NORDIC VOLCANOLOGICAL INSTITUTE 8601
UNIVERSITY OF ICELAND

PROGRESSIVE TILT IN THE KRAFLA-MÝVATN AREA 1976-1985

by

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REYKJAVÍK
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Abstract

The study of ground tilt in the Krafla area, North Iceland, 1976-1985 shows that several different processes are causing the observed tilt.

The deflation and following relatively rapid inflation associated with emptying and refilling of the Krafla shallow magma reservoir is one of these processes.

Another process is the rifting and associated widening of a narrow rift zone. The flanks of this narrow zone are uplifted, where rifting occurs, but downwarped where no rifting, but some widening occurs.

A third process was observed over a two year period prior to the September 1984 eruption when slow inflation occurred in the Krafla area, but the shape of the inflation bulge was quite different from that observed during the rapid inflation when the shallow reservoir is being refilled.

The fourth process is indicated in the secular tilt, a slow deformation lasting for many years. This secular deformation can best be described as inflation centered somewhere in the Krafla area. The inflation bulge extends further away from Krafla, than the inflation associated with the filling of the shallow Krafla reservoir, indicating a deeper source.

Introduction

Several optical level tilt stations were established in 1976 in the Krafla-Mývatn area and measurements were made at these stations about one each month during summer, but less frequently during winter. Several more stations were constructed in 1977 and again in 1981 (Fig. 1).

Measurements were gradually made at more irregular intervals and main emphasis has been on tilt observations soon after events of subsidence of the Krafla volcano and also at times of high inflation stage.

The tilt during events of subsidence of Krafla has been discussed (Tryggvason, 1980, 1982, 1986) and the early measurements were presented in mimeographed reports (Tryggvason, 1978, 1979) but no presentation of the progressive tilt over extended periods has been given. The present report is an attempt to give the reader a picture of how the tilt has progressed over the years with no emphasis on the tilt during early subsidence events.

To obtain this aim, drawings have been made which show the progress of tilt at each established tilt station. Two sets of drawings are presented.

One shows the average tilt from one year to the next by averaging all observations for each year although the year 1977 is split as values before September 8 are taken separately.

Another set presents the observed tilt from one measurement to the next over the period August 1981 through October 1985.

The average tilt between years as here expressed is subject to great uncertainities, especially at the stations which lie within about 5 km from the center of inflation/deflation at Leirhnjúkur. The large tilt variations associated with the periodic inflations and deflations of Krafla make the time of observations influence the average tilt. Although tilt observations were made at both high and low inflation stage in most years, the average inflation stage during observations was not the same as the average inflation stage throughout the year.

Very few tilt observations were made during winter. Thus no observation was made in 1977 before the late April subsidence event and none in 1980 before the March 16 subsidence event. These two events, together with the 1977 September 8 subsidence event were associated with significant rifting south of Leirhnjúkur, and as the majority of the tilt stations also lie to the south of Leirhnjúkur, these three events naturally effect many tilt stations more than other events. They fall between observations of 1976 and 1977A, 1977A and 1977B and 1979 and 1980.

Tilt observations in 1984 were made both before and after the September 4 deflation, but more observations were made after the deflation. This causes tilt changes 1983-1984 to be predominantly towards the center of inflation/deflation.

The second set of observations which is displayed on one drawing for each tilt station, gives all tilt observations at these stations from August 1981 through 1985. A total of 19 observational periods are included although all stations were occupied at 5 times only. The observational periods are identified by numerals on the drawings as follows:

August 27 - 31 1981
2 October 3 - 7 1981
3 November 6 - 9 1981
4 November 20 - 22 1981
5 February 21- 22 1982
6 May 14 - 16 1982
7 August 24 - September 3 1982
8 October 7 - 9 1983
9 June 21 - 24 1983
10 October 7 - 9 1983
11 June 8 - 10 1984
12 September 6 1984
13 September 28 - October 4 1984
14 October 26 - 28 1984

15 November 30 - December 4 1984

16 March 5 - 12 1985

17 April 18 1985

18 May 29 - June 4 1985

19 October 22 - 28 1985

On several occasions, individual stations were measured twice during the same observational period. Both measurements are shown on the illustrations (station 0010, period 7; 0000, 7; A, 18; and 0220, 9). The tilt difference observed in these cases indicates the accuracy of these observations, but a standard observational error is assumed to be 2-5 microradians.

