker 0083 was uplifted at the same times. Relative elevation of marker 0082 was not visibly affected by the deflation events, if no rifting occurred near the station. During several events of rifting, this marker was permanently displaced, downward during the event of 77 09 08 and upward during the events of 80 07 10, 81 11 18, and 84 09 04.

The observed tilt is dominated by the inflation/deflation cycle of Krafla volcano (Fig. J3). During inflations, tilt up toward east is observed and during deflations, tilt down toward east is seen. The north component of tilt is small, compared to the east component, especially before the event of July 1980, but from

July 1980 to about 1988, the north component of tilt, up towards north became quite prominent during periods of inflation of Krafla volcano (Fig. J3, top).

This northerly tilt appear to commence immediately after the eruption and rifting event of July 1980. It started with a tilt rate of about 100 μrad per year, but tilt rate decreased uniformly to near zero in 1988. This northerly tilt is related to uplift of a region about 5 km north of Leirhnjúkur (Tryggvason 1986).

Table J1

Observed ground tilt at the tilt station Ytri Bjarghóll (0080) during selected rifting events of the Krafla fissure swarm. Tilt is calculated from last observation before the rifting event and the first observation after the event.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of rifting event
77 08 16	77 09 11	71.2	5.5	199.4	77 09 08
77 12 02	78 01 11	139.5	4.3	256.9	78 01 07
78 06 28	78 08 05	66.2	1.7	264.5	77 08 10
78 09 30	78 11 12	101.0	3.0	256.3	78 11 10
80 06 30	80 07 14	93.7	2.8	265.9	80 07 10
81 11 06	81 11 21	85.0	1.4	270.6	81 11 18
84 06 10	84 09 06	100.3	1.6	266.9	84 09 04

The radial tilt (Fig. J4 bottom) shows general uplift towards the center of the volcano from 1977 (beginning of observations) to 1989, interrupted by brief tilt in the opposite direction during deflation events. Slow tilt down toward the center of the volcano is observed after 1989, and also for a period of about 1.5 years from early 1985 to late 1986 (Table J3). The transverse tilt (Fig. J4 top) is near zero from September 1978 to July 1980 followed by downward tilt (toward an azimuth of 170°) at decreasing rate. This tilt, down toward south (or up toward north) commenced abruptly in July 1980, and is related to uplift of a region about 5 km north of the center of deformation near Leirhnjúkur (Tryggvason 1986).

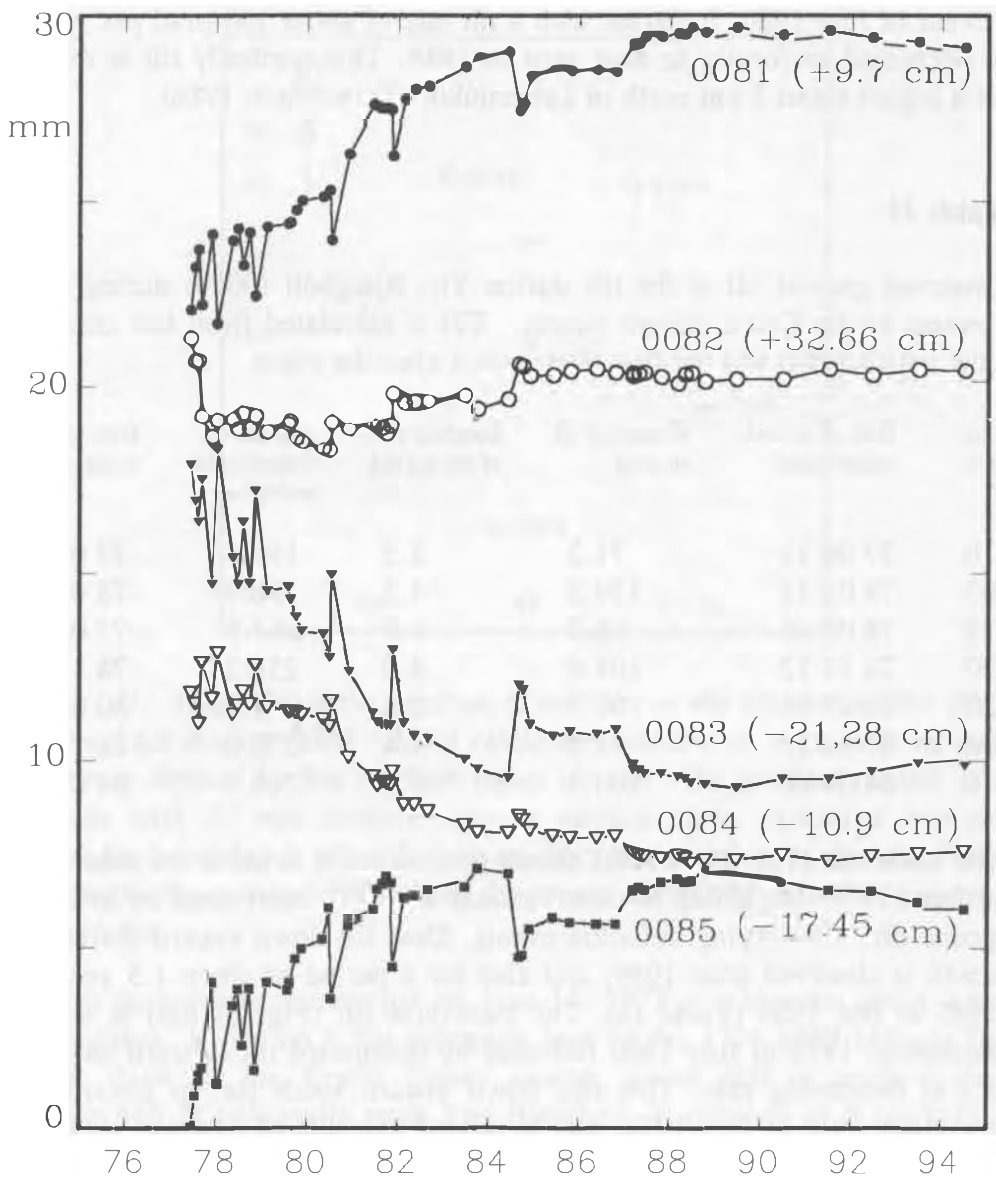


Fig. J2. Variation with time of the relative elevation of each of five markers forming the 25.0 m radius circle of the Ytri Bjarghóll tilt station. Note that markers 0081 (top) and 0085 (bottom) have subsided during each event of rifting of the Krafla fissure swarm, while marker 0083 (center) has been uplifted. Marker 0084 has been uplifted slightly during the rifting events while marker 0082 has remained steady through most rifting events, but certain events have displaced this marker permanently either downward (September 1977) or upward (July 1980, November 1981 and September 1984).

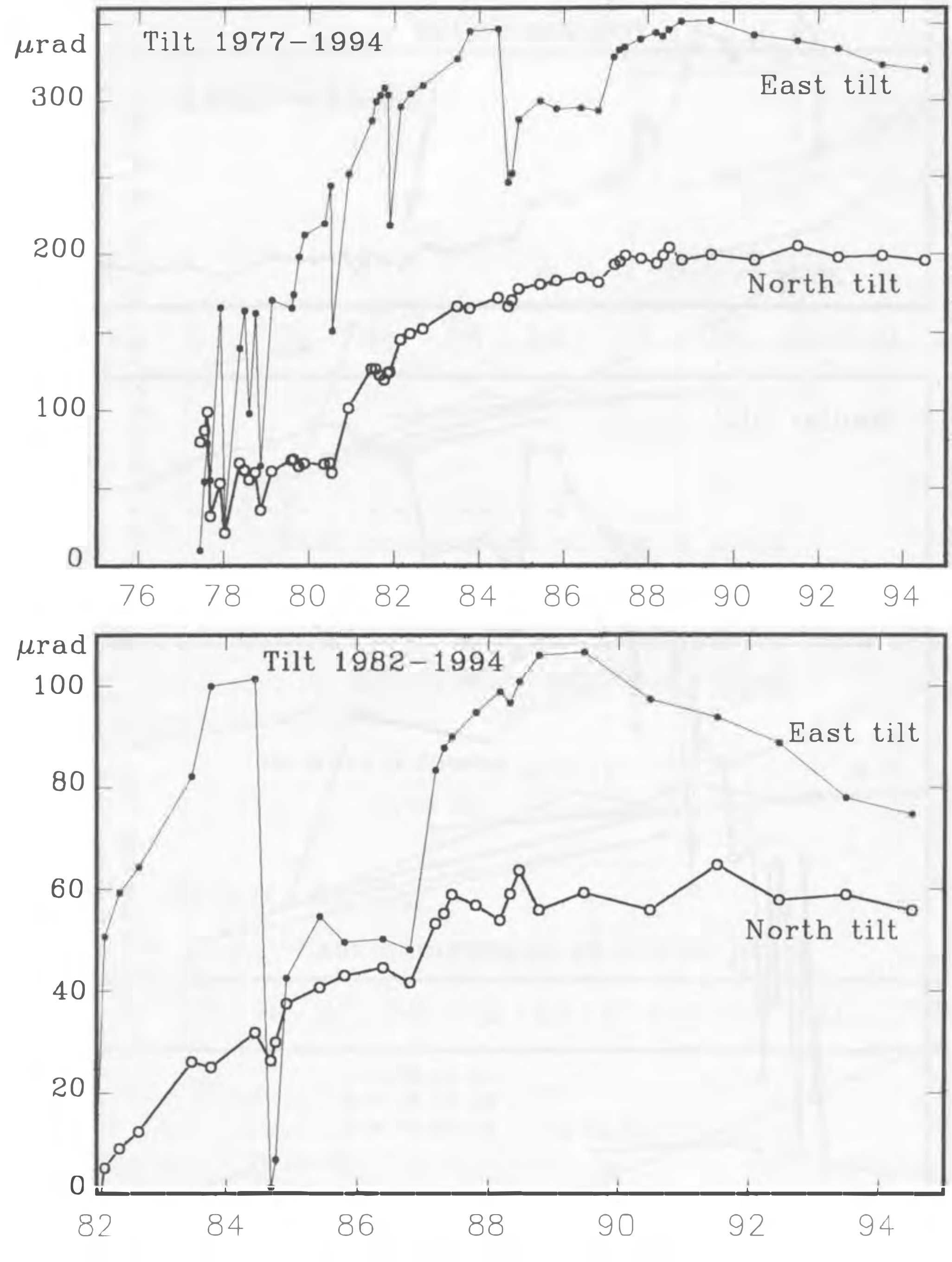


Fig. J3. Observed tilt of the ground at the tilt station Ytri Bjarghóll since first observation of June 14, 1977. East component of tilt is marked with solid dots connected by a thin line and north component of tilt is marked with open circles connected by a thick line. Bottom graph shows tilt variations after 1981 on expanded tilt scale to emphasise the relatively gentle tilt variations after the activity of Krafla volcano subsided. The east component of tilt shows primarily inflations and deflations of the shallow magma chamber below the central part of the Krafla caldera. The north component of tilt shows upward tilt commencing during or immediately after the July 1980 eruption, signifying uplift of an area centred about 5 km to the north of the shallow Krafla magma chamber.

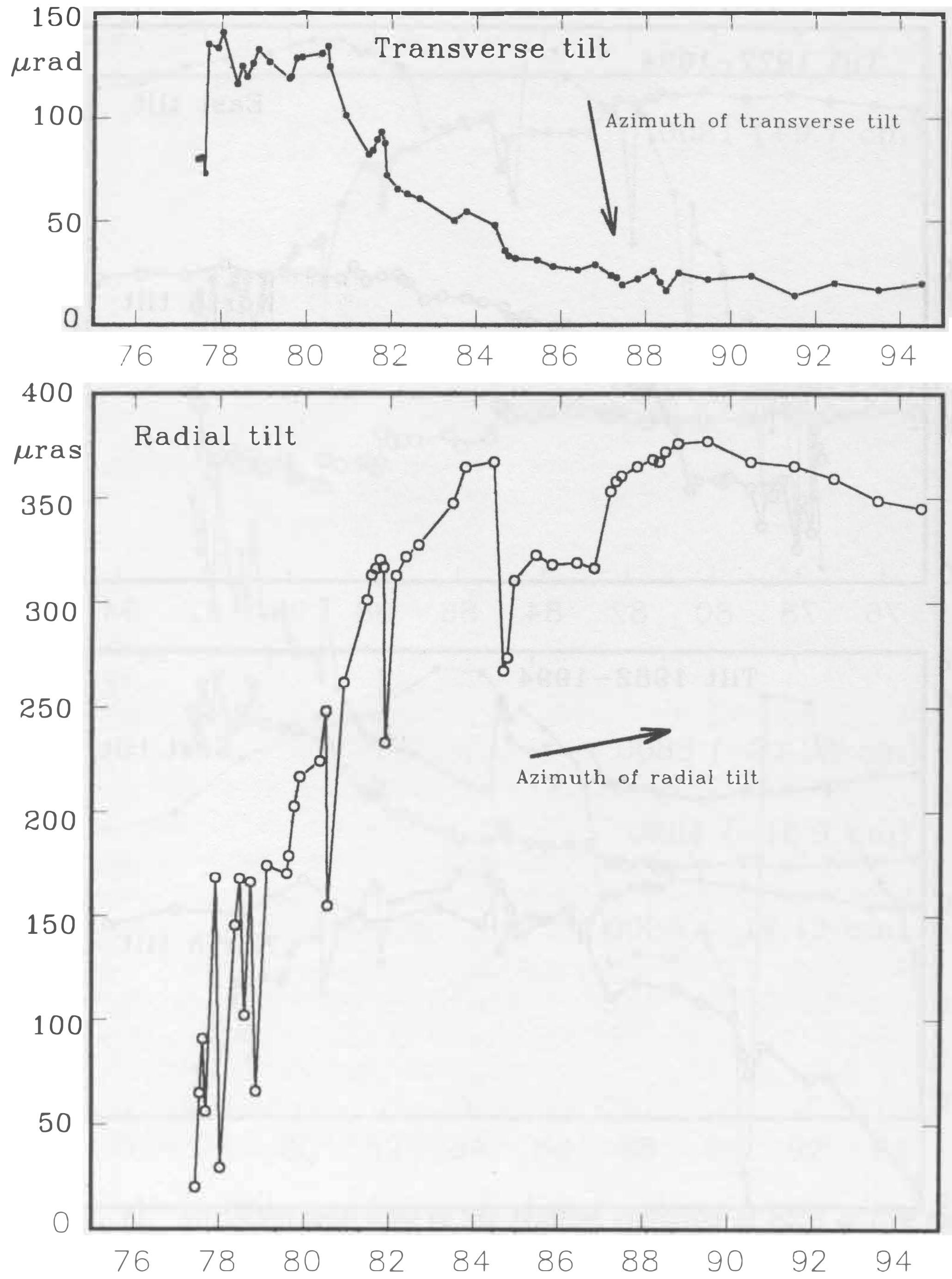


Fig. J4. Observed transverse (top) and radial (bottom) components of tilt at the tilt station Ytri Bjarghóll, relative to the center of deformation of the Krafla volcano. Direction to the center of deformation is taken to be 80°, the average direction of downward tilt during deflations of the Krafla volcano. Transverse tilt is positive toward an azimuth of 170°. Principal features of the transverse tilt is the abrupt commencing of downward tilt in July 1980, related to the uplift of a region about 5 km north of Krafla. Radial tilt shows an almost continuous uplift from 1977 to 1984, interrupted by brief events of subsidence. Definite subsidence is observed after 1989.

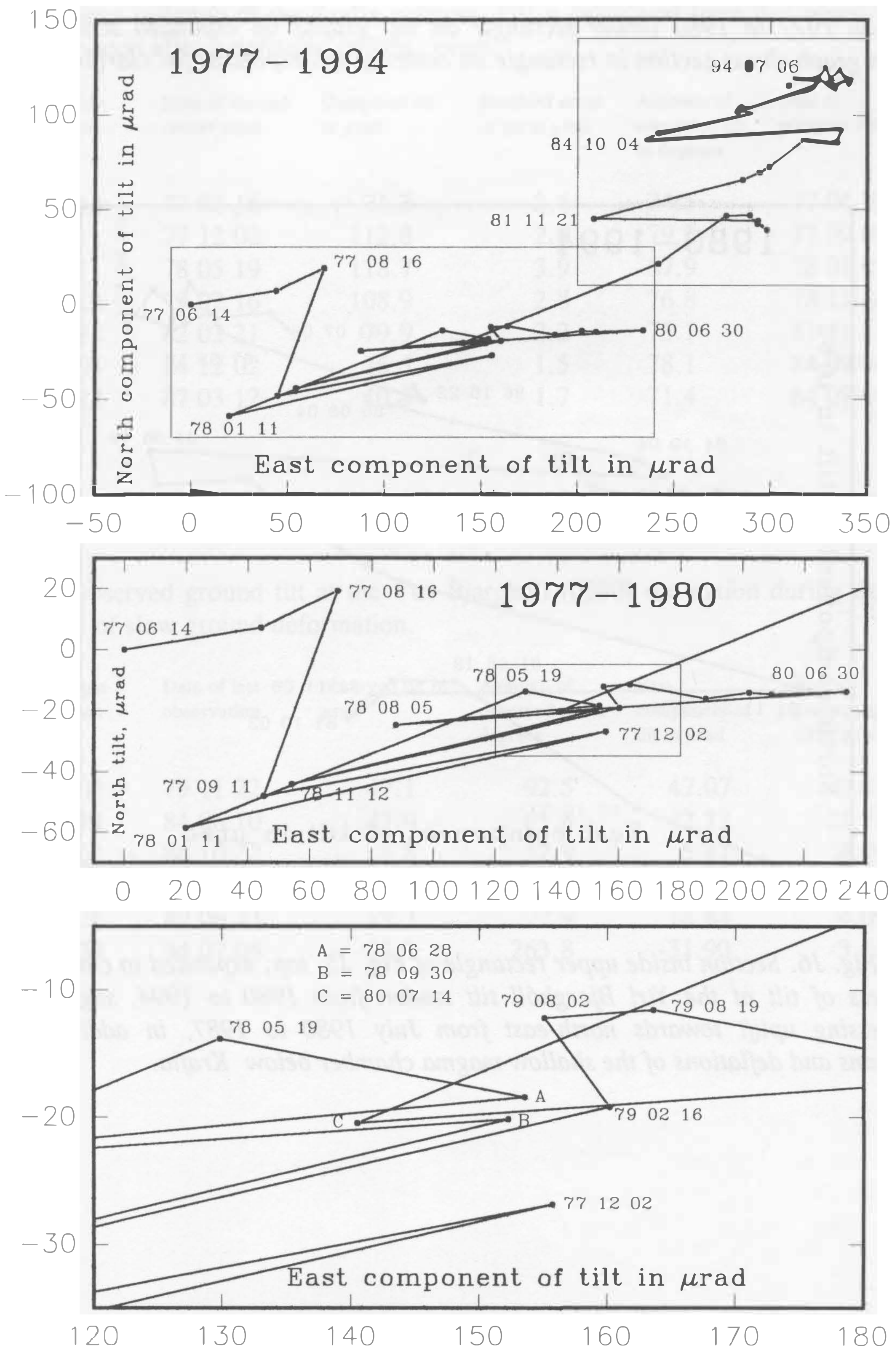


Fig. J5. Caption is on next page.

Fig. J5. North component of tilt plotted against east component of tilt at the tilt station Ytri Bjarghóll, showing the progress of the tilt vector through time. Top graph includes all observations from 1977 to 1994. Center graph shows observed tilt from 1977 to 1980 (lower rectangle on top graph) on expanded scale. The bottom graph shows section in rectangle on center graph expanded for clarification.

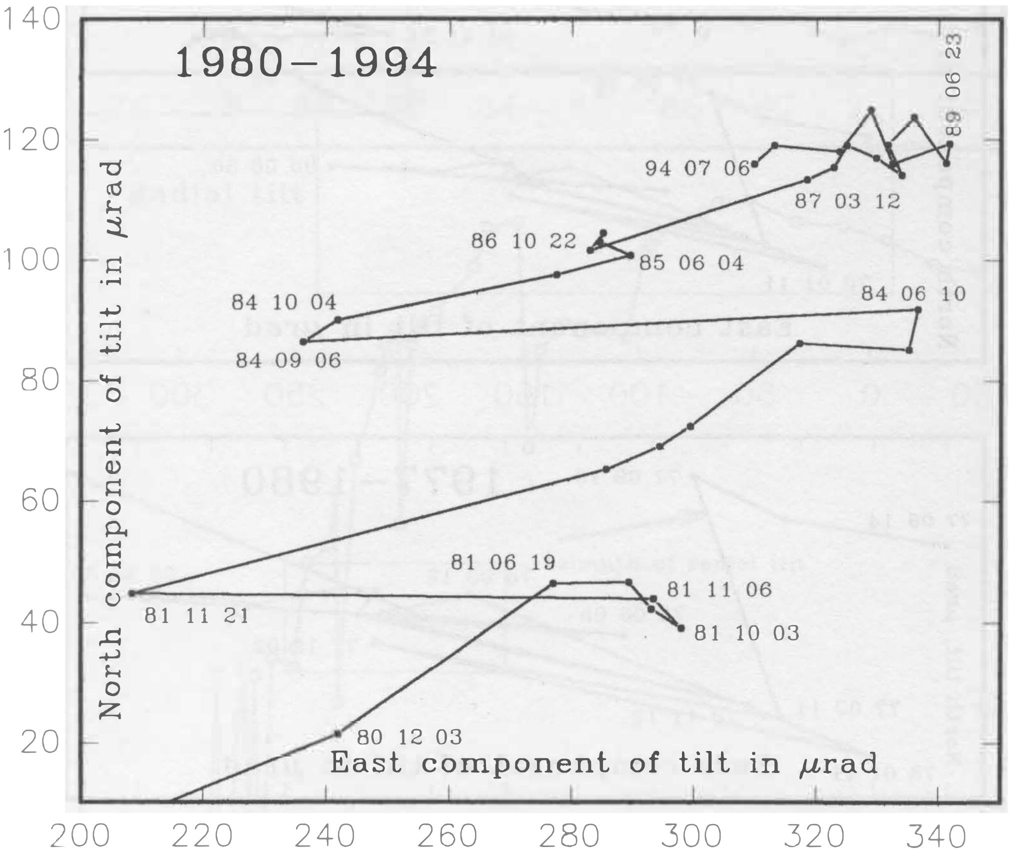


Fig. J6. Section inside upper rectangle of Fig. J5, top, expanded to clarify the progress of tilt at the Ytri Bjarghóll tilt station from 1980 to 1994, suggesting progressing uplift towards north-east from July 1980 to 1987, in addition to inflations and deflations of the shallow magma chamber below Krafla.

Table J2

Observed tilt at the tilt station Ytri Bjarghóll (0080) during selected periods of continuous inflation of the Krafla volcano. Tilt is calculated from two observations, usually soon after a deflation (rifting) event.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of previous rifting
77 06 14	77 08 16	71.3	2.6	74.5	77 04 28
77 09 11	77 12 02	112.8	2.0	79.2	77 09 08
78 01 11	78 05 19	118.7	3.9	67.9	78 01 07
78 11 12	79 02 16	108.9	2.8	76.8	78 11 10
81 11 21	82 02 21	79.9	2.2	75.1	81 11 18
84 10 04	84 12 02	36.5	1.5	78.1	84 09 04
86 10 22	87 03 12	40.3	1.7	71.4	84 09 04

Table J3

Observed ground tilt at the Ytri Bjarghóll (0080) tilt station during extended periods of slow ground deformation.

Date of first observation	Date of last observation	observed tilt in μrad	Azimuth of observed tilt in degrees	East component of tilt in μrad	North component of tilt in μrad
79 08 02	79 11 22	47.1	92.5	47.07	-2.07
82 05 14	84 06 10	47.9	61.6	42.12	22.78
84 12 02	86 10 22	6.8	52.9	5.41	4.09
85 06 04	86 10 22	6.7	278.0	-6.62	0.93
87 04 28	89 06 23	19.3	77.9	18.84	4.05
89 06 23	94 07 06	32.1	263.8	-31.90	-3.48

Table J4

Observed tilt at tilt station 0080, Ytri Bjarghóll. Minimum axis of the error ellipse is 94% of the maximum axis. Azimuth of maximum axis is 93°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
77 06 14			0.000	0.000		
77 07 18	44.186	7.008	44.186	7.008	6.571	6.571
77 08 16	24.517	12.052	68.703	19.060	2.608	5.587
77 09 11	-23.679	-67.161	45.024	-48.100	5.542	10.926
77 12 02	110.736	21.221	155.760	-26.880	2.030	9.237
78 01 11	-135.911	-31.658	19.849	-58.538	4.324	13.556
78 05 19	109.992	44.690	129.841	-13.848	3.891	11.254
78 06 28	23.762	-4.552	153.603	-18.400	3.802	8.984
78 08 05	-65.852	-6.284	87.751	-24.684	1.712	10.675
78 09 30	64.536	4.541	152.287	-20.142	2.418	8.370
78 11 12	-98.111	-23.939	54.176	-44.081	2.987	10.408
79 02 16	106.048	24.907	160.224	-19.174	2.762	8.703
79 08 02	-5.092	6.988	155.133	-12.186	0.334	8.771
79 08 19	8.486	0.636	163.618	-11.550	2.780	5.993
79 10 03	24.562	-4.515	188.180	-16.065	2.029	8.010
79 11 22	14.019	1.805	202.199	-14.260	0.881	7.935
80 05 09	7.320	-0.449	209.519	-14.708	2.200	9.586
80 06 30	24.474	0.921	233.993	-13.787	3.407	7.865
80 07 14	-93.459	-6.690	140.534	-20.477	2.830	7.388
80 12 03	101.335	41.920	241.869	21.443	0.920	8.305
81 06 19	35.184	25.023	277.052	46.465	5.416	9.136
81 07 22	12.305	0.233	289.357	46.698	4.979	6.495
81 08 30	3.744	-4.468	293.101	42.230	0.100	6.588
81 10 03	4.830	-3.053	297.931	39.178	1.359	7.573
81 11 06	-4.539	4.725	293.392	43.903	1.618	5.955
81 11 21	-84.978	0.835	208.414	44.738	1.438	6.172
82 02 21	77.238	20.551	285.653	65.289	2.208	5.121
82 05 14	8.669	3.796	294.322	69.085	2.460	4.069
82 09 01	5.031	3.283	299.353	72.369	1.335	4.295
83 06 24	17.891	13.842	317.244	86.210	1.163	3.361
83 10 07	17.703	-1.044	334.947	85.166	3.141	6.192
84 06 10	1.493	6.698	336.440	91.864	3.382	3.579
84 09 06	-100.170	-5.405	236.269	86.460	1.639	3.477
84 10 04	5.630	3.582	241.899	90.042	1.322	4.467
84 12 02	35.693	7.531	277.592	97.572	1.500	5.242
85 06 04	12.033	3.155	289.625	100.727	1.422	4.017
85 10 22	-5.023	2.274	284.602	103.001	0.144	4.056
86 05 24	0.511	1.545	285.113	104.546	0.927	3.362
86 10 22	-2.109	-2.885	283.004	101.661	1.118	4.372
87 03 12	38.158	12.867	321.161	114.528	1.721	2.839
87 03 12	-2.758	-1.310	318.403	113.218	1.523	3.999
87 04 28	4.381	1.986	322.784	115.204	0.854	3.148
87 06 12	2.142	3.727	324.926	118.931	1.636	3.734
87 10 25	4.740	-2.089	329.666	116.841	1.787	4.143
88 03 06	4.110	-2.908	333.776	113.933	1.290	5.259

88 05 02	-2.199	5.137	331.577	119.071	2.052	3.224
88 06 24	4.259	4.707	335.835	123.778	0.473	3.679
88 10 12	5.274	-7.830	341.109	115.948	1.586	3.958
89 06 23	0.516	3.308	341.626	119.256	1.855	3.833
90 06 27	-9.003	-3.380	332.623	115.876	0.195	4.001
91 07 08	-3.839	8.981	328.784	124.857	1.146	3.725
92 06 17	-5.051	-6.941	323.733	117.916	1.066	4.217
93 06 29	-10.665	1.079	313.068	118.994	0.799	4.540
94 07 06	-3.345	-3.213	309.724	115.781	0.793	3.940

Table J5

Marker coordinates and observed marker elevation at the tilt station 0080 (Ytri Bjarghóll) relative to the average value for all five markers at the tilt station

Marker	0081	0082	0083	0084	0085
Marker coordinates in meters surveyed 81 08 30					
East	14.29	-10.05	-24.15	-3.78	23.70
North	19.73	21.36	-4.32	-25.83	10.93
Y M D	Marker elevation, centimeters				
77 06 14	11.9089	34.7757	-19.5051	-9.7381	-17.4413
77 07 18	12.0219	34.7119	-19.6012	-9.7670	-17.3657
77 08 16	12.0706	34.7152	-19.6578	-9.8201	-17.3078
77 09 11	11.9217	34.5656	-19.5441	-9.6546	-17.2884
77 12 02	12.1107	34.5104	-19.8256	-9.7526	-17.0431
78 01 11	11.8703	34.5551	-19.4636	-9.6299	-17.3319
78 05 19	12.0939	34.5589	-19.7541	-9.7931	-17.1056
78 06 28	12.1261	34.5313	-19.8268	-9.7701	-17.0605
78 08 05	12.0272	34.5742	-19.6581	-9.7316	-17.2118
78 09 30	12.1167	34.5329	-19.8246	-9.7656	-17.0594
78 11 12	11.9460	34.5672	-19.5750	-9.6600	-17.2780
79 02 16	12.1314	34.5251	-19.8427	-9.7717	-17.0419
79 08 02	12.1395	34.5443	-19.8340	-9.7865	-17.0633
79 08 19	12.1422	34.5529	-19.8674	-9.7849	-17.0426
79 10 03	12.1747	34.5075	-19.9148	-9.7888	-16.9788
79 11 22	12.2016	34.4967	-19.9522	-9.7944	-16.9519
80 05 09	12.2112	34.4811	-19.9581	-9.8069	-16.9271
80 06 30	12.2289	34.4749	-20.0224	-9.8241	-16.8574
80 07 14	12.0948	34.5498	-19.8002	-9.7587	-17.0857
80 12 03	12.3251	34.5325	-20.0585	-9.9082	-16.8910
81 06 19	12.4454	34.5468	-20.1709	-9.9594	-16.8617
81 07 22	12.4386	34.5481	-20.1939	-9.9842	-16.8084
81 08 30	12.4353	34.5343	-20.2005	-9.9745	-16.7945
81 10 03	12.4353	34.5190	-20.2040	-9.9755	-16.7750
81 11 06	12.4332	34.5424	-20.2031	-9.9809	-16.7916
81 11 21	12.3203	34.6265	-20.0008	-9.9448	-17.0010
82 02 21	12.4590	34.6017	-20.1968	-10.0330	-16.8308
82 05 14	12.4845	34.6040	-20.2300	-10.0330	-16.8253
82 09 01	12.4940	34.6057	-20.2386	-10.0503	-16.8106
83 06 24	12.5462	34.9217	-20.2940	-10.0873	-16.7865
83 10 07	12.5732	34.5882	-20.3195	-10.1053	-16.7365

84 06 10	12.5876	34.6131	-20.3439	-10.1067	-16.7502
84 09 06	12.4268	34.7045	-20.0955	-10.0625	-16.9735
84 10 04	12.4492	34.6996	-20.1078	-10.0727	-16.9683
84 12 02	12.5229	34.6749	-20.1984	-10.1005	-16.8991
85 06 04	12.5384	34.6766	-20.2311	-10.1152	-16.8689
85 10 22	12.5354	34.6864	-20.2193	-10.1199	-16.8826
86 05 24	12.5382	34.6930	-20.2262	-10.1199	-16.8853
86 10 22	12.5324	34.6832	-20.2141	-10.1156	-16.8861
87 03 12	12.6078	34.6813	-20.3206	-10.1572	-16.8112
87 03 12	12.6032	34.6747	-20.3052	-10.1595	-16.8130
87 04 28	12.6097	34.6794	-20.3203	-10.1648	-16.8040
87 06 12	12.6274	34.6824	-20.3308	-10.1679	-16.8112
87 10 25	12.6267	34.6703	-20.3332	-10.1738	-16.7901
88 03 06	12.6339	34.6532	-20.3392	-10.1667	-16.7814
88 05 02	12.6325	34.6781	-20.3451	-10.1750	-16.7907
88 06 24	12.6504	34.6813	-20.3562	-10.1886	-16.7871
88 10 12	12.6376	34.6589	-20.3596	-10.1786	-16.7585
89 06 23	12.6512	34.6651	-20.3687	-10.1779	-16.7699
90 06 27	12.6328	34.6661	-20.3453	-10.1653	-16.7885
91 07 08	12.6455	34.6926	-20.3458	-10.1812	-16.8111
92 06 17	12.6257	34.6784	-20.3249	-10.1662	-16.8130
93 06 29	12.6156	34.6909	-20.3021	-10.1610	-16.8434
94 07 06	12.6004	34.6897	-20.2918	-10.1544	-16.8440

TILT STATION 0090, HVANNSTÓÐ

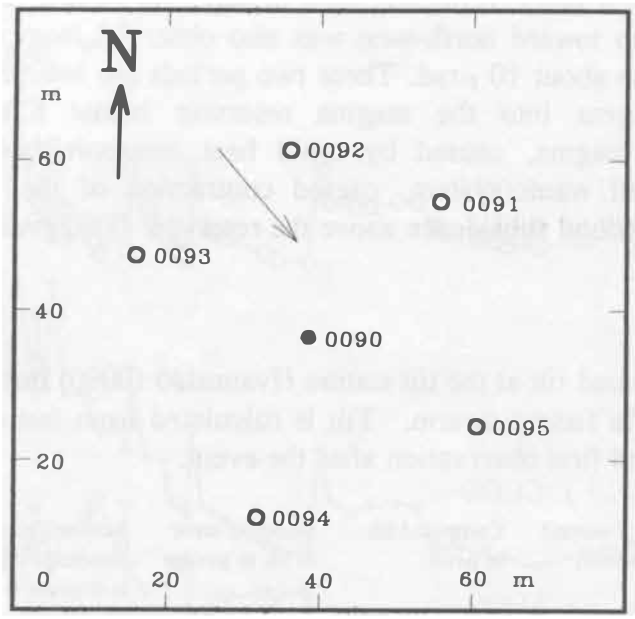


Fig. K1. Map of relative position of markers at the tilt station Hvannstóð, also named tilt station 0090. Solid circle is a marker at the center of a 25.0 m radius circle defined by five markers (open circles). The markers consist of copper alloy nails with a 37 mm diameter convex surface plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Thin arrow points in the average direction of downward tilt during subsidence events of the Krafla volcano.

This tilt station was constructed on June 14, 1977 at a location about 3 km north-west of Leirhnjúkur, but at that time, the center of subsidence during deflation events, was believed to be at or near the small ridge Leirhnjúkur. The station lies on rough pahoehoe lava of the 1724-1729 Mývatn fires, less than 100 m east of the east rim of the prehistoric explosion crater Hvannstóð. Six permanent markers were cemented in small holes drilled into solid lava, 5 markers form a circle of 25.0 m radius and the sixth marker identifies the center of the circle, marking the location where a level is placed during observations (Fig. K1).

The station was observed 55 times from June 1977 to July 1994. The observed marker displacements and ground tilt is dominated by the inflation/deflation cycle of Krafla volcano (Fig. K2 and K3). During inflations, tilt up towards SE was observed and during deflations tilt was up towards NW. In addition, general tilt up in an easterly direction was observed from 1977 to 1994 (Fig. K3), amounting to about 300 μrad.

There was a definite change in azimuth of this background tilt in the summer of 1980, the azimuth changing from south-easterly to north-easterly direction (Figs K4 and K5). This change of tilt azimuth is related to uplift of an area about 5 km north of Leirhnjúkur, where a north-south elongated area was uplifted an average of about 10 cm per year from 1979 to 1986 (Tryggvason 1986). Tilt observations at the stations Ytri Bjarghóll and Hvannstóð suggest that this regional uplift started in the summer of 1980, probably at the time of the July 1980 eruption.

From 1989 to 1994, tilt up towards north-west has been observed, amounting to about 50 μrad in 4 years, reflecting slow deflation of Krafla volcano (Table K3). Similar slow tilt up toward north-west was also observed from early 1985 to late 1986, amounting to about 10 μrad. These two periods are interpreted as periods of no influx of magma into the magma reservoir below Krafla volcano, but crystallisation of magma, caused by rapid heat transport from the magma to surrounding ground water system, caused contraction of the magma reservoir, resulting in slow ground subsidence above the reservoir (Tryggvason 1994).

Table K1

Observed ground tilt at the tilt station Hvannstóð (0090) during selected rifting events of the Krafla fissure swarm. Tilt is calculated from last observation before the rifting event and first observation after the event.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of rifting event
77 08 16	77 09 11	65.2	3.5	312.4	77 09 09
77 12 02	78 01 11	188.9	4.0	307.9	78 01 07
78 06 28	78 08 05	99.3	1.7	310.6	78 07 10
78 09 30	78 11 12	140.8	1.7	304.6	78 11 10
80 06 30	80 07 14	136.0	6.6	321.4	80 07 10
81 11 06	81 11 21	138.7	4.3	324.0	81 11 18
84 06 10	84 09 06	164.0	3.3	318.7	84 09 04

Table K2

Observed tilt at the tilt station Hvannstóð (0090) during selected periods of relatively fast, continuous inflation of the Krafla volcano. Tilt is computed from two successive observations, usually soon after deflation (rifting) events.

Date of first observation	Date of second observation	Computed tilt in μrad	Standard error of tilt in μrad	Azimuth of computed tilt in degrees	Date of previous rifting
77 06 14	77 08 16	87.1	3.9	133.6	77 04 28
77 09 11	77 12 02	153.0	2.7	124.0	77 09 08
78 01 11	78 05 19	152.1	7.5	127.0	78 01 07
78 08 05	78 09 30	94.3	1.7	122.1	78 07 10
78 11 12	79 02 16	141.9	1.3	122.1	78 11 10
81 11 21	82 02 21	109.8	0.8	127.9	81 11 18
84 10 04	84 12 02	60.0	6.2	124.5	84 09 04
86 10 22	87 03 03	51.4	2.4	118.8	84 09 04
86 10 22	87 03 12	50.2	(1,2)	124.7	84 09 04

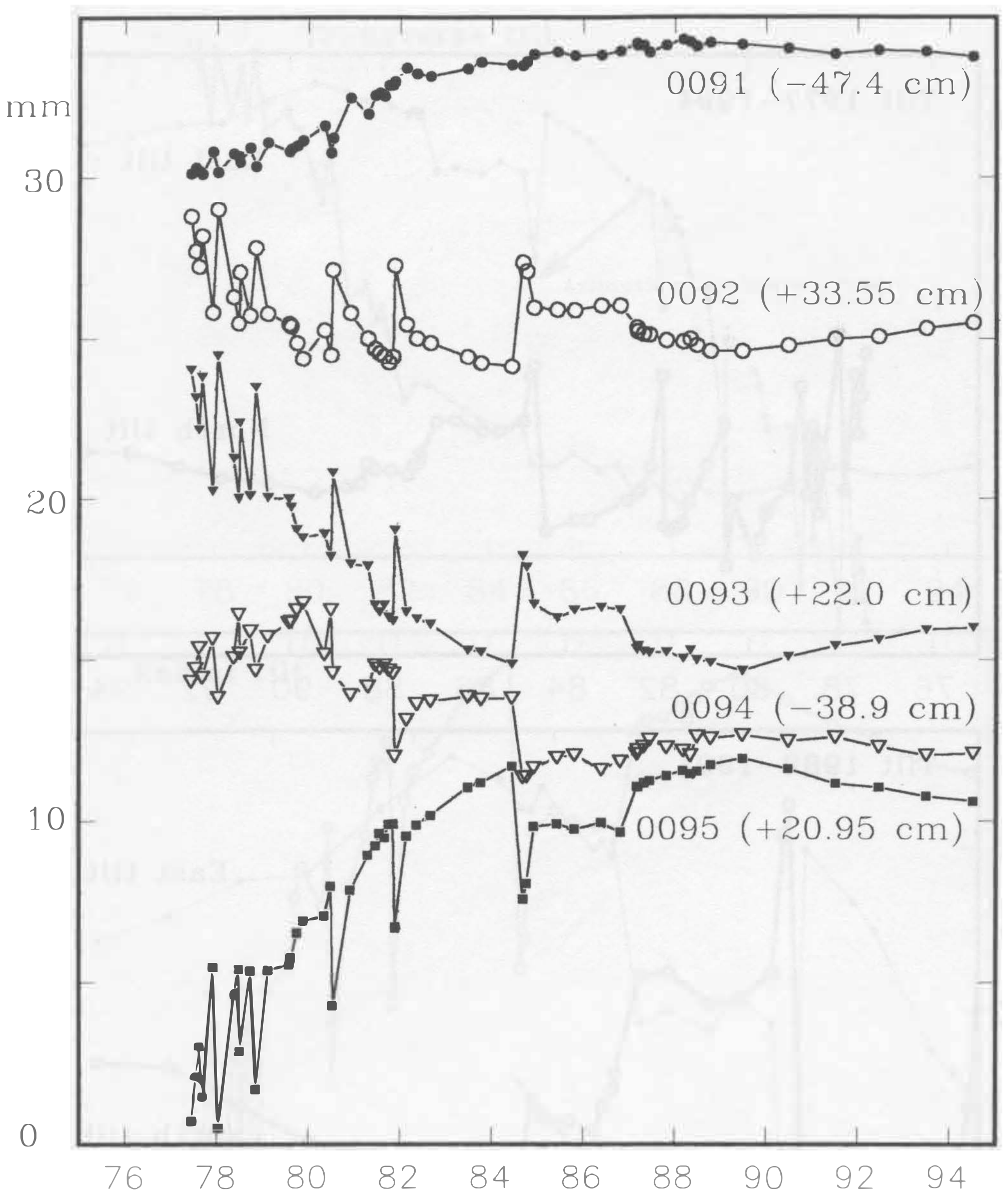


Fig. K2. Variation with time of the relative elevation of each of five markers forming the 25.0 m radius circle of the Hvannstóð tilt station. Markers 0092 and 0093 have been uplifted during each deflation event while marker 0095 subsided. Marker 0094 has subsided slightly during most deflation events but 0091 has not been affected notably during deflation events of the Krafla volcano.

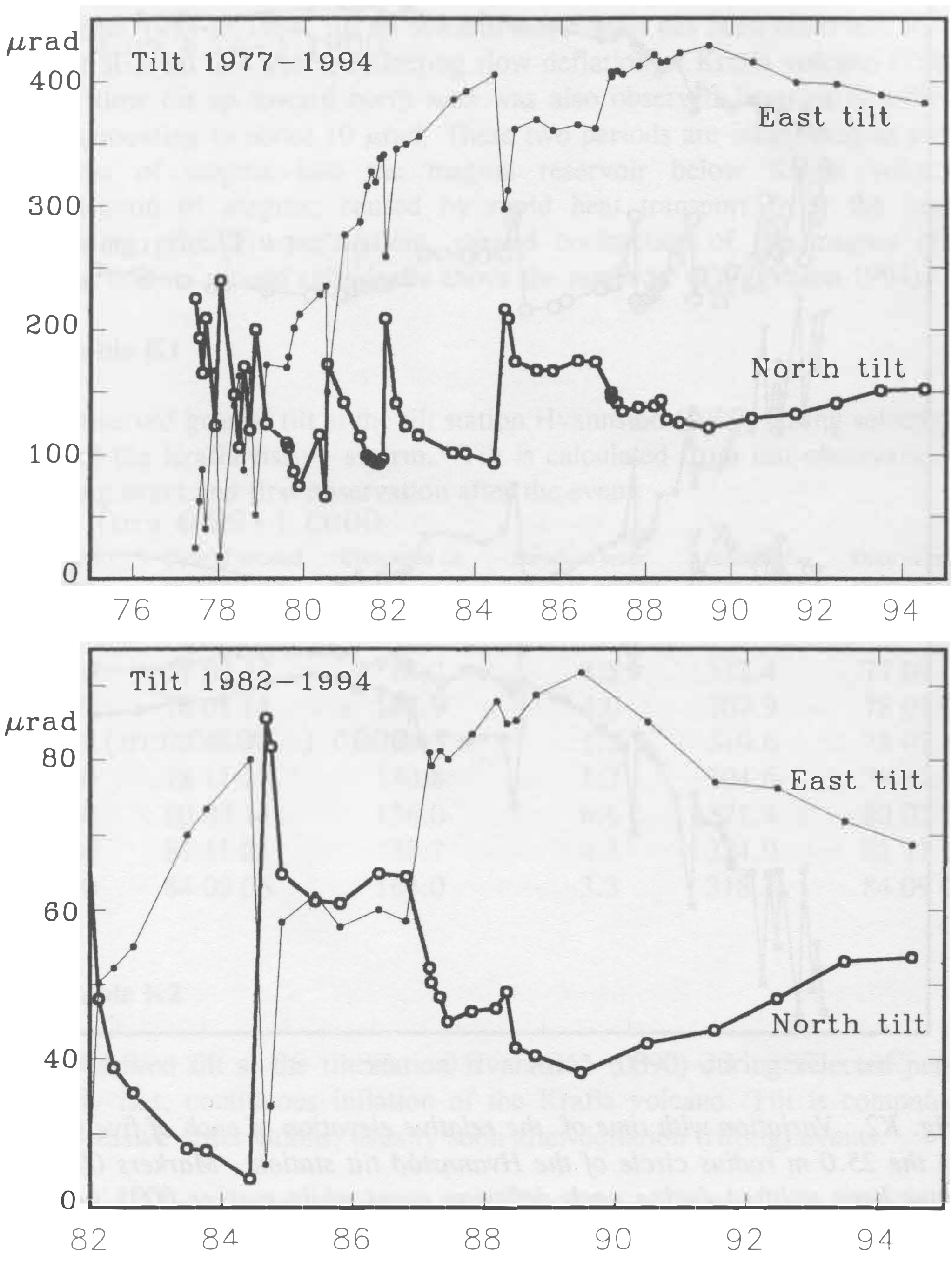


Fig. K3. Observed ground tilt at the tilt station Hvannstóð since first observation of June 14, 1977. East component of tilt is marked by small dots, connected by a thin line and north component of tilt is marked by open circles connected by a thick line. Bottom graph shows tilt variation after 1981 on expanded tilt scale to emphasise relatively gentle tilt variations after activity of Krafla volcano had subsided. Subsidence events are seen as negative east tilt and positive north tilt (tilt up towards west and north). The bottom graph shows clearly the reversal of tilt in 1989, and also the period of near zero tilt from early 1985 to late 1986, and rapid inflation from late 1986 to early 1987.

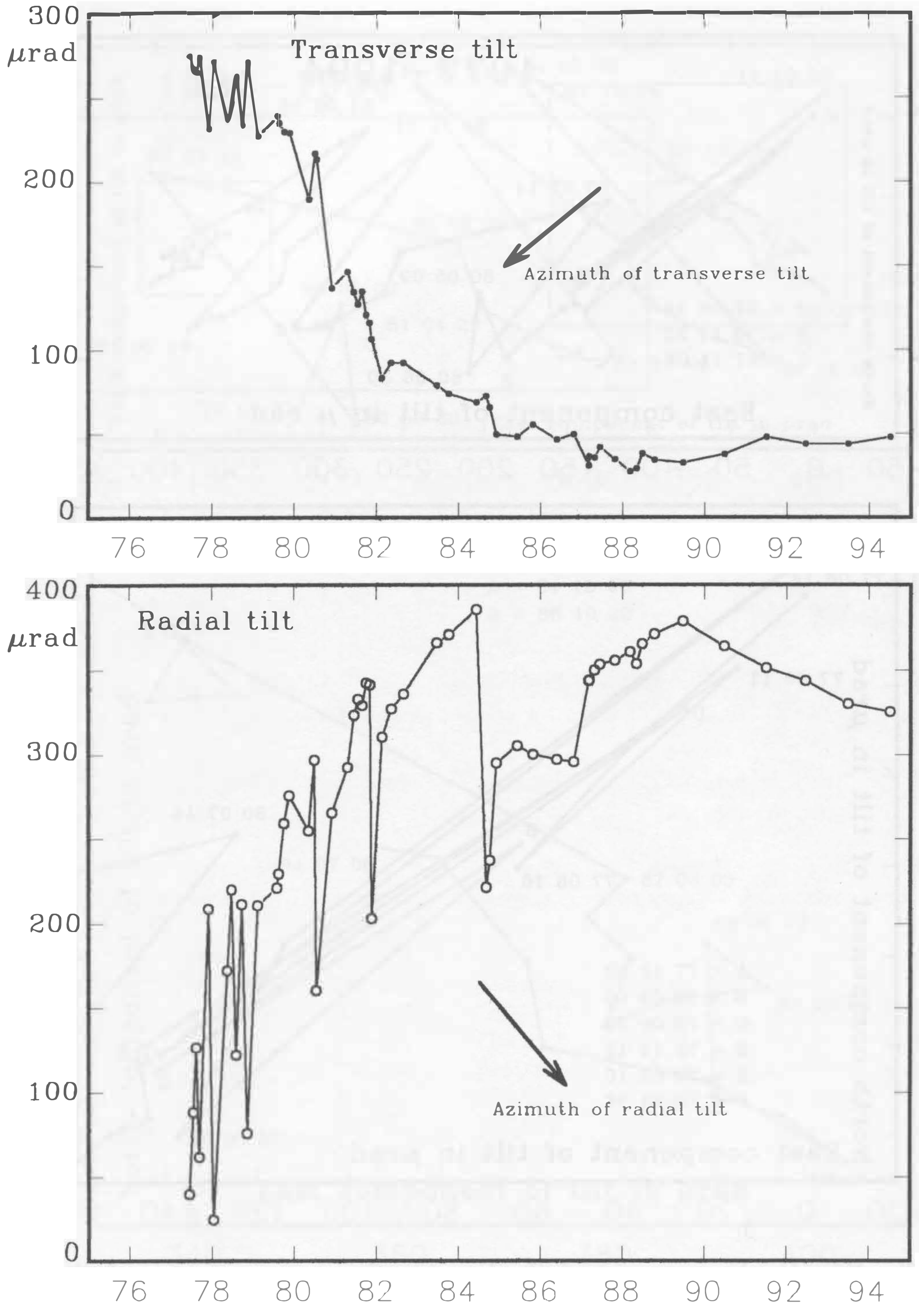


Fig. K4. Observed transverse (top) and radial (bottom) tilt at the tilt station Hvannstóð, relative to the center of deformation at Krafla. Direction to the center of deformation is taken to be 140°, the average direction of downward tilt during deflations of Krafla volcano. Transverse tilt is positive in azimuth 230°. Prominent features of the transverse tilt is negative tilt with highest rate in 1980 to 1982, but decreasing rate after 1982, terminating around 1988. This is related to uplift of a region about 5 km north of Krafla. Radial tilt shows inflation of Krafla volcano from 1977 to 1989, interrupted briefly during each deflation event, resulting in accumulated tilt of about 300 μrad. Deflation starting in 1989 is clearly seen.

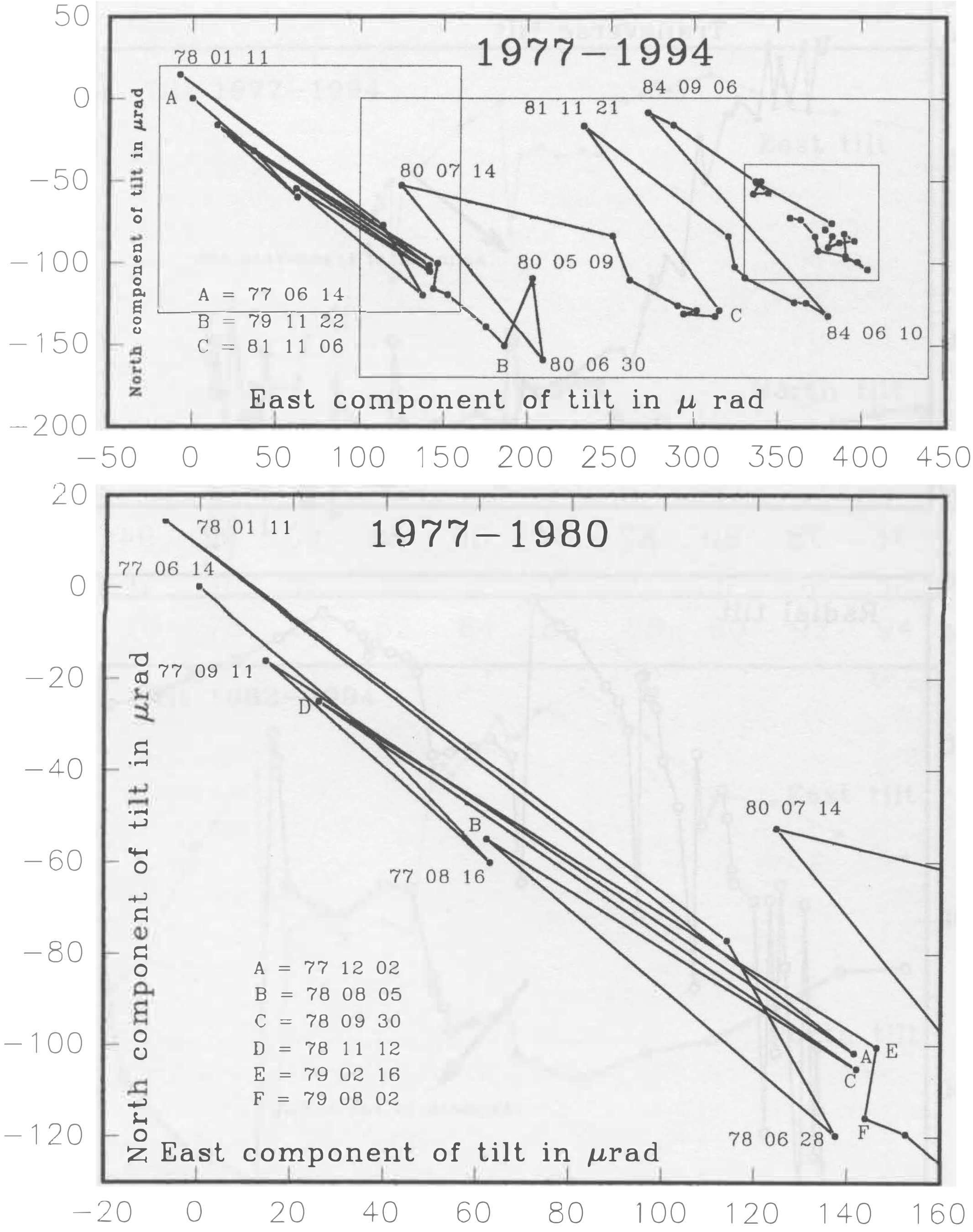


Fig. K5. North component of tilt plotted against east component of tilt at the tilt station Hvannstóð, showing progress of the tilt vector through time. Top graph shows observed tilt from 1977 to 1994. Before 1980 deflation tilt and inflation tilt falls on nearly the same line, but starting in 1980, inflation tilt follows a more easterly path. Bottom graph shows observed tilt from 1977 to 1980 (left rectangle on top graph) on expanded tilt scale.

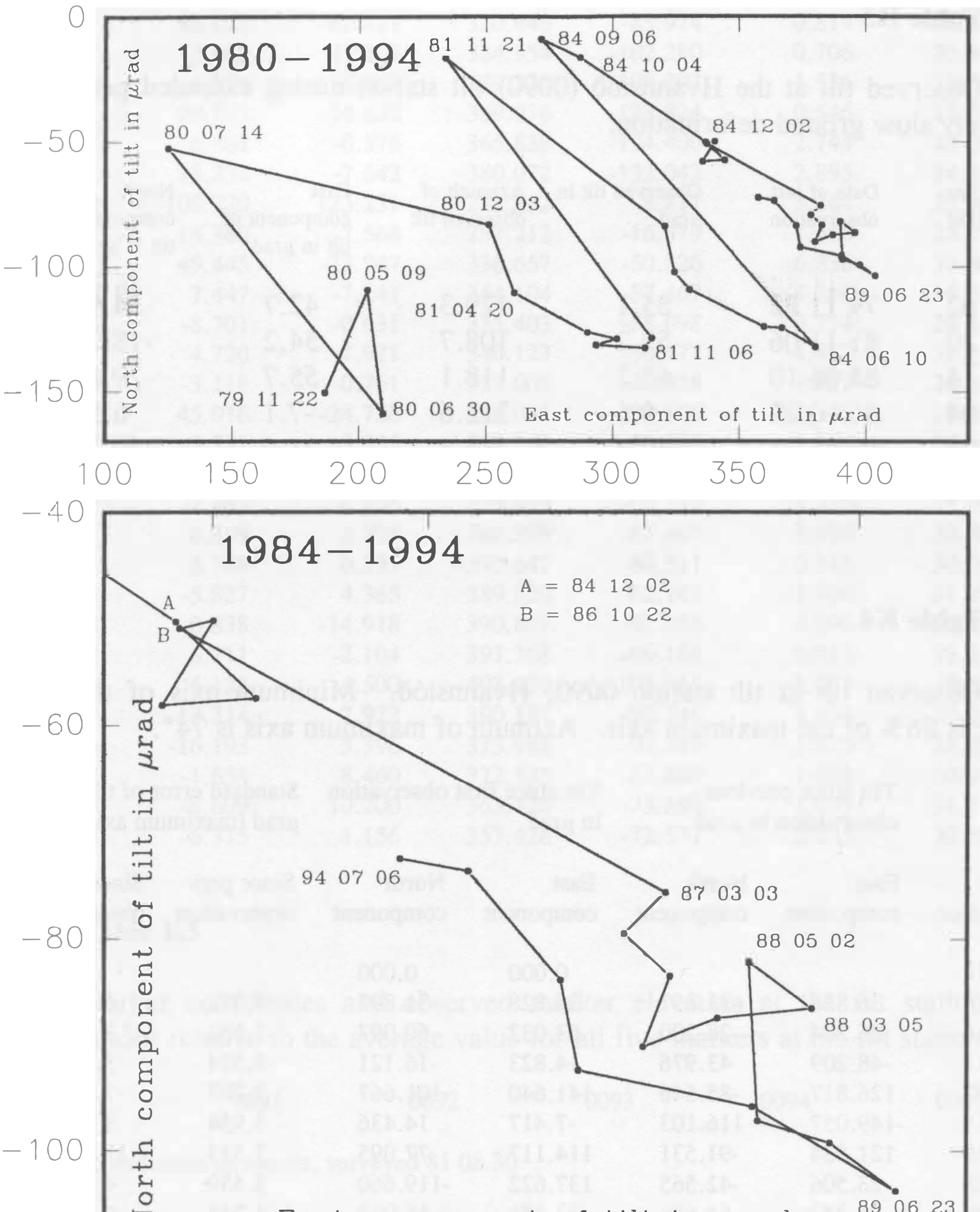


Fig. K6. North component of tilt plotted against east component of tilt at the tilt station Hvannstóð. Top graph shows the progress of the tilt vector from 1980 to 1994 (large right rectangle on Fig. K5, top) and bottom graph shows the tilt vector progress from 1984 to 1994 (small rectangle on Fig. K5, top) on an expanded scale. Irregularities in the tilt progress on the bottom graph suggest observational errors of possibly 5 μrad.

Table K3

Observed tilt at the Hvannstóð (0090) tilt station during extended periods of relatively slow ground deformation.

Date of first observation	Date of last observation	Observed tilt in μrad	Azimuth of observed tilt	East component of tilt in μrad	North component of tilt in μrad
79 08 02	79 11 22	55.1	129.3	42.7	-34.9
81 04 20	81 11 06	57.2	108.7	54.2	-18.3
82 05 14	84 06 10	63.2	118.1	55.7	-29.8
85 06 04	86 10 22	9.6	312.6	-7.1	6.5
87 04 28	89 06 23	29.1	133.8	21.0	-20.2
89 06 23	94 07 06	55.6	304.1	-46.1	31.1

Table K4

Observed tilt at tilt station 0090, Hvannstóð. Minimum axis of the error ellipse is 86% of the maximum axis. Azimuth of maximum axis is 74°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
77 06 14			0.000	0.000		
77 07 18	36.828	-31.897	36.828	-31.897	5.372	5.372
77 08 16	26.204	-28.200	63.032	-60.097	3.881	2.045
77 09 11	-48.209	43.976	14.823	-16.121	3.524	5.370
77 12 02	126.817	-85.546	141.640	-101.667	2.707	7.901
78 01 11	-149.057	116.103	-7.417	14.436	3.954	3.947
78 05 19	121.534	-91.531	114.117	-77.095	7.513	11.437
78 06 28	23.506	-42.565	137.622	-119.660	8.459	4.158
78 08 05	-75.442	64.626	62.181	-55.033	1.742	5.895
78 09 30	79.887	-50.063	142.067	-105.096	1.711	5.713
78 11 12	-115.875	79.995	26.192	-25.101	1.671	6.277
79 02 16	120.235	-75.304	146.427	-100.406	1.330	6.007
79 08 02	-2.455	-15.407	143.972	-115.812	0.177	6.125
79 08 19	8.663	-3.426	152.635	-119.238	0.541	5.643
79 10 03	22.904	-19.466	175.539	-138.704	0.341	5.729
79 11 22	11.089	-11.970	186.628	-150.675	3.529	8.697
80 05 09	16.638	41.277	203.267	-109.398	9.075	12.843
80 06 30	6.390	-49.638	209.657	-159.036	5.373	10.867
80 07 14	-84.908	106.298	124.749	-52.739	6.628	4.312
80 12 03	126.203	-30.698	250.951	-83.437	11.022	15.329
81 04 20	10.262	-27.014	261.213	-110.450	9.594	24.920
81 06 19	28.849	-15.697	290.063	-126.147	10.886	14.113
81 07 22	11.575	-2.761	301.638	-128.908	2.222	16.334
81 08 30	-8.129	-2.268	293.509	-131.176	1.238	16.791
81 10 03	19.159	-1.276	312.667	-132.452	1.823	17.898

81 11 06	2.723	3.699	315.390	-128.754	1.933	17.195
81 11 21	-81.567	112.190	233.823	-16.563	4.258	20.107
82 02 21	86.623	-67.411	320.446	-83.974	0.814	20.637
82 05 14	3.908	-18.306	324.354	-102.280	0.706	20.391
82 09 01	5.871	-6.923	330.225	-109.202	1.536	21.527
83 06 24	29.751	-14.622	359.976	-123.824	0.546	22.068
83 10 07	6.861	-0.576	366.838	-124.400	2.744	23.064
84 06 10	13.234	-7.642	380.072	-132.042	2.895	24.601
84 09 06	-108.220	123.231	271.852	-8.811	3.264	23.688
84 10 04	15.360	-7.568	287.212	-16.379	1.566	25.024
84 12 02	49.445	-33.947	336.657	-50.326	6.236	30.686
85 06 04	7.447	-7.141	344.104	-57.467	4.366	26.501
85 10 22	-8.701	-0.631	335.403	-58.098	0.774	26.856
86 05 24	4.720	7.921	340.123	-50.177	4.462	31.276
86 10 22	-3.118	-0.761	337.005	-50.938	4.851	26.524
87 03 03	45.016	-24.728	382.021	-75.666	2.379	28.526
87 03 12	-3.781	-3.835	378.240	-79.501	1.244	28.670
87 04 28	4.226	-3.985	382.466	-83.486	0.806	28.166
87 06 12	-2.467	-6.626	379.999	-90.112	1.736	28.067
87 10 25	6.899	2.705	386.899	-87.407	3.699	30.203
88 03 05	8.748	0.897	395.647	-86.511	0.515	30.093
88 05 02	-5.827	4.365	389.820	-82.146	1.900	31.993
88 06 24	0.838	-14.918	390,657	-97.064	4.096	28.006
88 10 12	6.711	-2.104	397.368	-99.168	2.015	29.389
89 06 23	6.127	-4.500	403.495	-103.668	2.035	28.832
90 06 27	-13.314	7.922	390.181	-95.746	1.634	30.447
91 07 08	-16.193	3.396	373.988	-92.349	1.825	28.665
92 06 17	-1.654	8.460	372.335	-83.889	1.933	30.101
93 06 29	-8.609	10.200	363.726	-73.690	1.099	31.152
94 07 06	-6.315	1.156	357.428	-72.537	2.235	30.507

Table K5

Marker coordinates and observed marker elevation at the tilt station 0090 (Hvannstóð) relative to the average value for all five markers at the tilt station.

Marker	0091	0092	0093	0094	0095
Marker coordinates in meters, surveyed 81 08 30					
East	15.73	-3.98	-24.05	-8.24	20.54
North	14.49	21.28	7.25	-27.68	-15.34
Y M D	Marker elevation, centimeters				
77 06 14	-44.3856	36.4307	24.4009	-37.4668	21.0207
77 07 18	-44.3674	36.3213	24.3146	-37.4264	21.1578
77 08 16	-44.3778	36.2730	24.2144	-37.3610	21.2514
77 09 11	-44.3867	36.3688	24.3790	-37.4550	21.0940
77 12 02	-44.3181	36.1313	24.0228	-37.3342	21.4981
78 01 11	-44.3804	36.4511	24.4473	-37.5167	20.9986
78 05 19	-44.3241	36.1781	24.1241	-37.3926	21.4144
78 06 28	-44.3308	36.0976	24.0011	-37.2584	21.4906
78 08 05	-44.3502	36.2550	24.2365	-37.3785	21.2372
78 09 30	-44.3060	36.1212	24.0099	-37.3108	21.4859
78 11 12	-44.3632	36.3311	24.3468	-37.4332	21.1186

79 02 16	-44.2903	36.1271	24.0039	-37.3274	21.4869
79 08 02	-44.3170	36.0950	23.9993	-37.2835	21.5063
79 08 19	-44.3104	36.0874	23.9739	-37.2804	21.5294
79 10 03	-44.3007	36.0355	23.9048	-37.2447	21.6050
79 11 22	-44.2839	35.9856	23.8793	-37.2217	21.6406
80 05 09	-44.2382	36.0745	23.8915	-37.3838	21.6562
80 06 30	-44.3212	35.9978	23.8205	-37.2448	21.7475
80 07 14	-44.2767	36.2610	24.0800	-37.4418	21.3777
80 12 03	-44.1536	36.1286	23.7968	-37.5074	21.7356
81 04 20	-44.2014	36.0499	23.7908	-37.4817	21.8423
81 06 19	-44.1450	36.0177	23.6700	-37.4163	21.8737
81 07 22	-44.1364	36.0031	23.6491	-37.4276	21.9119
81 08 30	-44.1477	35.9942	23.6715	-37.4163	21.8982
81 10 03	-44.1138	35.9734	23.6322	-37.4323	21.9407
81 11 06	-44.1122	35.9915	23.6217	-37.4428	21.9420
81 11 21	-44.1005	36.2747	23.9029	-37.6983	21.6214
82 02 21	-44.0606	36.0924	23.6494	-37.5856	21.9042
82 05 14	-44.0771	36.0486	23.6276	-37.5372	21.9381
82 09 01	-44.0859	36.0356	23.6101	-37.5274	21.9678
83 06 24	-44.0622	35.9923	23.5298	-37.5137	22.0540
83 10 07	-44.0425	35.9722	23.5235	-37.5223	22.0690
84 06 10	-44.0486	35.9617	23.4859	-37.5183	22.1194
84 09 06	-44.0516	36.2861	23.8226	-37.7646	21.7076
84 10 04	-44.0393	36.2580	23.7875	-37.7625	21.7564
84 12 02	-44.0160	36.1441	23.6728	-37.7344	21.9335
85 06 04	-44.0081	36.1388	23.6303	-37.7026	21.9418
85 10 22	-44.0206	36.1365	23.6541	-37.6955	21.9256
86 05 24	-44.0177	36.1491	23.6633	-37.7397	21.9449
86 10 22	-44.0052	36.1496	23.6551	-37.7154	21.9158
87 03 03	-43.9821	36.0838	23.5327	-37.6919	22.0575
87 03 12	-43.9883	36.0699	23.5432	-37.6793	22.0546
87 04 28	-43.9889	36.0640	23.5264	-37.6694	22.0679
87 06 12	-44.0099	36.0610	23.5219	-37.6476	22.0747
87 10 25	-43.9877	36.0440	23.5242	-37.6712	22.0908
88 03 05	-43.9700	36.0397	23.5047	-37.6806	22.1060
88 05 02	-43.9777	36.0479	23.5295	-37.6959	22.0961
88 06 24	-43.9914	36.0274	23.4986	-37.6382	22.1036
88 10 12	-43.9807	36.0097	23.4903	-37.6441	22.1246
89 06 23	-43.9853	36.0097	23.4648	-37.6338	22.1447
90 06 27	-43.9983	36.0281	23.5094	-37.6517	22.1124
91 07 08	-44.0155	36.0465	23.5429	-37.6401	22.0661
92 06 17	-44.0038	36.0557	23.5622	-37.6686	22.0545
93 06 29	-44.0070	36.0810	23.5935	-37.6941	22.0266
94 07 06	-44.0233	36.0991	23.6009	-37.6885	22.0119

TILT STATION 0200, HVERFJALL

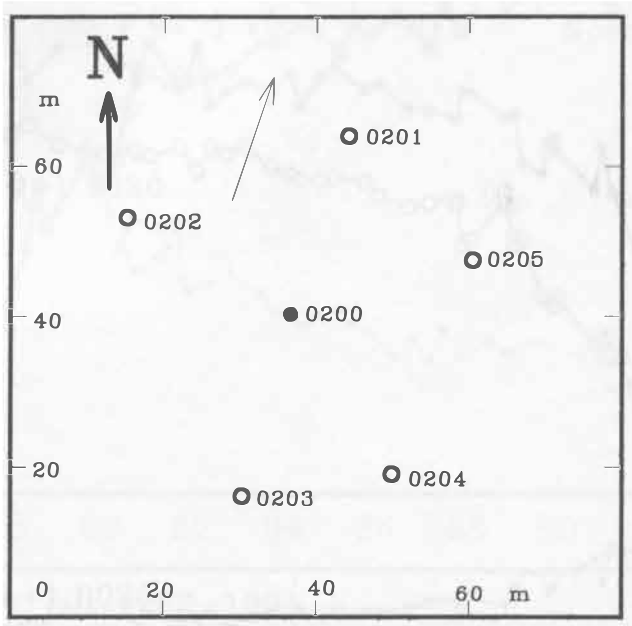


Fig. L1. Map of relative position of markers at the tilt station Hverfjall, also named tilt station 0200. Solid circle is a marker at the center of a 25.0 m radius circle defined by 5 markers (open circles). The markers consist of copper alloy nails with 37 mm diameter convex top plate, cemented into the lava surface. Each marker is identified by an inscribed number as shown. Thin arrow gives the approximate direction to the center of deformation at the Krafla volcano.

This tilt station was constructed on June 15, 1977 at a location in the western part of the Krafla fissure swarm, about 13.5 km south of Leirhnjúkur. The station lies on flat pahoehoe lava, probably originating in the large Þrengslaborgir eruption of about 2300 years ago. (Sæmundsson 1991). It has 5 markers on the periphery of a 25.0 m radius circle and a sixth marker at the center of the circle (Fig. L1).

The station was observed 46 times from June 1977 to July 1994. The observed marker displacements are characterised by almost continuos relative uplift of markers 0201 and 0202 (Fig. L2), and subsidence of the remaining markers, signifying ground tilt up in north-westerly direction (Fig. L3). Small tilt up in easterly direction was observed during the rifting event of September 1977 (Fig. L3) but other rifting or subsidence events are not clearly seen in the observations of the Hverfjall tilt station.

Accumulated tilt up towards north west amounts to about 120 μrad in 16 years, but the tilt rate has been decreasing continuously. The rapid tilt rate in 1977 to 1980 may be interpreted as relaxation of the strain created during the rifting event of April 1977, when fissures were displaced near this tilt station. Total accumulated tilt from June 1977 to July 1984 at the Hverfjall tilt station amounts to about 130 μrad (Fig. L5), up toward north-west. No reversal of tilt is seen in 1989 as at most stations closer to the center of deformation at Krafla.

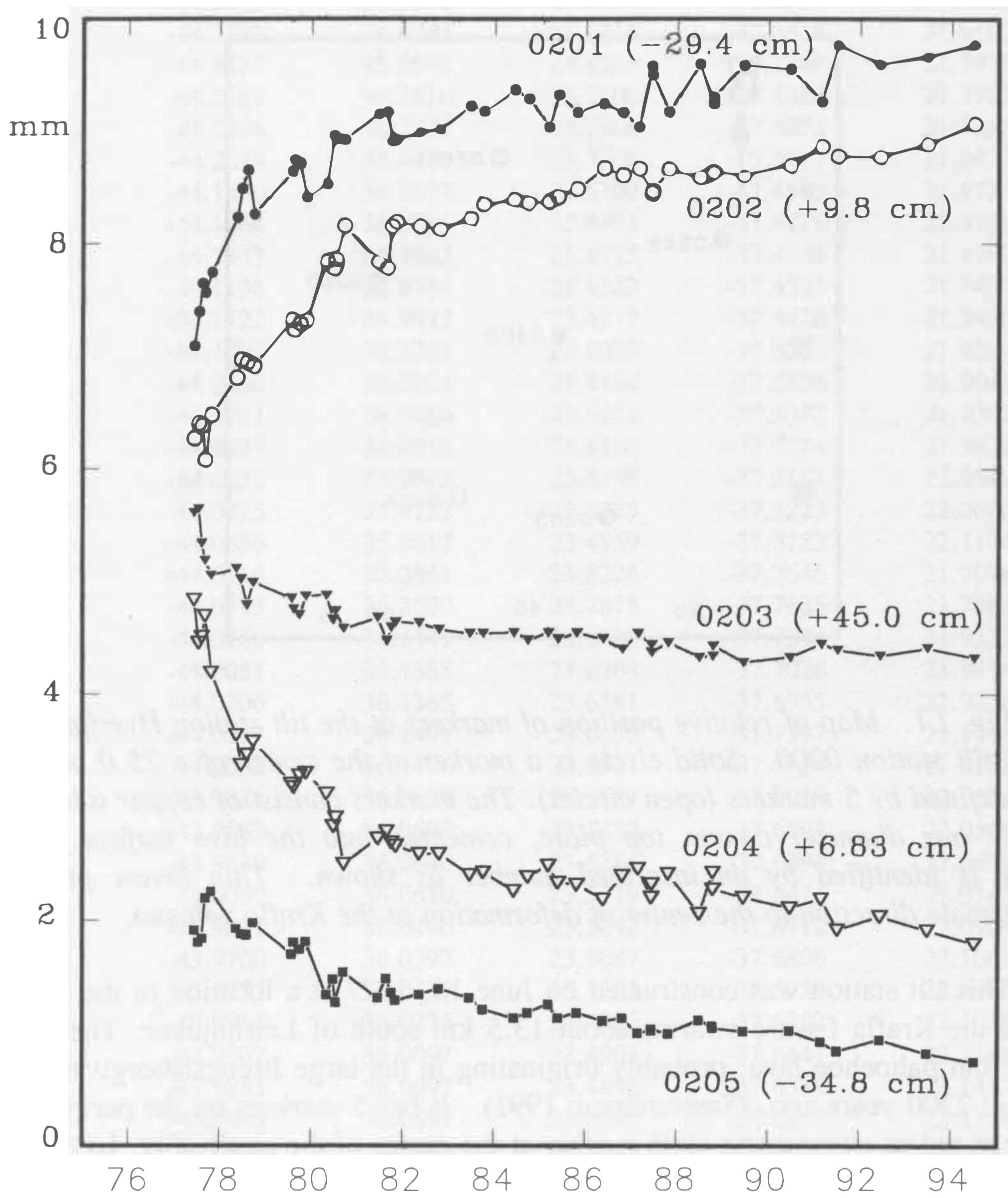


Fig. L2. Variation with time of the relative elevation of each of five markers of the 25.0 m radius circle of the Hverfjall tilt station. Markers 0201 and 0202 have been uplifted at decreasing rate throughout the whole period of observations, while markers 0203, 0204, and 02054 have similarly subsided. Markers 0204 and 0205 appear to have been uplifted slightly during the rifting event of September 8, 1977, and at the same time marker 0202 subsided slightly.

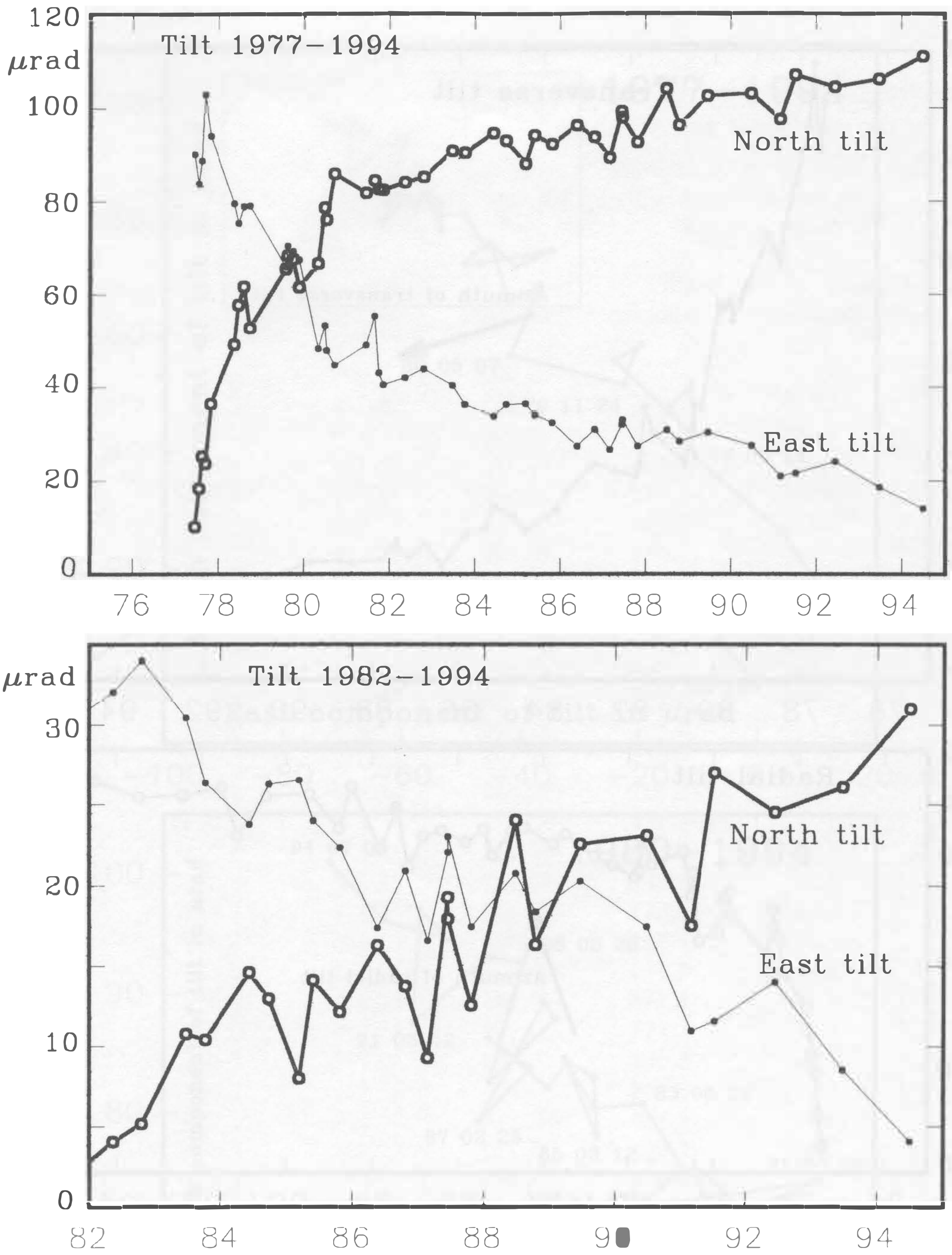


Fig. L3. Observed ground tilt at the tilt station Hverfjall since first observation of June 15, 1977. East component of tilt is marked by small dots connected by a thin line and the north component is marked by open circles connected by a thick line. Bottom graph shows tilt variation after 1981 on expanded scale to emphasise relatively gentle tilt variations during this period. No reversal of tilt is seen around 1989.

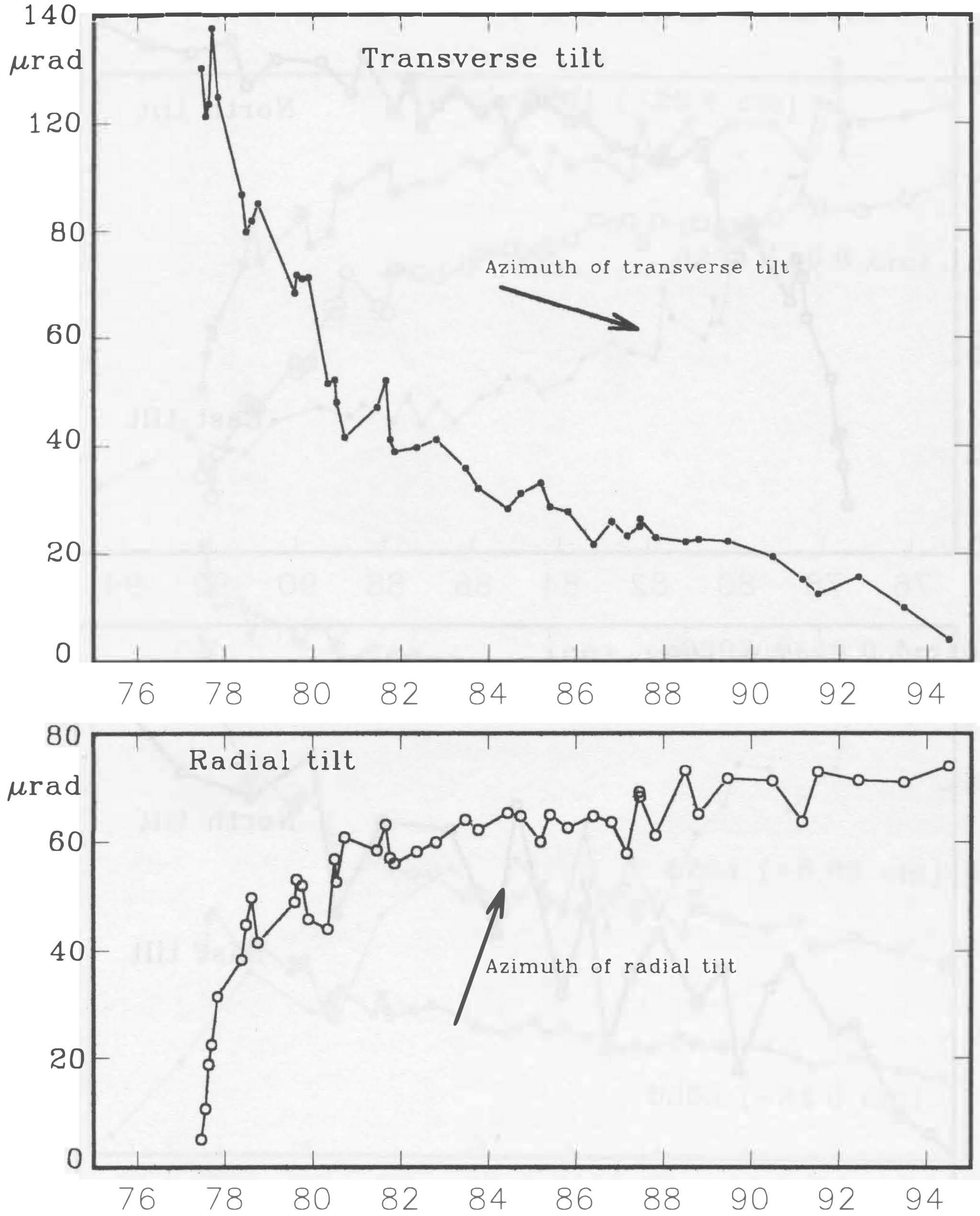
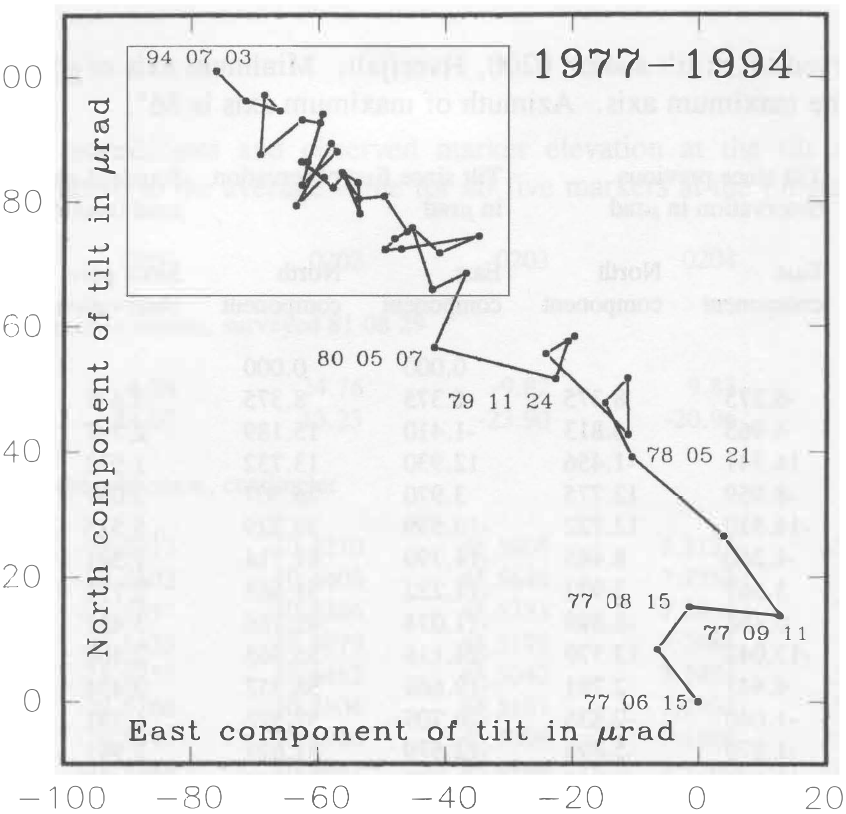


Fig. L4. Observed transverse (top) and radial (bottom) tilt at the tilt station Hverfjall, relative to the center of deformation at Krafla. Direction to the center of deformation is taken as 20° and positive transverse tilt is up towards an azimuth of 110°. The radial tilt was quite rapid, up towards Krafla, during the first year of observation, but the rate has been about one μrad per year since 1980. The transverse tilt rate was high, up towards 290°, from 1977 to 1980 and slower, about 3 μrad per year from 1980 to 1994.