On two occasions (stations A and 0020) the tilt during the November 1981 deflation is estimated. This estimate is based on the observed tilt during the September 1984 deflation and the average ratio of September 1984/November 1981 deflation tilt.

The tilt stations

Station 0010, Leirhnjúkur

This tilt station was established in July 1976 and has been measured frequently. It lies some 500 m northeast of the center of inflation/deflation.

The great computed tilt (Fig. 2), especially in April 1977, September 1977, and March 1980 is largely the effect of deformation within the 50 m diameter bench mark array. Anomalous tilt occurred in September 1984. Otherwise the secular tilt is apparently towards east, indicating gradual uplift west of the station.

Tilt during the brief deflations is towards southwest and during the rapid inflation it is towards northeast (Fig. 3), but during periods of slow inflation the direction of tilt is approximately east, similar as the secular tilt.

Stations 0000, Hlídardalur and A, Námaskard

These stations lie about 3.7 and 7.4 km south of the center of inflation/deflation respectively. They were established in 1976, station 0000 in July and station A in January.

These two stations have similar behavior with secular tilt towards south (Figs. 4 and 5), although slightly west of south at A. Four subsidence events caused large permanent tilt anomalies, April 1977 and September 1977 towards east or southeast, March 1980 towards west at A and September 1984 towards north. The secular southerly tilt has gradually slowed down, especially at station A.

The tilt during rapid subsidences is chiefly towards north, although slightly west of north at 0000 and slightly east of north at A (Figs. 6 and 7). Individual tilt observations at A show irregular tilt over short periods because the observational errors of 2 to 5 microradians are large compared with actual tilt.

Stations 0080, Ytri Bjarghóll and 0090, Hvannstód

These stations lie 3.2 km WSW and 2.6 km WNW of the center of inflation/deflation respectively. They were established in June 1977, after the subsidence and rifting event of April 1977. The secular tilt appear to be away from the center of inflation deflation (Figs. 8 and 9) but significant tilt anomalies are evident during several subsidence events. The most noticeable anomalies occurred in October 1980 and September 1984.

The observed tilt since August 1981 (Figs. 10 and 11) indicates that the center of uplift during inflation lies farther north than the center of subsidence during deflation. The tilt direction during inflation is not noticeably influenced by rate of inflation as observed at Leirhnjúkur. The inflation tilt after September 1985 appears to have terminated when only half of the deflation tilt has been eliminated.

Stations 0250, Sydri Bjarghóll, 0240, Hlídarfjall and 0210, Eldá

These stations were established in October 1981 and are located 4.2 to 7.8 km SSW of the center of inflation/deflation at Leirhnjúkur.

The tilt during the rapid deflations is towards north to northeast (Figs. 12, 13 and 14) and the tilt during rapid inflation is in opposite direction between south and southwest. During slow inflation the tilt direction is between south and southeast. This indicates a more westerly center of inflation during slow inflation.

The secular tilt is apparently towards southeast, although the brief period of observations makes this uncertain.

Station 0040, Jörundur

This station was established in July 1976. It lies about 6 km northeast of the center of inflation/deflation.

Rather few observations were made at this station because of difficult access to the site. Therefore, very limited information exist on its behavior during the cycles of inflations and deflations.

A clear secular tilt towards southeast is observed (Fig. 15). The tilt rate appears to be much slower after 1980 than before. The tilt associated with the deflation of 1984 is toards WNW (Fig. 16). The tilt during the inflation following the 1984 deflation amounts to only one half of the deflation tilt.

Station 0020, Mývatn N

This station was established in July 1976. It lies about 9.5 km northwest of the center of inflation/deflation.

The observed secular tilt appears to be towards south, but three subsidence and rifting events caused rather large permanent westward tilt (Fig. 17). These are the events of April 1977, September 1977 and March 1980. Rifting towards south from Leirhnjúkur was observed in all of these events and uplift of the west flank of the rifted zone caused the westward tilt at this station. Since 1980 slow southerly tilt has prevailed.

The event of March 1980 which caused westward tilt at this station, caused also westward tilt at station A (Fig. 5) which lies on the east side of the rifted zone due east of station 0020. This fact makes it difficult to interpret the tilt as due to uplift of the flanks of the rifted zone.

Tilt observations since 1981 (Fig. 18) show that the tilt during the September 1984 subsidence was towards northeast, but secular southerly tilt continues.