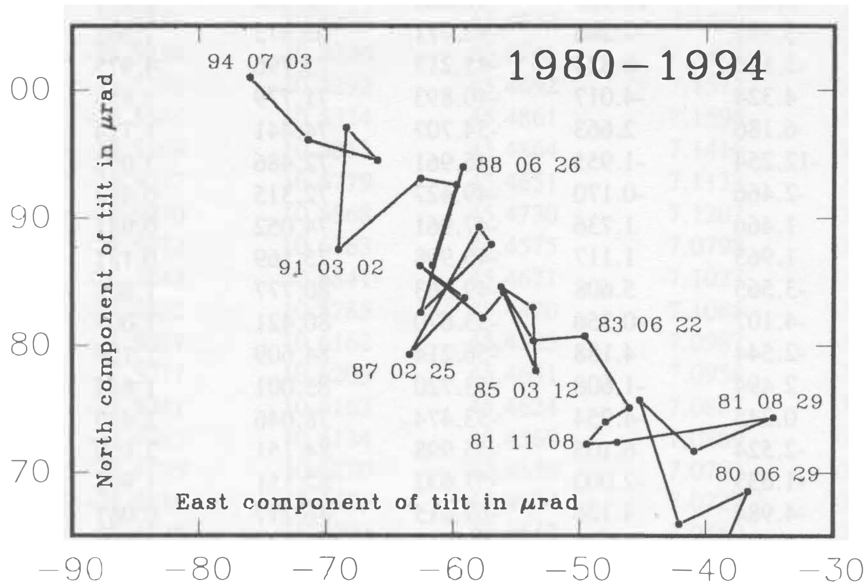


Fig. L5. North component of tilt plotted against east component of tilt at the Hverfjall tilt station, showing progress of the tilt vector through time. Top graph shows observed tilt from 1977 to 1994 and bottom graph covers the period 1980 to 1994 (rectangle on top graph) on expanded scale. Average tilt azimuth has changed from about 317° before 1980 to about 310° after 1980.

Table L1

Observed tilt at tilt station 0200, Hverfjall. Minimum axis of the error ellipse is 83% of the maximum axis. Azimuth of maximum axis is 86°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
77 06 15			0.000	0.000		
77 07 19	-6.375	8.375	-6.375	8.375	3.677	3.677
77 08 15	4.965	6.813	-1.410	15.189	2.767	3.647
77 09 11	14.341	-1.456	12.930	13.732	1.922	1.760
77 10 29	-8.959	12.775	3.970	26.507	3.037	2.280
78 05 21	-14.510	12.722	-10.539	39.229	5.515	6.998
78 06 29	-4.260	8.485	-14.799	47.714	1.541	8.526
78 08 12	3.567	3.972	-11.232	51.685	2.710	7.803
78 10 02	0.158	-8.899	-11.074	42.786	3.457	5.901
79 08 02	-13.042	12.779	-24.116	55.565	2.400	7.525
79 08 20	4.447	2.791	-19.669	58.357	0.434	7.958
79 10 06	-1.040	-0.835	-20.709	57.522	1.741	6.786
79 11 24	-1.870	-5.895	-22.579	51.627	2.941	5.525
80 05 07	-19.104	5.015	-41.683	56.642	2.425	5.388
80 06 29	5.000	11.903	-36.683	68.544	2.861	8.224
80 07 18	-5.392	-2.586	-42.071	65.972	1.501	8.613
80 09 21	-3.145	9.824	-45.217	75.796	4.975	6.887
81 06 20	4.324	-4.017	-40.893	71.779	5.855	10.546
81 08 29	6.186	2.663	-34.707	74.441	1.714	8.928
81 10 05	-12.254	-1.955	-46.961	72.486	3.098	6.185
81 11 08	-2.466	-0.170	-49.427	72.315	0.492	6.671
82 05 16	1.466	1.736	-47.961	74.052	0.981	7.467
82 10 20	1.963	1.117	-45.998	75.169	0.181	7.289
83 06 22	-3.565	5.608	-49.563	80.777	1.802	9.062
83 10 08	-4.107	-0.356	-53.670	80.421	1.007	8.312
84 06 09	-2.544	4.188	-56.214	84.609	2.159	10.471
84 09 28	2.494	-1.608	-53.720	83.001	1.645	8.981
85 03 12	0.245	-4.954	-53.474	78.046	2.489	6.748
85 05 29	-2.524	6.105	-55.998	84.151	2.866	9.386
85 10 26	-1.633	-2.000	-57.632	82.151	1.993	7.982
86 05 22	-4.984	4.126	-62.615	86.277	0.067	7.944
86 10 23	3.546	-2.529	-59.069	83.748	2.298	6.320
87 02 25	-4.350	-4.434	-63.419	79.315	0.301	6.149
87 06 13	5.470	9.973	-57.949	89.287	5.680	11.820
87 06 14	0.979	-1.345	-56.970	87.942	1.832	10.406
87 10 24	-5.577	-5.355	-62.547	82.587	3.335	7.070
88 06 26	3.313	11.446	-59.234	94.033	3.769	10.432
88 10 14	-0.236	-8.900	-59.470	85.133	4.231	6.964
88 10 17	-2.162	1.204	-61.633	86.337	1.985	8.143
89 06 22	1.918	6.244	-59.715	92.581	2.378	10.190
90 06 25	-2.825	0.525	-62.540	93.106	1.203	9.771
91 03 02	-6.494	-5.577	-69.033	87.529	2.391	7.384
91 07 09	0.624	9.499	-68.410	97.028	5.298	12.682
92 06 13	2.436	-2.523	-65.973	94.505	2.394	10.292

93 06 24	-5.456	1.593	-71.429	96.098	1.177	11.408
94 07 03	-4.517	4.882	-75.946	100.981	0.474	11.384

Table L2

Marker coordinates and observed marker elevation at the tilt station 0200 (Hverfjall) relative to the average value for all five markers at the tilt station

Marker	0201	0202	0203	0204	0205
Marker coordinates in meters, surveyed 81 08 29					
East	4.24	-24.76	-9.82	9.83	20.52
North	24.07	13.23	-23.90	-20.96	7.57
Y M D	Marker elevation, centimeter				
77 06 15	-28.6313	10.4270	45.5608	7.3125	-34.6092
77 07 19	-28.6602	10.4408	45.5640	7.2753	-34.6200
77 08 15	-28.6357	10.4386	45.5331	7.2804	-34.6162
77 09 11	-28.6433	10.4079	45.5176	7.2984	-34.5804
77 10 29	-28.6258	10.4482	45.5042	7.2484	-34.5748
78 05 21	-28.5764	10.4804	45.5101	7.1934	-34.6076
78 06 29	-28.5514	10.4966	45.5008	7.1666	-34.6124
78 08 12	-28.5348	10.4942	45.4780	7.1760	-34.6133
78 10 02	-28.5739	10.4910	45.4978	7.1878	-34.6025
79 08 02	-28.5358	10.5326	45.4839	7.1499	-34.6304
79 08 20	-28.5254	10.5236	45.4746	7.1471	-34.6201
79 10 06	-28.5296	10.5292	45.4692	7.1572	-34.6261
79 11 24	-28.5586	10.5324	45.4861	7.1596	-34.6194
80 05 07	-28.5469	10.5851	45.4864	7.1416	-34.6664
80 06 29	-28.5037	10.5779	45.4651	7.1133	-34.6527
80 07 18	-28.5070	10.5868	45.4730	7.1202	-34.6730
80 09 21	-28.5072	10.6163	45.4575	7.0798	-34.6465
81 06 20	-28.4844	10.5841	45.4671	7.1023	-34.6692
81 08 29	-28.4822	10.5785	45.4470	7.1085	-34.6520
81 10 05	-28.5087	10.6162	45.4585	7.0987	-34.6648
81 11 08	-28.5077	10.6203	45.4631	7.0958	-34.6714
82 05 16	-28.5011	10.6162	45.4624	7.0887	-34.6661
82 10 20	-28.4983	10.6134	45.4569	7.0889	-34.6611
83 06 22	-28.4775	10.6230	45.4535	7.0703	-34.6693
83 10 08	-28.4816	10.6354	45.4534	7.0722	-34.6793
84 06 09	-28.4625	10.6392	45.4542	7.0560	-34.6868
84 09 28	-28.4707	10.6365	45.4477	7.0685	-34.6820
85 03 12	-28.4959	10.6376	45.4542	7.0786	-34.6747
85 05 29	-28.4669	10.6422	45.4487	7.0631	-34.6869
85 10 26	-28.4828	10.6488	45.4540	7.0618	-34.6820
86 05 22	-28.4749	10.6668	45.4488	7.0487	-34.6892
86 10 23	-28.4831	10.6608	45.4399	7.0692	-34.6868
87 02 25	-28.4960	10.6665	45.4533	7.0758	-34.6995
87 06 13	-28.4417	10.6451	45.4439	7.0504	-34.6977
87 06 14	-28.4498	10.6469	45.4372	7.0622	-34.6965
87 10 24	-28.4823	10.6657	45.4457	7.0712	-34.7001
87 06 26	-28.4399	10.6593	45.4326	7.0362	-34.6883
88 10 14	-28.4748	10.6624	45.4337	7.0722	-34.6937
88 10 17	-28.4691	10.6638	45.4429	7.0577	-34.6952

89 06 22	-28.4408	10.6607	45.4279	7.0504	-34.6981
90 06 25	-28.4447	10.6691	45.4325	7.0410	-34.6977
91 03 02	-28.4731	10.6865	45.4446	7.0493	-34.7073
91 07 09	-28.4235	10.6780	45.4392	7.0217	-34.7153
92 06 13	-28.4402	10.6775	45.4342	7.0339	-34.7054
93 06 24	-28.4339	10.6888	45.4409	7.0214	-34.7173
94 07 03	-28.4232	10.7068	45.4319	7.0093	-34.7247

TILT STATION 0210, ELDÁ

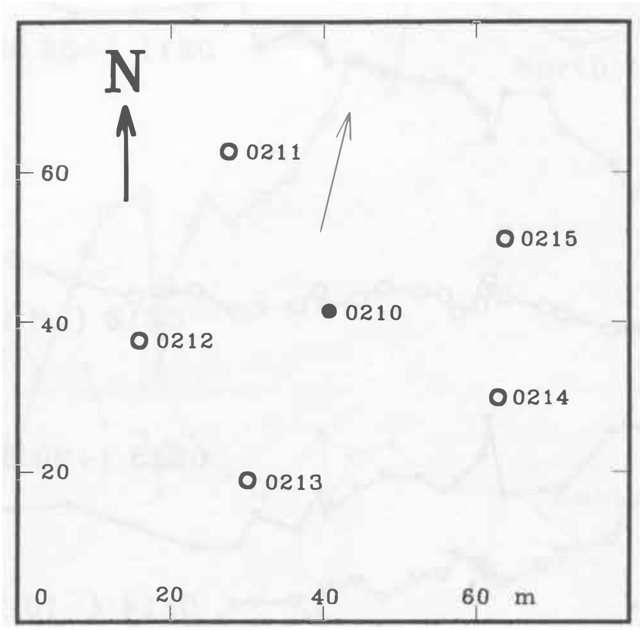


Fig. M1. Map of relative position of markers at the tilt station Eldá, also named tilt station 0210. Solid circle is a marker at the center of a 25.0 m radius circle defined by 5 markers (open circles). The markers consist of 12.5 mm diameter copper alloy rods with rounded tops, cemented into the lava and extending one to two cm above the lava surface. Each marker is identified by a number as shown, inscribed on a washer. Thin arrow gives the direction of downward tilt during deflation events of Krafla volcano.

This station was constructed on October 4, 1981 on the lava flow of 1729 where it follows a narrow channel named Eldá (the river of fire) toward Mývatn. It consists of 5 markers forming a circle of 25.0 m radius and a sixth marker at the center of the circle (Fig. 1). The markers are made of copper rods of 12.5 mm diameter, cemented into holes drilled into solid lava. Usually the holes are 5 to 8 cm deep and the rods extend one to two cm above the lava surface. A metal washer on each marker carries an identification number.

Observations were made 28 times from October 1981 to July 1994. The observed ground deformation is characterised by uplift toward an azimuth of about 340° interrupted by brief tilt excursion at times of the two deflation events and eruptions which occurred at Krafla volcano after foundation of this station. This is observed as progressing relative uplift of the marker 0211 and subsidence of markers 0213 and 0214 but during deflation events, marker 0213 was uplifted and markers 0211 and 0215 subsided (Fig. M2).

The ground tilt up toward NNW terminated in late 1988 or 1989 (Fig. M3). However, the transverse tilt (Fig M4) continued after 1989, resulting in tilt up toward W or WSW (Fig. M5).

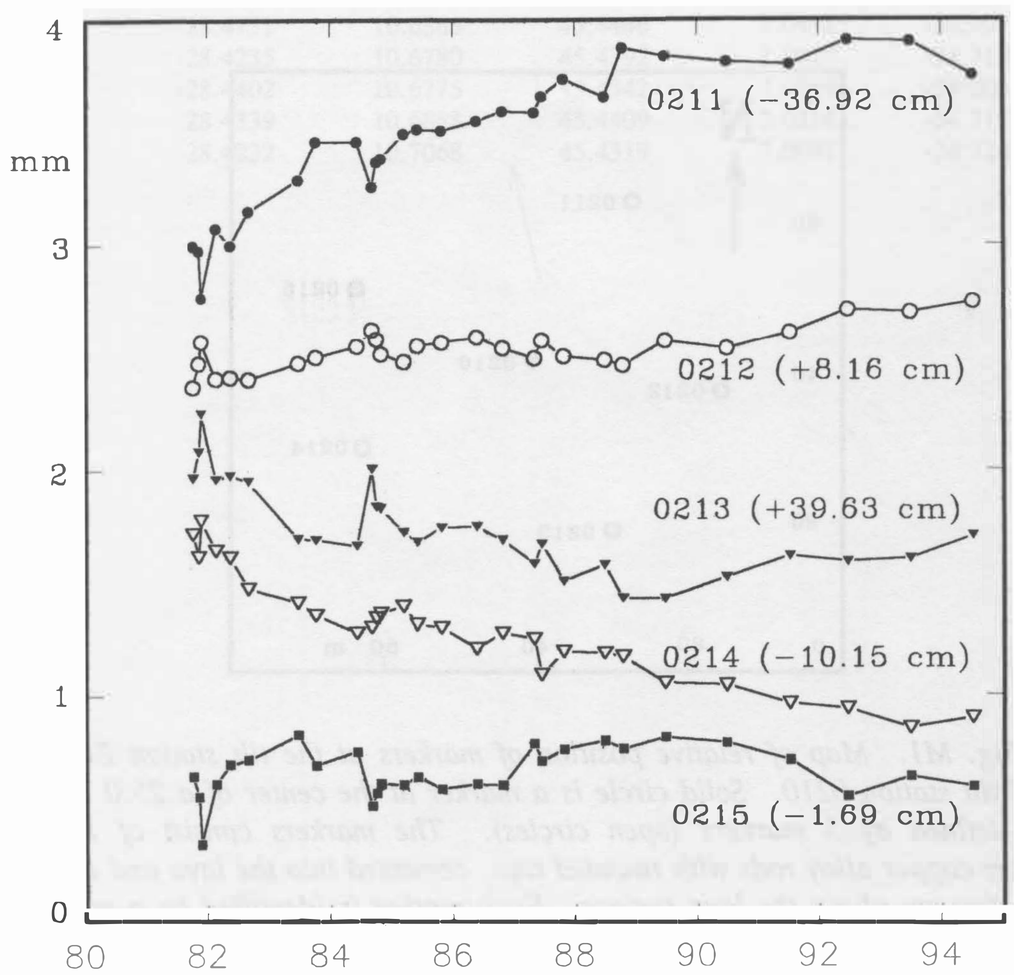


Fig. M2. Variation with time of the relative elevation of each marker forming the 25.0 m radius circle of the Eldá tilt station. Marker 0211 has been uplifted notably from 1981 to 1988 and markers 0213 and 0214 subsided at the same time. Deflation events of November 1981 and September 1984 are seen as uplift of marker 0213 and subsidence of markers 0211 and 0215.

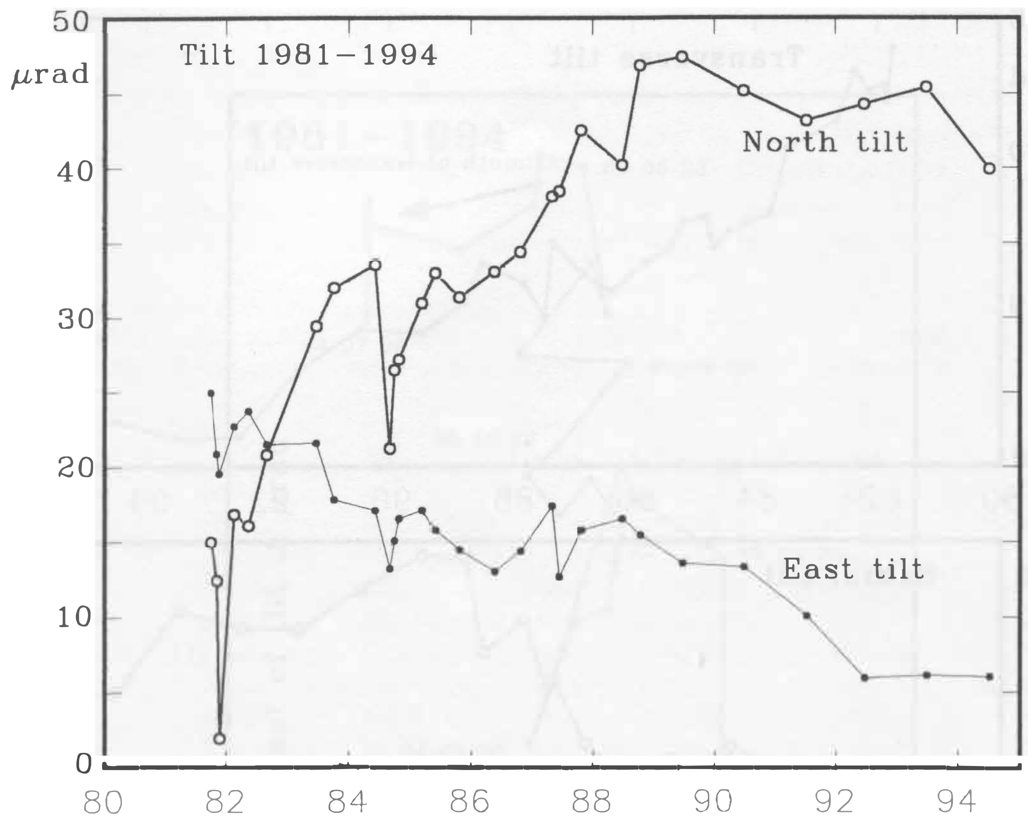


Fig. M3. Observed ground tilt at the tilt station Eldá since it was first observed on October 4, 1981. East component of tilt is marked by small dots connected by a thin line and the north component is marked by open circles connected by a thick line. Reversal of the north component of tilt is suggested in 1988 or 1989, but the east component progresses down towards east throughout the period of observations.

Table M1

Observed tilt at the tilt station Eldá (0210) during selected periods of fast and slow rate of deformation of the Krafla volcano. Standard error of observed tilt is usually less than 3 μrad.

Date of first observation	Date of second observation	Computed tilt in μrad	Azimuth of computed tilt in degrees	Remarks
81 11 08	81 11 22	10.5	187.0	fast deflation
81 11 22	82 02 21	15.3	11.8	fast inflation
82 02 21	84 06 08	18.7	339.2	slow inflation
84 06 08	84 09 06	12.9	197.6	fast deflation
84 09 06	85 03 12	10.5	21.9	fast inflation
85 03 12	89 06 23	16.8	347.7	slow inflation
89 06 23	94 07 06	10.6	225.1	slow deflation

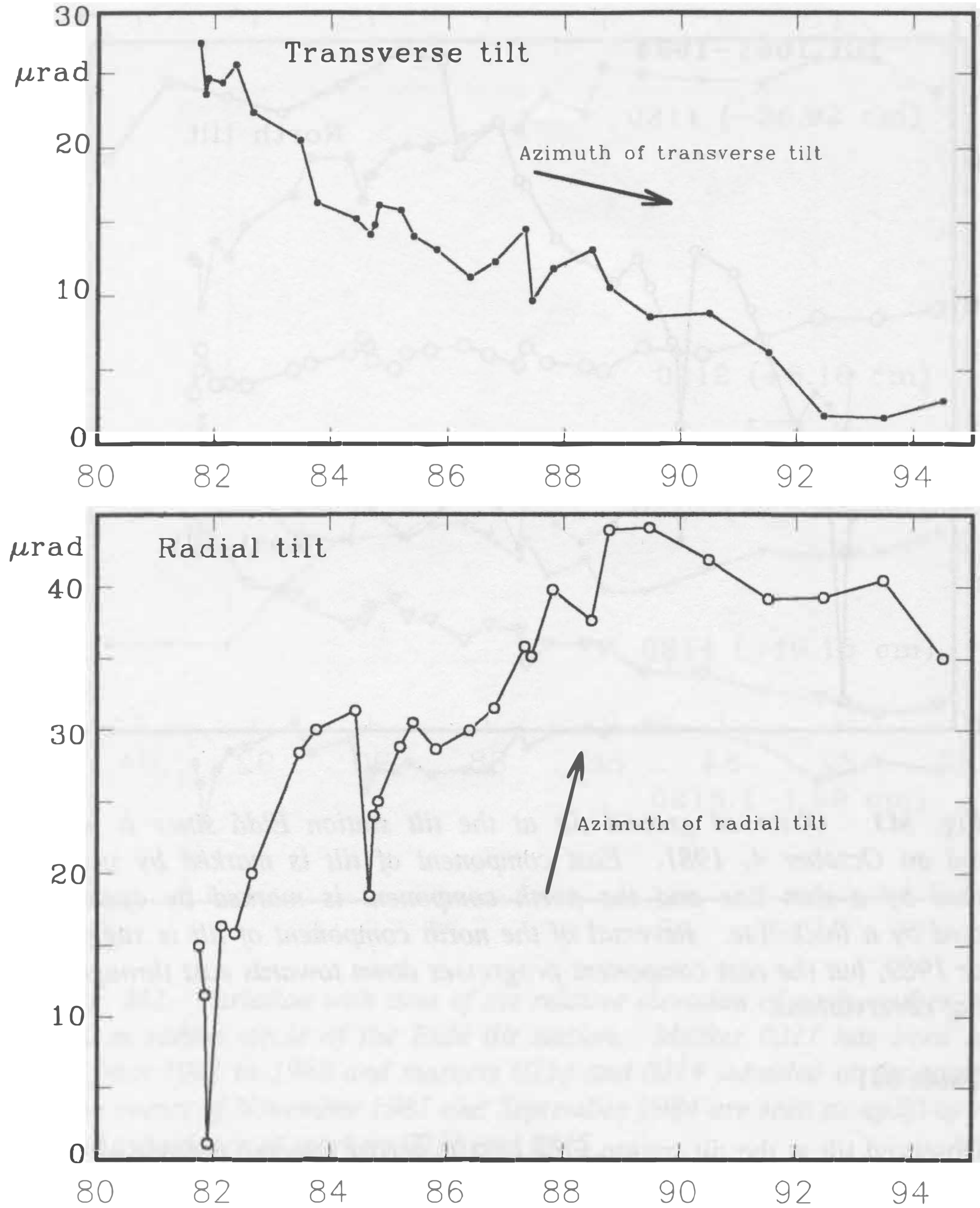


Fig. M4. Observed transverse (top) and radial (bottom) tilt at the tilt station Eldá, relative to the center of deformation at Krafla. Radial tilt is taken to be tilt component towards an azimuth of 13°, in the direction of downward tilt during deflations of the Krafla volcano. Transverse tilt towards an azimuth of 103° is dominated by downward tilt at near constant rate throughout the period of observation. Radial tilt is characterised by positive tilt (up toward 13°) from 1981 to 1988, interrupted briefly by deflations of November 1981 and September 1984, and slow downward tilt after 1989.

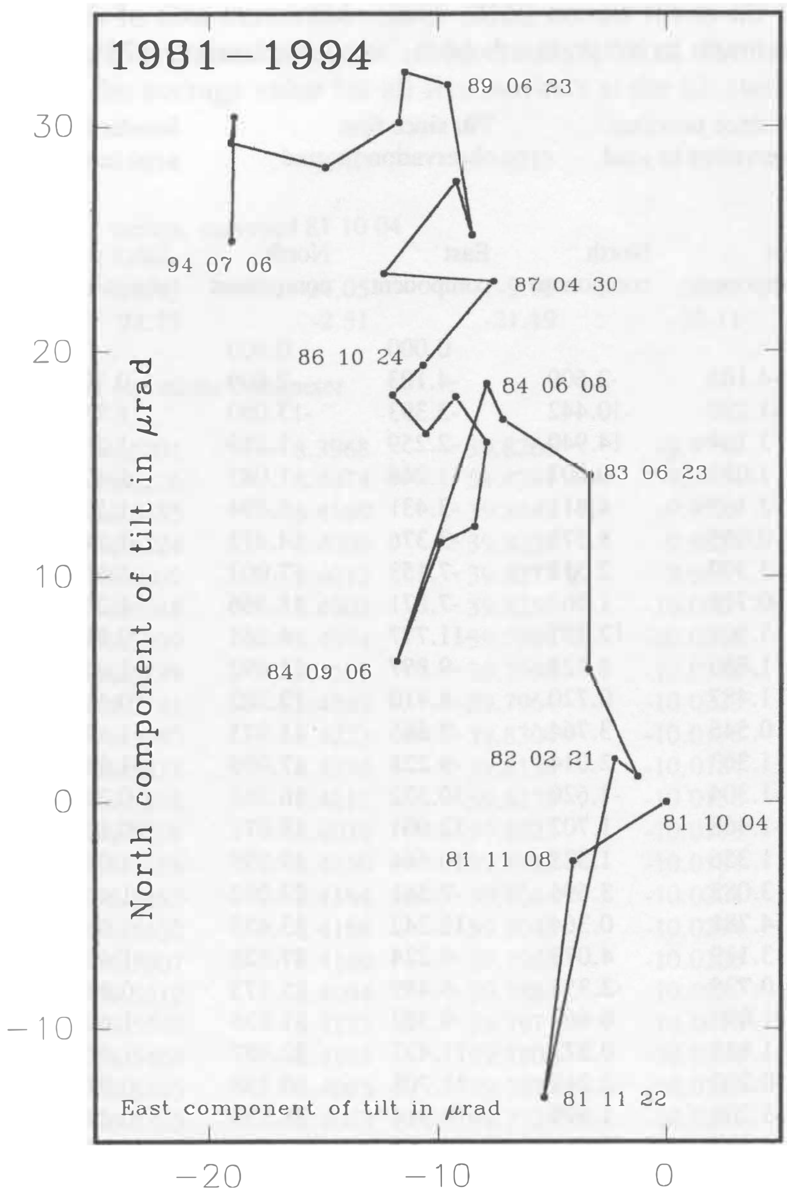


Fig. M5. North component of tilt plotted against east component of tilt at the tilt station Eldá, showing progress of the tilt vector through time. The general ground tilt is up toward an azimuth of about 340° from 1981 to 1989, interrupted by tilt up towards 193° during deflations of November 1981 and September 1984, and subsequent inflation tilt up toward an azimuth of about 13°. After 1989, tilt up towards west is suggested.

Table M2

Observed tilt at tilt station 0210, Eldá. Minimum axis of the error ellipse is 79% of the maximum axis. Azimuth of the maximum axis is 178°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
81 10 04			0.000	0.000		
81 11 08	-4.103	-2.609	-4.103	-2.609	0.751	0.751
81 11 22	-1.290	-10.442	-5.393	-13.050	1.750	1.107
82 02 21	3.134	14.940	-2.259	1.889	1.286	0.216
82 05 15	1.013	-0.807	-1.246	1.083	1.404	1.391
82 09 01	-2.185	4.811	-3.431	5.894	1.125	2.088
83 06 23	0.055	8.578	-3.376	14.472	1.744	2.135
83 10 08	-3.777	2.531	-7.153	17.003	1.653	0.566
84 06 08	-0.718	1.563	-7.871	18.566	1.244	1.764
84 09 06	-3.906	-12.297	-11.777	6.268	0.960	1.706
84 10 03	1.880	5.223	-9.897	11.492	1.059	0.661
84 10 28	1.487	0.720	-8.410	12.202	0.519	0.899
85 03 12	0.545	3.764	-7.865	15.975	1.197	0.824
85 06 03	-1.363	2.014	-9.228	17.989	1.058	0.281
85 10 26	-1.304	-1.620	-10.532	16.369	0.398	0.416
86 05 23	-1.468	1.702	-12.001	18.071	0.822	1.177
86 10 24	1.356	1.325	-10.644	19.395	1.059	0.644
87 04 30	3.083	3.696	-7.561	23.092	1.406	1.288
87 06 13	-4.781	0.364	-12.342	23.455	1.068	2.219
87 10 25	3.119	4.073	-9.224	27.528	1.462	0.779
88 06 26	0.735	-2.355	-8.489	25.173	0.977	1.724
88 10 13	-1.093	6.662	-9.582	31.835	1.696	1.015
89 06 23	-1.855	0.572	-11.437	32.407	1.927	1.603
90 06 27	-0.270	-2.249	-11.708	30.158	0.970	2.115
91 07 10	-3.206	-1.999	-14.914	28.159	0.537	2.651
92 06 20	-4.137	1.082	-19.051	29.241	1.594	1.215
93 06 29	0.162	1.171	-18.889	30.412	1.508	2.565
94 07 06	-0.083	-5.502	-18.972	24.910	0.632	2.679

Table M3

Marker coordinates and observed marker elevation at the tilt station 0210 (Eldá) relative to the average value for all five markers at the tilt station

Marker	0211	0212	0213	0214	0215
Marker coordinates in meters, surveyed 81 10 04					
East	-12.47	-24.05	-9.98	22.81	23.70
North	22.73	-2.51	-21.19	-10.11	11.10
Y M D	Marker elevation, centimeter				
81 10 04	-36.6201	8.3968	39.8266	-9.9779	-1.6254
81 11 08	-36.6226	8.4074	39.8381	-9.9884	-1.6344
81 11 22	-36.6435	8.4169	39.8547	-9.9721	-1.6558
82 02 21	-36.6124	8.4006	39.8258	-9.9854	-1.6287
82 05 15	-36.6202	8.4012	39.8277	-9.9885	-1.6203
82 09 01	-36.6048	8.4002	39.8250	-10.0023	-1.6183
83 06 23	-36.5909	8.4074	39.7994	-10.0086	-1.6072
83 10 08	-36.5739	8.4100	39.7990	-10.0142	-1.6207
84 06 08	-36.5741	8.4149	39.7964	-10.0223	-1.6148
84 09 06	-36.5940	8.4222	39.8304	-10.0198	-1.6386
84 10 03	-36.5831	8.4178	39.8138	-10.0154	-1.6329
84 10 28	-36.5818	8.4112	39.8130	-10.0136	-1.6289
85 03 12	-36.5706	8.4079	39.8023	-10.0103	-1.6293
85 06 03	-36.5686	8.4150	39.7980	-10.0184	-1.6259
85 10 26	-36.5693	8.4164	39.8044	-10.0201	-1.6312
86 05 23	-36.5650	8.4188	39.8048	-10.0294	-1.6291
86 10 24	-36.5607	8.4140	39.7988	-10.0226	-1.6297
87 04 30	-36.5612	8.4094	39.7883	-10.0250	-1.6115
87 06 13	-36.5540	8.4173	39.7971	-10.0410	-1.6192
87 10 25	-36.5464	8.4101	39.7806	-10.0306	-1.6139
88 06 26	-36.5545	8.4085	39.7877	-10.0315	-1.6102
88 10 13	-36.5325	8.4063	39.7729	-10.0331	-1.6138
89 06 23	-36.5363	8.4171	39.7727	-10.0447	-1.6087
90 06 27	-36.5389	8.4135	39.7823	-10.0457	-1.6111
91 07 10	-36.5400	8.4208	39.7917	-10.0537	-1.6187
92 06 20	-36.5291	8.4309	39.7892	-10.0561	-1.6348
93 06 29	-36.5298	8.4299	39.7906	-10.0646	-1.6260
94 07 06	-36.5448	8.4346	39.8006	-10.0601	-1.6304

TILT STATION 0220, HVERARÖND

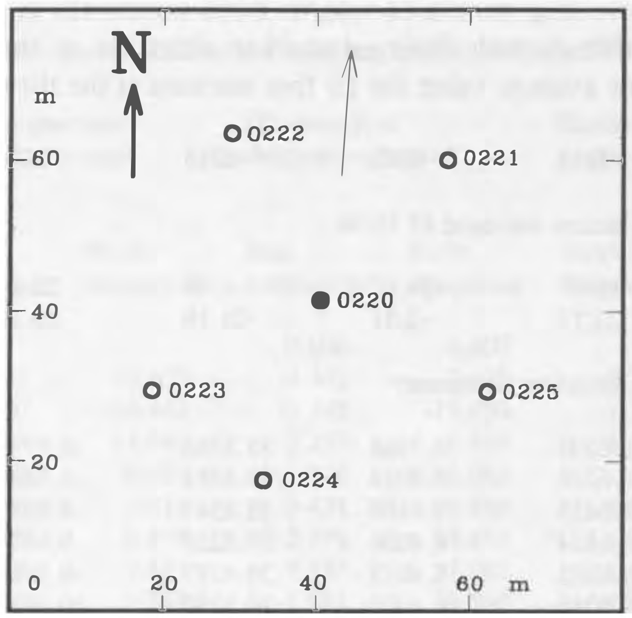


Fig. N1. Map of relative position of markers at the tilt station Hveraröndá, also named tilt station 0220. Solid circle is a marker at the center of a 25.0 m radius circle defined by 5 markers (open circles). The markers consist of 12.5 mm diameter copper alloy rods with rounded tops, cemented into the lava and extending one to two cm above the lava surface. Each marker is identified by a number as shown, inscribed on a washer. Thin arrow gives the approximate direction to the center of deformation at Krafla.

This station was constructed and observed for the first time on October 4, 1981, at a location about 9 km south of Leirhnjúkur. The station lies on very flat pahoehoe lava within the Námafjall geothermal field, about 500 m south of highway 1 and about 200 m east of the ridge Námafjall. The ground is warm and faint steam vents are visible within the area of the station.

The 5 permanent markers form a circle of 25.0 m radius and a sixth marker is placed in the center of the circle to mark the point where to place the level during observations. The station was observed 26 times from October 1981 to July 1994. The observed ground deformation (Fig. N2 and N3) is rather irregular. Marker 0222 appear to have subsided about 0.7 mm between observations of 88 10 11 and 89 06 22, then gradually been elevated until June 1993 to subside again 0.6 mm between June 1993 and July 1994. This erratic movement of marker 0222 has not been explained, but the lava where the marker is located must have been displaced vertically.

Observation on June 21, 1983 was judged as of inferior quality and another observation vas made the next day. Comparison of these two observations, one of poor quality, another of good quality, shows a standard deviation of observed marker elevation of 0.08 mm between these two observations. This suggest that observational errors are generally smaller than 0.1 mm.

East component of tilt (Fig. N3) shows a continuous increase and tilt up toward east amounts to about 25 μrad in 13 years. The deflation of September 1984 is seen as radial tilt (Fig. N4) of about 12 μrad, down towards Krafla.

Progress of the tilt vector (Fig. N5) is rather irregular, suggesting considerable deformation of the ground within the 25 m radius circular area of the tilt station. This irregular tilt progress can not been explained by observational errors, which will cause tilt errors of about 3 μrad or less. This erratic behaviour of the tilt station can not be related to freezing and thawing of the ground, as the station is within the Námafjall geothermal field and the ground is warm.

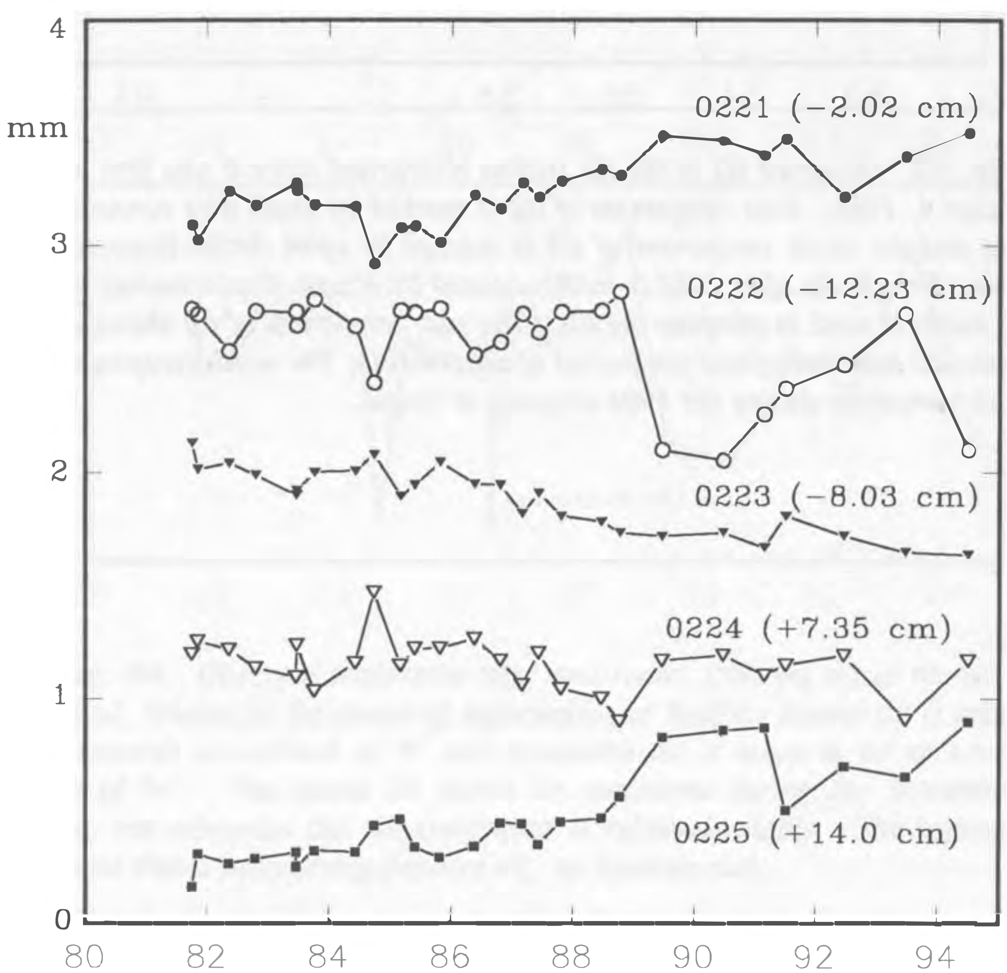


Fig. N2. Variation with time of the relative elevation of each marker forming the 25.0 m radius circle of the Hveraröndd tilt station. Marker 0222 has erratic movement after 1988. Marker 0223 had subsided at relatively constant rate and 0221 has similarly been uplifted.

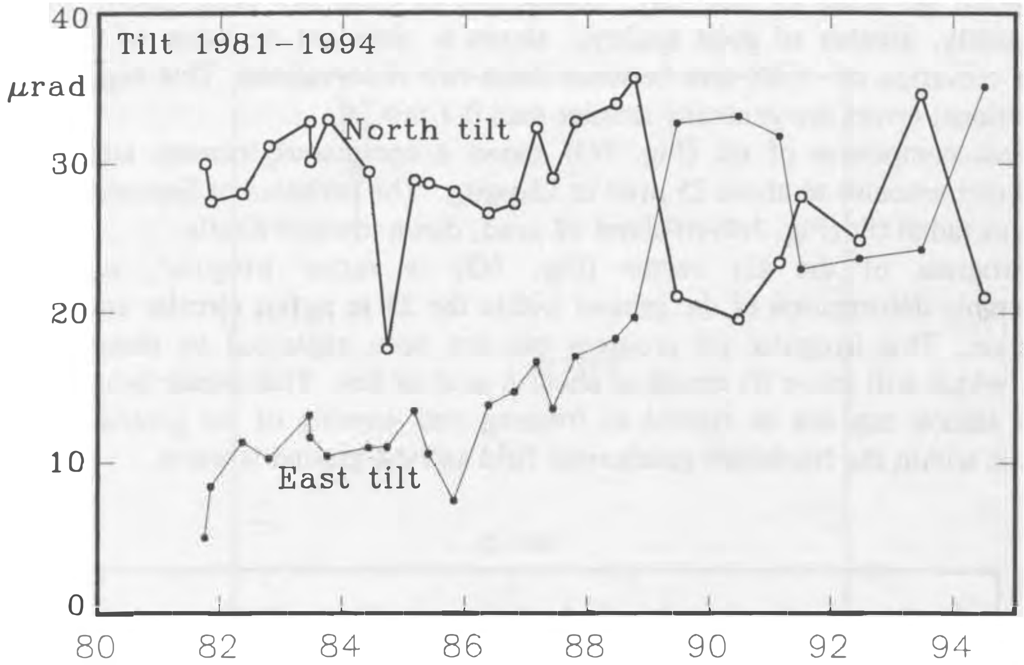


Fig. N3. Observed tilt at the tilt station Hveraröndd since it was first observed on October 4, 1981. East component of tilt is marked by small dots connected by a thin line and the north component of tilt is marked by open circles connected by a thick line. Erratic tilt after 1988 is mostly caused by erratic displacements of one of the five markers used to compute the tilt. The east component of tilt shows a steady tilt up toward east throughout the period of observation. The north component of tilt shows tilt variations during the 1984 eruption of Krafla.