Stations 0070, Reykjahlíd, 0060, Grjótagjá N and 0050, Grjótagjá S

These three stations all lie within a small area 9.8 to 11.4 km SSW from the center of inflation/deflation at

Leirhnjúkur and on the west flank of the zone of rifting. The region of these stations was known to have tilted in westerly direction, 50 to 100 microradians, during the April 1977 event (Tryggvason, 1978) and in the September 1977 event it was tilted towards southwest 60 to 100 microradians (Figs. 19, 20, and 21). Secular tilt after September 1977 has been in easterly direction, gradually rotating clockwise towards southeast and south with a significant permanent tilt towards east during the March 1980 event. This March 1980 event is puzzling as tilt is here in opposite direction to that at station 0020 (Fig. 17). Tilt at these stations appears to be related to processes within the rift zone south of Leirhnjúkur while inflations and deflations of Krafla are not noticeable.

Tilt since 1981 (Figs. 22, 23, and 24) is irregular and dominated by observational errors.

Station 0200, Hverfjall

The station lies 13.6 km SSW of the center of inflation/deflation, within the zone of intense fissuring. Only the event of April 1977 has caused fissuring as far south as this station, but it was established in June 1977.

Observed secular tilt (Fig. 25) is towards southeast at decreasing rate, but in September 1977, tilt towards southwest was observed. Observed tilt from one measurement to the next (Fig. 26) is dominated by observational errors or irregular unexplained tilt.

Stations 0220, Hverarönd and 0230 Námafjall S

These stations, established in October 1981, lie to the east of the zone of fissuring, 8.8 and 10.1 km south of the center of inflation/deflation respectively. Tilt observations 1981-1985 show no significant tilt, but rather large and apparently random observed tilt variations are probably caused by observational errors (Figs. 27 and 28). There is a indication of a secular westerly tilt at station 0230. Observations at two consecutive days in June 1983, both marked "9" on Fig. 27 indicate how much observations scatter while no ground deformation occurs. Similar double observations were made within 10 days in late August and early September 1982 at the stations 0010 and 0000 (Figs. 3 and 6) and in 1985 at the station A.

Discussion

The progressive tilt 1976-1985 is generally away from the center of inflation/deflation showing a marked uplift centered in the vicinity of Leirhnjúkur. This general direction of progressive or secular tilt is disturbed at several times, especially between 1976 and 1977A, 1977A and 1978, 1979 and 1980 and 1983 and 1984. Each of these major disturbances in the progressive tilt is linked to deflation events with rifting to the south of Leirhnjúkur. The April 1977 event which caused 2 m widening of the fissure swarm near Reykjahlíd, the September 1977 event which caused 1.1 m widening near Reykjahlíd, the March 1980 event where widening extended almost as far south as Reykjahlíd and the September 1984 event with rifting some 2 to 3 km south of Leirhnjúkur (Tryggvason, 1984).

The event of April 1977 caused tilt of 50-100 microradians away from the fissure zone at all existing stations except at 0010 immediately east of Leirhnjúkur. This tilt is the result of uplift of the flanks of the fissure zone. The station 0010 lies inside the zone of fissuring which may be the cause of anomalous tilt at that station. Further, some rifting occurred within the 50 m diameter of the 0010 tiltmeter array.

The event of September 1977 caused similar permanent tilt as that of April 1977 or 50-100 microradians away from the fissure zone although a southerly component is evident. At the stations west of the fissure zone (0020, 0070, 0050, 0060, 0200) this tilt away from the fissure zone is clear but the direction turns more southerly the farther south the station lies (Figs. 17, 19, 20, 21, and 25). This is supposedly because the widening of the fissure zone decreases rapidly southwards at the latitude of these stations. The station 0010 (Fig. 2) tilted towards the fissure zone, but less so than in April 1977.

The event of March 1980 caused tilt away from the fissure zone at the stations 0000, 0040, and 0020, but tilt towards the fissure zone at the more southern stations, A, 0070, 0060, 0050, and 0200 (Figs. 4, 5, 15, 17, 19, 20, 21, and 25). As rifting was terminated southward at the latitude of A or 0020 approximately, these observations show that tilt away from the fissure zone is observed only where rifting occurs while outside the zone of rifting the tilt is towards the fissure zone. The station 0010 (Fig. 2) exhibits extreme tilt towards the fissure zone, probably because of fault displacement within the tilt station. The stations 0000, 0080 and 0090 (Figs. 4, 8 and 9) show no obvious anomaly during this event.