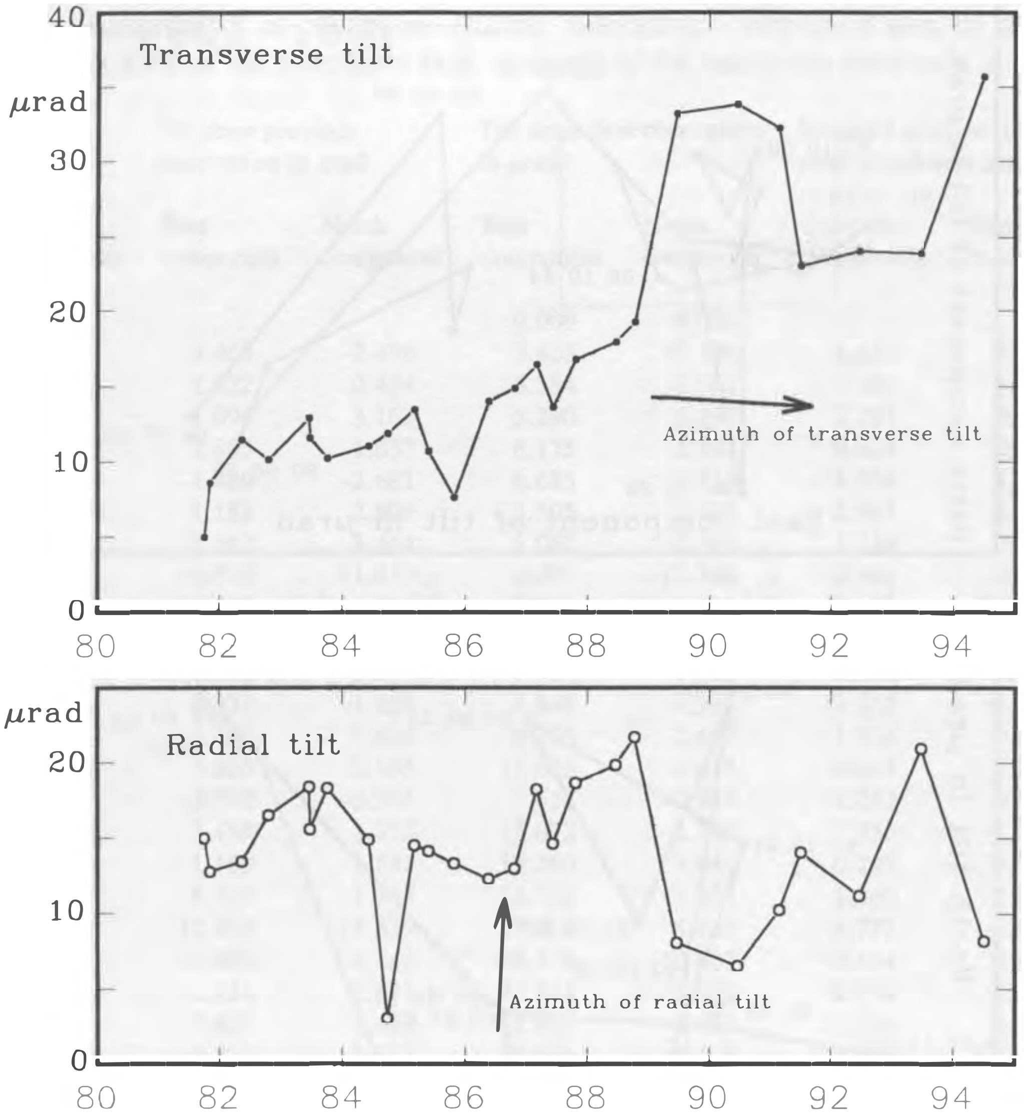


Fig. N4. Observed transverse (top) and radial (bottom) tilt at the tilt station Hveraröndd, relative to the center of deformation at Krafla. Radial tilt is taken to be tilt up towards an azimuth of 4° and transverse tilt is taken to be up towards an azimuth of 94°. The radial tilt shows tilt variations during the September 1984 eruption, but otherwise this tilt component is relatively stable. The transverse tilt component shows progressing positive tilt, up towards east.

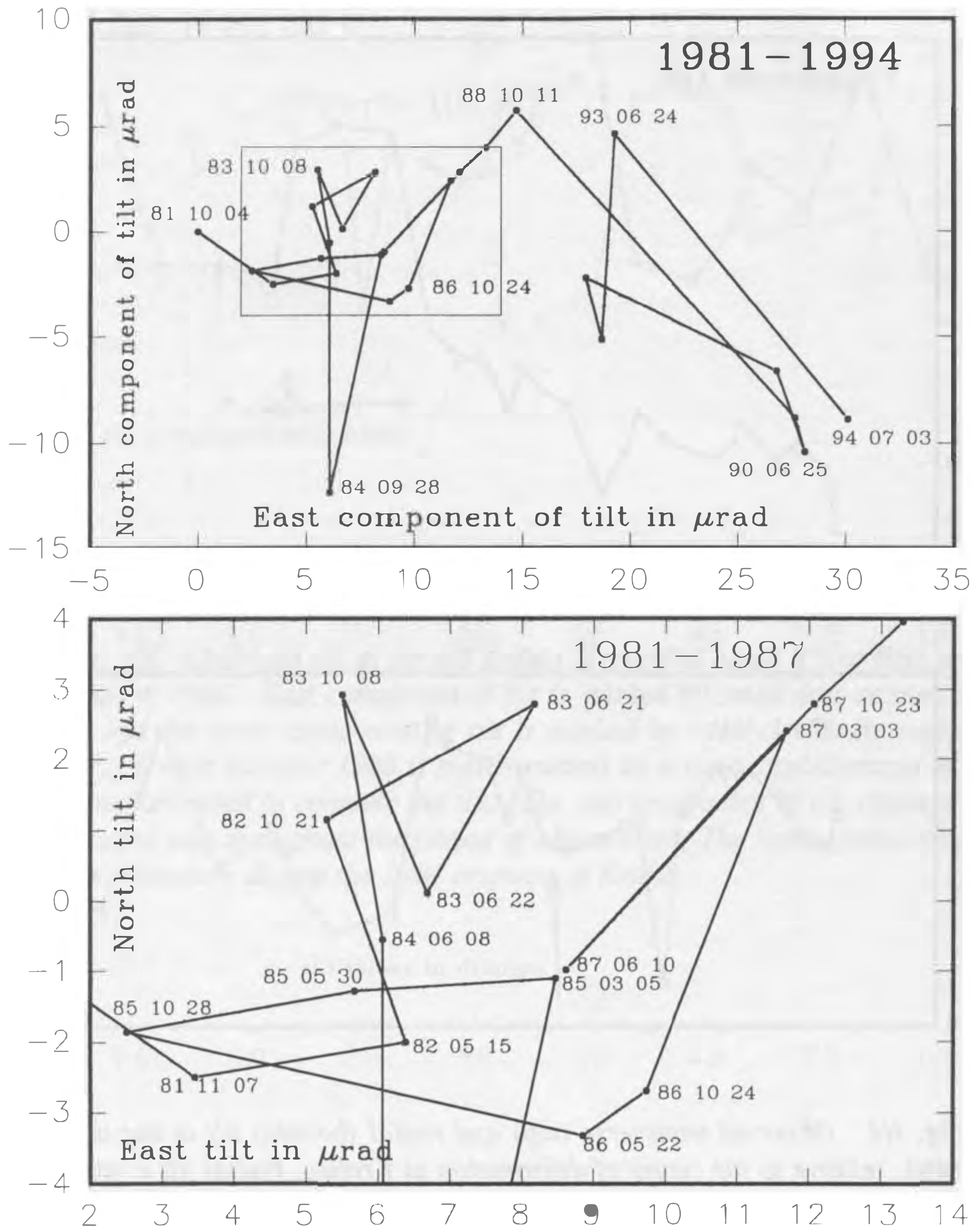


Fig. N5. North component of tilt plotted against east component of tilt at the tilt station Hverarönd, showing progress of the tilt vector through time. Top graph presents tilt progress from October 4, 1981 to July 7, 1994 and the bottom graph shows the section inside the rectangle of the top graph in expanded scale for clarification. The tilt progress appear rather irregular, suggesting random tilt variations, sometimes amounting to about 10 μrad, on top of continuous eastward tilt.

Table N1

Observed tilt at tilt station A0220, Hveraröndd. Minimum axis of the error ellipse is 85% of the maximum axis. Azimuth of the maximum error axis is 120°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
81 10 04			0.000	0.000		
81 11 07	3.463	-2.496	3.463	-2.496	1.653	1.653
82 05 15	2.922	0.494	6.384	-2.002	3.147	1.587
82 10 21	-1.094	3.162	5.290	1.160	2.091	0.509
83 06 21	2.885	1.637	8.175	2.797	0.431	0.403
83 06 22	-1.489	-2.681	6.685	0.116	1.366	1.595
83 10 08	-1.181	2.805	5.505	2.921	2.951	1.459
84 06 08	0.563	-3.464	6.067	-0.543	1.215	0.244
84 09 28	0.010	-11.817	6.077	-12.360	0.985	0.933
85 03 05	2.396	11.261	8.473	-1.100	2.159	2.622
85 05 30	-2.803	-0.181	5.670	-1.281	1.351	1.719
85 10 28	-3.158	-0.578	2.512	-1.859	0.585	1.633
86 05 22	6.337	-1.458	8.849	-3.316	2.555	1.209
86 10 24	0.886	0.626	9.735	-2.690	1.934	0.760
87 03 03	1.950	5.105	11.685	2.415	0.644	1.216
87 06 10	-3.072	-3.392	8.614	-0.977	1.252	0.802
87 10 23	3.458	3.775	12.072	2.798	1.355	1.277
88 06 23	1.188	1.141	13.260	3.940	0.223	1.150
88 10 11	1.455	1.745	14.714	5.684	1.769	2.886
89 06 22	12.953	-14.539	27.667	-8.855	4.772	2.233
90 06 25	0.461	-1.552	28.129	-10.407	0.154	2.331
91 03 01	-1.314	3.777	26.814	-6.630	2.254	1.044
91 07 07	-8.853	4.415	17.961	-2.214	2.744	2.287
92 06 20	0.723	-2.912	18.684	-5.126	4.138	1.895
93 06 24	0.589	9.723	19.273	4.597	1.154	2.322
94 07 03	10.844	-13.500	30.117	-8.903	3.694	1.588

Table N2

Marker coordinates and observed marker elevation at the tilt station 0220 (Hveraröndd) relative to the average value for all five markers at the tilt station

Marker	0221	0222	0223	0224	0225
Marker coordinates in meters, surveyed 81 10 04					
East	17.11	-11.17	-21.45	-6.89	22.39
North	20.09	23.59	-10.55	-22.52	-10.63
Y M D	Marker elevation, centimeter				
81 10 04	-1.7109	-11.9582	-7.8172	7.4698	14.0165
81 11 07	-1.7174	-11.9604	-7.8286	7.4756	14.0308
82 05 15	-1.6958	-11.9768	-7.8258	7.4717	14.0267
82 10 21	-1.7021	-11.9591	-7.8311	7.4634	14.0289
83 06 21	-1.6921	-11.9593	-7.8398	7.4597	14.0317
83 06 22	-1.6957	-11.9654	-7.8379	7.4738	14.0254
83 10 08	-1.7018	-11.9541	-7.8298	7.4532	14.0324
84 06 08	-1.7026	-11.9657	-7.8292	7.4658	14.0318
84 09 28	-1.7279	-11.9906	-7.8221	7.4971	14.0434
85 03 05	-1.7121	-11.9588	-7.8403	7.4647	14.0463
85 05 30	-1.7111	-11.9598	-7.8354	7.4722	14.0340
85 10 28	-1.7185	-11.9580	-7.8254	7.4724	14.0295
86 05 22	-1.6975	-11.9785	-7.8349	7.4765	14.0343
86 10 24	-1.7034	-11.9727	-7.8354	7.4671	14.0446
87 03 03	-1.6922	-11.9601	-7.8481	7.4561	14.0443
87 06 10	-1.6984	-11.9683	-7.8388	7.4704	14.0353
87 10 23	-1.6912	-11.9595	-7.8491	7.4544	14.0452
88 06 23	-1.6862	-11.9589	-7.8516	7.4502	14.0467
88 10 11	-1.6889	-11.9505	-7.8565	7.4399	14.0561
89 06 22	-1.6715	-12.0202	-7.8581	7.4669	14.0828
90 06 25	-1.6737	-12.0247	-7.8566	7.4693	14.0858
91 03 01	-1.6799	-12.0044	-7.8631	7.4604	14.0871
91 07 07	-1.6728	-11.9932	-7.8491	7.4650	14.0501
92 06 20	-1.6985	-11.9825	-7.8580	7.4694	14.0696
93 06 24	-1.6805	-11.9602	-7.8650	7.4407	14.0649
94 07 03	-1.6700	-12.0201	-7.8662	7.4669	14.0895

TILT STATION 0230, NÁMAFJALL-S

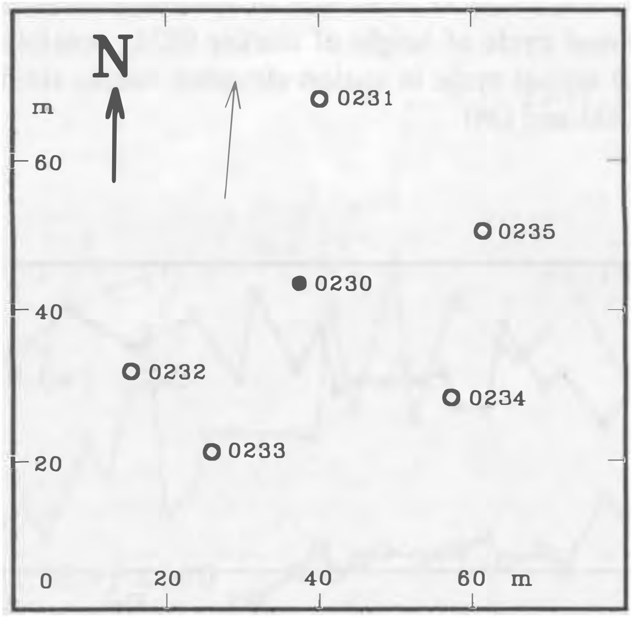


Fig. O1. Map of relative position of markers at the tilt station Námafjall-S, also named tilt station 0230. Solid circle is a marker at the center of a 25.0 m radius circle defined by 5 markers (open circles). The markers consist of 12.5 mm diameter copper alloy rods with rounded tops, cemented into the lava and extending one to two cm above the lava surface. Each marker is identified by a number as shown, inscribed on a washer. Thin arrow gives the approximate direction to the center of deformation at Krafla.

This station was constructed and first observed on October 4, 1981, about 10 km south of the center of deformation at Krafla, east of the central axis of the Krafla fissure swarm. It lies on rather rough lava below but very close to the east slope of the ridge Námafjall near its south end, about 2 km south of highway 1. Five permanent markers form a circle of 25.0 m radius and a sixth marker is located at the center of this circle to define site for the level during tilt measurements (Fig. O1).

The station was observed 24 times from October 1981 to July 1994. The observed ground deformation is small, but two markers, 0232 and 0233 have subsided at a near constant rate (Fig. O2), and the other three markers have been uplifted. This suggests a ground tilt is up towards NE or ENE of about 20 μrad in 12 years (Figs. O3 and O4). Observational noise in considerable (Fig. O5), suggesting errors in excess of 5 μrad in computed tilt.

Observations were made at least two times per year before 1989, but once per year in 1989 and later. Careful study of marker elevation with time (Fig O2) shows several prominent peaks in elevation of marker 0231, especially at observations of 84 06 08, 87 06 10, and 88 06 21. The time of observations of these peak are all in June, suggesting annual cycle of height of marker 0231, possibly amounting to 0.4 mm. This suggested annual cycle in station elevation causes similar annual cycle in computed tilt (Figs O3 and O4).

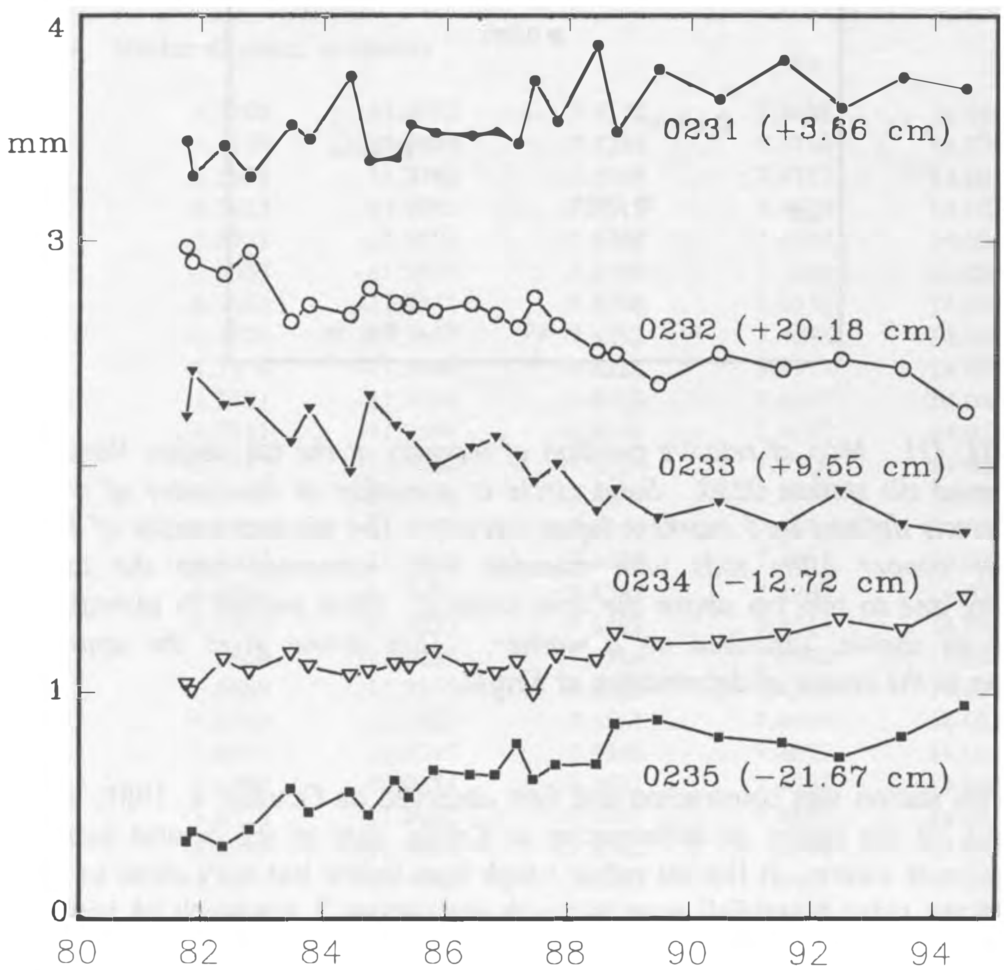


Fig. O2. Variation with time of the relative elevation of each marker forming the 25.0 m radius circle of the Námafjall-S tilt station. Marker 0231 shows several prominent peaks suggesting annual cycle in its elevation of possibly 0.4 mm amplitude. Markers 0231, 0234, and 0235 have drifted upwards while markers 0232 and 0233 have subsided at near constant rate. Elevation of each marker, relative to average elevation of all five markers, is found by adding number in parenthesis to the scale number at the left.

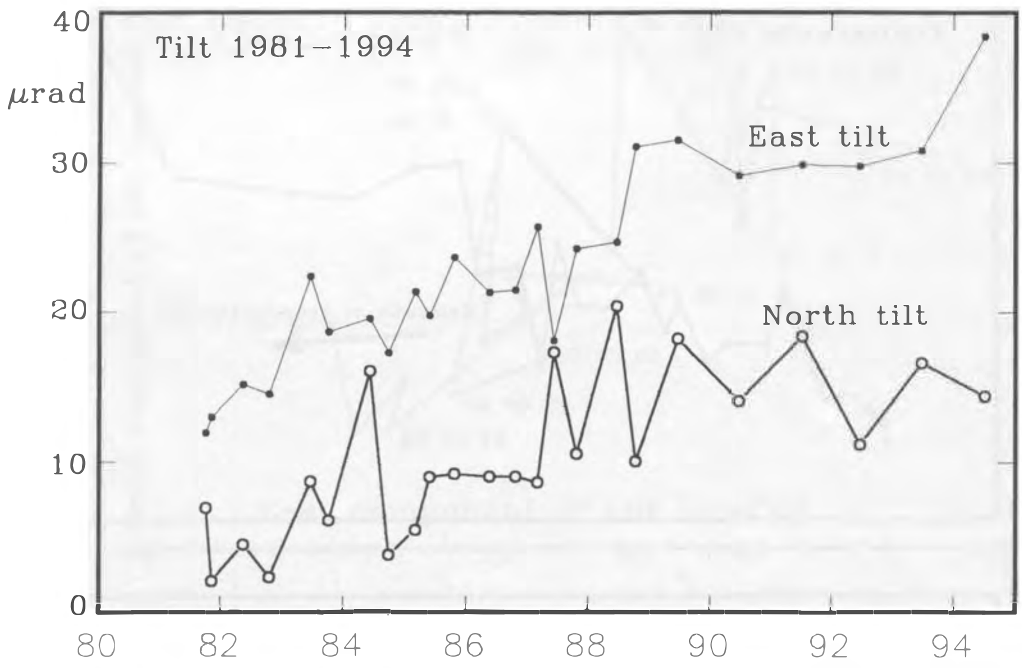


Fig. O3. Observed tilt at the tilt station Námafjall-S since it was first observed on October 4, 1981. East component of tilt is marked by small dots connected by a thin line and the north component of tilt is marked by open circles connected by a thick line. General tilt up towards east is observed, amounting to about 2 µrad per year, and slight tilt up towards north is suggested. This northerly tilt may have terminated around 1990, but before 1990, tilt rate of about 2 µrad per year is indicated.

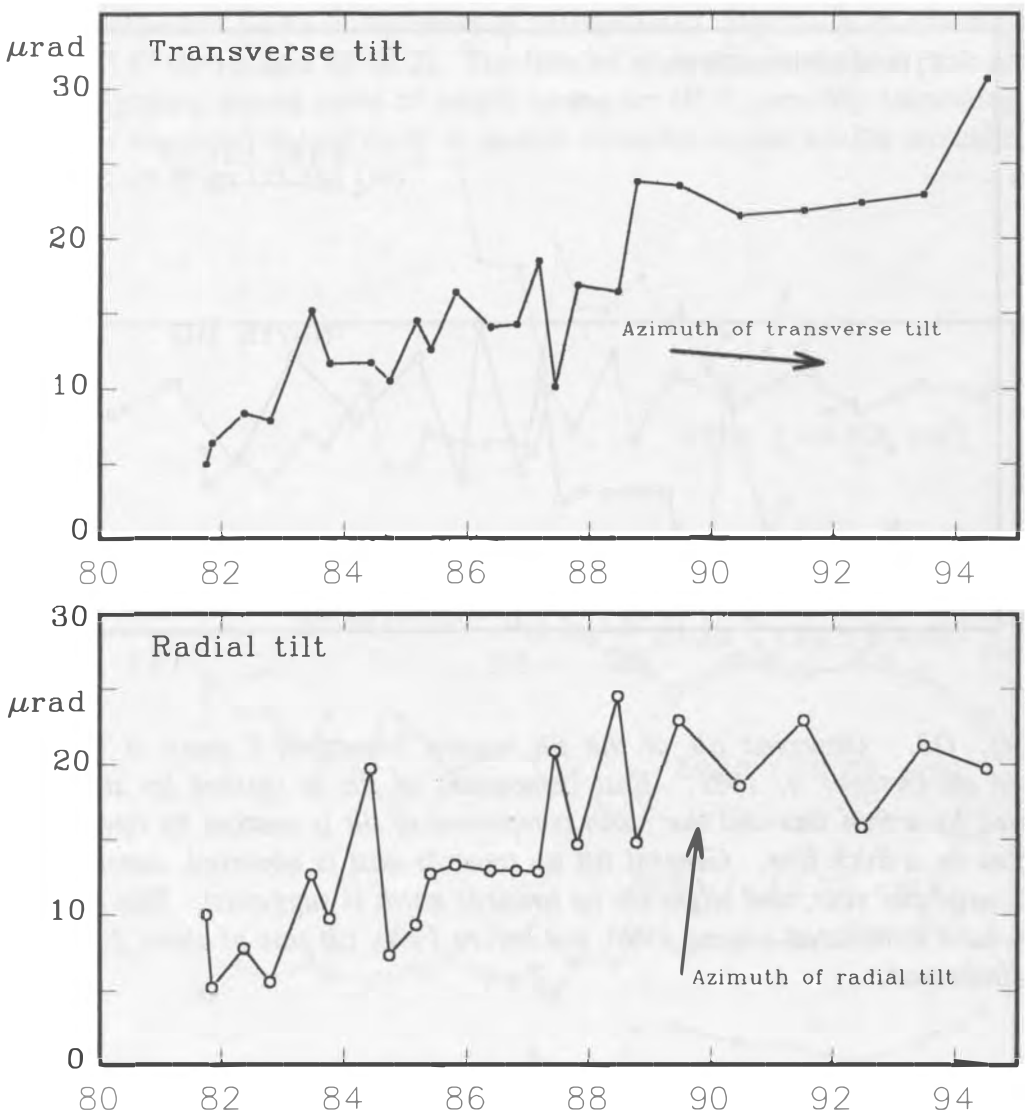


Fig. O4. Observed transverse (top) and radial (bottom) tilt at the tilt station Námafjall-S, relative to the center of deformation at Krafla. Radial tilt is taken to be tilt up towards an azimuth of 5° and transverse tilt is taken to be up towards an azimuth of 95°. The subsidence events of November 1981 and September 1984 are not observed at this tilt station.

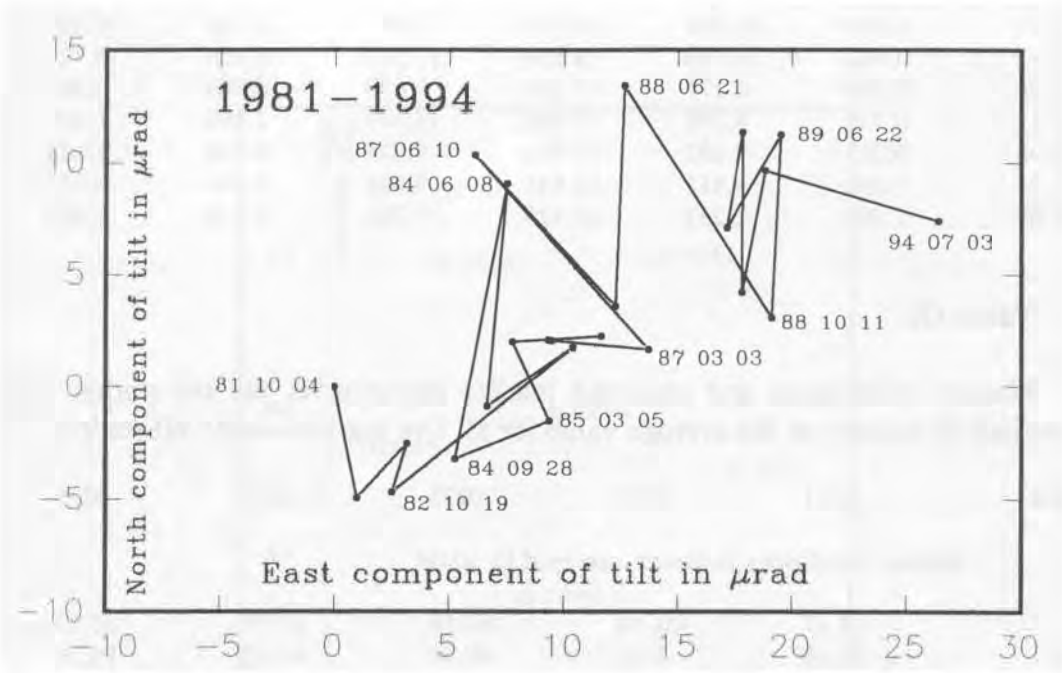


Fig. O5. North component of tilt plotted against east component of tilt at the tilt station Námafjall-S, showing progress of the tilt vector through time from 1981 to 1994. The tilt progress appear rather irregular, suggesting random or possibly seasonal variations of computed tilt, amounting to 5 to 10 μrad.

Table O1

Observed tilt at tilt station 0230, Námafjall-S. Minimum axis of the error ellipse is 71% of the maximum axis. Azimuth of the maximum error axis is 138°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
81 10 04			0.000	0.000		
81 11 07	0.985	-4.900	0.985	-4.900	2.749	2.749
82 05 15	2.191	2.423	3.176	-2.477	3.012	1.634
82 10 19	-0.638	-2.161	2.538	-4.638	2.339	0.984
83 06 21	7.852	6.391	10.390	1.753	1.550	1.346
83 10 08	-3.728	-2.601	6.662	-0.848	0.974	2.310
84 06 08	0.876	9.924	7.538	9.076	1.757	1.043
84 09 28	-2.257	-12.233	5.281	-3.157	2.053	2.191
85 03 05	4.107	1.653	9.388	-1.504	1.257	2.032
85 05 29	-1.610	3.533	7.778	2.029	1.529	1.322
85 10 24	3.870	0.228	11.648	2.258	1.735	0.857
86 05 28	-2.315	-0.154	9.334	2.104	1.079	1.565
86 10 24	0.153	-0.038	9.487	2.065	0.990	2.098
87 03 03	4.229	-0.382	13.716	1.684	1.253	2.577
87 06 10	-7.610	8.675	6.106	10.358	1.975	0.708
87 10 24	6.156	-6.757	12.262	3.601	0.669	0.958

88 06 21	0.409	9.836	12.671	13.437	2.183	1.465
88 10 11	6.463	-10.346	19.134	3.091	3.035	1.609
89 06 22	0.402	8.158	19.536	11.249	1.656	0.795
90 06 25	-2.396	-4.171	17.140	7.078	0.900	0.481
91 07 11	0.728	4.298	17.868	11.376	1.698	1.225
92 06 20	-0.053	-7.152	17.816	4.224	0.424	1.020
93 06 24	1.030	5.411	18.845	9.635	0.684	0.813
94 07 03	7.583	-2.233	26.429	7.703	0.558	0.695

Table O2

Marker coordinates and observed marker elevation at the tilt station 0230 (Námafjall-S) relative to the average value for all five markers at the tilt station.

Marker	0231	0232	0233	0234	0235
	Marker coordinates in meters, surveyed 81 10 04				
East	0.17	-24.56	-14.18	17.27	21.32
North	28.19	-8.21	-18.86	-11.70	10.56
Y M D	Marker elevation, centimeters				
81 10 04	4.0039	20.4772	9.7717	-12.6168	-21.6358
81 11 07	3.9888	20.4708	9.7918	-12.6199	-21.6314
82 05 15	4.0019	20.4651	9.7768	-12.6057	-21.6379
82 10 19	3.9884	20.4749	9.7784	-12.6113	-21.6306
83 06 21	4.0112	20.4442	9.7604	-12.6030	-21.6126
83 10 08	4.0048	20.4513	9.7755	-12.6087	-21.6230
84 06 08	4.0327	20.4471	9.7471	-12.6128	-21.6141
84 09 28	3.9956	20.4589	9.7809	-12.6111	-21.6241
85 03 05	3.9966	20.4525	9.7678	-12.6077	-21.6091
85 05 29	4.0110	20.4508	9.7635	-12.6090	-21.6165
85 10 24	4.0077	20.4490	9.7497	-12.6020	-21.6046
86 05 22	4.0066	20.4520	9.7580	-12.6100	-21.6064
86 10 24	4.0079	20.4472	9.7628	-12.6115	-21.6065
87 03 03	4.0030	20.4416	9.7543	-12.6064	-21.5927
87 06 10	4.0310	20.4550	9.7432	-12.6210	-21.6084
87 10 24	4.0128	20.4427	9.7507	-12.6040	-21.6020
88 06 21	4.0465	20.4313	9.7299	-12.6060	-21.6017
88 10 11	4.0084	20.4296	9.7396	-12.5938	-21.5837
89 06 22	4.0366	20.4167	9.7268	-12.5983	-21.5817
90 06 25	4.0227	20.4301	9.7340	-12.5973	-21.5894
91 07 11	4.0395	20.4230	9.7236	-12.5942	-21.5918
92 06 20	4.0192	20.4277	9.7391	-12.5875	-21.5984
93 06 24	4.0328	20.4238	9.7244	-12.5920	-21.5890
94 07 03	4.0273	20.4046	9.7207	-12.5775	-21.5751

TILT STATION 0240, HLÍÐARFJALL

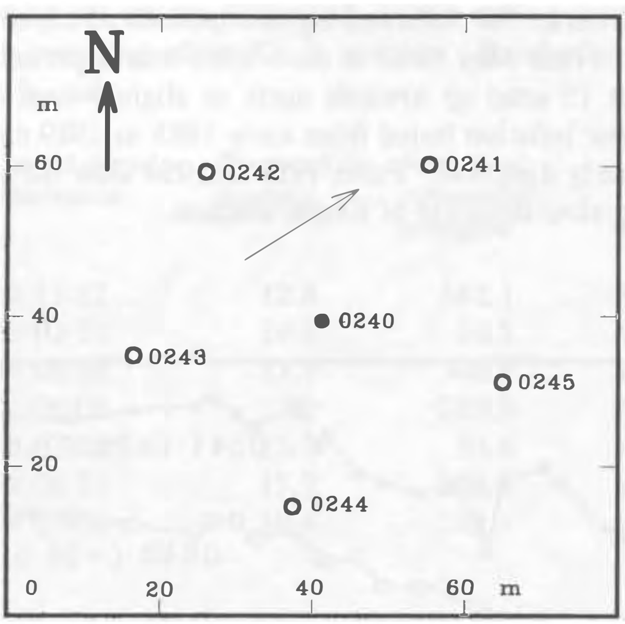


Fig. P1. Map of relative position of markers at the tilt station Hlíðarfjall, also named tilt station 0240. Solid circle is a marker at the center of a 25.0 m radius circle defined by 5 markers (open circles). The markers consist of 12.5 mm diameter copper alloy rods with rounded tops, cemented into the lava and extending 1 to 2 cm above the lava surface. Each marker is identified by a number as shown, inscribed on a washer. Thin arrow points in the direction of downward tilt during deflation events of Krafla volcano.

This station was constructed and first observed on October 7, 1981. It lies on a narrow stream of rather smooth pahoehoe lava that brought lava towards Mývatn in 1729, about one km upstream from station 0210. Its location is within the Krafla fissure swarm with distinct east facing fault scarps immediately west of the station, but the zone of greatest deformation during the 1975-1984 volcanic episode lies east of this station. Five permanent markers form a circle of 25.0 m radius and the sixth marker is located at the center of this circle (Fig. P1).

The station was observed 29 times from October 1981 to July 1994. The observed marker displacements (Fig. P2) are characterised by continuous uplift of marker 0242 and similar subsidence of markers 0244 and 0245. The deflation events of November 1981 and September 1984 show up as tilt up towards south and west (Fig P3) followed by tilt of about same amount in the opposite direction. The transverse tilt (Fig. P4) is down toward south-east at decreasing rate, but the radial tilt is dominated by the subsidence events of November 1981 and September 1984, in addition to steady uplift towards the center of deformation from 1981 to 1989 followed by continuous subsidence towards the center of deformation from 1989 to 1994.

The progress of tilt (Fig. P5) suggests that the period of observation of tilt station 0240 can be divided into seven period, each with distinct tilt characteristics. Two brief subsidence periods in November 1981 and September 1984 caused tilt of 10 to 15 μrad up towards SW followed by two periods of rapid inflations causing tilt up towards NE. From May 1982 to June 1984 was a period of slow inflation causing tilt of about 15 μrad up towards north or slightly west of north. Another similar period of slow inflation lasted from early 1985 to 1989 causing tilt of 15 to 20 μrad up in northerly direction. From 1989 to 1994 slow tilt up towards west is observed, signifying slow deflation of Krafla volcano.

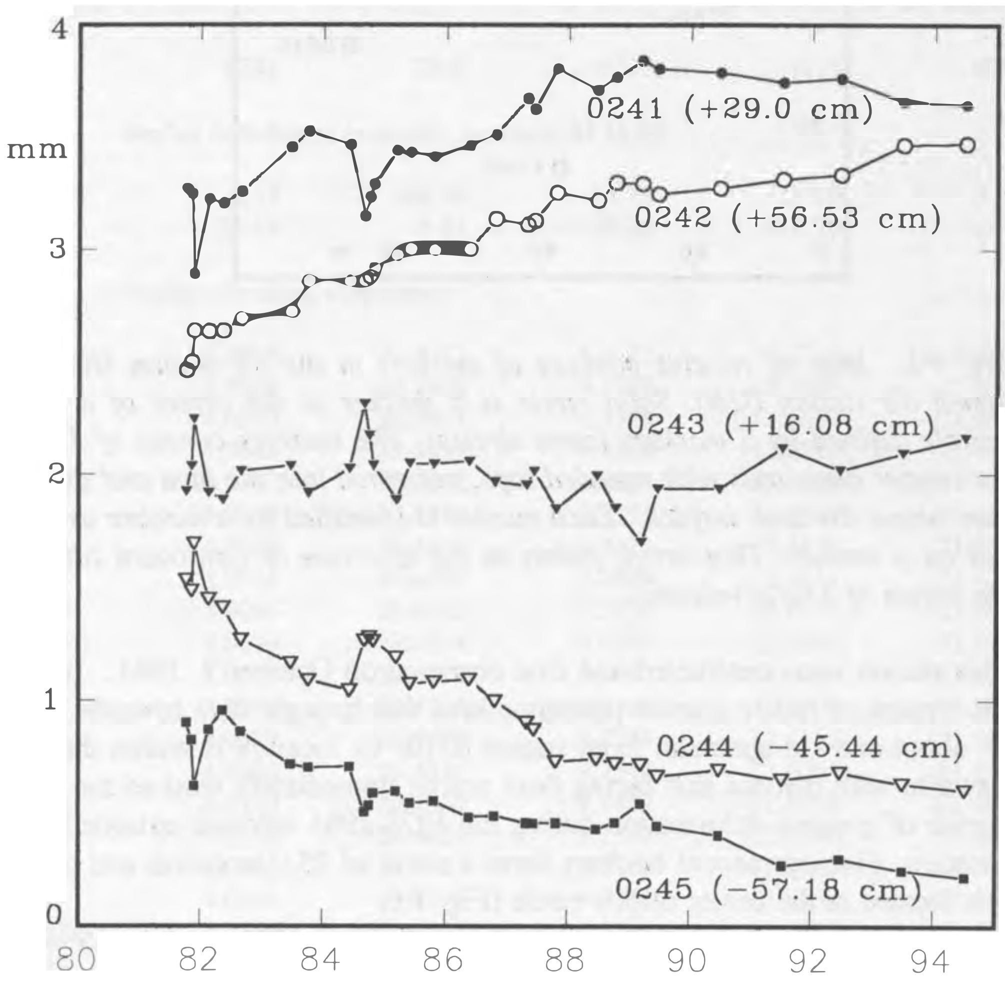


Fig. P2. Variation with time of the relative elevation of each marker forming the 25.0 m radius circle of the Hlíðarfjall tilt station. Marker 0242 has been uplifted continuously at slowly decreasing rate and marker 0244 has subsided similarly, although uplifted during the subsidence events of November 1981 and September 1984. Marker 0241 has been uplifted from 1981 to 1989, except for subsidence during the deflation events, and subsided slowly from 1989 to 1994.

Table P1

Observed tilt at tilt station Hlíðarfjall (0240) during selected periods of fast and slow rate of deformation of the Krafla volcano. Standard error of computed tilt is estimated about 3 μrad.

Date of first observation	Date of second observation	Computed tilt in μrad	Azimuth of computed tilt in degrees	Remarks
81 11 08	81 11 22	12.6	242.1	fast deflation
81 11 22	82 02 21	14.6	56.5	fast inflation
82 02 21	84 06 08	13.7	346.9	slow inflation
84 06 08	84 09 06	13.2	233.9	fast deflation
84 09 06	85 03 12	12.2	50.6	fast inflation
85 03 12	89 06 23	17.7	356.1	slow inflation
89 06 23	94 07 06	10.4	282.1	slow deflation

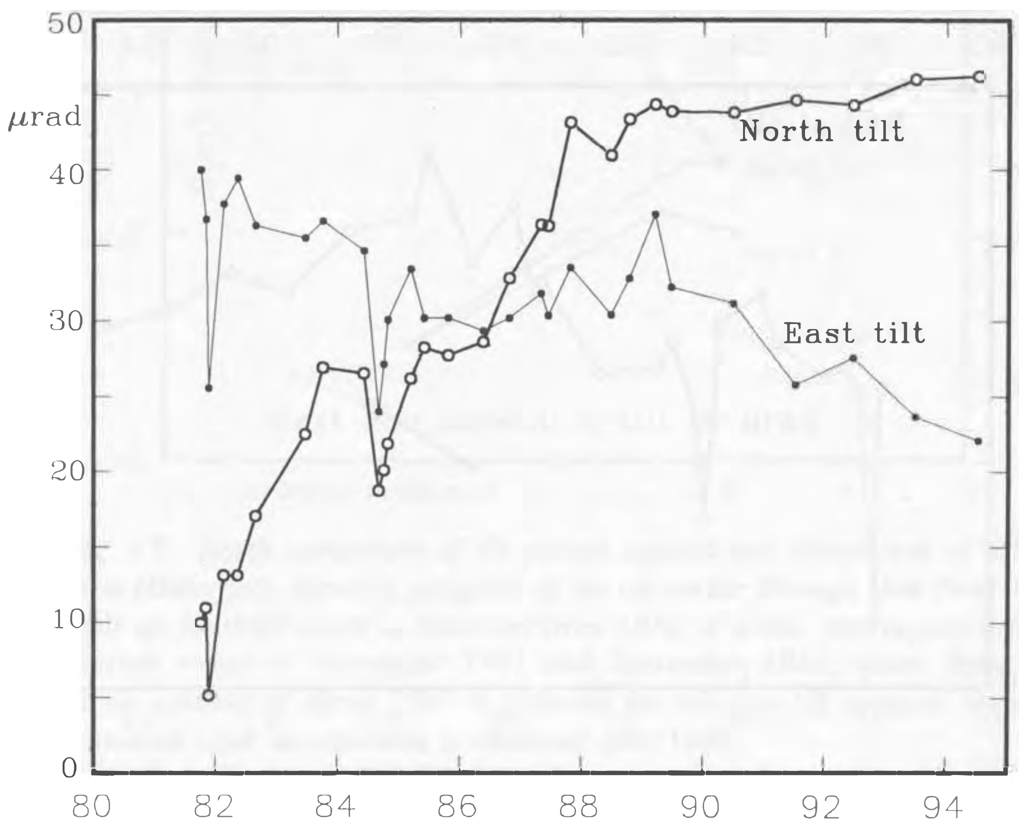


Fig. P3. Observed tilt at the tilt station Hlíðarfjall since it was first observed on October 7, 1981. East component of tilt is marked with small dots connected by a thin line and the north component of tilt is marked with open circles connected by a thick line. A distinct change of tilt rate is seen at around 1988-1989 when uplift toward north ceased and rate of westward uplift increased. Subsidence events of November 1981 and September 1984 are distinct.