The September 1984 event is characterized by a permanent tilt towards the center of inflation/deflation at most stations (Figs. 2, 4, 5, 8, and 9). This shows in fact that inflation after the subsidence event is less than deflation during the event.

The three southern stations 0070, 0060 and 0050, which lie west of the active fissure swarm, show similar secular tilt after the September 1977 subsidence and rifting event. This is tilt in easterly direction, gradually turning southerly and tilt rate gradually decreasing. The eastward tilt of March 1980 is superimposed on this secular tilt. The direction of the secular tilt starts in northeasterly direction at 0070 and towards east at 0060 and slightly south of east at 0050. This indicates clockwise rotation with distance towards south along the west flank of the fissure swarm east of Mývatn. Similar trend of secular tilt is observed at 0200, although this station lies within the zone of rifting of April 1977.

The 1981-1985 progressive tilt shows the effect of the two subsidence events of November 1981 and September 1984 at several tilt stations. These two subsidence events express themselves similarly on the tilt stations with tilt towards the center of inflation/deflation followed by tilt away from this center (Figs. 3, 6, 10, 11, 12, 13, and 14). During the rapid inflation over a few months following the deflation, the inflation tilt is in opposite direction to the deflation tilt. However, as the inflation rate gets slow, 3 to 6 months after the subsidence event, the inflation tilt obtains a new direction which deviates greatly from the direction away from the center of inflation/deflation at some stations (Figs. 3, 12, 13, and 14), and less obvious change in tilt direction at other stations (Figs. 10, 11, and 16). This change in direction of inflation tilt, as tilt rate decreases, is not observed at station 0000 (Fig. 6), and at the stations which lie more than 6 km away from the center of inflation/deflation the behavior of tilt direction as inflation tilt progresses is not detected in the presented data, possibly because the observational errors are similar or greater than tilt changes between observations.

These observations of systematic change in tilt direction as certain inflation stage is reached or tilt rate has dropped below some critical value, show that the shape of the inflation bulge changes at this stage or inflation rate. It is not clear if the center of inflation is displaced but the addition to the bulge becomes more irregular in shape. These irregularities are of permanent nature and are not reversed during deflation events.

Conclusion

This discussion leads to the conclusion that four modes of deformation of the Krafla area can be deduced from the tilt observations. These are:

1. The rapid deflation during eruptions and rifting at the Krafla fissure swarm, and the following slower, but rather fast inflation (Fig. 1). These are caused by emptying and subsequent filling of the shallow Krafla magma chamber. This mode of deformation has been the subject of extensive discussion (Björnsson et al., 1979, Tryggvason, 1980 and 1986).

2. Slow inflation following the rapid inflation. This is most clearly observed in May 1982 through June 1984, an extended period of no deflation events (Fig. 29). The direction of tilt during this slow inflation is, at several stations, rather different from that during fast inflation. This is particularly noticeable at the stations 0010, 0210, 0240 and 0250. The tilt vectors do not point towards one common point, indicating that a point source model is not adequate to explain this mode of deformation. The magnitude of tilt decreases with distance from Leirhnjúkur, but more slowly than in case of fast inflation. This may be interpreted as indicating deeper source.

3. Secular tilt. This may not be separable from the slow inflation tilt, but is here taken as the tilt over an extended period. The period selected for demonstration is August 1977 through October 1985 (Fig. 30). The secular tilt is generally away from the Leirhnjúkur region. It is greatest in the vicinity of Leirhnjúkur and decreases with distance, but more slowly so than the slow inflation tilt. The tilt vectors seem not to point towards a single point, but the slow decrease in tilt magnitude with distance from Leirhnjúkur indicates a deep source, still deeper than the source of the slow inflation. Comparison of tilt at different distances

indicate a source depth greater than 4 km but less than 8 km.

4. Tilt associated with rifting and widening of the Krafla fissure swarm. This process causes tilt away from the fissure zone, where rifting occurred but tilt towards the fissure zone where widening, but no rifting, occurred. The tilt associated with rifting is a rapid process caused by uplift of the flanks of the fissure zone at the same time as the fissure zone widens and simultaneously with deflation of the Krafla volcano.