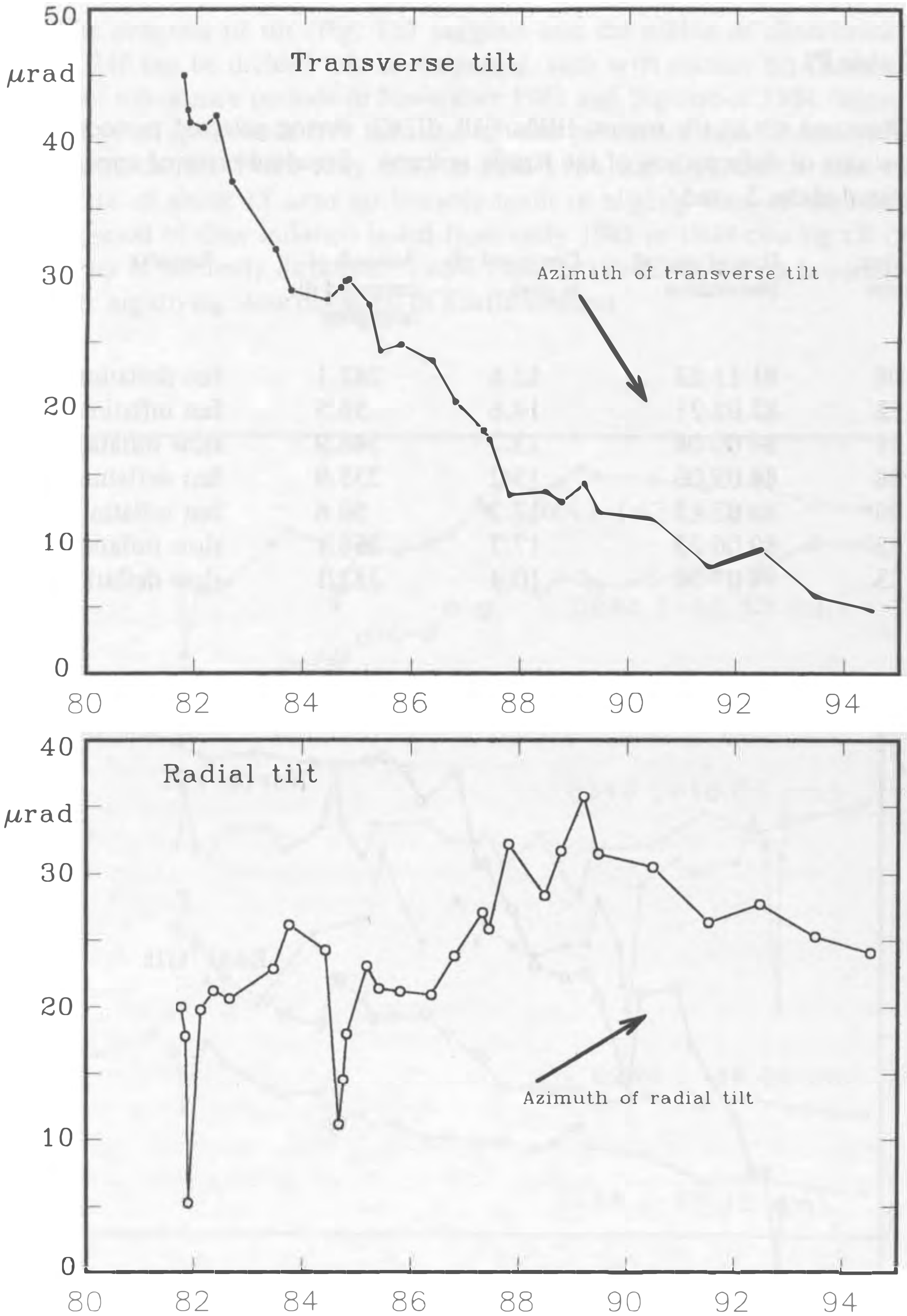


Fig. P4. Observed transverse (top) and radial (bottom) tilt at the tilt station Hlíðarfjall relative to the center of deformation at Krafla. Radial tilt is taken to be tilt component toward an azimuth of 58°, the average direction of downward tilt during deflations of Krafla volcano. Transverse tilt toward an azimuth of 148° is dominated by downward tilt at slightly decreasing rate. Radial tilt is characterised by positive tilt (up toward 58°) at slow rate from 1981 to 1989, interrupted briefly by deflations of November 1981 and September 1984, and slow downward tilt after 1989.

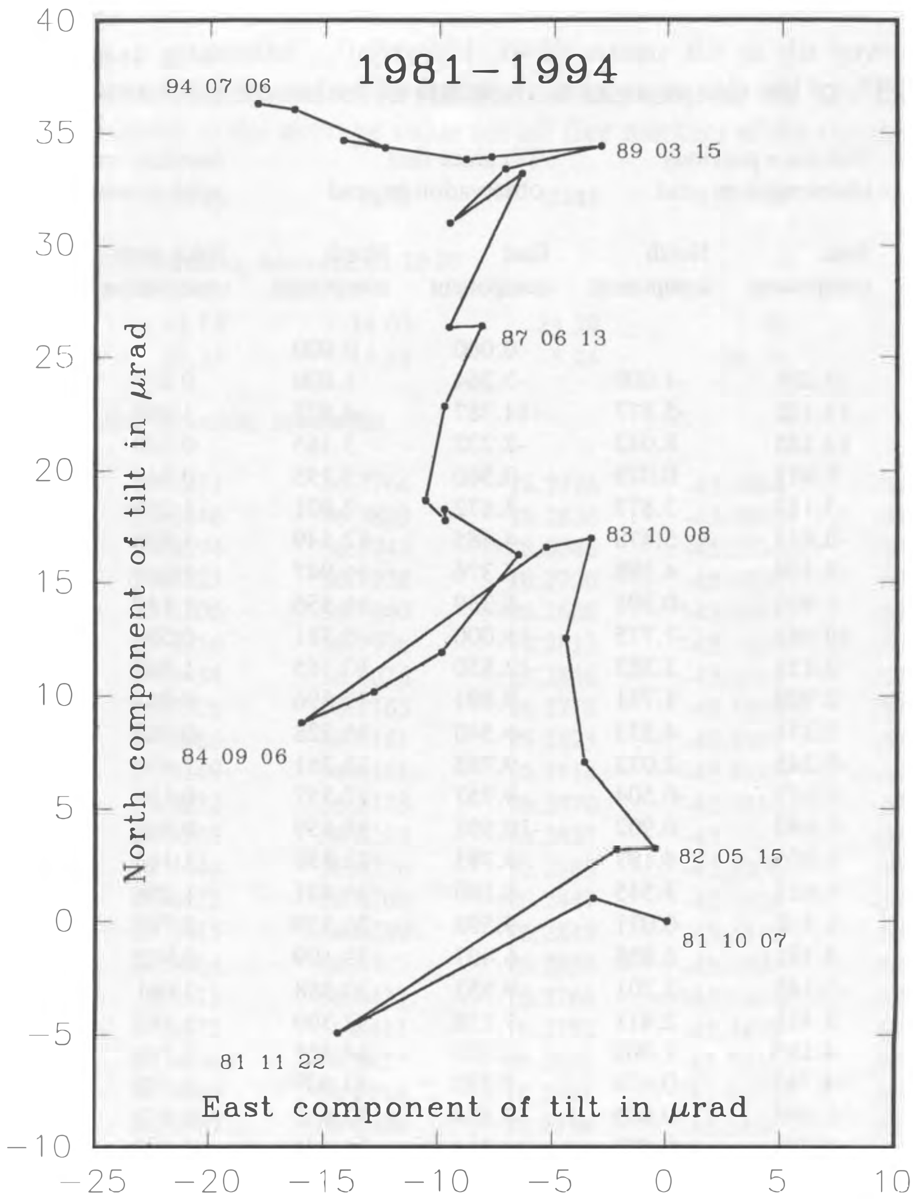


Fig. P5. North component of tilt plotted against east component of tilt at the tilt station Hlíðarfjall, showing progress of the tilt vector through time from 1981 to 1994. Tilt up towards north is observed from 1981 to 1989, interrupted briefly by the deflation events of November 1981 and September 1984, when deflation tilt towards an azimuth of about 238° is followed by inflation tilt towards about 58°. Tilt up towards west at slow rate is observed after 1989.

Table P2

Observed tilt at tilt station 0240, Hlíðarfjall. Minimum axis of the error ellipse is 98% of the maximum axis. Azimuth of maximum error axis is 175°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
81 10 07			0.000	0.000		
81 11 08	-3.264	1.000	-3.264	1.000	0.677	0.677
81 11 22	-11.122	-5.877	-14.387	-4.877	1.660	1.206
82 02 21	12.155	8.042	-2.232	3.165	0.343	1.497
82 05 15	1.671	0.029	-0.560	3.193	0.844	2.229
82 09 01	-3.112	3.877	-3.672	7.071	1.264	2.167
83 06 23	-0.813	5.478	-4.485	12.549	1.836	1.269
83 10 08	1.109	4.398	-3.376	16.947	1.259	0.696
84 06 08	-1.963	-0.391	-5.339	16.556	1.149	1.635
84 09 06	-10.662	-7.775	-16.000	8.781	0.020	1.660
84 10 04	3.151	1.383	-12.850	10.165	1.149	0.929
84 10 28	2.959	1.731	-9.891	11.896	0.961	1.515
85 03 12	3.351	4.333	-6.540	16.228	0.909	1.942
85 06 03	-3.245	2.033	-9.785	18.261	1.630	1.104
85 10 26	0.027	-0.504	-9.757	17.757	0.126	1.225
86 05 23	-0.840	0.902	-10.598	18.659	0.823	0.516
86 10 22	0.805	4.197	-9.793	22.856	1.103	1.606
87 04 30	1.613	3.545	-8.180	26.401	1.290	0.458
87 06 13	-1.418	-0.071	-9.598	26.330	0.703	0.597
87 10 25	3.191	6.858	-6.407	33.189	0.922	1.067
88 06 24	-3.145	-2.201	-9.553	30.988	1.061	0.840
88 10 13	2.415	2.411	-7.138	33.399	1.302	1.586
89 03 15	4.185	1.002	-2.953	34.401	0.749	2.198
89 06 23	-4.785	-0.474	-7.737	33.927	2.072	0.751
90 06 27	-1.097	-0.095	-8.834	33.832	0.473	0.667
91 07 10	-5.380	0.822	-14.214	34.654	1.009	0.785
92 06 20	1.824	0.123	-12.390	34.776	0.961	0.516
93 06 29	-3.923	1.262	-16.313	36.039	1.218	1.700
94 07 06	-1.596	0.246	-17.909	36.285	0.553	1.681

Table P3

Marker coordinates and observed marker elevation at the tilt station 0240 (Hlíðarfjall) relative to the average value for all five markers at the tilt station.

Marker	0241	0242	0243	0244	0245
Marker coordinates in meters, surveyed 81 10 07					
East	15.15	-14.03	-23.39	-2.58	24.87
North	20.22	19.21	-5.24	-25.39	-8.80
Y M D	Marker elevation, centimeter				
81 10 07	29.3271	56.7766	16.2726	-45.2864	-57.0899
81 11 08	29.3246	56.7803	16.2836	-45.2912	-57.0974
81 11 22	29.2894	56.7941	16.3046	-45.2704	-57.1179
82 02 21	29.3223	56.7938	16.2720	-45.2950	-57.0930
82 05 15	29.3206	56.7940	16.2688	-45.2987	-57.0845
82 09 01	29.3256	56.7998	16.2813	-45.3129	-57.0939
83 06 23	29.3454	56.8026	16.2836	-45.3234	-57.1084
83 10 08	29.3526	56.8163	16.2718	-45.3309	-57.1097
84 06 08	29.3466	56.8161	16.2823	-45.3357	-57.1094
84 09 06	29.3149	56.8161	16.3114	-45.3131	-57.1291
84 10 04	29.3232	56.8178	16.2970	-45.3116	-57.1263
84 10 28	29.3289	56.8219	16.2837	-45.3135	-57.1211
85 03 12	29.3440	56.8276	16.2689	-45.3206	-57.1201
85 06 03	29.3432	56.8303	16.2847	-45.3328	-57.1253
85 10 26	29.3415	56.8299	16.2845	-45.3317	-57.1244
86 05 23	29.3464	56.8303	16.2856	-45.3307	-57.1314
86 10 22	29.3511	56.8437	16.2766	-45.3404	-57.1309
87 04 30	29.3672	56.8411	16.2752	-45.3496	-57.1339
87 06 13	29.3626	56.8427	16.2813	-45.3528	-57.1340
87 10 25	29.3804	56.8554	16.2649	-45.3670	-57.1339
88 06 24	26.3710	56.8520	16.2794	-45.3658	-57.1366
88 10 13	29.3767	56.8599	16.2651	-45.3679	-57.1337
89 03 15	29.3841	56.8593	16.2504	-45.3684	-57.1255
89 06 23	29.3802	56.8547	16.2737	-45.3735	-57.1351
90 06 27	29.3786	56.8575	16.2737	-45.3706	-57.1393
91 07 10	29.3743	56.8615	16.2916	-45.3749	-57.1526
92 06 20	29.3760	56.8636	16.2817	-45.3717	-57.1497
93 06 29	29.3660	56.8767	16.2892	-45.3770	-57.1549
94 07 06	29.3645	56.8771	16.2960	-45.3797	-57.1579

TILT STATION 0250, SYÐRI BJARGHÓLL

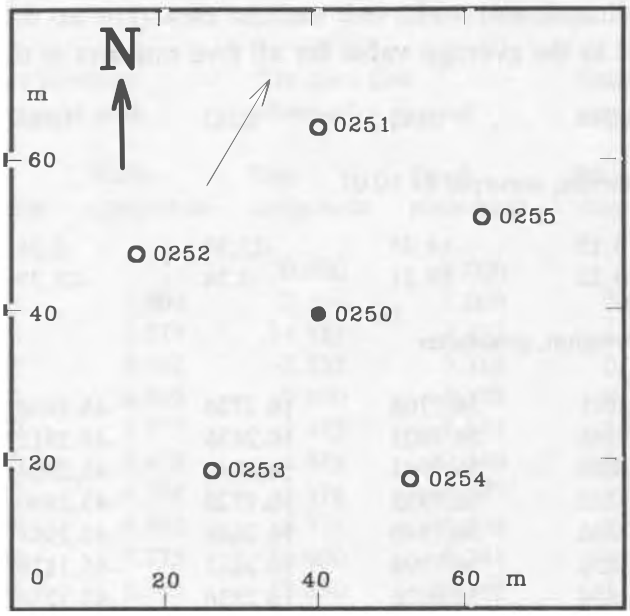


Fig. Q1. Map of relative position of markers at the tilt station Syðri Bjarghóll, also named tilt station 0250. Solid circle is a marker at the center of a 25.0 m radius circle defined by 5 markers (open circles). The markers consist of 12.5 mm diameter copper alloy rods with rounded tops, cemented into the lava and extending 1 to 2 cm above the lava surface. Each marker is identified by a number as shown, inscribed on a washer. Thin arrow points in the direction of downward tilt during deflation events of the Krafla volcano.

This station was first observed on October 7, 1981. It lies on pahoehoe lava of the 1724-1729 Myvatn fires, about 500 m south-east of the small but prominent peak Syðri Bjarghóll. The Krafla fissure swarm is not clearly outlined at this location but open fissures of the 1975-1984 episode were seen to the west of this tilt station, although the most active part of the fissure swarm lies east of the station, suggesting that this tilt station is inside, although near the western limit of the part of the Krafla fissure swarm that was active during the 1975-1984 volcanic and tectonic episode. Five permanent markers form a circle of 25.0 m radius and a sixth marker is at the center of this circle (Fig. Q1), where the level is placed during observations.

This station was observed 31 times from October 1981 to July 1994. These observations show uplift of markers 0251 and 0252 from 1981 to 1989, and similar subsidence of markers 0253 and 0254 (Fig. Q2). Marker 0253 has been uplifted from 1989 to 1994 while markers 0251, 0252, and 0254 were apparently stable. The subsidence events of November 1981 and September 1984 are clearly seen in displacements of four markers, but marker 0252 is not affected by these events.

The North component of observed tilt (Fig. Q3) is generally positive (up toward north) from 1981 to 1989 and negative at slower rate after 1989. The east component of tilt is generally negative (down toward east) throughout the whole period of observations, 1981 to 1994, at a near constant rate. Some irregularity in the tilt rate is observed 1988 to 1989. This is caused by upward displacement of marker 0252 and simultaneous downward displacement of marker 0253 between observations of 88 06 24 and 88 10 12. These markers apparently moved back to normal elevation between observations of 89 03 15 and 89 06 23.

The radial tilt, up towards an azimuth of about 31°, is characterised by continuous uplift to the center of deformation from 1981 to 1989, with brief tilt reversal during the deflations of November 1981 and September 1984, and continuous subsidence from 1989 to 1994 (Fig Q4). The transverse tilt is generally negative, down towards an azimuth of 121°, during the whole period of observations, but the tilt rate decreased abruptly in 1989, from about 14 μrad per year before 1989 to about 3 μrad per year after 1989.

The ground tilt at tilt station 0250 has been progressing up towards an azimuth of 325° to 330° from 1981 to 1989 with brief tilt excursion during the deflation events of November 1981 and 1984 (Fig. Q5), but after 1989, tilt up towards about 225° has been observed. There is a striking difference in tilt azimuth during fast inflation first after major deflation, and the slower inflation one to five years after the deflation events (Table Q1, Fig. Q5). There is less difference in tilt azimuth between fast deflation during deflation events and slow deflation from 1989 to 1994.

Table Q1

Observed tilt at tilt station Syðri Bjarghóll (0250) during selected periods of fast and slow rate of deformation of the Krafla volcano. Standard error of tilt is estimated 2 to 5 μrad.

Date of first observation	Date of second observation	Computed tilt in μrad	Azimuth of computed tilt in degrees	Remarks
81 11 06	81 11 21	38.5	211.9	fast deflation
81 11 21	82 02 21	37.0	36.0	fast inflation
82 02 21	84 06 08	54.3	326.4	slow inflation
84 06 08	84 09 06	45.8	209.8	fast deflation
84 09 06	85 03 12	29.5	21.3	fast inflation
85 03 12	89 06 23	72.5	334.4	slow inflation
89 06 23	94 07 06	25.1	241.1	slow deflation

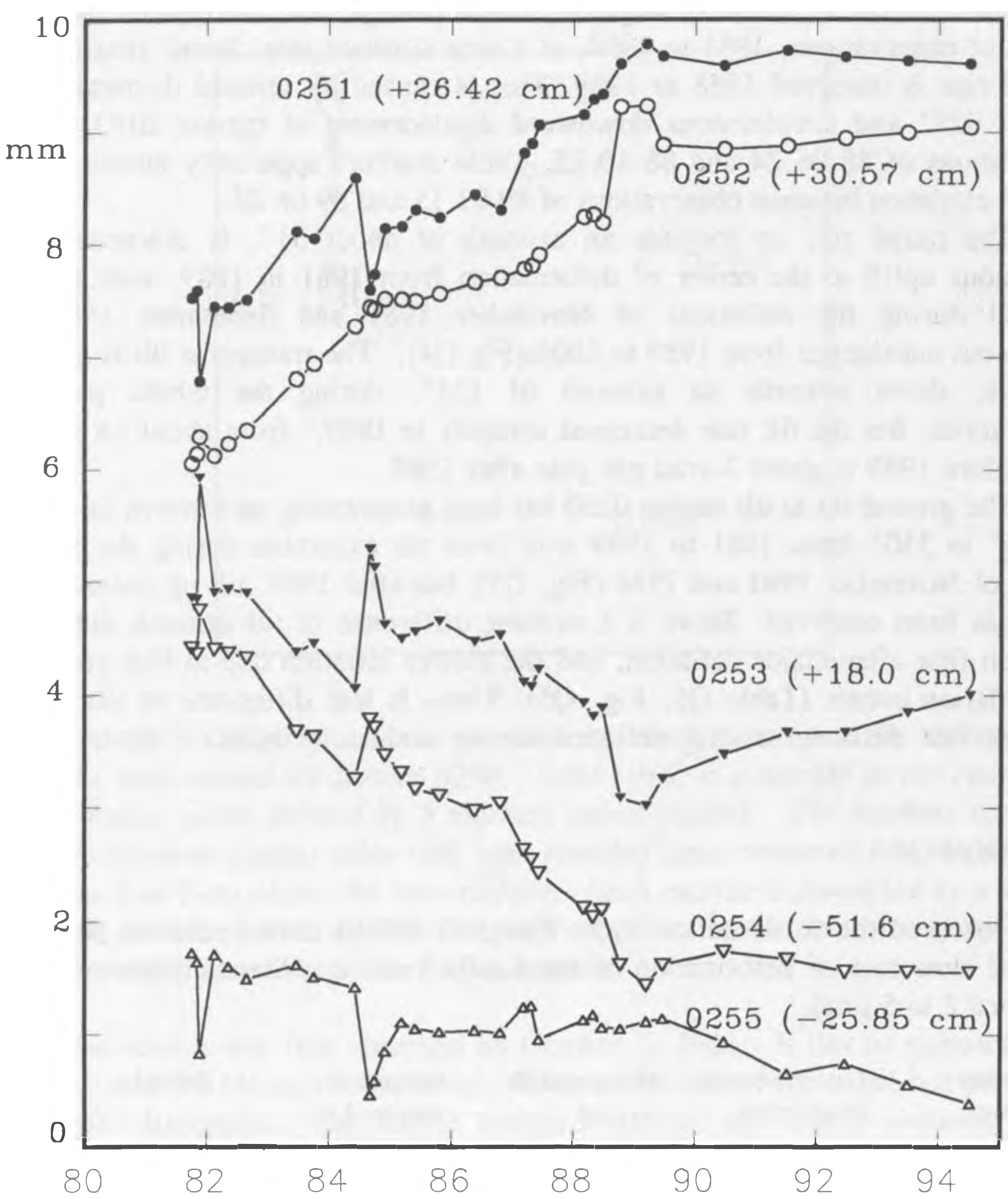


Fig. Q2. Variation with time of the relative elevation of each marker of the 25.0 m radius circle of the Syðri Bjarghóll tilt station. Markers 0251 and 0252 have been uplifted at near constant rate from 1981 to 1989 but remained stable after 1989. The remaining three marker did subside from 1981 to 1989, although 0255 subsided very slowly. After 1989, the station 0253 has been uplifted, 0254 remained stable but 0255 continued to subside. The deflation events of November 1981 and September 1984 are seen as subsidence of markers 0251 and 0255 and uplift of markers 0253 and 0254.

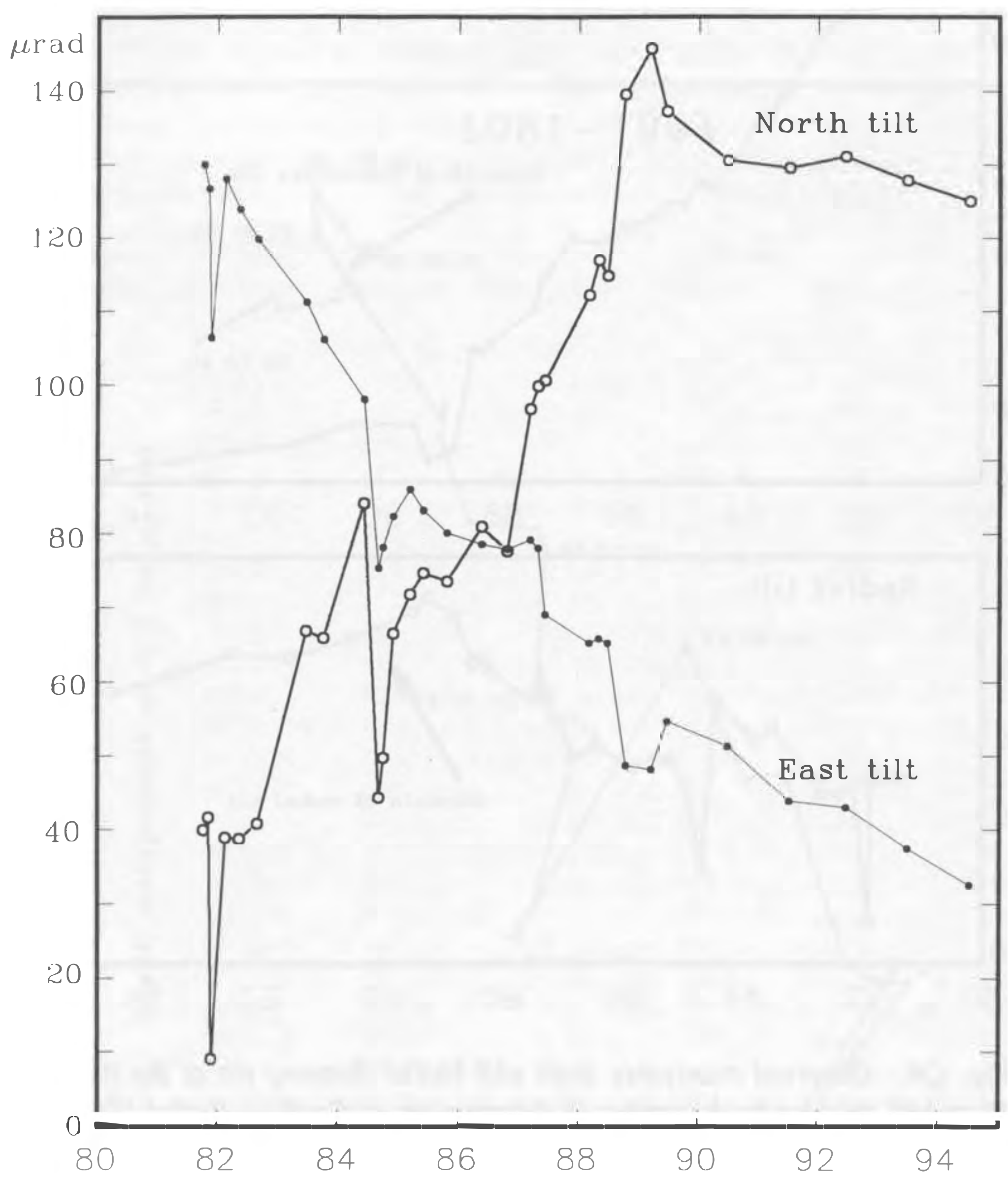


Fig. Q3. Observed tilt at the tilt station Syðri Bjarghóll since it was first observed on October 7, 1981. East component of tilt is marked with small dots connected by a thin line and the north component is marked with open circles connected by a thick line. A distinct change in north component of tilt is seen in 1989, signifying the end of expansion of the shallow Krafla magma reservoir. East component of tilt has progressed at relatively constant rate, down toward east, except for brief effect of the deflation events of November 1981 and September 1984.

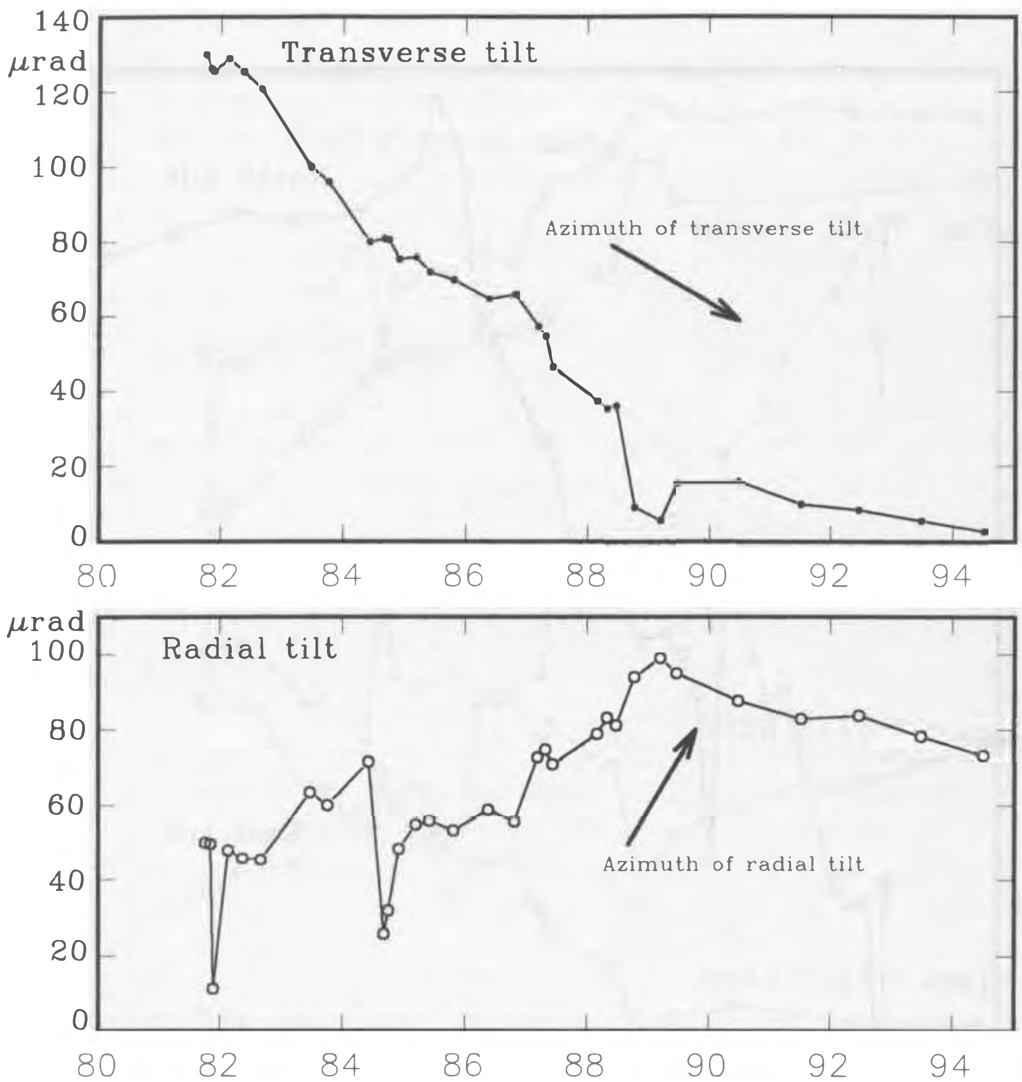


Fig. Q4. Observed transverse (top) and radial (bottom) tilt at the tilt station Syðri Bjarghóll relative to the center of deformation at Krafla. Radial tilt is taken to be tilt components towards an azimuth of 31°, the average direction of downward tilt during deflations of Krafla volcano. The transverse tilt, towards an azimuth of 121° is generally downward, at a rate of about 14 µrad per year from 1981 to 1989 but much slower rate of about 3 µrad per year after 1989. The radial tilt shows general inflation of Krafla volcano from 1981 to 1989, except for brief deflation during the deflation and volcanic events of November 1981 and September 1984. After 1989, deflation of Krafla volcano is observed.

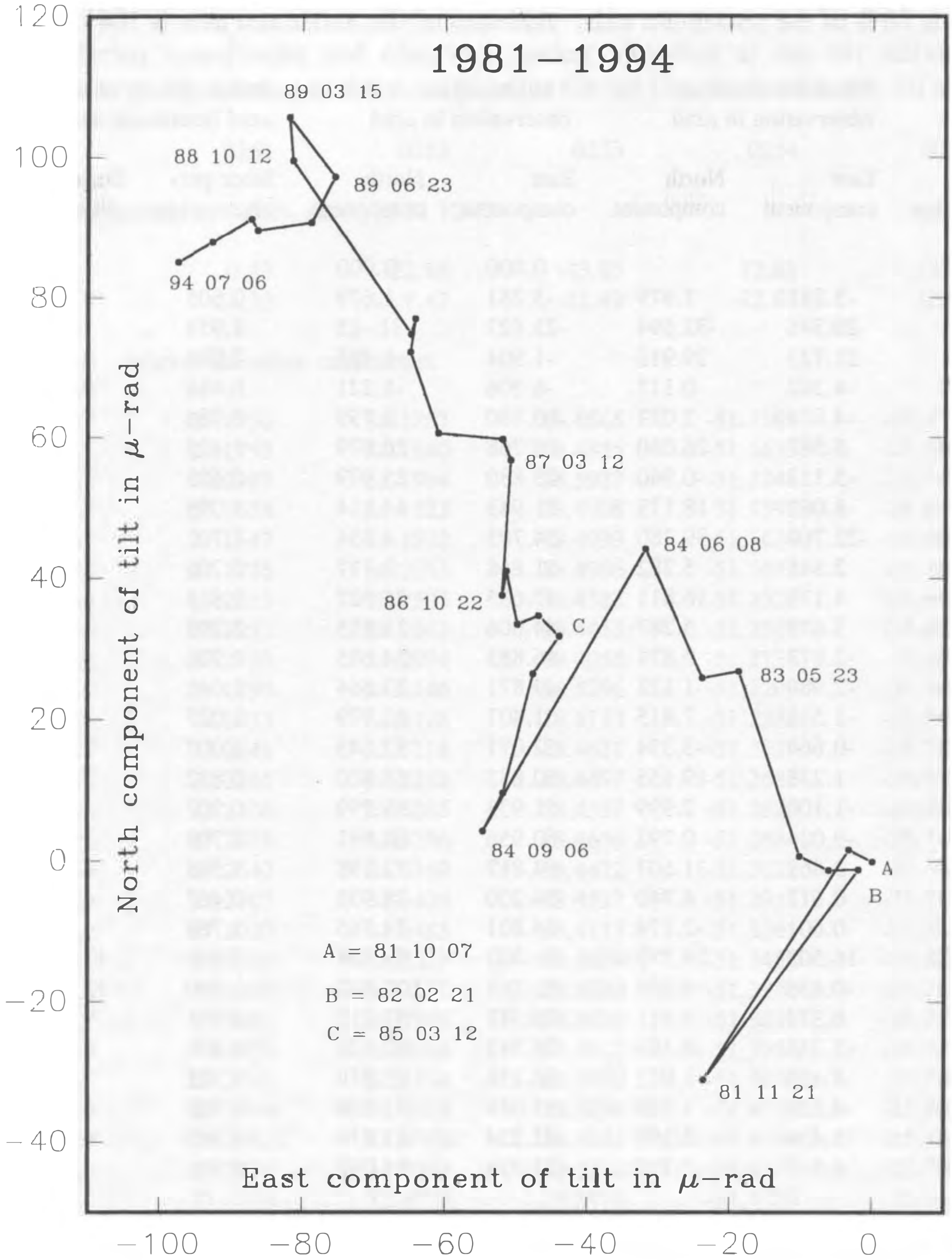


Fig. Q5. North component of tilt plotted against east component of tilt at the tilt station Syðri Bjarghóll, showing progress of the tilt vector through time from October 1981 to July 1994. Tilt up towards an azimuth of 325° to 330° is observed from 1981 to 1989, with exception of the deflation events of November 1981 and September 1984. After 1989, tilt up towards an azimuth of about 250° is suggested.

Table Q2

Observed tilt at tilt station 0250, Syðri Bjarghóll. Maximum axis of the error ellipse is 86% of the maximum axis. Azimuth of the maximum axis is 104°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
81 10 07			0.000	0.000		
81 11 06	-3.281	1.679	-3.281	1.679	0.605	0.605
81 11 21	-20.346	-32.694	-23.627	-31.-15	1.959	1.667
82 02 21	21.723	29.910	-1.904	-1.105	2.098	0.877
82 05 14	-4.202	-0.117	-6.106	-1.221	0.486	0.951
82 09 01	-4.074	2.021	-10.180	0.799	0.986	1.382
83 05 23	-8.587	26.080	-18.768	26.879	1.425	2.806
83 10 07	-5.112	-0.940	-23.880	25.939	0.623	3.202
84 06 08	-8.062	18.175	-31.943	44.114	3.095	5.297
84 09 06	-22.760	-39.780	-54.703	4.334	1.701	3.597
84 10 03	2.845	5.382	-51.858	9.717	0.206	3.803
84 12 04	4.173	16.811	-47.685	26.527	1.813	5.610
85 03 12	3.679	5.287	-44.006	31.815	2.293	4.874
85 06 04	-2.877	2.871	-46.883	34.685	1.926	3.197
85 10 26	-2.989	-1.121	-49.871	33.564	1.041	2.650
86 05 23	-1.536	7.415	-51.407	40.979	1.027	3.380
86 10 22	-0.664	-3.334	-52.071	37.645	1.007	3.977
87 03 12	1.238	19.155	-50.833	56.800	0.832	3.603
87 04 28	-1.100	2.999	-51.933	59.799	0.307	3.346
87 06 11	-9.024	0.792	-60.956	60.591	2.798	3.504
88 03 06	-3.861	11.607	-64.817	72.198	3.548	4.152
88 05 02	0.617	4.740	-64.200	76.938	0.467	4.375
88 06 24	-0.601	-2.174	-64.801	74.765	1.789	4.274
88 10 12	-16.502	24.773	-81.303	99.538	9.848	13.090
89 03 15	-0.458	6.104	-81.761	105.642	1.040	12.063
89 06 23	6.374	-8.431	-75.387	97.211	2.971	9.189
90 06 23	-3.356	-6.589	-78.743	90.622	1.426	8.654
91 07 08	-7.493	-1.042	-86.236	89.579	3.122	7.909
92 06 20	-0.853	1.589	-87.089	91.169	1.918	6.899
93 06 29	-5.434	-3.298	-92.524	87.871	0.980	6.508
94 07 06	-4.812	-2.779	-97.336	85.092	0.906	6.246

Table Q3

Marker coordinates and observed marker elevation at the tilt station 0250 (Syðri Bjarghóll) relative to the average value for all five markers at the tilt station.

Marker	0251	0252	0253	0254	0255
Marker coordinates in meters, surveyed 81 10 07					
East	0.83	-22.86	-13.03	12.81	22.27
North	24.33	7.43	-21.49	-22.61	12.33
Y M D	Marker elevation, centimeters				
81 10 07	27.1730	31.1757	18.4865	-51.1580	-25.6770
81 11 06	27.1793	31.1840	18.4855	-51.1635	-25.6852
81 11 21	27.0989	31.1994	18.5927	-51.1246	-25.7666
82 02 21	27.1653	31.1823	18.4908	-51.1595	-25.6787
82 05 14	27.1647	31.1932	18.4939	-51.1624	-25.6896
82 09 01	27.1716	31.2053	18.4906	-51.1674	-25.7002
83 06 23	27.2313	31.2505	18.4382	-51.2320	-25.6882
83 10 07	27.2253	31.2643	18.4455	-51.2365	-25.6985
84 06 08	27.2789	31.2974	18.4056	-51.2736	-25.7081
84 09 06	27.1799	31.3146	18.5296	-51.2209	-25.8034
84 10 03	27.1933	31.3128	18.5133	-51.2284	-25.7909
84 12 04	27.2341	31.3218	18.4621	-51.2527	-25.7651
85 03 12	27.2361	31.3212	18.4497	-51.2681	-25.7391
85 06 04	27.2506	31.3205	18.4558	-51.2825	-25.7445
85 10 26	27.2439	31.3266	18.4656	-51.2884	-25.7476
86 05 23	27.2642	31.3369	18.4472	-51.3022	-25.7461
86 10 22	27.2507	31.3405	18.4527	-51.2955	-25.7483
87 03 12	27.3020	31.3485	18.4113	-51.3365	-25.7252
87 04 28	27.3104	31.3517	18.4076	-51.3454	-25.7244
87 06 11	27.3269	31.3611	18.4230	-51.3570	-25.7541
88 03 06	27.3362	31.3948	18.3936	-51.3876	-25.7369
88 05 02	27.3496	31.3966	18.3812	-51.3956	-25.7320
88 06 24	27.3542	31.3894	18.3890	-51.3893	-25.7434
88 10 12	27.3804	31.4926	18.3094	-51.4379	-25.7445
89 03 15	27.3982	31.4933	18.3021	-51.4557	-25.7381
89 06 23	27.3876	31.4584	18.3266	-51.4375	-25.7353
90 06 27	27.3792	31.4553	18.3478	-51.4258	-25.7563
91 07 08	27.3928	31.4578	18.3672	-51.4325	-25.7851
92 06 20	27.3870	31.4647	18.3675	-51.4436	-25.7756
93 06 29	27.3834	31.4700	18.3849	-51.4439	-25.7944
94 07 06	27.3807	31.4746	18.4002	-51.4446	-25.8109

TILT STATION 0260, HREINDÝRAHÓLL

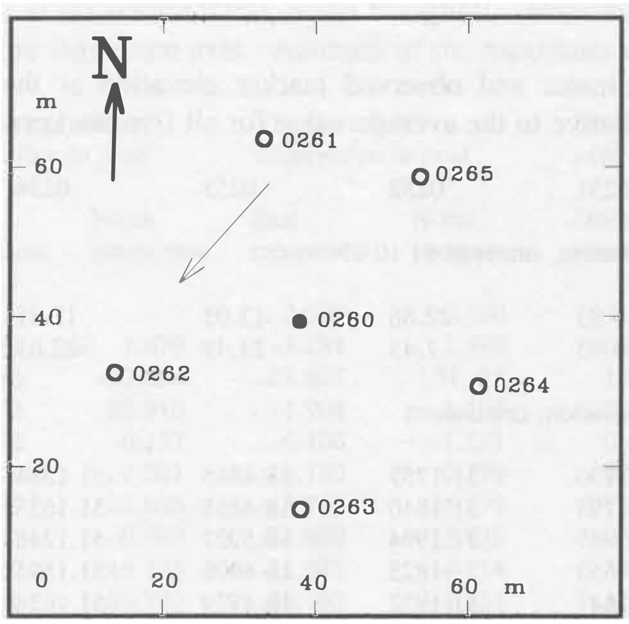


Fig. R1. Map of relative position of markers at the tilt station Hreindýrahóll, also named tilt station 0260. Solid circle is a marker at the center of a 25.0 m radius circle defined by 5 markers (open circles). The markers consist of 12.5 mm diameter copper alloy rods with rounded tops, cemented into the lava and extending one to two cm above the lava surface. Each marker is identified by a number as shown, inscribed on a washer. Thin arrow gives the approximate direction to the center of deformation at Krafla volcano.

This station was established and first observed on October 3, 1984, during the inflation period that followed the September 1984 deflation and eruption. It lies on smooth pahoehoe lava which was erupted 2000 to 2500 years before present (Sæmundsson 1991). Five permanent markers form a circle of 25.0 m radius and a sixth marker is at the center of this circle (Fig. R1) to mark the location of the level during observations. It was observed 19 times from October 1984 to July 1994.

Two markers, 0262 and 0263, were uplifted from 1984 to 1989 and subsided after 1989, relative to the average elevation of all five markers of the circle (Fig. R2). Marker 0265 subsided from 1984 to 1989 and was uplifted after 1989, while the two markers 0261 and 0264 moved in somewhat irregular manner. The observed tilt is up towards SW from 1984 to 1989, about 38 μrad in 5 years followed by tilt up towards NE or ENE in 1989 to 1993, about 13 μrad (Fig. R3)

The transverse tilt (towards an azimuth of 310°) is small, probably down at a rate of one to two μrad per year (Fig. R4), but radial tilt (towards an azimuth of 220°) is upward from 1984 to 1989 and downward from 1989 to 1992. First after observations were started at this station, rapid inflation following the September 1984 eruption was going on, causing rapid raise in radial tilt but from early 1985 to 1989, the average radial tilt rate was about 5 μrad per year upward, and from 1989 to 1994 the radial tilt rate was about 2 to 3 μrad per year downward.

The average tilt from 1984 to 1989 was up towards an azimuth of about 220° (Fig. R5), but considerable irregularities in rate of tilt can be attributed to observational errors or random marker displacements caused by thermal strain in the underlying lava. From 1989 to 1994, tilt up towards an azimuth of about 70° is suggested.

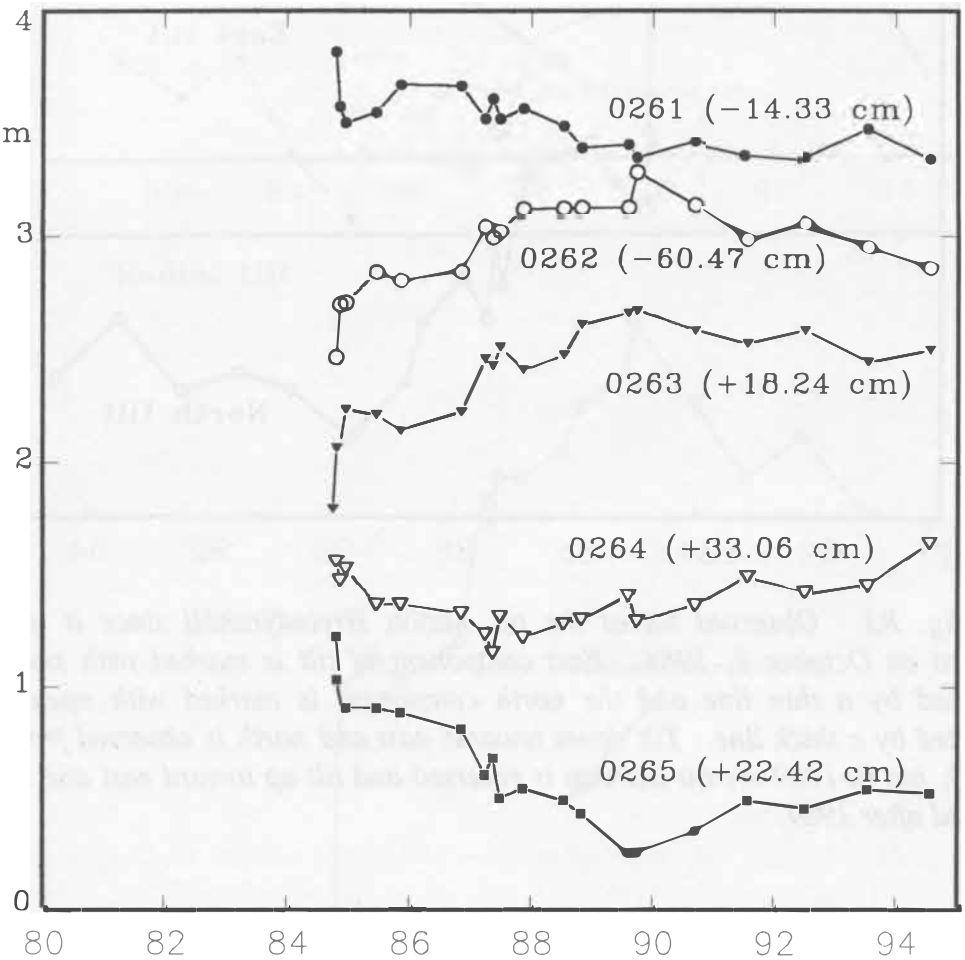


Fig. R2. Variations with time of the relative elevation of each marker of the 25.0 m radius circle at the Hreindýrahóll tilt station. Rapid elevation changes are observed from October to November 1984, the result of rapid inflation after the September 1984 eruption and subsidence event. Reversal in vertical displacements in 1989 are seen, especially at markers 0262, 0263, and 0265.

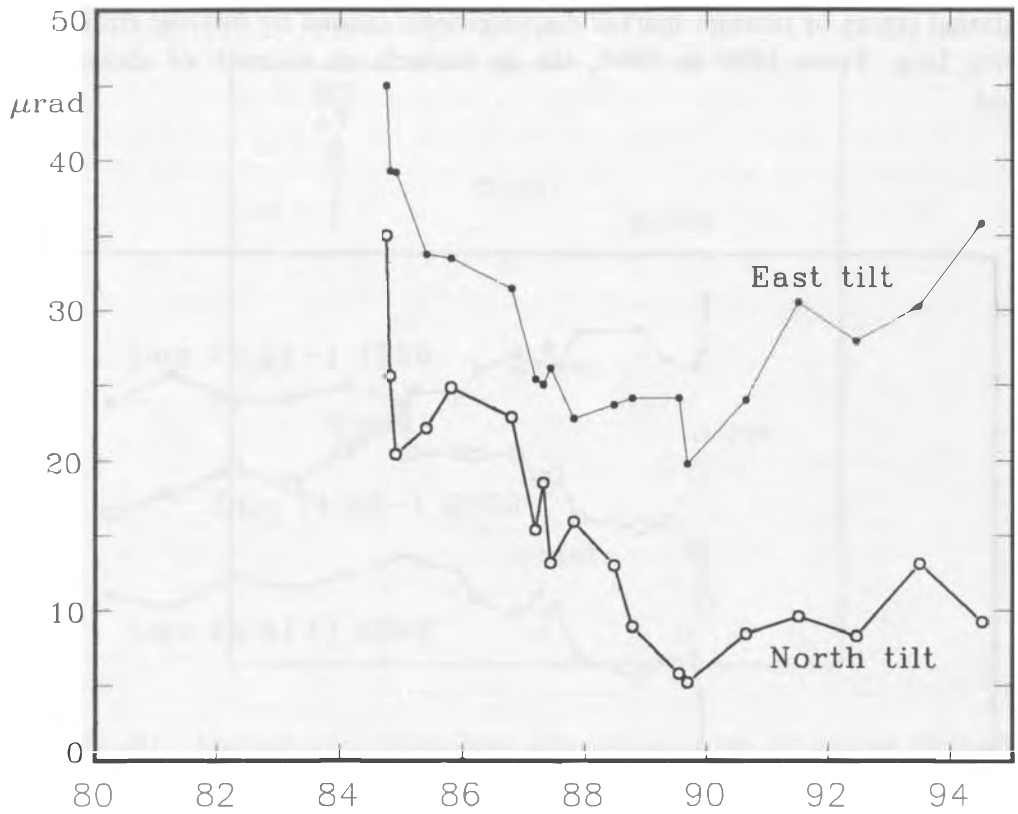


Fig. R3. Observed tilt at the tilt station Hreindýrahóll since it was first observed on October 3, 1984. East component of tilt is marked with small dots connected by a thin line and the north component is marked with open circles connected by a thick line. Tilt down towards east and north is observed from 1984 to 1989, but in 1989 the tilt azimuth is reversed and tilt up toward east and north is observed after 1989.

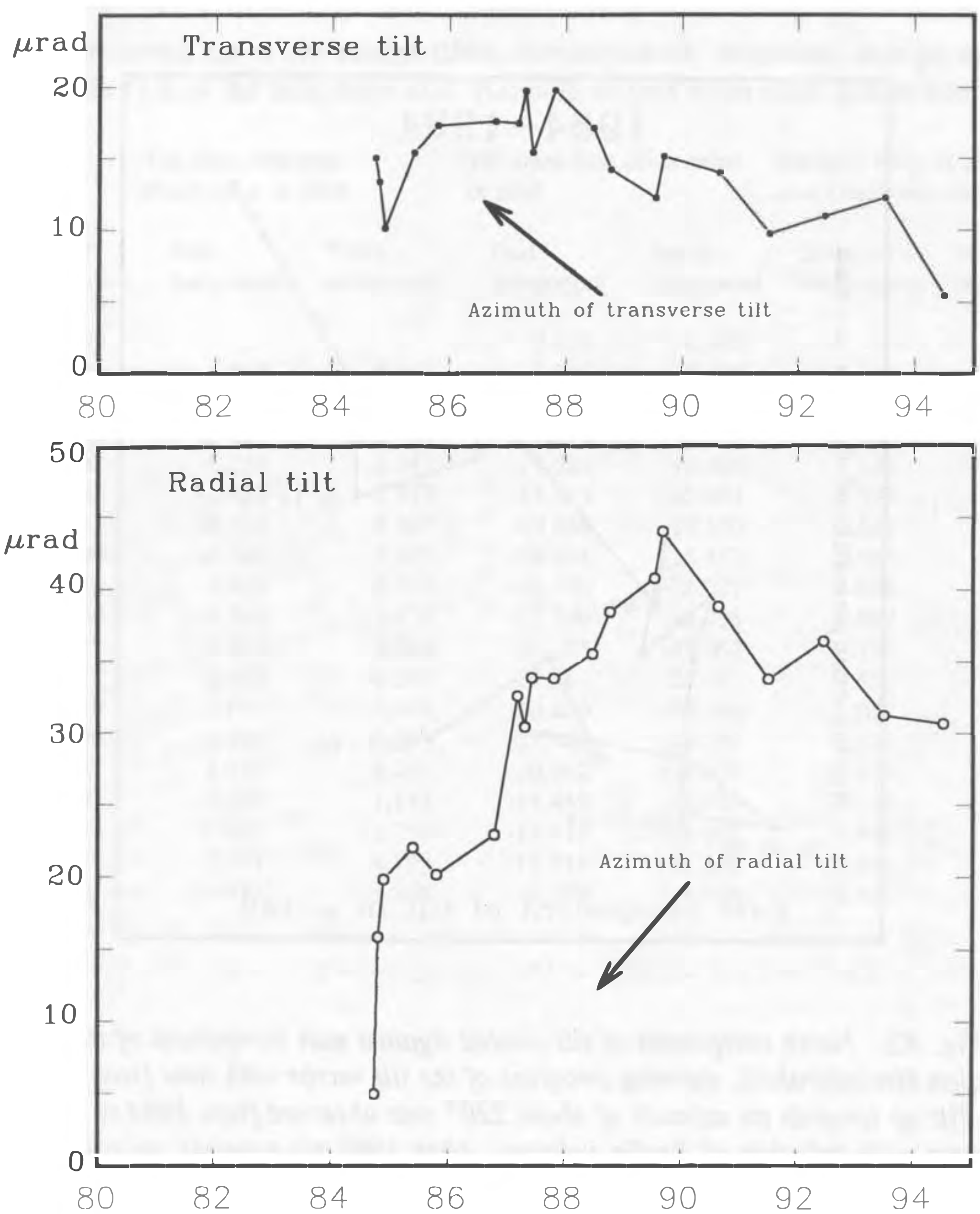


Fig. R4. Observed transverse (top) and radial (bottom) tilt at the tilt station Hreindýrahóll, relative to the center of deformation at Krafla. Radial tilt is taken to be tilt component toward an azimuth of 220°, the direction toward the accepted center of deformation at Krafla volcano during the 1975-1984 period of frequent inflations and deflations. Transverse tilt is taken to be the tilt component toward an azimuth of 310°. The transverse tilt is generally downward, at an average rate of 1.5 μrad per year or less. The radial tilt is upward (inflation) from 1984 to 1989 and downward (deflation) after 1989. The average tilt rate from 1985 to 1989 is about 5 μrad per year and from 1989 to 1994 about 3 μrad per year.

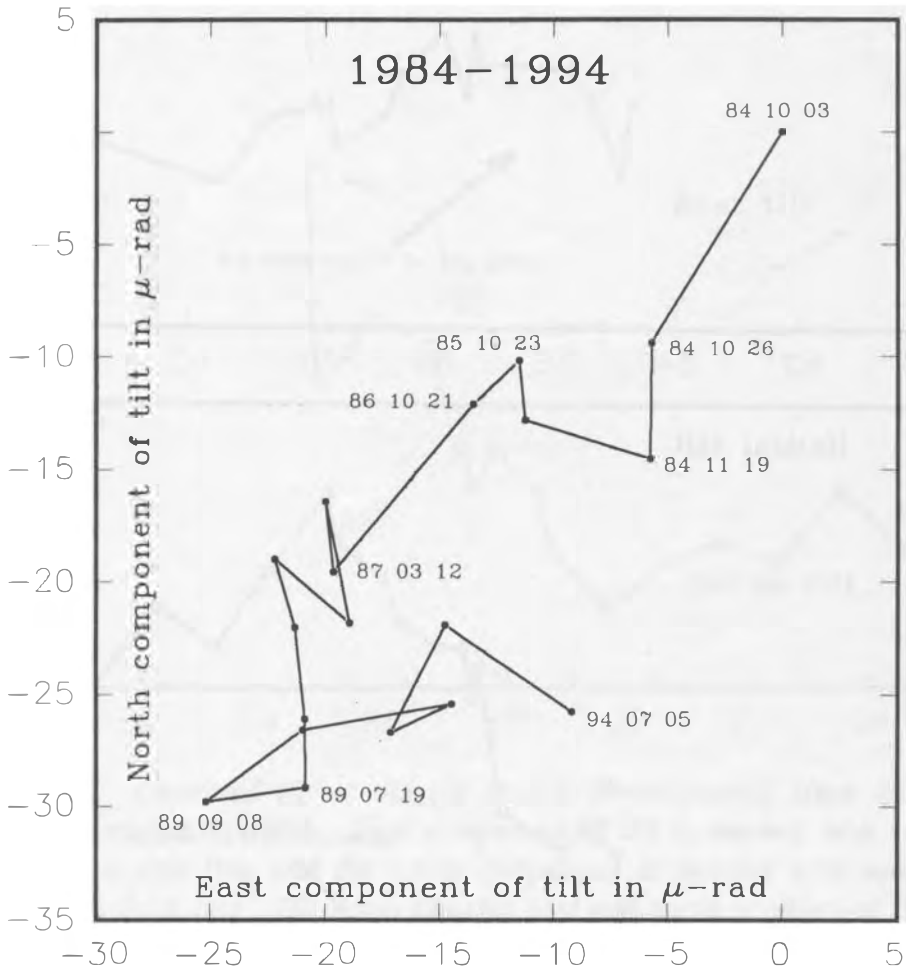


Fig. R5. North component of tilt plotted against east component of tilt at the tilt station Hreindýrahóll, showing progress of the tilt vector with time from 1984 to 1994. Tilt up towards an azimuth of about 220° was observed from 1984 to 1989 in agreement with inflation of Krafla volcano. After 1989 tilt towards an azimuth of about 75° is suggested. Irregular progress of the tilt vector indicates considerable observational errors.

Table R1

Observed tilt at tilt station 0260, Hreindýrahóll. Minimum axis of the error ellipse is 87% of the maximum axis. Azimuth of maximum error axis is 110°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
84 10 03			0.000	0.000		
84 10 26	-5.725	-9.403	-5.725	-9.409	1.373	1.373
84 11 19	-0.065	-5.118	-5.790	-14.527	0.935	-0.899
85 05 31	-5.480	1.720	-11.270	-12.807	0.760	1.548
85 10 23	-0.254	2.641	-11.525	-10.166	1.193	0.978
86 10 21	-1.988	-1.917	-13.512	-12.083	0.577	1.495
87 03 12	-6.122	-7.487	-19.634	-19.570	0.653	2.026
87 04 29	-0.341	3.137	-19.975	-16.433	0.983	3.001
87 06 10	1.055	-5.395	-18.920	-21.827	1.804	2.232
87 10 26	-3.260	2.830	-22.180	-18.998	0.927	1.370
88 06 27	0.895	-3.004	-21.285	-22.002	0.199	1.244
88 10 11	0.420	-4.095	-20.865	-26.097	0.550	1.708
89 07 19	0.015	-3.071	-20.850	-29.168	2.077	2.722
89 09 08	-4.329	-0.599	-25.179	-29.767	1.388	1.425
90 08 27	4.217	3.208	-20.962	-26.559	0.417	1.789
91 07 07	6.496	1.141	-14.465	-25.418	0.615	1.175
92 06 15	-2.647	-1.262	-17.112	-26.681	0.534	1.210
93 06 27	2.371	4.793	-14.741	-21.888	0.675	1.508
94 07 05	5.532	-3.868	-9.209	-25.756	0.709	1.491

Table R2

Marker coordinates and observed marker elevation at the tilt station 0260 (Hreindýrahóll) relative to the average value for all five markers at the tilt station.

Marker	0261	0262	0263	0264	0265
Marker coordinates in meters, surveyed 84 10 03					
East	-6.844	-26.190	-1.958	21.356	13.636
North	23.830	-7.491	-25.720	-9.304	18.687
Y M D	Marker elevation, centimeter				
84 10 03	-13.9495	-60.2253	18.4192	33.2147	22.5409
84 10 26	-13.9738	-60.2020	18.4463	33.2061	22.5233
84 11 29	-13.9810	-60.2012	18.4617	33.2113	22.5094
85 05 31	-13.9764	-60.1875	18.4593	33.1951	22.5094
85 10 23	-13.9641	-60.1913	18.4527	33.1952	22.5073
86 10 21	-13.9648	-60.1871	18.4607	33.1915	22.4999
87 03 12	-13.9791	-60.1670	18.4840	33.1820	22.4800
87 04 29	-13.9704	-60.1718	18.4811	33.1737	22.4875
87 06 10	-13.9791	-60.1691	18.4891	33.1896	22.4697
87 10 26	-13.9747	-60.1589	18.4792	33.1808	22.4738
88 06 27	-13.9824	-60.1585	18.4858	33.1865	22.4687
88 10 11	-13.9919	-60.1584	18.4991	33.1886	22.4628
89 07 19	-13.9905	-60.1582	18.5043	33.1991	22.4452
89 09 08	-13.9961	-60.1428	18.5054	33.1877	22.4456
90 08 27	-13.9892	-60.1572	18.4966	33.1947	22.4551
91 07 07	-13.9941	-60.1728	18.4908	33.2074	22.4688
92 06 15	-13.9963	-60.1658	18.4966	33.2002	22.4652
93 06 27	-13.9838	-60.1760	18.4827	33.2035	22.4736
94 07 05	-13.9971	-60.1854	18.4880	33.2224	22.4720

TILT STATION NE84011, SANDMÚLI

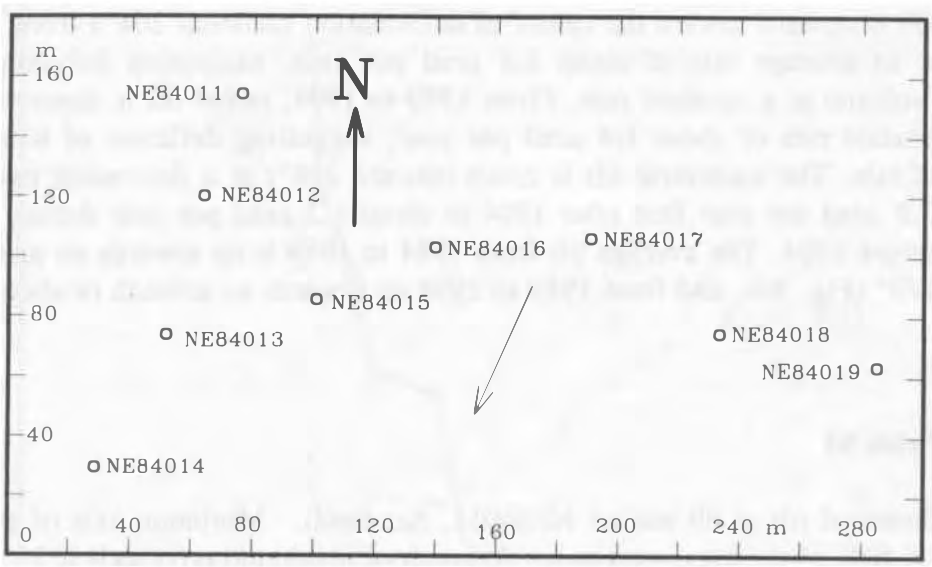


Fig S1. Map of relative position of markers at the tilt station Sandmúli, also named tilt station NE84011, the identification of the marker first installed. The markers (open circles) consist of 12.5 mm diameter copper alloy rods with rounded tops, cemented into the lava and extending 1 to 2 cm above the lava surface. Each marker is identified by a number as shown, inscribed on a washer. The north-south leg of the tilt station (markers NE84011 to NE84014) is parallel to a prominent west facing fault scarp and open fissure, with the markers 2 to 5 m east of the fissure. The east-west leg (markers NE84013 and NE84015 to NE84019) extend eastward from the fault scarp in direction approximately perpendicular to the strike of the fault. Thin arrow gives the approximate direction to the center of deformation at Krafla. The marker NE84011 carries the same identification as a marker used as GPS station and end station in a levelling line at Askja.

This station was established on October 3, 1984 on smooth pahoehoe lava of early Holocene age (Sæmundsson 1991) about 1.5 km south of the prominent peak Sandmúli. It is basically a T-shaped array of 9 markers with about 130 m long N-S line and about 240 m E-W line (Fig. S1). It lies within the eastern part of the Krafla fissure swarm, one to two km east of the zone where greatest deformation and eruptions occurred during the 1975-1984 period. A prominent west facing fault scarp is found few meter west of the N-S leg of the tilt station. The station lies about 6 km north-north-east of the center of deformation at Krafla, but near the south end of the zone where greatest amount of lava was erupted during the eruptions of 1980-1984. The eruption fissures extended about 6 km south of the station, and about 6 km north of the station. Most of the lava was erupted within the northern half of the zone of eruption fissures.

The Sandmúli tilt station was observed 12 times from October 1984 to August 1994. The observed ground tilt (Fig. S2) is characterised by tilt towards south and east from 1984 to 1989 and toward north and east from 1989 to 1994. The radial tilt (Fig. S3) is upward toward the center of deformation (azimuth 204°) from 1984 to 1989 at an average rate of about 3.5 μrad per year, suggesting inflation of the Krafla volcano at a constant rate. From 1989 to 1994, radial tilt is downward at a near constant rate of about 1.4 μrad per year, suggesting deflation of Krafla at a constant rate. The transverse tilt is down (toward 294°) at a decreasing rate, from about 2.5 μrad per year first after 1984 to about 1.2 μrad per year during the last years before 1994. The average tilt from 1984 to 1989 is up towards an azimuth of about 170° (Fig. S4), and from 1989 to 1994 up towards an azimuth of about 60°.

Table S1

Observed tilt at tilt station NE84011, Sandmúli. Minimum axis of the error ellipse is 40% of the maximum axis. Azimuth of maximum error axis is 2°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
84 10 03			0.000	0.000		
84 12 04	-2.975	-3.965	-2.975	-3.965	0.995	0.995
85 05 31	1.222	-2.085	-1.754	-6.051	1.776	2.173
85 10 23	0.666	-2.736	-1.088	-8.786	1.047	1.375
86 10 21	-0.163	-0.571	-1.251	-9.357	1.255	1.865
87 10 26	0.468	-8.078	-0.783	-17.435	0.501	1.651
89 09 08	2.730	-4.811	1.946	-22.247	0.667	2.047
90 08 27	0.970	1.150	2.913	-21.094	0.711	1.565
91 07 07	2.641	-0.098	5.554	-21.191	0.591	1.315
92 06 15	-1.174	0.971	4.380	-20.221	0.913	1.732
93 06 27	2.036	0.310	6.416	-19.911	0.982	1.947
94 08 15	1.404	0.764	7.820	-19.047	1.342	1.237

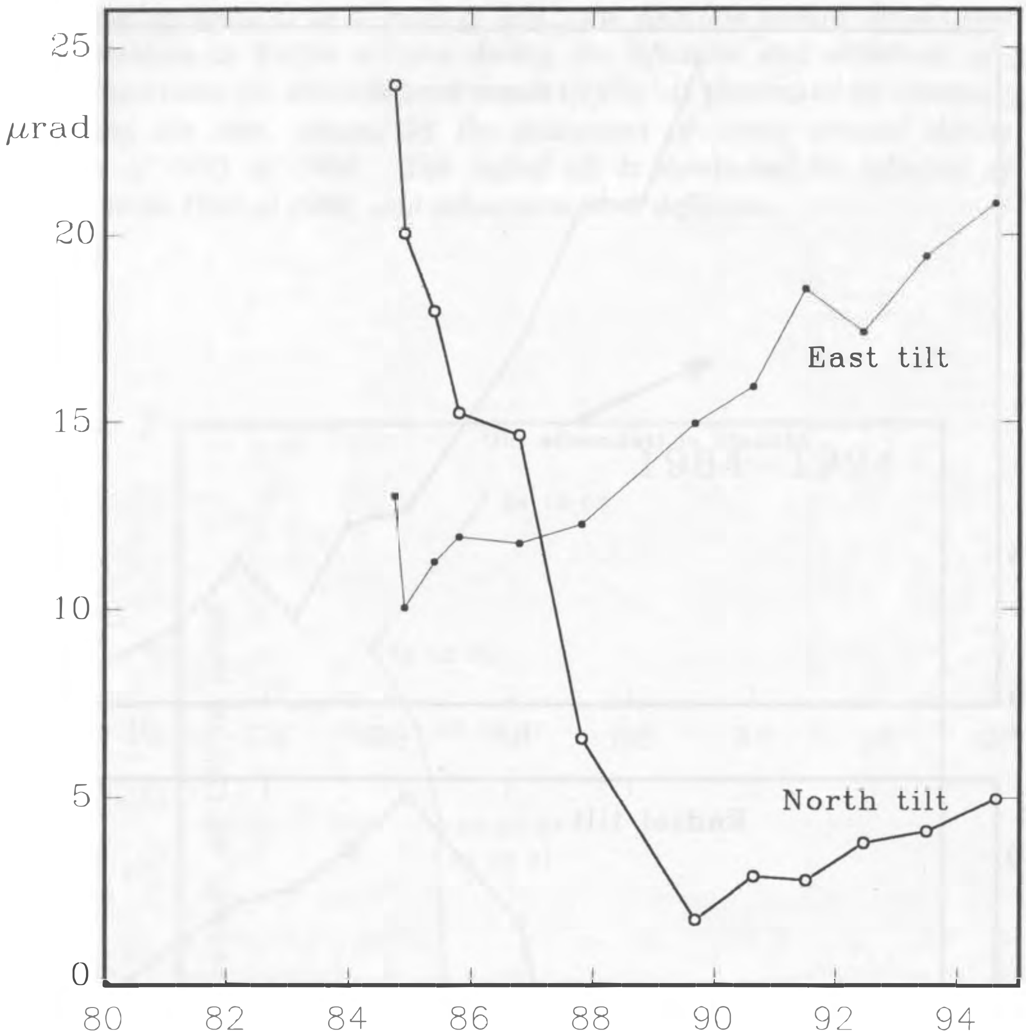


Fig. S2. Observed tilt at the tilt station Sandmúli since it was first observed on October 3, 1984. East component of tilt is marked with small dots connected by a thin line and the north component of tilt is marked with open circles connected by a thick line. The east component is generally rising, up towards east, while the north component was going downward (toward north) from 1984 to 1989 and upward from 1989 to 1994.

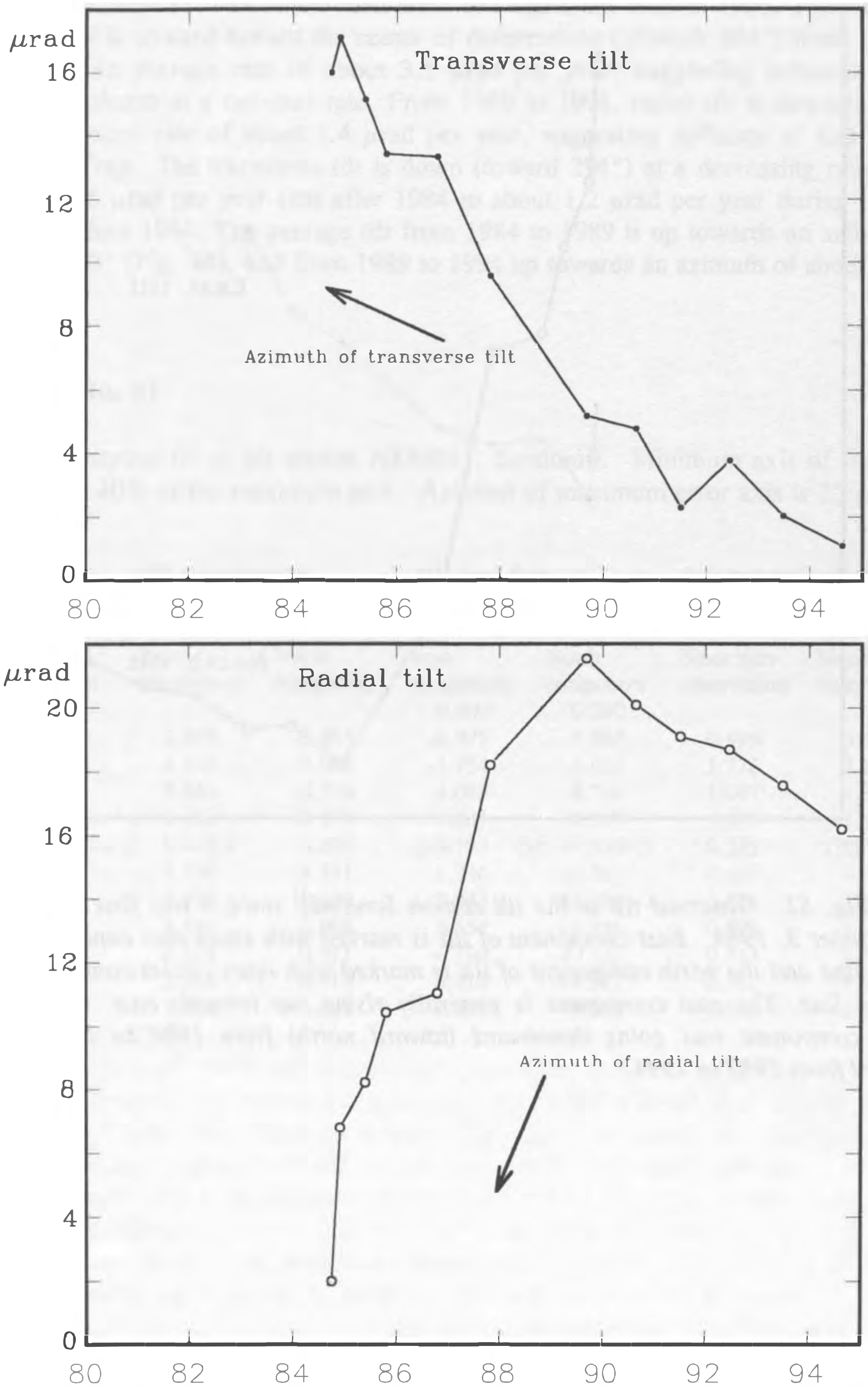


Fig. S3. Caption on next page.

Fig. S3. Observed transverse (top) and radial (bottom) tilt at the tilt station Sandmúli relative to the center of deformation at Krafla. Radial tilt is taken to be tilt component towards an azimuth of 204°, the direction toward the accepted center of deformation at Krafla volcano during the inflations and deflations of 1975 to 1984. Transverse tilt towards an azimuth of 294° is dominated by downward tilt at decreasing tilt rate, caused by the relaxation of strain created during rifting episodes of 1975 to 1984. The radial tilt is dominated by inflation of Krafla volcano from 1984 to 1989, and subsequent slow deflation.

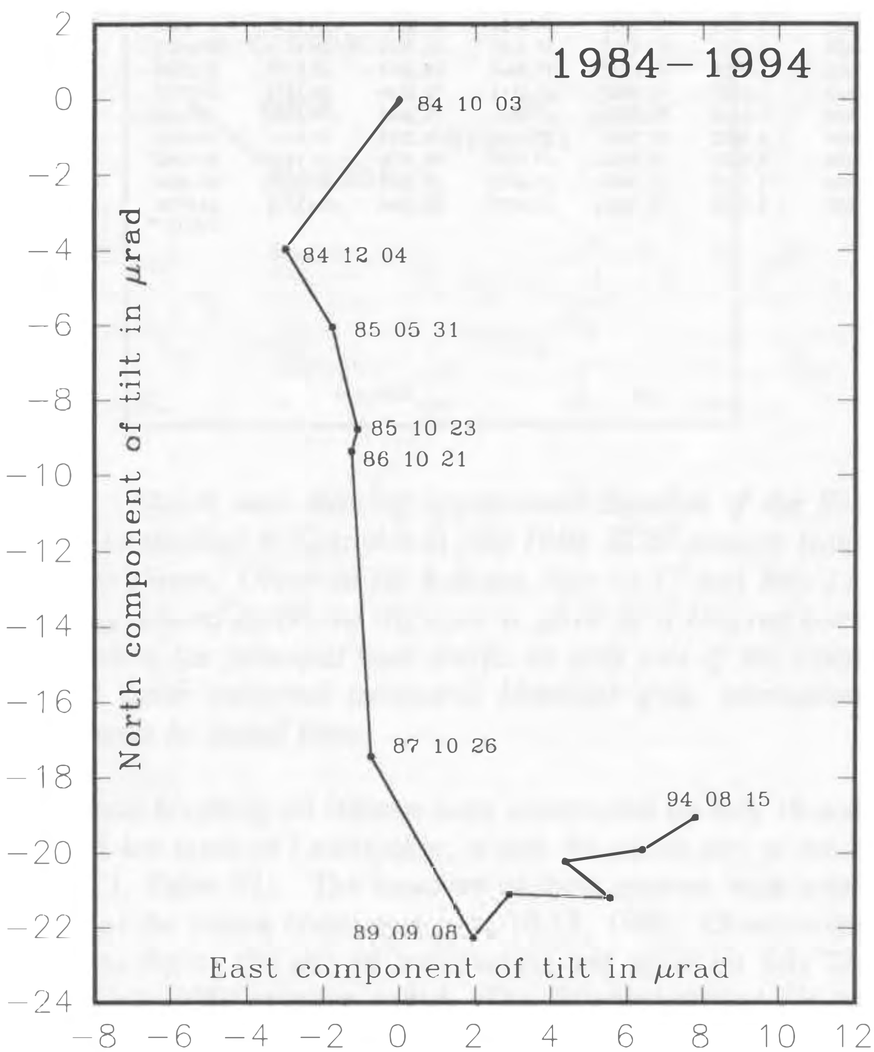


Fig. S4. North component of tilt plotted against east component of tilt at the tilt station Sandmúli, showing progress of the tilt vector through time from October 1984 to August 1994. Tilt up towards south was observed from 1984 to 1989 and up towards east-north-east from 1989 to 1994.

Table S2

Marker coordinates and observed marker elevation at the T-shaped tilt station Sandmúli (84011) relative to the average value for all nine markers of the tilt station

Marker	84011	84012	84013	84014	84015	84016	84017	84018	84019
Marker coordinates in meters, surveyed 84 10 03									
East	-53.93	-65.96	-78.27	-101.49	-29.00	9.58	60.75	103.34	154.97
North	63.72	30.23	-16.12	-60.56	-4.52	13.24	15.83	-15.35	-26.51
Y M D	Marker elevation, centimeter								
84 10 03	61.2177	3.8984	-71.7023	17.3782	-58.2845	-29.1235	15.0368	-8.7095	70.2890
84 12 04	61.2124	3.9006	-71.6809	17.4424	-58.2804	-29.1406	15.0306	-8.7249	70.2409
85 05 31	61.1734	3.8811	-71.7054	17.4439	-58.2681	-29.1075	15.0467	-8.7051	70.2414
85 10 23	61.1542	3.8723	-71.6857	17.4424	-58.2687	-29.1267	15.0387	-8.6959	70.2695
86 10 21	61.1626	3.8751	-71.6897	17.4593	-58.2834	-29.1513	15.0457	-8.6817	70.2635
87 10 26	61.1045	3.8525	-71.6833	17.5044	-58.2837	-29.1534	15.0354	-8.6735	70.2971
89 09 08	61.0583	3.8122	-71.7067	17.5111	-58.2856	-29.1472	15.0523	-8.6408	70.3460
90 08 27	61.0538	3.8138	-71.7050	17.4842	-58.2848	-29.1399	15.0523	-8.6387	70.3641
91 07 07	61.0396	3.7992	-71.7293	17.4583	-58.2915	-29.1293	15.0575	-8.6180	70.4135
92 06 15	61.0606	3.8038	-71.7324	17.4718	-58.2838	-29.1414	15.0562	-8.6175	70.3831
93 06 27	61.0396	3.7912	-71.7460	17.4375	-58.2690	-29.1286	15.0640	-8.5977	70.4091
94 08 15	61.0500	3.7858	-71.7515	17.4273	-58.3040	-29.1318	15.0756	-8.5960	70.4446

TILT STATIONS IN GJÁSTYKKI

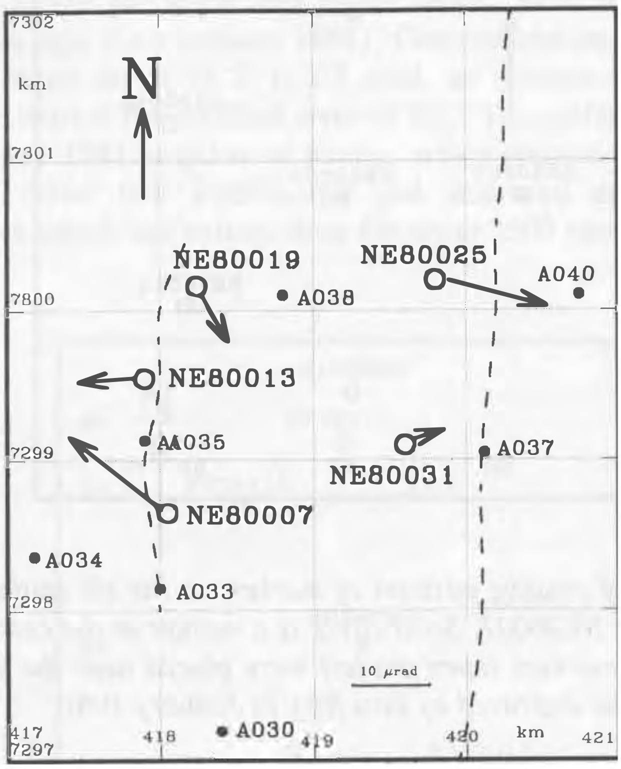


Fig. T1. Sketch map showing approximate location of the five tilt stations (open circles) established in Gjástykki in July 1980. EDM stations (solid dots) in the region are also shown. Observed tilt between July 16-17 and July 22 is shown by arrows pointing toward uplift, the tilt scale is given by a 10-μrad bar near bottom. Dashed lines show the principal fault scarps on both side of the Gjástykki graben. One thousand meter universal transverse Mercator grid, international spheroid, zone 28, is shown by dotted lines.

Five optical levelling tilt stations were constructed on July 16 and 17, 1980 in an area 9 to 11 km north of Leirhnjúkur, within the active part of the Krafla fissure swarm (Fig. T1, Table T1). The locations of these stations were selected near and on both sides of the fissure eruption of July 10-18, 1980. Observations were made at these stations during the day of construction and again on July 22, 1980, four days after the July 1980 eruption ended. The observed ground tilt during the five days at the end of the July 10-18, 1980 eruption suggest considerable subsidence of the region of the erupting fissure, with tilt up toward west at stations NE80007 and NE80013 west of the fissure and tilt up toward east at stations NE80025 and NE80031 east of the fissure (Fig. T1). Three of these stations, NE80007, NE80025, and NE80031, were destroyed by lava covering the stations during the October 1980 and January 1981 eruptions of Krafla. The other two stations have been observed a few times but not regularly, with no observation between 1981 and 1993.

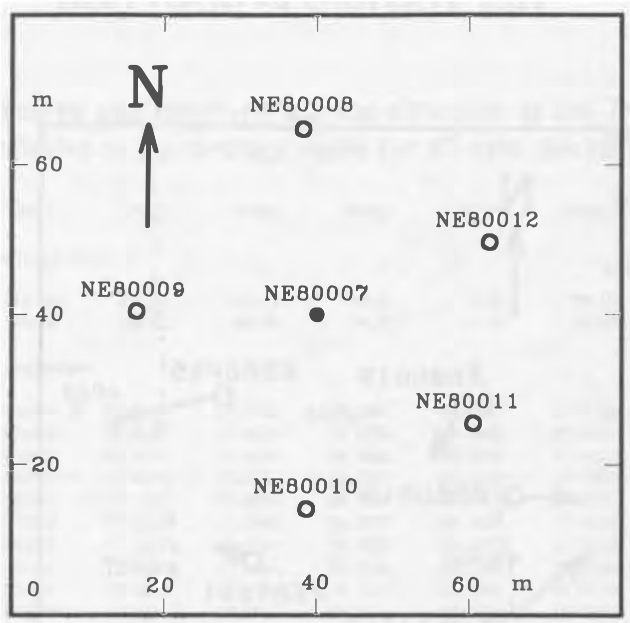


Fig. T2. Map of relative position of markers at the tilt station Éthólaborgir, also named tilt station NE80007. Solid circle is a marker at the center of a circle of 25 m radius and five markers (open circles) were placed near the periphery of this circle. This station was destroyed by lava flow in January 1981.

Table T1

Approximate location of the tilt stations in Gjástykki which were constructed in July, 1980 while an eruption was in progress in Gjástykki. Three stations were located west of the north-south trending eruption fissure and two were east of the fissure. These stations were observed two times in July 1980. Observed ground tilt between observations on July 16 or 17, and July 22, 1980 is given in the two last columns.