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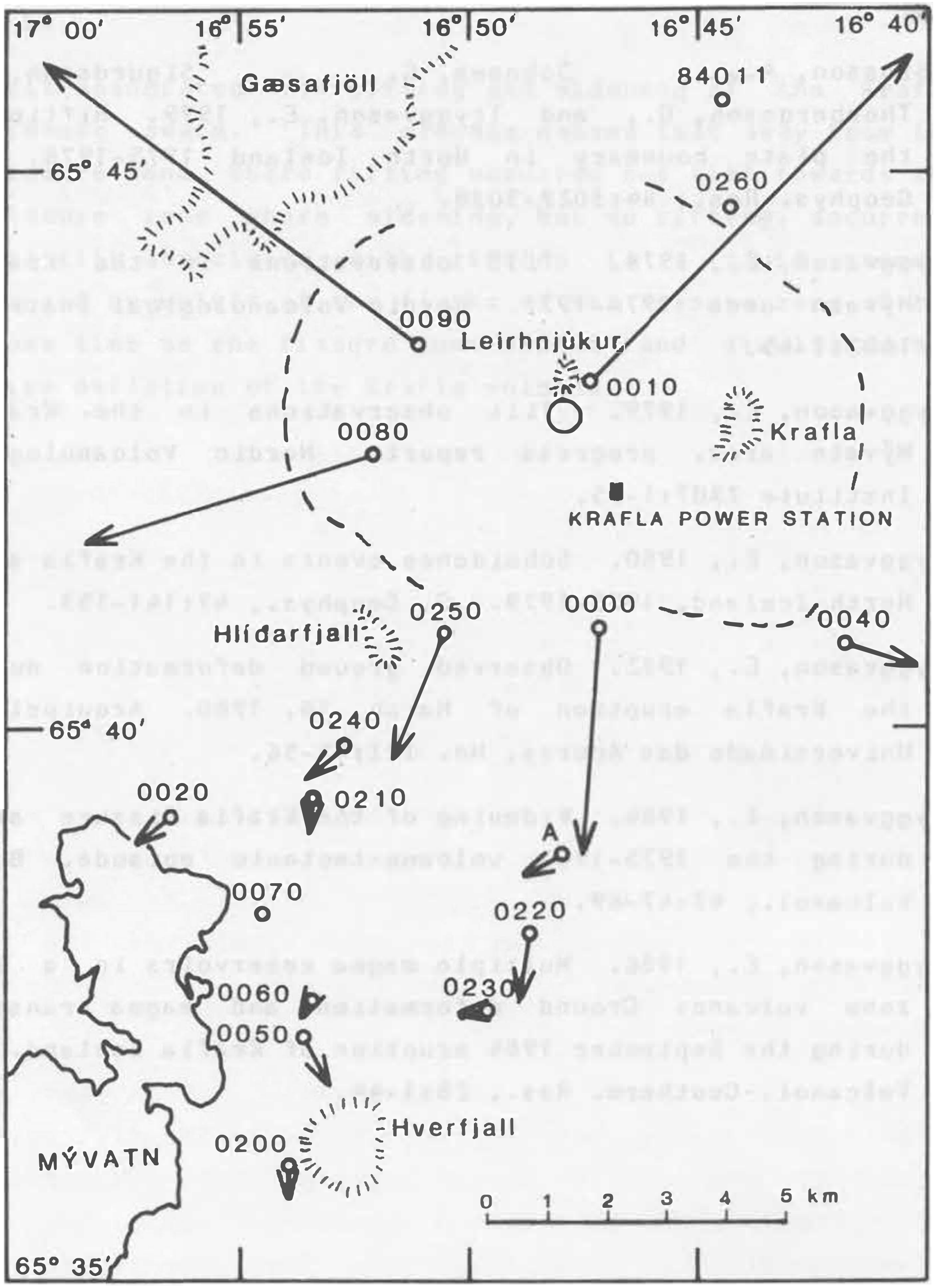


Fig. 1. Map showing the tilt stations in the Krafla-Mývatn area. Filled circles are recording tilt stations, open circles are optical level tilt stations. Two stations, 0260 and 84011 were established in October 1984 and are not included in the present discussion. Arrows show relative tilt from late September to beginning of December 1984. This is characteristic tilt during rapid inflation, following deflation of the volcano Krafla.