	Geographic coordinates		Observed tilt 16 to 22 July 1980	
Station	North	East	μrad	Azimuth
NE80007	65° 47' 48"	16° 47' 28"	14.7	307.7°
NE80013	65° 48' 21"	16° 47' 42"	7.6	253.0°
NE80019	65° 48' 39"	16° 47' 20"	6.6	162.1°
NE80025	65° 48' 57"	16° 45' 16"	13.2	106.3°
NE80031	65° 48' 07"	16° 45' 32"	2.9	78.8°

Station NE80007, Éthólaborgir (fig. T2, Table T2) was located 50 to 70 m east of prominent, east facing fault scarp, about 250 m west of the crater row Éthólaborgir It consisted of six markers made of 12.5 mm copper alloy rods cemented into smooth pahoehoe lava which flowed from the Éthólaborgir craters about 2500 years ago (Sæmundsson 1991). Observations on July 16 and July 22, 1980 suggest ground tilt of 14.7 ± 5.3 μrad, up towards an azimuth of 307.7°. The given error limit is the standard error of tilt. This station was covered by lava during the January 1981 eruption of Krafla, which erupted through a fissure very near the older crater row Éthólaborgir and destroyed these very regular and prominent craters which had existed there for about 2500 years.

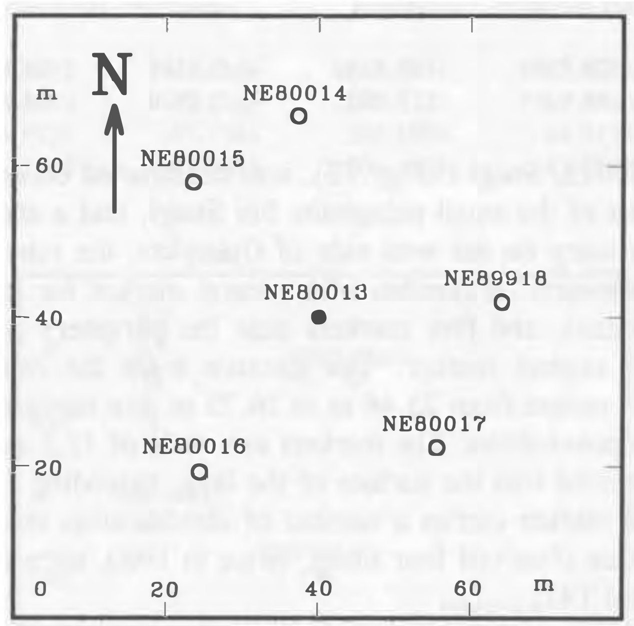


Fig. T3. Map of relative position of markers at the tilt station Snagi I, also named tilt station NE80013. Solid circle is a marker at the center of a circle of 25 m radius and five markers (open circles) are placed near the periphery of this circle. The markers consist of 12.5 mm copper alloy rods with rounded tops, cemented into the underlying lava, extending one to two centimeters above the lava surface. Each marker is identified by a number as shown, inscribed on a washer.

Table T2

Marker coordinates relative to marker NE80007 and observed marker elevation relative to average elevation of the five stations of the circle at the tilt station 80007 (Éthólaborgir).

Marker	NE80008	NE80009	NE80010	NE80011	NE80012
Approximate marker coordinates in meters					
East	-1.74	-23.66	-1.35	20.60	22.82
North	24.83	0.41	-25.82	-14.43	9.69
Y M D	Marker elevation, centimeters				
80 07 16	29.9180	132.4346	-0.0186	-84.1459	-78.1880
80 07 22	29.9284	132.4905	-0.0626	-84.1591	-78.0973

Station NE80013, Snagi I (Fig. T3), was constructed on July 16, 1980 on old pahoehoe lava west of the small palagonite hill Snagi, and a short distance west of the principal fault scarp on the west side of Gjástykki, the subsided central part of the Krafla fissure swarm. It consists of a central marker for location of the level during tilt observation, and five markers near the periphery of a circle of 25 m radius around the central marker. The distance from the central marker to the peripheral markers ranges from 23.46 m to 26.75 m, but topography and vegetation restricted location possibilities. The markers are made of 12.5 mm diameter rods of copper alloy, cemented into the surface of the lava, extending 1 to 2 cm above the lava surface. Each marker carries a number of identification inscribed on a washer. This station has been observed four times, twice in 1980, once in 1981 and once in 1993 (Table T3 and T4).

Table T3

Observed tilt at tilt station NE80013, Snagi I. Minimum axis of the error ellipse is 94% of the maximum axis. Azimuth of maximum error axis is 65°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
80 07 16			0.000	0.000		
80 07 22	-7.238	-2.207	-7.238	-2.207	0.388	0.388
81 08 07	-35.497	-78.884	-42.735	-81.090	2.461	2.6 08
93 06 27	-92.097	-16.100	-134.832	-97.191	7.382	7.464

Table T4

Marker coordinates at the tilt station NE80013 (Snagi I) relative to marker NE80013, and marker elevation relative to average elevation of all 5 markers of the circle.

Marker	NE80014	NE80015	NE80016	NE80017	NE80018
Approximate coordinates of markers in meters					
East	-2.69	-16.53	-15.63	15.59	24.10
North	26.61	17.76	-20.82	-17.53	1.91
Y M D	Marker elevation, centimeter				
80 07 16	-86.1533	-43.1354	105.9074	43.9086	-20.5271
80 07 22	-86.1570	-43.1248	105.9230	43.9040	-20.5450
81 08 07	-86.3321	-43.1961	106.1559	44.0132	-20.6411
93 06 27	-86.3130	-43.0966	106.3695	43.8841	-20.8439

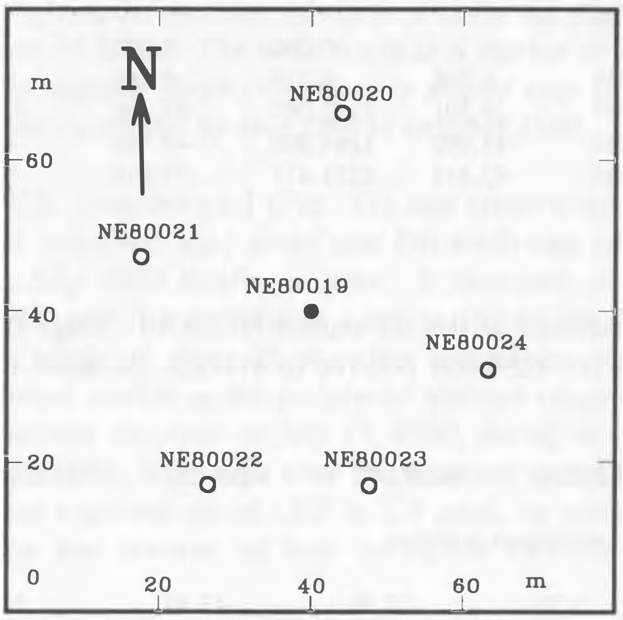


Fig. T4. Map of relative position of markers at the tilt station Snagi II, also named tilt station NE80019. Solid circle is a marker at the center of a 25 m radius circle and five markers (open circle) lie near the periphery of this circle. The markers consist of 12.5 mm diameter copper alloy rods with rounded tops, cemented into the lava, extending one to two cm above the lava surface. Each marker is identified by a number as shown, inscribed on a washer.

Station NE80019, Snagi II (Fig. T4), was constructed on July 16, 1980 on old pahoehoe lava, west of the hill Snagi and east of the prominent east facing fault scarp on the west side of Gjástykki. It consists of six markers, a central marker carrying the inscription NE80019, marking the location of the level is during observations, and peripheral markers (NE80020 through NE80024) forming an irregular circle of about 25 m radius around the central marker. The markers consist of 12.5 mm copper alloy rods cemented into the lava, extending 1 to 2 cm above the lava surface. This station was observed twice in 1980, twice in 1981 and once in 1983 (Table T5 and T6).

Table T5

Observed tilt at tilt station NE80019, Snagi II. Minimum axis of the error ellipse is 84% of the maximum axis. Azimuth of maximum error axis is 78°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
80 07 16			0,000	0,000		
80 07 22	2.028	-6.266	2.028	-6.266	1.374	1.374
81 08 07	1350.039	-29.201	1352.067	-35.466	31.141	30.876
81 09 01	-7.858	-13.002	1344.209	-48.468	4.521	31.819
93 06 27	-80.595	-42.451	1271.471	-77.919	5.742	30.727

Table T6

Marker coordinates at the tilt station NE80019 (Snagi II) relative to marker NE80019 and marker elevation relative to average elevation of all five marker of the circle.

Marker	NE80020	NE80021	NE80022	NE80023	NE80034
Approximate marker coordinates in meters					
East	3.99	-22.39	-13.48	7.71	23.21
North	26.32	7.24	-23.12	-23.22	-7.86
Y M D	Marker elevation, centimeter				
80 07 16	-150.6702	68.5558	124.0931	110.6316	-152.6104
80 07 22	-150.6931	68.5507	124.0957	110.6477	-152.6009
81 08 07	-150.2591	65.5238	122.4536	111.5848	-149.3029
81 09 01	-150.3197	65.5483	122.4708	111.6033	-149.3027
93 06 27	-150.4424	65.6818	122.6142	111.6108	-149.4644

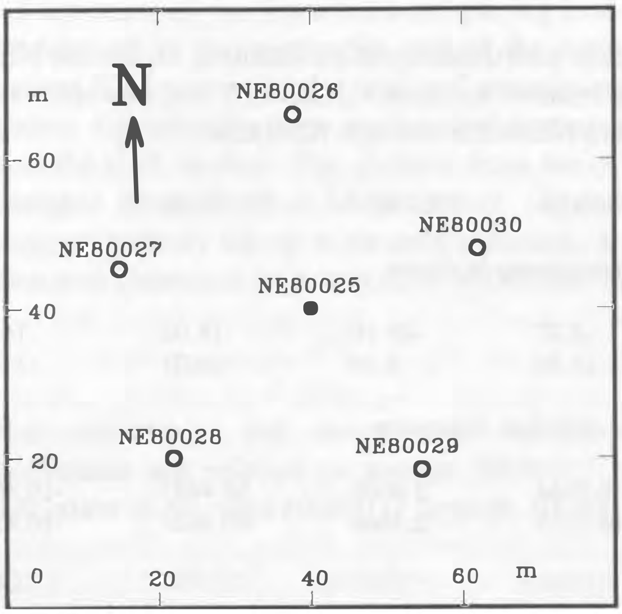


Fig. T5. Map of relative position of markers at the tilt station Snagaborgir I, also named tilt station NE80025. The solid circle is a marker at the center of 25 m radius circle and five markers (open circles) were placed near the periphery of this circle. This station was destroyed by lava flow in October 1980.

Station NE80025, Snagaborgir I (Fig. T5) was constructed on July 17, 1980 on pahoehoe lava of unknown age, about one km north-east of Snagaborgir, the main craters of the July 1980 Krafla eruption. It consisted of a central marker identified as NE80025 and five peripheral markers (NE80026 through NE80030) forming an irregular circle of about 25 m radius around the central marker. The distance from the central marker to the peripheral markers ranged from 23.37 m to 26.93 m. This station was observed on July 17, 1980, during an eruption of Krafla, and again on July 22, 1980, four days after the eruption ended (Table T7). These observations suggested a ground tilt of 13.2 ± 2.6 μrad, up towards an azimuth of 106.3°. This station was covered by lava during the October 1980 eruption of Krafla.

Table T7

Relative marker coordinates and elevation at tilt station NE80025, Snagaborgir I. Coordinates are relative to marker NE80025 and elevation is relative to average elevation of markers NE80026 through NE80030.

Marker	NE80026	NE80027	NE80028	NE80029	NE80030
Approximate marker coordinates in meters					
East	-2.27	-25.10	-18.02	14.56	21.96
North	25.95	5.34	-20.01	-21.59	7.99
Y M D	Marker elevation, centimeter				
80 07 17	-118.0664	2.4086	60.4697	-10.4691	65.6574
80 07 22	-118.2628	2.3640	60.4624	-10.4366	65.6734

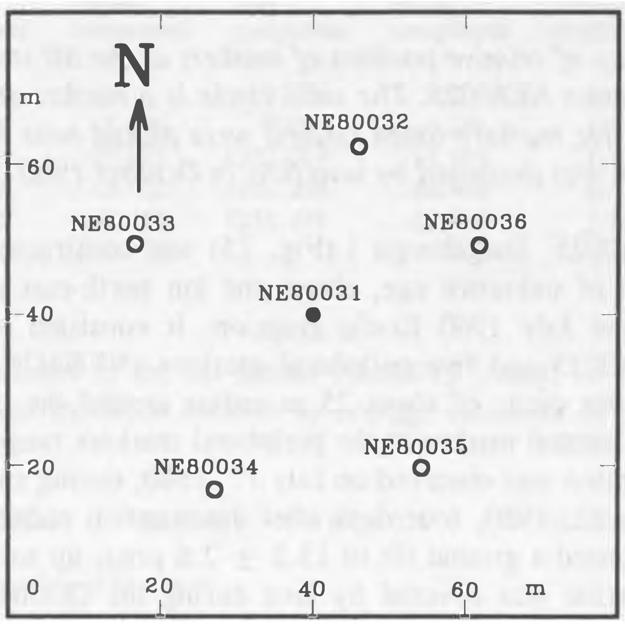


Fig. T6. Map of relative position of markers at the tilt station Snagaborgir II, also named tilt station NE80031. The solid circle is a marker at the center of a 25 m radius circle and five markers (open circles) were placed near the periphery of this circle. This station was destroyed by lava flow in October 1980.

Station NE80031, Snagaborgir II (Fig. T6) was constructed on July 17, 1980, on old lava about 0.5 km north of the fence between grazing land (afrétt) of Mývatn to the south and Kelduhverfi to the north, due east of the main vents of the July 1980 eruption, and about 0.5 km west of the principal west facing fault scarp on the east side of the graben Gjástykki. Five markers of copper alloy rods formed irregular circle around the sixth marker. The distance from the central marker to the peripheral markers ranged from 23.10 to 26.54 meters. Observations of July 17 and July 22, 1980 suggest vaguely tilt up in easterly direction, amounting to 2.9 ± 2.5 μrad. This station was destroyed by a lava flow in October 1980.

Table T8

Relative marker coordinates and elevation at the tilt station NE80031, Snagaborgir II. Coordinates are relative to marker NE80031 and elevations are relative to average elevation of markers NE80032 through NE80036

Marker	NE80032	NE80033	NE80034	NE80035	NE80036
Approximate marker coordinates in meters					
East	5.98	-23.29	-12.87	14.24	21.75
North	22.31	9.41	-23.21	-20.33	9.23
Y M D	Marker elevation, centimeter				
80 07 17	15.6684	-9.8095	-30.2001	1.8962	22.4452
80 07 22	15.6590	-9.8120	-30.2030	1.8905	22.4653

TILT STATIONS IN KELDUHVERFI

Two stations were constructed on July 28, 1976 in Kelduhverfi, about 40 km north of Leirhnjúkur, but near the location of greatest ground movement during the first phase of the Krafla fires December 1975 to February 1976 (Tryggvason 1976). One station, Hóll, was placed near the west edge of the zone where notable rifting and subsidence was seen in December 1975 and January 1976. A prominent open fissure, Hólsgjá, marks the west side of a graben, which is a northward continuation of the Gjástykki graben. The tilt station is immediately to the west of Hólsgjá with nearest markers less than 10 m from the gaping fissure. The other tilt station in Kelduhverfi, Lón, is located about 10 km west of the Gjástykki graben, well outside the region where major ground deformation was seen in 1975-1976.

The Kelduhverfi tilt stations have not been surveyed for precise geographic location and relative position of the individual markers is not precisely known. The estimated geographic coordinates of these stations are:

Hóll: Latitude 66° 02' 53" N, Longitude 16° 38' 11" W, elevation 10 m.

Lón: Latitude 66° 06' 01" N, Longitude 16° 54' 11" W, elevation 40 m.

Fig. U1. Map of relative position of markers at the tilt station Hóll, also named tilt station 0100. The solid circle is a marker at the center of a circle of 27.0 m radius defined by four markers (open circles). The markers consist of copper alloy nails with 37 mm diameter convex top plate, cemented into the lava surface. Few lava exposures are found in the area of this station because of thick soil cover. For this reason, only four markers were constructed on the periphery of the circle. Each marker is identified by an inscribed number as shown.

Tilt station 0100, Hóll: This station lies on old Holocene pahoehoe lava in the western part of the Krafla fissure swarm in Kelduhverfi, about 100 m south of the main road (highway 1) and immediately west of a large north-south trending fissure which have been displaced downwards to the east. It contains 4 bench marks at 27.0 m distance from a marked central point (Fig. U1).

Observations were made 13 times from July 1976 to July 1994. The observed ground deformation is dominated by the event of January 1978 when intense earthquake swarm was observed in Kelduhverfi and significant horizontal and vertical displacements were seen on faults and fissures crossing the main highway. This event caused upward displacement of markers 0101 and 0104 and downward displacement of markers 0102 and 0103 (Fig. U2). This represents tilt up towards north of about 210 μrad (Fig. U3).

Deformation after the January 1978 event is slight. Tilt up towards north is indicated from 1978 to 1987, but down toward north from 1987 to 1994 (Fig. U3 and U4). The east component of computed tilt is downward, but too small to be significant. The rate of ground tilt after 1978 is generally about or less than one μrad per year.

Table U1

Observed tilt at tilt station 0100, Hóll. Minimum axis of the error ellipse is 69% of the maximum axis. Azimuth of maximum error axis is 156°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
76 07 28			0.000	0.000		
77 05 17	-9.182	9.055	-9.182	9.055	2.865	2.865
77 07 15	2.495	-12.801	-6.663	-3.681	8.939	6.088
78 05 21	3.138	209.784	-3.526	206.104	2.108	8.196
78 08 11	-1.242	1.818	-4.767	207.922	4.572	3.624
79 10 06	-7.421	1.912	-12.188	209.834	0.564	3.059
80 07 23	-1.692	1.071	-13.880	210.905	0.886	2.174
84 06 11	0.080	4.153	-13.800	215.058	1.348	3.522
86 05 25	-5.242	0.654	-19.042	215.712	1.217	4.739
89 06 24	-3.443	-0.841	-22.484	214.871	0.681	5.420
91 07 13	3.381	-3.687	-19.104	211.184	0.048	5.468
93 06 28	-0.638	1.954	-19.742	213.138	0.697	4.771
94 07 04	-0.842	-2.030	-20.584	211.108	0.750	4.021

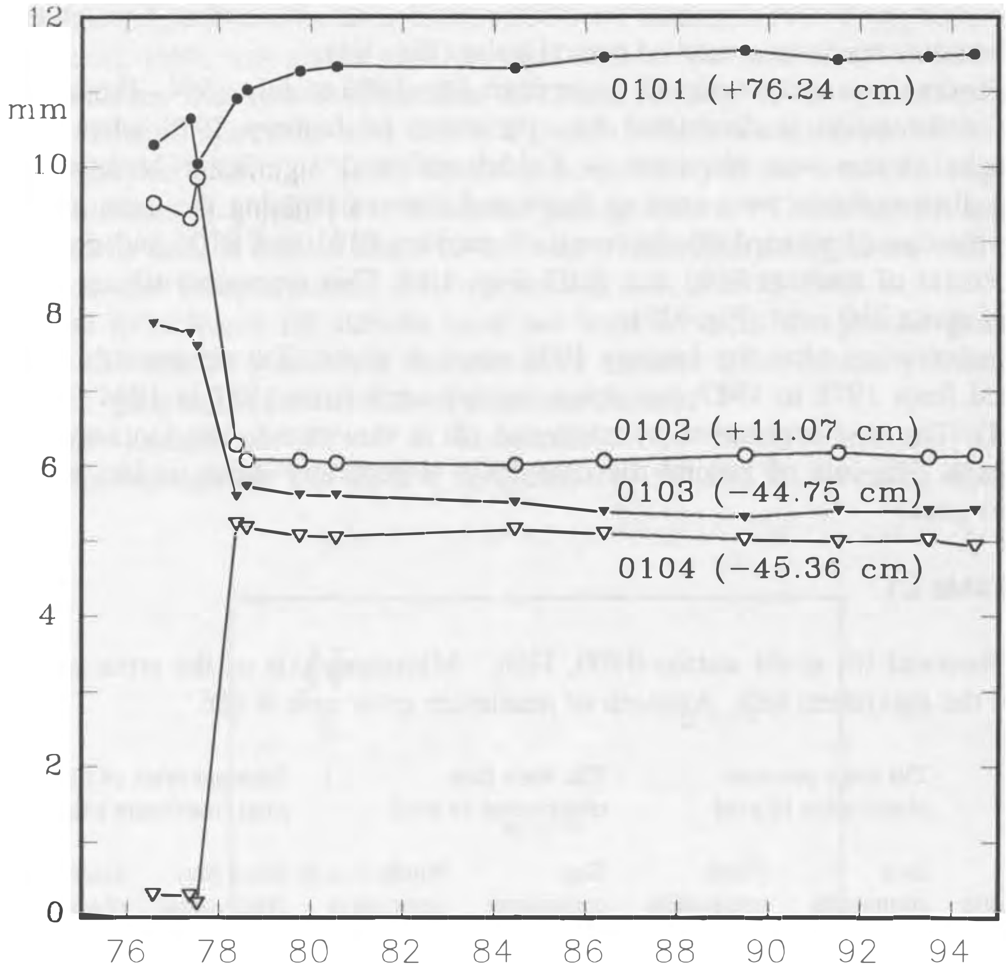


Fig. U2. Variation with time of the relative elevation of each marker on the circle periphery of the Hóll tilt station. Marker 0104 was uplifted about 5 mm during the rifting event of January 1978, and marker 0101 was uplifted slightly and markers 0102 and 0103 subsided about 3.5 and 2.0 mm respectively during this event. Rather large relative movements of markers 0101 and 0102 before the January 1978 event suggest some unrest of this area in 1977. Relative elevation of each marker is found by adding scale values at the left to values in parenthesis besides the marker identification.

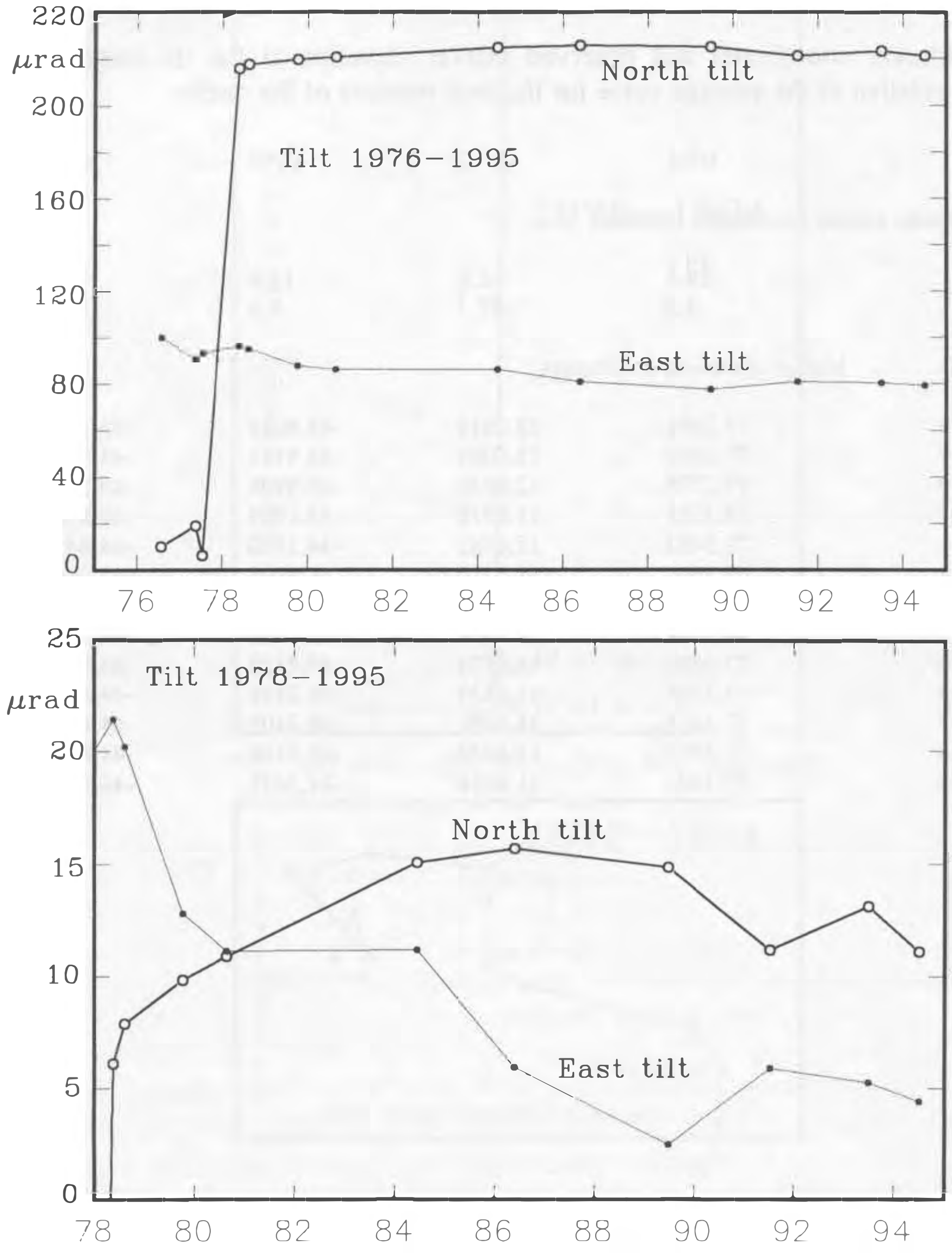


Fig. U3. Observed tilt at the tilt station Hóll since it was first observed on July 28, 1976. East component of tilt is marked with small dots connected by a thin line and the north component of tilt is marked with open circles connected by a thick line. Top graph shows all observations made before 1995 and bottom graph covers the period 1978 to 1994 in extended tilt scale to emphasise slight tilt variations after the January 1978 event. Tilt during the January 1978 rifting event is up toward north, about 210 μrad.

Table U2

Marker coordinates and observed marker elevation at the tilt station 0100 (Hóll) relative to the average value for the four markers of the circle.

Marker	0101	0102	0103	0104
Approximate marker coordinates in meters				
East	-29.6	-6.0	15.8	19.7
North	3.2	-17.3	-9.4	23.6
Y M D	Marker elevation, centimeters			
76 07 28	77.2691	12.0219	-43.9614	-45.3297
77 05 17	77.3039	12.0009	-43.9741	-45.3306
77 07 15	77.2775	12.0552	-43.9905	-45.3421
78 05 21	77.3313	11.6978	-44.1909	-44.8381
78 08 11	77.3432	11.6782	-44.1780	-44.8433
79 10 06	77.3667	11.6772	-44.1895	-44.8543
80 07 23	77.3735	11.6730	-44.1900	-44.8565
84 06 11	77.3723	11.6708	-44.1987	-44.8445
86 05 25	77.3860	11.6774	-44.2120	-44.8514
89 06 24	77.3948	11.6835	-44.2191	-44.8591
91 07 13	77.3835	11.6880	-44.2105	-44.8611
93 06 28	77.3872	11.6824	-44.2108	-44.8588
94 07 04	77.3903	11.6836	-44.2075	-44.8664

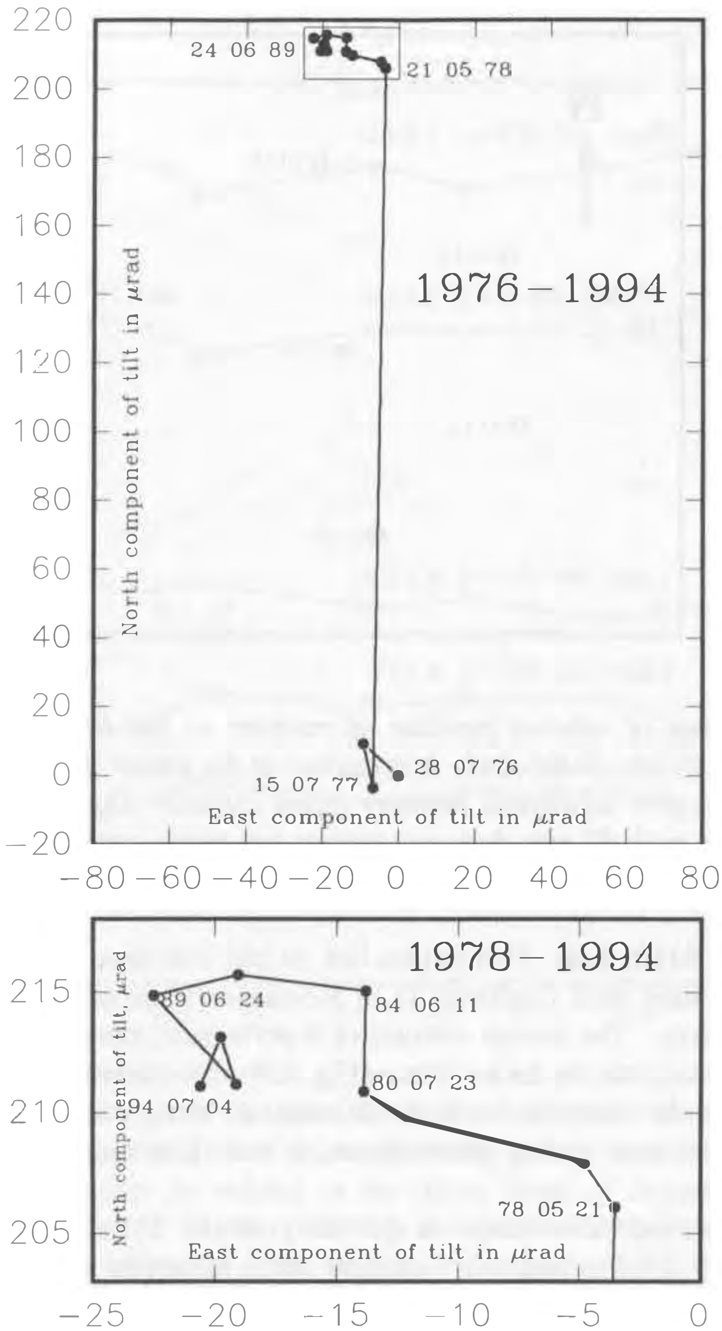


Fig. U4. North component of tilt plotted against east component of tilt at the tilt station Hóll, showing progress of the tilt vector through time from 1976 to 1994. Top graph covers all observations from 1976 to 1994 and the bottom graph shows tilt progress after the 1978 rifting event (rectangle on top graph) on expanded scale by magnifying rectangle on the top graph. Tilt is dominated by the event of January 1978 but after that event, tilt up in westerly or north-westerly direction is suggested.

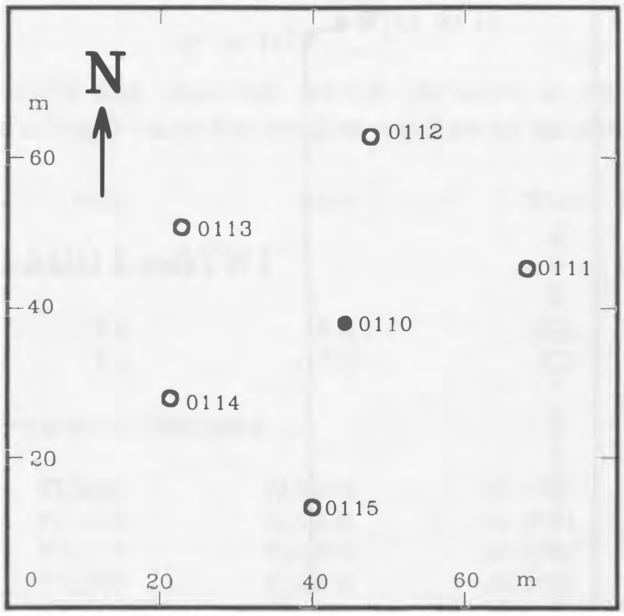


Fig. U5. Map of relative position of markers at the tilt station Lón, also named tilt station 0110. Solid circle is a marker at the center of a circle of 25.0 m radius, defined by five additional markers (open circles). The markers consist of copper alloy nails with 37 mm diameter convex top plate, cemented into the lava. Each marker is identified by an inscribed number as shown.

Tilt station 0110, Lón: This station lies on old Holocene pahoehoe lava near and north of the main road (highway 1) in Kelduhverfi, about 10 km west of the Krafla fissure swarm. The station consists of 6 permanent marker made of copper alloy nails, cemented into the lava surface (Fig. U5). Five markers form a circle of 25.0 m radius and the sixth marker is at the center of this circle, marking the place where to install the level during observations. It was observed 13 times from July 1976 to July 1994.

Observed ground deformation is generally small. Three observations made before the January 1978 rifting event suggest some instability of the markers with first and last of these three observations showing very similar results (Figures U6 and U7) but the observation of May 15, 1977 shows marker 0113 significantly higher relative to other markers (Fig. U6). This may be caused by observational error, or else the ground has not come to rest after the large deformation event of December 1975 to January 1976. Ground tilt during the January 1978 rifting event is clearly observed, about 15 μrad up towards east (Fig. U7). Deformation after the January 1978 event is probably not significant, although tilt up towards south-east is vaguely suggested (Fig. U8).

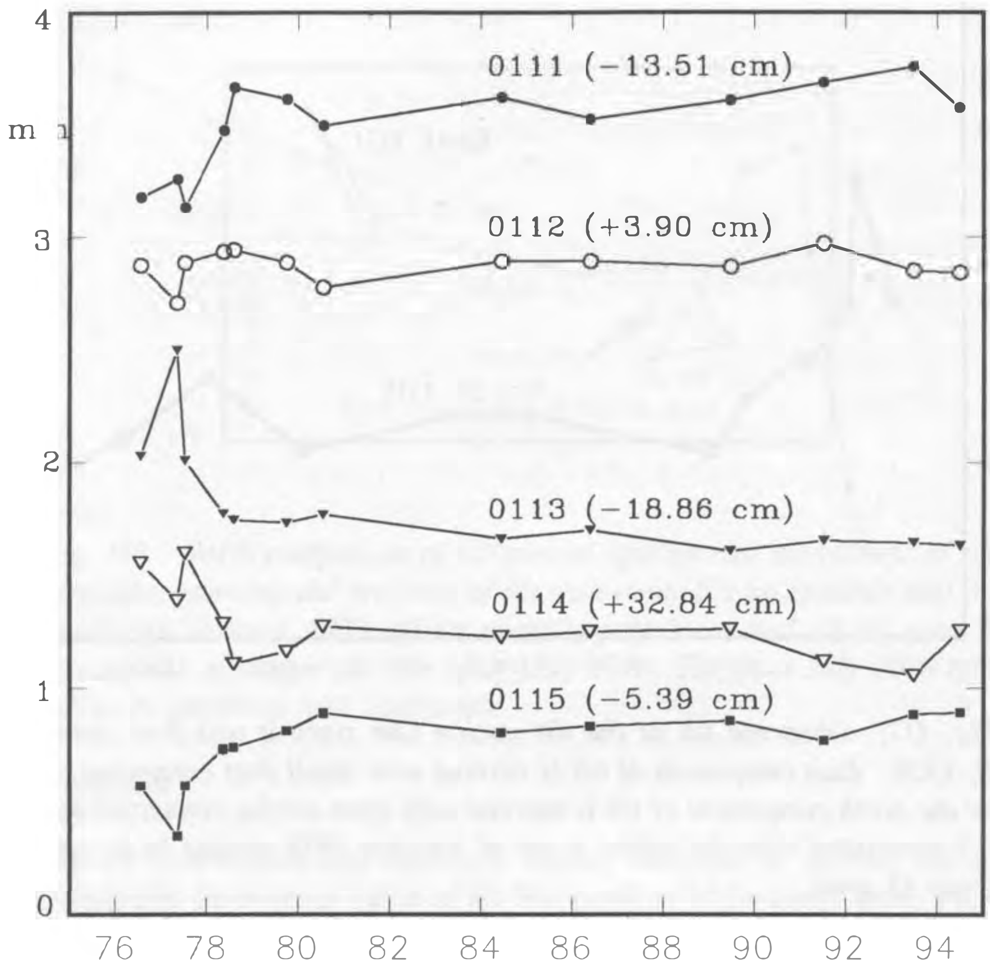


Fig. U6. Variation with time of the relative elevation of each marker forming the 25.0 m radius circle of the Lón tilt station. Irregular marker elevations are observed during the first 3 or 4 years after this station was established. Some of these irregularities may be related to the rifting event of January 1978, but high position of marker 0113 in May, 1977 is unexplained. Elevation variations after 1978 do not exceed the error limit. Relative elevation of each marker is found by adding the scale value at the left to values parenthesis besides the marker identifications.

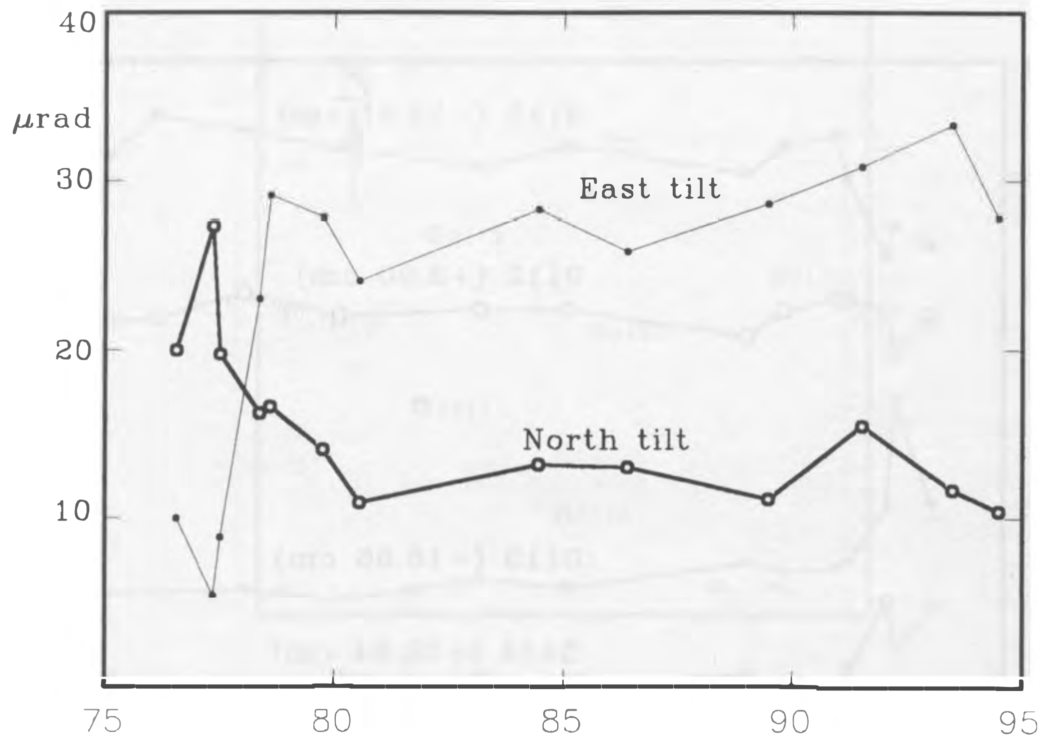


Fig. U7. Observed tilt at the tilt station Lón since it was first observed on July 28, 1976. East component of tilt is marked with small dots connected by a thin line and the north component of tilt is marked with open circles connected by a thick line. Tilt associated with the rifting event of January 1978 appear to be up toward east, about 15 μrad.

Table U3

Observed tilt at tilt station 0110, Lón. Minimum axis of the error ellipse is 78% of the maximum axis. Azimuth of maximum error axis is 134°.

	Tilt since previous observation in μrad		Tilt since first observation in μrad		Standard error of tilt in μrad (maximum axis)	
Date of observation	East component	North component	East component	North component	Since prev observation	Since first observation
76 07 28			0.000	0.000		
77 05 17	-4.564	7.320	-4.564	7.320	6.485	6.485
77 07 15	3.431	-7.598	-1.133	-0.279	7.198	0.746
78 05 21	14.130	-3.528	12.997	-3.807	1.753	1.515
78 08 11	6.120	0.396	19.117	-3.411	1.423	2.283
79 10 06	-1.272	-2.534	17.845	-5.945	0.213	2.277
80 07 23	-3.763	-3.151	14.082	-9.097	0.186	2.247
84 06 11	4.239	2.287	18.321	-6.809	1.246	1.311
86 05 25	-2.501	-0.157	15.820	-6.967	0.633	1.923
89 06 24	2.816	-1.897	18.636	-8.864	0.727	1.341
91 07 13	2..188	4.313	20.824	-4.551	0.907	1.932
93 06 28	2.520	-3.792	23.344	-8.343	1.485	2.840
94 07 04	-5.521	-1.223	17.823	-9.566	1.881	1.716

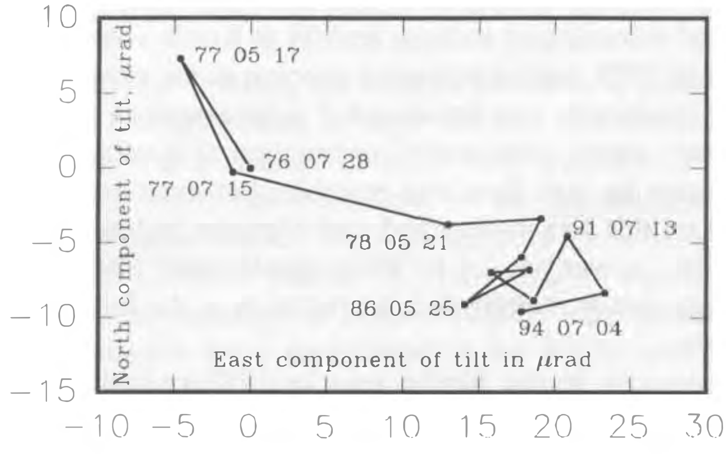


Fig. U8. North component of tilt plotted against east component of tilt at the tilt station Lón, showing the progress of tilt with time. Tilt up towards east or south-east during the January 1978 rifting event is prominent and tilt in same azimuth seem to continue at slower tilt rate after May 1978. Tilt from July 1978 to 1994 is too small to be observed with confidence.

Table U4

Marker coordinates and observed marker elevation at the tilt station 0110 (Lón) relative to the average value of all five markers of the circle at the station.

Marker	0111	0112	0113	0114	0115
Approximate marker coordinates in meters					
East	28.2	7.6	-17.2	-18.6	0.0
North	5.3	22.8	10.7	-12.1	-26.6
Y M D	Marker elevation, centimeters				
76 07 28	-13.1918	4.1876	-18.6570	32.9946	-5.3334
77 05 15	-13.1839	4.1708	-18.6102	32.9788	-5.3557
77 07 15	-13.1963	4.1889	-18.6591	32.9999	-5.3333
78 05 21	-13.1623	4.1935	-18.6827	32.9685	-5.3170
78 08 11	-13.1432	4.1943	-18.6857	32.9506	-5.3162
79 10 06	-13.1488	4.1887	-18.6870	32.9562	-5.3090
80 07 23	-13.1604	4.1777	-18.6833	32.9671	-5.3011
84 06 11	-13.1477	4.1892	-18.6941	32.9625	-5.3098
86 05 25	-13.1572	4.1892	-18.6902	32.9649	-5.3069
89 06 24	-13.1489	4.1868	-18.6993	32.9660	-5.3045
91 07 13	-13.1411	4.1972	-18.6947	32.9518	-5.3133
93 06 28	-13.1340	4.1853	-18.6956	32.9457	-5.3015
94 07 04	-13.1523	4.1845	-18.6968	32.9655	-5.3008

APPENDIX

Monitoring of Krafla volcano, various methods.

The episode of volcanic and tectonic activity at Krafla volcano, North Iceland, which commenced in 1975, caused extensive concern as the existence of the Mývatn community of 500 inhabitants was threatened if large eruptions were to occur. Also the geothermal power plant, then under construction at Krafla, was located in an area where destruction by lava flow was possible, but great amount of money hat already been spent on this power plant and commitments had been made for further expenses. Therefore, it was natural to make considerable effort to determine the nature of this activity and to investigate if a prediction of the future behaviour of the volcano was feasible.

Increased seismicity in the Krafla area in 1975 caused some concern and additional seismometers were installed in the Krafla region. After the first rifting event of December 20, 1975, a wide variety of observations were planned in order to determine the nature of this event.

Limited levelling in January 1976 demonstrated that significant ground deformation had taken place. This was also evident by widespread fault displacements which damaged roads at several locations, and by opening of fissures and associated horizontal ground displacements which broke fences at several locations and stretched telephone and power lines dangerously.

A variety of geodetic observations were made on more or less regular basis in 1976, and subsequent years to determine the extend, magnitude and rate of ground *deformation associated with the Krafla tectonic episode, but it soon became evident* that the rifting and volcanic event of December 20, 1975 was only the beginning of a series of events. These observations included precise levelling of pre-existing levelling lines, installation and regular observations of a water tube tiltmeter in the Krafla power station, then under construction, establishment of stations for observing variations of ground tilt by means of precise optical levelling of small arrays of markers, repeated measurements of fissure widths, and electronic distance measurements. More geodetic observations were added in subsequent years, including gravity measurements, recording tiltmeters and recording strain meters. Additional observations include chemical analysis of gas and liquids of the Krafla geothermal field and measurements of ground water temperatures.

This report describes the results of optical levelling tilt observations made by the Nordic Volcanological Institute.

Observations

The tilt observations discussed in this present report are what is frequently named "dry tilt". "tilt levelling", "spirit levelling tilt" or "optical levelling tilt". The tilt stations consist of several permanent markers of corrosion resistant material, securely attached to stable bedrock. The permanent markers are usually arranged in two-dimensional arrays.

The optical levelling tilt stations are described as I-stations, L-stations, T-stations or O-stations, according to the shape of the two-dimensional arrays. The I-stations consist of a single line of markers, allowing tilt determination along the azimuth of the line only. The L-stations and T-stations consist of two connected lines, roughly orthogonal to each other, in L-stations, one end of a line is connected to the end of the other lines, in T-stations one end of a line is connected to the other line near its center. The O-stations consist of several markers, usually 5, forming a circular array.

Most of the optical levelling tilt stations which were established in the Krafla area during the 1975-1989 period of high volcanic and tectonic activity were O-station with 5 markers at a distance of 25 m from a marked central point. One O-station (station 0100, Hóll) has 4 markers on the periphery of a circle of 27 m radius and another station (station 0000, Hlíðardalur) consists of 6 markers in the circular array. One L-station (station A, Námaskarð) was established in 1976, consisting of two linear segments of 3 markers each, one marker common for both segments. Two T-stations were constructed in the Krafla network of tilt stations, station 0030, Mývatn-E, first observed in 1976 and abandoned in 1977, and station NE84011, Sandmúli, constructed in 1984 and consisting of 9 markers, where 4 markers form one linear segment and the remaining 5 markers form another linear segments together with one markers of the first segment.

All the tilt observations at the optical levelling tilt stations are made by using high quality optical level (spirit level), with an optical micrometer. A Wild N-3 level was used from 1976 to 1981 and a Wild NAK2 level after 1981. Measuring rods were always the same, 3 m long Kern invar rods with 5 mm graduation. The observations at the O-stations were made by placing a sturdy tripod at the center of the circular marker array, and place a invar levelling rod in exactly vertical position on one of the markers at the periphery of the circle. Readings are made on both scales of the levelling rod, usually two readings of each scale. Then the levelling rod is moved to another marker and readings are made. When all the markers have been occupied by the levelling rod, the observation is repeated with the rod on the first marker. Then the whole procedure is repeated, by moving the levelling rod to each marker of the circular array in reverse order. Observations always begin at the same marker, the marker of lowest numerical identification. Usually, the levelling rod is carries from one marker to the next, anti-clockwise around the circle, during the first part of the observation, and clockwise around the circle during the second part of the observation.

If level readings are greatly different at the two observations of the same marker, then a third observation of that marker is made. If readings of the second half of the observation differ significantly (> 0.2 mm) from that of the first half of the observation, then all the markers are observed for the third time.

The T-stations and L-stations are observed by conducting conventional precision levelling, using one or two invar rods and observing each linear segment twice to avoid possible large observational errors.

Other deformation measurements

The 1975-1989 episode of tectonic and volcanic activity at Krafla was studied extensively by various observing techniques. This report concentrates on ground tilt observations made by the Nordic Volcanological Institute, but the same institution also studied ground deformation by conducting extensive electronic distance measurements (Tryggvason 1993), measurements of variations of the level at lake

Mývatn (Tryggvason 1987) and operating recording tiltmeters (Tryggvason 1982). Other institutions conducted extensive distance measurements, levelling, crack measurements, lake level measurements and gravity observations (Björnsson et al. 1984, Björnsson et al. 1985, Johnsen 1979, Möller and Ritter 1980, Torge and Kanngieser 1980, Spickernagel 1980). Very many more papers report these deformation measurements or are based on the measured deformation.

The observed ground deformation in the Krafla area 1975-1989 can be classified as deformation associated with pressure variation in a shallow magma chamber below the Krafla volcano, and deformation associated with rifting of a 80-km segment of the boundary between the European and American crustal plates. Ground deformation during this 1975-1989 sequence of events was first observed on December 20, 1975 as displacements of fissures and faults of the Krafla fissure swarm. The end of the period of activity in 1989 is rather arbitrary. The last significant rifting and eruptive event of the sequence occurred in September 1984, but after that event, measurements indicated magma movement towards the shallow Krafla magma chamber at variable rate for about 5 years. These measurements suggest that no underground magma movement have occurred at shallow depth in the Krafla region since early 1989. Therefore, the period of activity is taken to end in 1989. Ground deformation is observed in the Krafla region after 1989, but at relatively slow rate as compared to rate of deformation 1975-1989, and the nature of the deformation suggest that after 1989, crustal strain has been in progress of relaxation after the violent strain variations at the plate boundary region during the period of intense deformation, especially during 1975-1981.

Spreading rate and direction

A model of global crustal spreading (model NUVEL-1, DeMets et al. 1990) gives the present spreading rate in north Iceland as 1.9 cm per year in azimuth between 105° and 110°. Distance measurements across the Krafla fissure swarm in March 1978 and April 1981 demonstrated an azimuth of relative horizontal plate displacement of 104° (± 3°) and 99° (± 3°) at two locations, 2 and 10 km north of the center of deformation at Krafla respectively (Tryggvason 1984). GPS measurements in Askja in 1987 to 1993 (Camitz et al. 1995) suggest spreading rate of 2.4 (± 0.5) cm/year in azimuth 99° (± 12°), and GPS measurements in the Krafla region 1987-1990 (Heki et al. 1993) suggest azimuth of relative plate displacements of close to 100°.

The maximum accumulated widening of the Krafla fissure swarm during the rifting events of 1975-1984 amounts to close to 9 m (Tryggvason 1984). The average widening along the 80 km segment of the fissure swarm which was affected, is considerable less, probably about 5 m. A similar rifting episode occurred in the same region in 1724-1729. We can assume that the widening in 1975-1984 did release tensile strain that had accumulated during 255 years period, 1729 to 1984. It may be assumed that some tensile strain in the area of the 1975-1984 rifting has been released in earlier events. A rifting episode in 1875 in the Askja fissure swarm may have released tensile strain in the most southerly part of the Krafla fissure swarm. Large earthquakes in the Tjörnes fracture zone in 1755, 1838, 1872, 1885, 1910, 1963 (Tryggvason 1973) must have affected the strain field in the northern part of the Krafla fissure swarm, and released some of the tensile strain accumulated there. Therefore, the maximum widening, not the average widening, in 1975-1984 is considered to represent the tensile strain build-up since previous release of the tensile strain in the Krafla fissure swarm.

The 9 m maximum widening in 1975-1981 may be interpreted as average annual plate displacement of about 35 mm, almost twice that of the NUVEL-1 model. This can be explained either by assuming that the NUVEL-1 model is approximately correct, but the 1724-1729 episode did not release all of the tensile strain that had accumulated in the vicinity of the Krafla fissure swarm at that time. Another possible explanation is that the plate velocities are presently much greater than predicted by the NUVEL-1 model. The first alternative, that not all the tensile strain of 1724 was released in the 1724-1729 episode, is considered more realistic. That would also mean that in any rifting episode, only a fraction of the stored tensile strain at the beginning of the episode, is released during the episode. It also means, that the about 250 year between the two last rifting episodes in the Krafla fissure swarm is an abnormally short interval between this large rifting events. A 500 years interval between rifting episodes is more in agreement with the long-time average plate velocities, and the magnitude of the 1975-1984 rifting.

Pressure variations in the Krafla magma chamber

The Mogi model (Mogi 1958) relates particle displacement of an elastic half space to pressure and volume of a small source and the elastic moduli of the half space. For a constant source volume, the model states that the magnitude of particle displacement is proportional to the pressure variations in the source.

Although the observed ground deformation at Krafla deviates from that predicted by the Mogi model, these deviations are small compared to the deformation. Therefore, the Mogi model is frequently used to develop a model of the processes at work at Krafla during the 1975-1989 period of volcanic and tectonic activity.

The magnitude of ground deformation at Krafla volcano which is related to inflations and deflations of the volcano, is considered to reflect linearly the pressure variations in the Krafla magma chamber.

An effort has been made to relate pressure variations in the Krafla magma chamber to subsidence at the center of deformation (Tryggvason 1981). The result was that a pressure drop of one MPa in the magma chamber caused subsidence of 5 cm at the center of deformation. This is based on correlation between observed subsidence at the center of deformation at Krafla, and ground elevation where magma came to rest, in deflation and rifting events. This problem will be considered further as additional observational data has become available.

Each major subsidence event of the Krafla volcano was associated with widening of a portion of the Krafla fissure swarm. The magma which left the magma chamber is considered to have come to rest below the part of the fissure swarm where widening occurred. The ground elevation of the Krafla fissure swarm is about 600 m above the Krafla magma chamber, but drops to below sea level about 50 km to the north, and to 300 m, about 10 km south of Krafla. The lithostatic pressure at a selected shallow horizontal level is proportional to the ground elevation, and increases about 3 MPa for each 100 m increase of ground elevation. It is assumed that pressure in the Krafla magma chamber, at any selected horizontal plane, at the end of each deflation event is equal the lithostatic pressure at the same horizon at the location where the magma which escaped the magma chamber came to rest (Table 1 in Appendix).

Table 1 in Appendix

Subsidence events of Krafla volcano. Only events of observed rifting and widening of the Krafla fissure swarm are included. Maximum subsidence is based on tilt observations at the Krafla geothermal power station. Time from the beginning to the end of subsidence is given. The estimated lowest ground elevation where rifting occurred is shown and last column gives lithostatic pressure at a shallow horizontal plane, relative to that in the Krafla magma chamber.

Year	Date of beginning of event	Maximum subsidence, cm	Duration of subsidence, hours	Ground elevation, m	Lithostatic pressure MPa
1975	20 Dec. 2)	241	1440	-200	-24
1976	31 Oct. 1)	55	39	400	-6
1977	19 Jan. 1)	34	20	500	-3
1977	27 Apr. 2)	98	31	300	-9
1977	8 Sept. 2)	65	26	300	-9
1978	7 Jan. 1)	111	500	0	-18
1978	10 July 1)	60	70	300	-9
1978	10 Nov. 1)	73	100	200	-12
1979	13 May 1)	72	125	200	-12
1980	16 Mar. 2)	69	10	350	-7.5
1980	10 July 3)	52	100	400	-6
1980	18 Oct. 3)	36	105	500	-3
1981	30 Jan. 3)	33	120	450	-4.5
1981	18 Nov. 3)	38	80	500	-3
1984	4 Sept. 3)	65	340	450	-4.5

1) Subsidence events of no eruption and no ground rifting near the center of deformation at Krafla.

2) Subsidence events with minor eruptions and ground rifting at the center of deformation.

3) Subsidence events with significant basalt eruptions.

The subsidence rate was high during the first part of each subsidence event, to decrease asymptotically towards zero at the end of the subsidence. This suggests that a sort of a pressure equilibrium was reached, indicating the same pressure at the same level in the magma chamber and in the new magma deposit. The observed subsidence of the fissure swarm, where widening occurred, together with numerous fissure in the subsided area, suggest that pressure on the new magma deposit was similar to lithostatic pressure (Fig. 1 in Appendix).

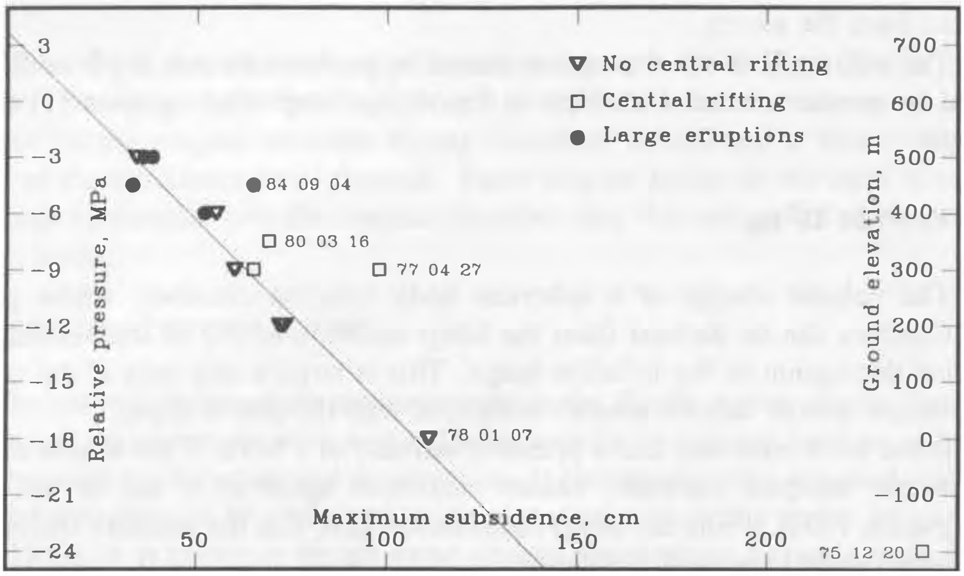


Fig. 1 in Appendix. Relation between maximum subsidence of the ground, and ground elevation where magma came to rest in Krafla deflation events. Vertical scale is lowest ground elevation where magma came to rest in fissures or where most lava erupted in eruptions (right) and corresponding lithostatic pressure relative to that in the magma chamber (left). A linear relation is suggested, with a few exceptions. Subsidence during the event of 20 December, 1975 (near lower right corner) is almost twice what the linear relation predicts. Events of 27 April, 1977, 16 March, 1980, and 4 September 1984 were all associated with rifting and major anelastic ground deformation near the center of deformation at Krafla causing uncertainty of estimated maximum subsidence. Thin line shows regression line based on deflation events of no rifting near the center of deformation, and no eruption. This line corresponds to 4.94 cm maximum subsidence for each MPa lowering of magma pressure in the shallow Krafla magma chamber.

The observational data show definite relation between maximum subsidence of each subsidence event and ground elevation where magma was deposited (Fig. 1 in Appendix). If magma pressure at place of deposition is equal lithostatic pressure, and pressure equilibrium was reached between the magma chamber and deposited magma at end of each subsidence event, then pressure drop of one MPa in the magma chamber corresponds to about 5 cm maximum subsidence.

Magma volume, transport and storage

According to the Mogi theory (Mogi 1958), the vertical component of ground deformation caused by pressure variation in a point source at some depth below a flat surface can be described by the equation:

$$\mathbf{h = h_0 (H^3/(H^2 + R^2)^{3/2})} \qquad (1)$$

Where **h** is vertical ground displacement, $\mathbf{h_0}$ is vertical displacement at zero horizontal distance from the source, **H** is depth of the source and **R** is horizontal distance from the source.

The volume **V** of the depression caused by pressure drop at depth or the bulge caused by pressure increase at depth is found, by integrating equation (1) to be as follows:

$$\mathbf{V = 2\pi\, H^2\, h_0} \qquad (2)$$

The volume change of a spherical body (magma chamber) where pressure change occurs can be derived from the Mogi equation as 2/3 of the volume of the deflation depression or the inflation bulge. This is strictly true only if the radius of the spherical source volume is small compared with the source depth.

It has been estimated that a pressure increase of 1 MPa in the Krafla source of deformation (magma chamber) causes maximum uplift of 5 cm of the ground (Tryggvason 1981). From the Mogi equation we have that the pressure increase **P** in the source can be expressed as follows:

$$\mathbf{P = 4\, H^2\, \mu\, h_0 / a^3} \qquad (3)$$

Here μ is the rigidity of the solid crust, and **a** is the radius of the spherical source volume. Taking μ to be 17 GPa, **H** to be 2500 or 3000 m, **P** = 1 MPa and $\mathbf{h_0}$ = 5 cm, the value of **a** becomes 2197m or 2483 m respectively, corresponding to source volume of 44.4 or 64.1 km^3 respectively.

The source volume is considered equivalent to the volume of the shallow Krafla magma chamber. The volume of molten magma in the magma chamber may be smaller because of partially molten magma.

Considering the volume of completely molten basaltic magma in the shallow Krafla magma chamber to be either 50 km^3 and 25 km^3 respectively, and accepting that a 5 cm deep subsidence bowl shaped as if a point source is located at 2.5 km depth is caused by 1 MPa pressure drop in the magma. Then the volume of the subsidence bowl is 1.96 10^6 m^3 and the volume decrease of the magma chamber is 1.31 10^6 m^3.

When magma pressure decreases, the magma density decreases. This density decrease is equivalent to increase of specific volume of the magma, and is proportional to the pressure decrease **dP** and inversely proportional to the bulk modulus **Kl** of the liquid magma which is about 14 GPa (Blake 1981). Then the increase of specific magma volume **dV** is given by:

$$\mathbf{dV = dP/Kl = 1/14000} \qquad (4)$$

The volume of magma **Vr** that needs to be removed from the magma chamber to produce a subsidence bowl of 1.96 10^6 m^3 is the sum of volume decrease of the magma chamber (1.31 10^6 m^3) and the volume expansion of the magma in the chamber (**dV Vl** = [(25 or 50)/14] 10^6 m^3).

$Vr = dV\ Vl + 1.31\ 10^6\ m^3$ (5)

$Vr = 3.10\ 10^6\ m^3$ if melt volume is 25 km^3

$Vr = 4.88\ 10^6\ m^3$ if melt volume is 50 km^3

Where **Vl** is the total volume of molten magma in the shallow Krafla magma chamber. Based on these considerations, it is estimated that the volume of magma taken out of the magma chamber during events of subsidence is about twice the volume of the subsidence bowl formed. Same relation holds for the ratio of volume of magma introduced into the magma chamber and the volume of corresponding inflation bulge.

Location of magma storage

The various deformation measurements in the Krafla region during the 1975-1989 period of intense tectonic and volcanic activity have been used to estimate a source location for the observed deformation. It has usually been assumed that most of the deformation can be explained by a point source according to the Mogi theory (Mogi 1958). It is common for all those attempt to construct a simple point source model to explain the ground deformation at Krafla, but it must be realised that not all the deformation can be explained by such a simple model as the requirements of the Mogi theory are not met.

It became obvious already at the beginning of the 1975-1989 active period, that the ground deformation could partly be explained by processes below the Krafla volcano, and partly by processes along the elongated zone of fissures and faults, which has been named the Krafla fissure swarm. The part of the deformation which is controlled by processes below the Krafla volcano, inflation or deflation of the volcano, resembles the deformation predicted by Mogi for a point source of pressure change within an elastic half space.

The various deformation measurements can be used to search for a location of a hypothetical point source which can explain largest possible fraction of the observed deformation. This is done by comparing the observations with a point source model, and change location of the hypothetical point source until correlation between predicted model deformation and observed deformation is the greatest possible for the data set used. A similar approach is to search for a source location and source magnitude which gives minimum standard deviation between predicted model deformation and observed deformation.

The observations of ground tilt in the Krafla region can be and have been used to search for a best location for a point source. This source point has been located south of but very near Leirhnjúkur, a palagonite ridge at the center of the mapped Krafla caldera. If only stations within about 5 km from this hypothetical source are used to search for the point source, a well defined point is found at **65° 42' 54" N, 16° 47' 51" W** at a depth of 2.5 km below the ground surface.

This accepted location is found if all optical levelling tilt stations within 5 km distance from this location are used in the search for best source location. If other stations are used in the search, slightly different location is indicated. If stations at greater distance from the hypothetical source are also used in the search, greater apparent error of the source location is indicated, mostly because the observed tilt at the distant stations is generally too small to be determined with accuracy.

If observations other than tilt observations are used in search for a point source of the Mogi type, then slightly different location is found. Repeated distance measurements generally locate the apparent source some hundredths of meters farther east than the source indicated by tilt observations. This may be due to distribution of lines of distance measurements which are not symmetrically located around the source. The same is true for the tilt observations. The lines of distance measurements are concentrated east of the apparent source while more tilt stations are west of the source.

Although a search has been made for a hypothetical point source of deformation in the Krafla region, it is quite clear that no such point source exists. Further the physical conditions of the region deviates from the requirements of the Mogi model. The earth is not flat nor homogeneous, nor perfectly elastic, and the source of variable pressure can not be considered as very small compared with the source depth. These deviations from the Mogi model are expected to explain many of the irregular spatial pattern of observed ground deformation.

It can be argued that some systematic error in a point source model are caused by the relatively large source volume. If the source is a large spherical volume of magma, as is strongly indicated by various observations, then the actual center of the spherical volume is deeper than the calculated depth of a point source causing similar ground deformation. As an example, if the radius of the spherical source is 2 km and the best fit to the Mogi model is a depth of 3.0 km, then the actual depth to the center of the spherical source is about 3.6 km (Tryggvason 1981). In general, the calculated depth of a point source which fits the observed deformation, is shallower than the depth to a center of large spherical source volume causing the deformation. This difference can exceed 20% of the computed depth.

Propagation of seismic waves in the Krafla area suggest two magma bodies on an east-west line (Einarsson 1978). If this is true, and the volume of the two bodies are similar, then the search for a point source of deformation should locate a point between the two magma bodies. Also, observations made to the east of the source will be more affected by the eastern magma body, and locate a hypothetical single source farther east than the center of gravity of all magma stored at shallow depth. Similarly observations to the west of the source will locate a hypothetical single source too far west. This may explain the slight difference in computed source location from distance measurements and tilt measurements, but more distance measurements are made east of the source while more tilt measurements are made west of the source.

It is argued above that computed single source depth is shallower than the center of large spherical body causing the observed deformation. Thus if the best point source solution gives a depth of 2.5 or 3 km, then the center of large spherical source is probably at about 3.0 and 3.6 km depth respectively. Further, the calculated point source depth is generally poorly restrained, and the error limits are rather large, but very different for different data sets. It is quite possible that location errors of 1 km in vertical direction are typical, in addition to some 0.5 km systematic error. The horizontal location errors are smaller than the vertical errors, probably no more than 0.3 to 0.5 km in well recorded deformation events.

In conclusion, the ground deformation at Krafla during the 1975-1989 episode was not caused by a point source of increased or decreased pressure, but by a large volume, possibly about 50 km^3 of magma, at varying pressure. The horizontal source coordinates **(65° 42' 54" N, 16° 47' 51" W)** are accurate within 500 meters and represent the center of gravity of the large magma body. The computed source depth (**2.5 km**) is an underestimate. The probable depth to the center of the shallow Krafla magma chamber is 3 to 4 km from the ground level, or 2.5 to 3.5 km below sea level.

Direction of tilt during deflations and inflations

In the main part of this report, radial tilt is taken as tilt component parallel to observed tilt during rapid deflations of Krafla volcano at all optical levelling tilt station where azimuth of deflation tilt was well recorded. The center of the Krafla volcano is not well defined but a center of deformation has been defined as the point where a hypothetical point source of increased or decreased pressure can explain the greatest portion of the observed ground deformation during deflation events and inflation periods of the Krafla volcano during the 1975-1989 sequence of events. This center of deformation is found at **65° 42' 54" N, 16° 47' 51" W.** Direction to this point differs from the direction of downward tilt during deflation events (Table 2 in Appendix)

Table 2 in Appendix

Azimuth of line from each tilt station to the accepted center of deformation at Krafla (65° 42' 54" N, 16° 47' 51" W) and the average azimuth of downward tilt at these stations during deflations of Krafla volcano in the period 1976-1984.

	Azimuth to point source	Azimuth of tilt during deflations	Tilt azim. minus point azimuth.
Station A	358.9°	8.6°	9.7°
Station 0000	348.2°	354.1°	5.9°
Station 0010	232.3°	210.0°	-22.3°
Station 0020	43.1°	62.0°	18.9°
Station 0040	303.7°	290.5°	-19.2°
Station 0080	78.5°	80.0°	1.5°
Station 0090	114.3°	140.0°	25.7°
Station 0210	31.3°	12.8°	-18.5°
Station 0240	32.3°	57.9°	25.6°
Station 0250	26.2°	30.7°	4.5°

The difference between tilt azimuth during deflations and direction toward the hypothetical point source is greater than 20° at three tilt stations, either positive or negative, greater than 15° at three other stations, and less than 10° at only four of the 10 stations where direction of deflation tilt could be determined. There is no apparent regional pattern in this difference. As an example of great variation in the deflation tilt azimuth are the stations 0210 and 0240, both at nearly the same azimuth from the hypothetical point source, but azimuth of deflation tilt differs by 45.1°. The distance from the point source is similar, 7.61 and 6.63 km respectively. A possible reason for the great difference of direction of deflation tilt at these two station is a north striking normal fault immediately west of station 0240 and a short distance east of station 0210. This fault is distinct in the topography as steep east facing slope, 10 to 20 m high, near station 0240 but disappears near station 0210.

It is clear that the deviation of tilt direction from the direction to the source of deformation is caused by deviation from the requirements of the Mogi model. Which deviations are not known. It may be inhomogeneity of the solid earth with respect to elastic properties. It may be the rugged topography in contrast to the flat surface required by the model. It may be deviation from perfect elasticity. Regardless of the reason, the observed azimuth of ground tilt may deviate as much as 25° from the direction predicted by the Mogi theory.

Tilt associated with rifting (on fissure zone flanks)

During a rifting event in April 1977, widening of about 2 m of the Krafla fissure swarm occurred along highway 1, the main road from Mývatn toward East Iceland and the west flank of the fissure swarm was uplifted about 40 cm (Björnsson et al. 1979).

The tilt station 0030 is located on the west flank of the fissure swarm, immediately south of Highway 1. It showed tilt of about 70 μrad, up towards ENE between observations of September 19, 1976 and May 20, 1977. Most of this tilt supposedly happened during the April rifting event. Tilt station 0020 is located about 4 km west of the active part of the Krafla fissure swarm, also near Highway 1. It showed a tilt of about 45 μrad, up toward east, between observations of 23 October, 1976 and 16 May 1977. This tilt is believed to have occurred during the rifting event of April 1977. Station A (Námaskarð) is located about 1 km east of the east flank of the Krafla fissure swarm. It showed a tilt of about 64 μrad, up towards WNW, between observations of September 19, 1976 and May 16, 1977. This tilt is also believed to have occurred during the April 1977 rifting event.

These observations suggest symmetrical deformation on both sides of the fissure swarm, with ground tilt up towards the swarm, decreasing from about 70 μrad immediately outside the 1-km wide active part of the fissure swarm, to 45 μrad at 4 km distance. A linear decrease of tilt with distance from the fissure swarm would mean that tilt caused by the rifting event terminated at 11 km distance from the fissure swarm, and that uplift of the flanks of the fissure swarm amounted to 38.5 cm, in good agreement with the 40 cm uplift obtained by levelling.

Another event, that of September 8, 1977, produced rifting and widening of the Krafla fissure swarm of about 1.05 m along Highway 1 east of Mývatn (Tryggvason 1980). Tilt stations 0050 and 0060 immediately to the west of the zone of rifting showed tilt of 76 μrad and 86 μrad respectively, up toward NE. Station 0070 about 1 km west of the rifted zone showed tilt of 89 μrad, up toward NE, and station A (Námaskarð) about 1 km east of the rifted zone showed tilt of 82 μrad up toward NW. Station 0020 about 4 km west of the rifted zone showed tilt of 39 μrad up toward ENE. All these stations were observed about 3 weeks before the rifting event and 2 to 4 days after the event.

The observed tilt during the September 8, 1977 rifting event also suggest symmetrical vertical component of deformation with respect to the axis of the active

Krafla fissure swarm. The northerly component of tilt at the stations discussed are due to the fact that rifting terminated southward very near these stations.

The flank uplift appear near identical in these two events. However, the northerly component of tilt during the September 1977 event suggests greater flank uplift at some distance north of the observing tilt stations here discussed, but stations farther north were heavily affected by deflation of the Krafla volcano, and effect of rifting on the tilt at those stations can not be separated from the deflation tilt.

After the rifting events of April and September 1977, the stations 0020, 0050, 0060, and 0070, all west of the active central axis of the Krafla fissure swarm and about 10 km south of the center of deformation at Krafla, demonstrated continuing tilt up in westerly direction (or down in easterly direction), suggesting continuous subsidence of the flanks of the fissure swarm. Another interpretation is that the uplift of the fissure swarm flanks migrated away from the fissure swarm.

Model of the rifting process

To understand the mechanism of the rifting episode in the Krafla region, it must be kept in mind that a realistic model of the rifting process must not contradict any observed facts.

The Krafla central volcano possesses a large volume of molten magma at relatively shallow depth. We call this the shallow Krafla magma chamber. It is probably roughly spherical, although other shapes have been postulated. Its volume may be estimated as about 50 km^3, and the depth from the earth's surface to the center of the sphere may be estimated as 3 - 4 km. This magma chamber has been in existence for many millennia, and it will exist for a long time into the future, although increased steam production for power generation may accelerate the solidification of the magma.

The subsidence of the Krafla region 1989-1994 (Tryggvason 1994) may be caused by crystallisation and corresponding volume decrease of the molten magma. The maximum subsidence amounts to about 4 cm per year, corresponding to an annual volume increase of the subsidence bowl of about or somewhat less than 10^6 m^3, but about 10 times that volume must be crystallised, as the density of crystallised rock is about 10% higher than that of molten magma at same temperature. At this rate of crystallisation, one km^3 of magma will be solidified in about 100 years. The rate of magma solidification will slow down as the volume of molten magma decreases, suggesting that complete solidification of 50 km^3 of magma will take tens of thousands of years.

The crustal plate movement is considered to be relatively constant over millions of years, and can, therefore, be regarded as constant throughout the lifetime of each central volcano. During the periods of no rifting, the elastic lithosphere is stretched at a rate of about 2 cm per year in the North Iceland plate boundary. The relative stretching or tensional strain varies spatially with the thickness of the lithosphere, being greatest where the lithosphere is thinnest. The stretching extends over a wide areas, and uniform plate velocity will not be observed within this zone of stretching.

Below the lithosphere lies the asthenosphere consisting of viscous material which yields to movement of the crustal plates without accumulating elastic stress.

However the highly viscous asthenosphere restricts any rapid movements of the lithosphere.

The stretching of the plate boundary region in the Krafla area had been going on since about 1729, without any lithosphere failure, when the Krafla shallow magma chamber started to inflate at some time between 1970 and early 1975. This inflation was observed as horizontal expansion between observations of 1971 and 1975 while no expansion had been observed between 1965 and 1971 (Möller and Ritter 1980). The source of magma entering the shallow Krafla magma chamber between 1970 and 1975 is not known, but its potential was sufficient to raise the magma chamber pressure well above the local lithostatic pressure.

The pressure in the shallow Krafla magma chamber increased steadily until December 20, 1975, then the sum of the magma pressure and the tensile lithosphere stress reached the breaking strength of the lithosphere at the boundary of the shallow magma chamber. Fissure opened, striking orthogonal to the direction of maximum tensile strain, and propagated rapidly away from the magma chamber, in two directions, S13°W and N13°E. Magma flowed into the fissure, at high rate at the beginning, but the flow rate decreased gradually with time and ceased in February 1976. Most of the magma flowed northward, reaching the Grímsey transform fault zone, about 60 km north of the Krafla volcano. The high flow rate of magma into the fissure at the beginning of the event demonstrates that pressure in the fissure was much lower than in the magma chamber. The gradually decreasing flow rate suggest that magma pressure in the fissure approached that in the magma chamber and when the flow stopped, equilibrium between magma pressure in the fissure, and in the magma chamber, had been reached.

Widening of the Krafla fissure swarm near the north coast of Iceland, about 60 km north of the Krafla volcano, suggests that the magma which flowed away from the magma chamber during this first subsidence and rifting event was deposited in fissures where ground level was near or below sea level, 600 to 800 m lower than above the Krafla magma chamber. Subsidence of the 5 km wide fissure swarm by about one meter (Sigurdsson 1980) and the numerous open surface fissures in this subsided area suggests that the roof of the opening fissure has collapsed into the void created above the magma in the new fissure. This collapsed and shattered roof had lost its strength and rests with its weight on the magma in the fissure, creating a lithostatic pressure in agreement with the ground elevation.

This model suggests that pressure in the Krafla magma chamber at end of the subsidence and rifting event, in late February, 1976, is lower than lithostatic pressure by equivalence of 600 to 800 m column of rock, or about 20 MPa. The magma chamber roof was sufficiently strong, not to collapse under this condition.

The conduit from the magma chamber to the part of the fissure system where magma was deposited was temporarily sealed at the end of the subsidence and no magma flowed out of the shallow magma chamber until a new break occurred.

During this first event of the Krafla fires, land subsided roughly 2.5 m at center of subsidence at Krafla. It has been estimated (Tryggvason 1981 and this paper), that a subsidence of 5 cm corresponds to pressure drop of one MPa in the shallow Krafla magma chamber. This suggest that the pressure drop in the Krafla magma chamber was about 50 MPa during the event which started on December 20, 1975. This subsidence event lasted for about two months (See table on page 204), much longer than any other subsidence event of the 1975-1989 activity at Krafla. It may be argued that some of the subsidence was caused by non-elastic processes, and that pressure drop in the magma chamber was less than 50 MPa.

However, if the pressure drop in the Krafla magma chamber was about 50 MPa during the deflation which started on December 20, 1975, then the magma pressure before that event was much higher than before later subsidence events, the difference being about 20 MPa (see Fig. 1 in Appendix on page 205). This suggests greater tensile strength of the lithosphere prior to the first rifting event, than later during the 1975-1989 period of activity at Krafla.

Following the first subsidence and rifting event, magma flowed into the Krafla magma chamber at a rate which decreased with increasing magma pressure in the chamber. The magma pressure in the shallow Krafla magma chamber reached a value of about 4 MPa above the lithostatic pressure before a new rifting event occurred (see Fig. 1 in Appendix on page 205). Again the magma flowed into the fissure and was deposited at depth, and magma flow continued until pressure equilibrium was again reached between the magma chamber and the magma deposited in the fissure. This sequence was repeated about 20 times, the magma pressure in the shallow magma chamber increased over a period of a few months to about a year, then a break occurred and the magma pressure in the magma chamber dropped below the lithostatic pressure and the conduit into the fissure zone was sealed again.

The tilt observations in the Krafla area, and particularly the water tube tiltmeter in the Krafla geothermal power station (Fig, 13 on page 18), show gradual increase in ground elevation at the center of deformation, the elevation before each deflation event being higher than before preceding event. The elevation increase from late 1976, immediately before the October 31 deflation, to September 1984, immediately before the September 4 deflation, is about 175 cm, if ratio of tilt at the power station and ground elevation at the center of deformation has remained constant. It is known that the tilt to ground elevation ratio was greatly disturbed during certain rifting events when rifting occurred above the magma chamber. Still, ground tilt is considered as a fair measure of pressure variations in the magma chamber. However, 175 cm increase in ground elevation above the magma chamber corresponds to 35 MPa pressure increase in the magma chamber according to the above discussion. This much increase in breaking limit pressure of the shallow magma chamber is considered unrealistic, leading to the assumption that the ration of 5 cm vertical displacement for 1 MPa pressure change is valid only if the pressure change is very rapid, lasting for one week or less.

The rifting events of 1975 to 1979 were not associated with eruptions of any significance. The first large event of 1980, on March 16, also produced insignificant amount of lava, although greater than the previous eruptions. The following 5 major rifting events produces lava of volume similar to the volume of magma which escaped from the shallow Krafla magma chamber. However, each of these 5 events also caused widening of about 1 m of portion of the Krafla fissure swarm, suggesting that significant amount of magma was deposited as dikes below the ground surface. Relatively large eruptions during the last 5 major rifting events, while the first about 15 large rifting events produced no or entirely insignificant amount of lava (compared to volume of magma leaving the magma chamber), suggest the decrease of tensile stress at the plate boundary of North Iceland. Before 1980, the equilibrium pressure in the magma chamber and in the fissure where magma was deposited, was equal or possibly lower than the lithostatic pressure at the location of deposition, as otherwise magma would have flowed to the surface. After March 16, 1980, the equilibrium pressure was higher than the lithostatic pressure at location of magma deposition (eruption), and magma flowed to the surface as lava until the pressure in the magma chamber dropped to the lithostatic pressure at the site of the eruption.

After the rifting and eruptive event of November 1981, inflation continued for almost 3 years at very slow rate as compared with earlier inflation rates. The pressure in the magma chamber rose to higher values than at any time after December 20, 1977. The inflation and pressure increase almost ceased in 1984, but then, on September 4, 1984, the walls of the shallow magma chamber failed and large quantities of magma escaped, partly to fill new fissures, partly to flow to the surface as lava. The volume of lava flow is poorly known, estimated 60 to 140 million m^3 (Tryggvason 1986a), but the lava of the September 1984 eruption may have been as great as accumulated volume of all previous eruptions of the 1975-1989 sequence of events at Krafla. However, the magma which left the shallow Krafla magma chamber during the September 1984 event was much less than the magma leaving the chamber during the event which started on December 20, 1975, and probably also less than that of the event of January, 1978, but similar to those of the events of April 1977, July 1978, November 1978, May 1979, and March 1980 (see Table 1 on page 4).

Each rifting event which was not associated with significant eruption, was associated with subsidence of an elongated zone along the central part of the Krafla fissure swarm. A cross section of this subsidence has been published along the main road (highway 1) from Mývatn toward east (Björnsson et al. 1979), and along the main road in Kelduhverfi (Sigurdsson 1980). The subsided zone coincides with the zone of intense rifting and opening of fissures, although some narrow fissures were seen to open outside the zone of subsidence.

On the highway east of Mývatn, subsidence occurred during rifting events of April 1977 and September 1997 between the faults Grjótagjá on the west side, and Krummaskarð on the east side of the subsided zone. The width of the subsided zone was 1.2 to 1.4 km, and the land inside this zone subsided irregularly, probably about one meter in each rifting event on the average.

In Kelduhverfi subsidence occurred in two rifting events, the first event which commenced on December 20, 1975, and in the event of January 1978. Similar subsidence occurred on the Kelduhverfi highway in both events. The subsided zone was about 5 km wide, and subsidence in each event was rather uniform along the road, about 1.0 m in each event, a total of 2 m in these two events.

The subsidence of the zone of widening is taken as caused by collapse into the void caused by the widening. It can be viewed as a triangular wedge between two normal faults facing each other. At the surface, these normal faults are almost vertical, but below a shallow depth, they are assumed to dip about 60°, making the depth to the bottom of the down going wedge about the same as the width of the subsided zone. Below that depth, the fissure is supposedly filled with magma which escaped from the Krafla shallow magma chamber during the rifting and subsidence event. This argument places the depth to the top of the dike formed in April 1977 and September 1977 below the rift zone east of Mývatn as about one km. In

Kelduhverfi, the same argument places the top of the dike formed in December 1975 to January 1976, and January 1978 at about 5 km depth.

The width of the subsided zone along the Krafla fissure swarm has not been mapped, but along the section near Leirhnjúkur, this width is roughly one km. Farther north the width increases to about 5 km in the vicinity of the Kelduhverfi highway.

The thickness of the lithosphere along the plate boundary in north Iceland can be said to be equal the bottom of the region where fissures or faults were displaced during the rifting events. This depth can be estimated from depth of earthquake hypocenters. Study of hypocenter depth during the rifting event of July 1978 gives the maximum depth of well located hypocenters about 10 km north of the center of deformation as 3.0 to 3.5 km (Einarsson and Brandsdóttir 1980). Another study of earthquakes in the Krafla area states that "hypocenters are ,mostly at depths of 3 km or less" (Einarsson 1978). These observations suggest that the brittle lithosphere may be as thin as 3 km, and below that depth, strain is released by viscous deformation. It should be emphasised that computed hypocentral depth is reliable only if seismometers are located very near the epicenters.

The repeated rifting of the same section of the Krafla fissure swarm during the 1975-1984 period of rifting is somewhat puzzling. Why was not all the accumulated tensile strain released in one rifting event? Why was widening of the Krafla fissure swarm usually one or two meter in each rifting event while accumulated widening of all rifting events exceeded 8 m where maximum widening was observed? There is evidence for more than 2 m widening in the first rifting event near the north end of the zone where rifting occurred (Tryggvason 1984).

The reason for this multiple rifting of the same section of the fissure swarm may be related to coupling between the brittle lithosphere and the asthenosphere. If tensile stress was about the same before each rifting event, then the widening in each event should be proportional to the thickness of the brittle lithosphere. If the tensile stress across the fissure swarm has decreased with time, then the widening in each rifting event is expected to be smaller in later events than in the earlier events, a trend which has not been observed.

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