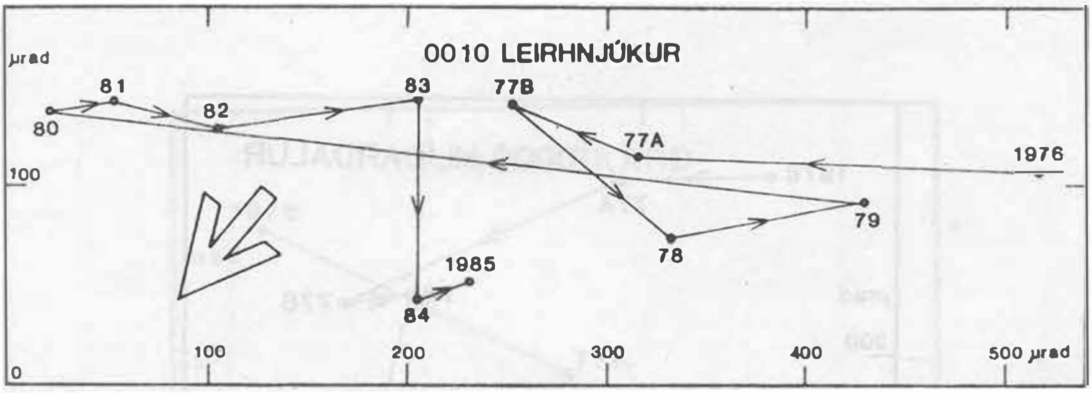


Fig. 2. Progressive tilt at the station 0010 from 1976-1985. Each data point gives average tilt stage of each year, although the year 1977 is split showing the average tilt stage before and after the September 8 deflation event. large arrow shows direction to the center of inflation/deflation. See Fig. 1 for location of the station.

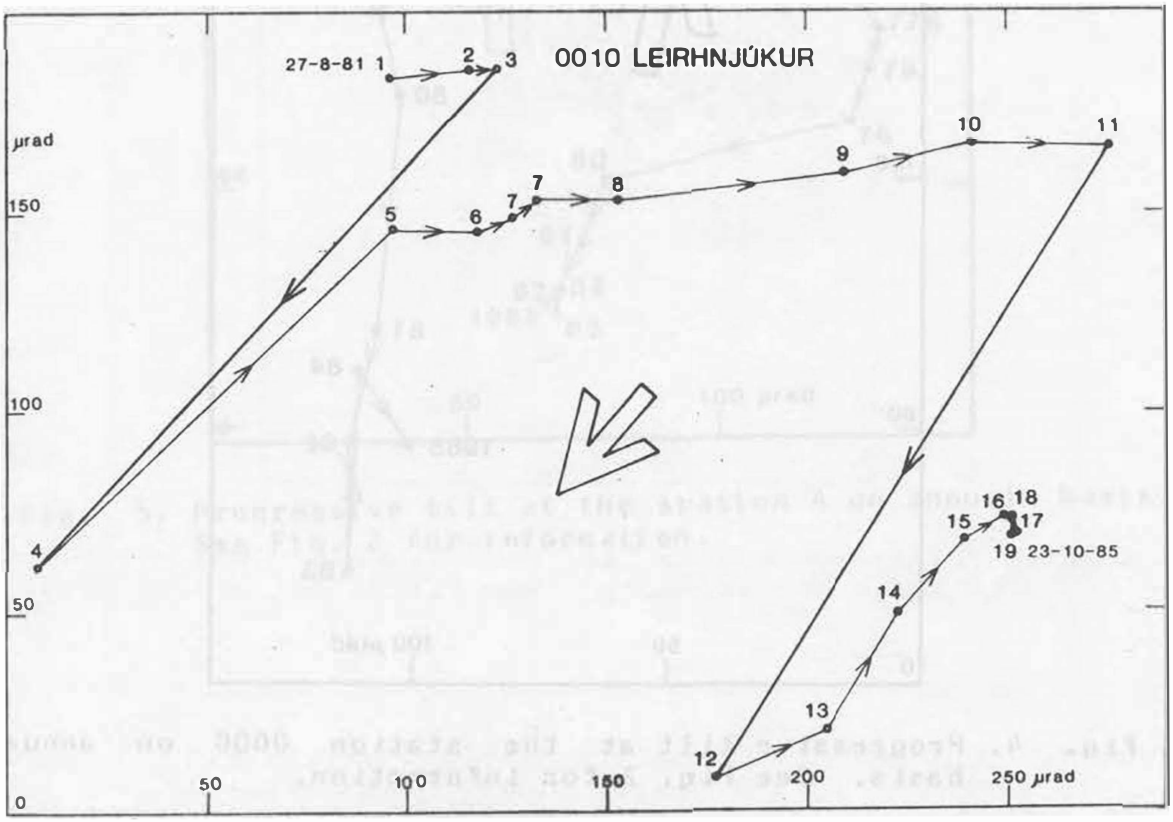


Fig. 3. Progressive tilt at the station 0010 August 1981 through October 1985. Data points show observed tilt stage at each tilt observation. Thick lines show tilt during deflation of Krafla. Numerals indicate times of observations as explained in the text. Date of first and last observation is given (dd-mm-yy). Large arrow shows direction to the center of inflation/deflation. See Fig. 1 for location of the station.

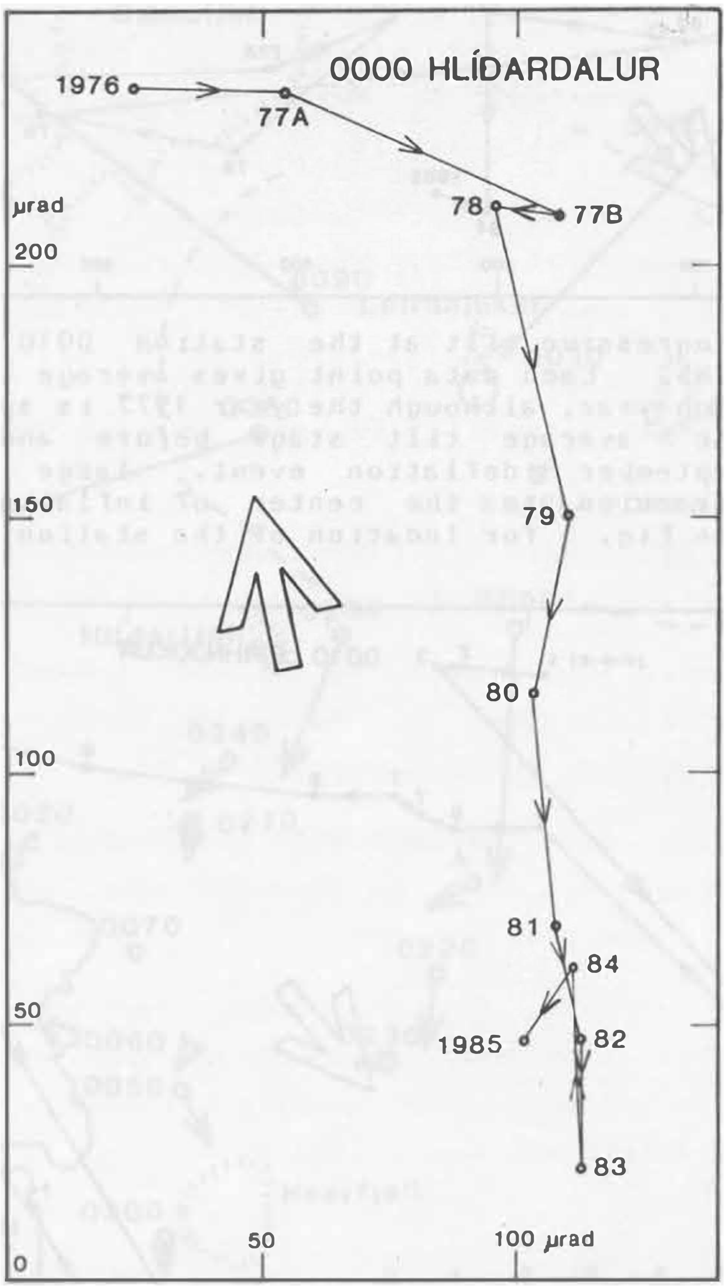


Fig. 4. Progressive tilt at the station 0000 on annual basis. See Fig. 2 for information.

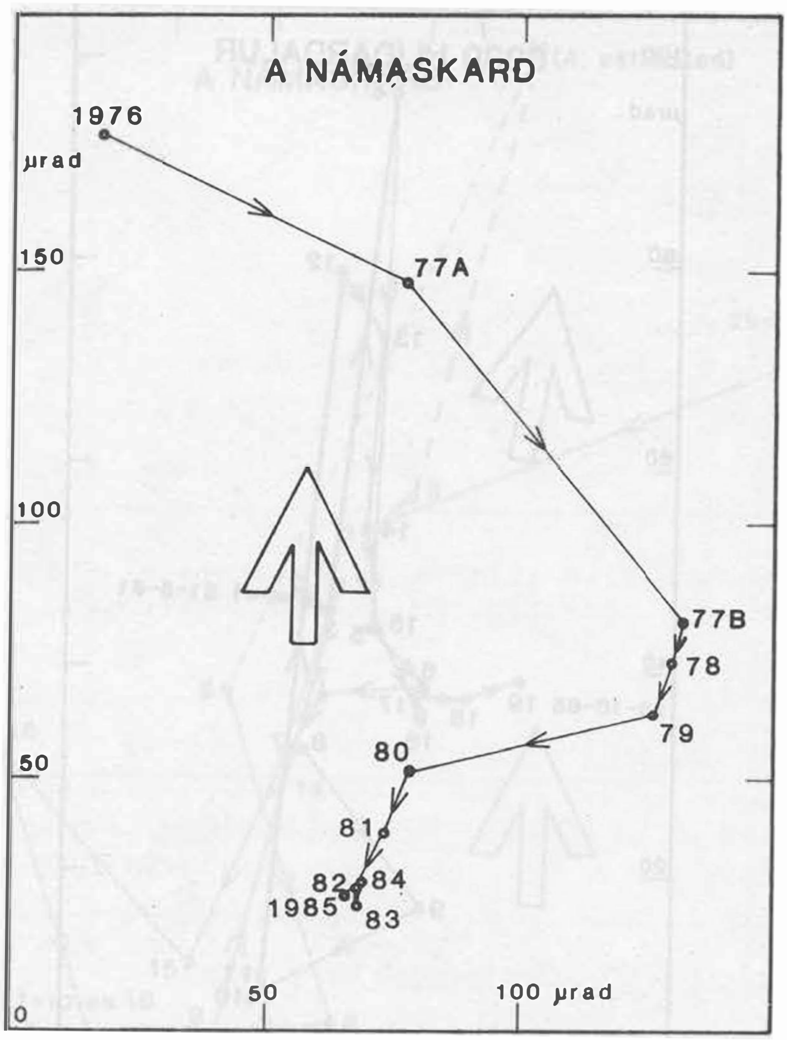


Fig. 5. Progressive tilt at the station A on annual basis. See Fig. 2 for information.

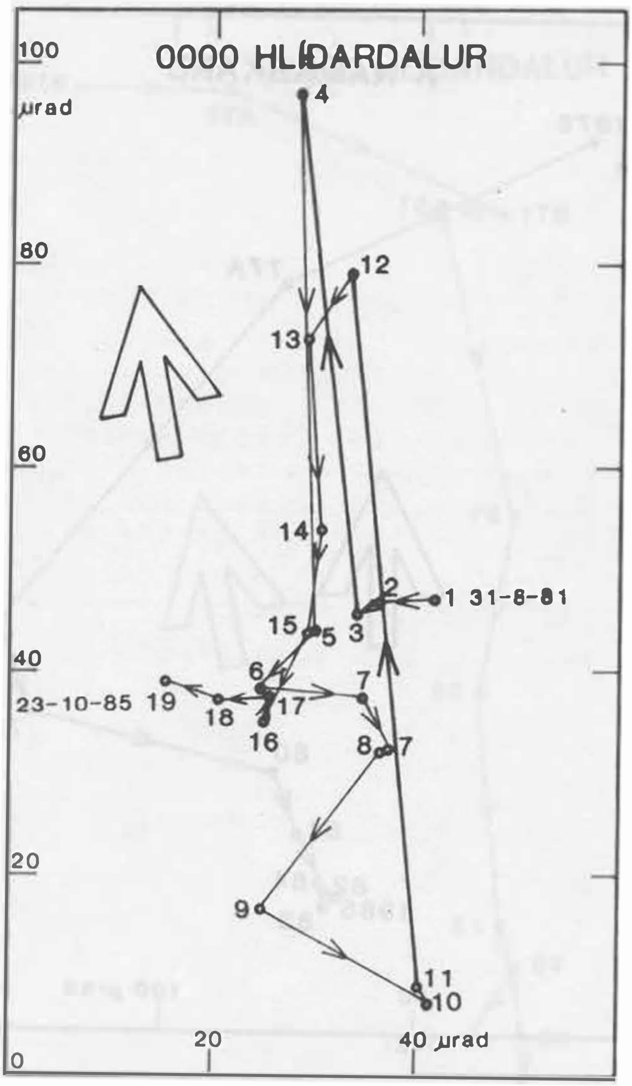


Fig. 6. Progressive tilt at the station 0000 based on single observations. See Fig. 3 for explanation.

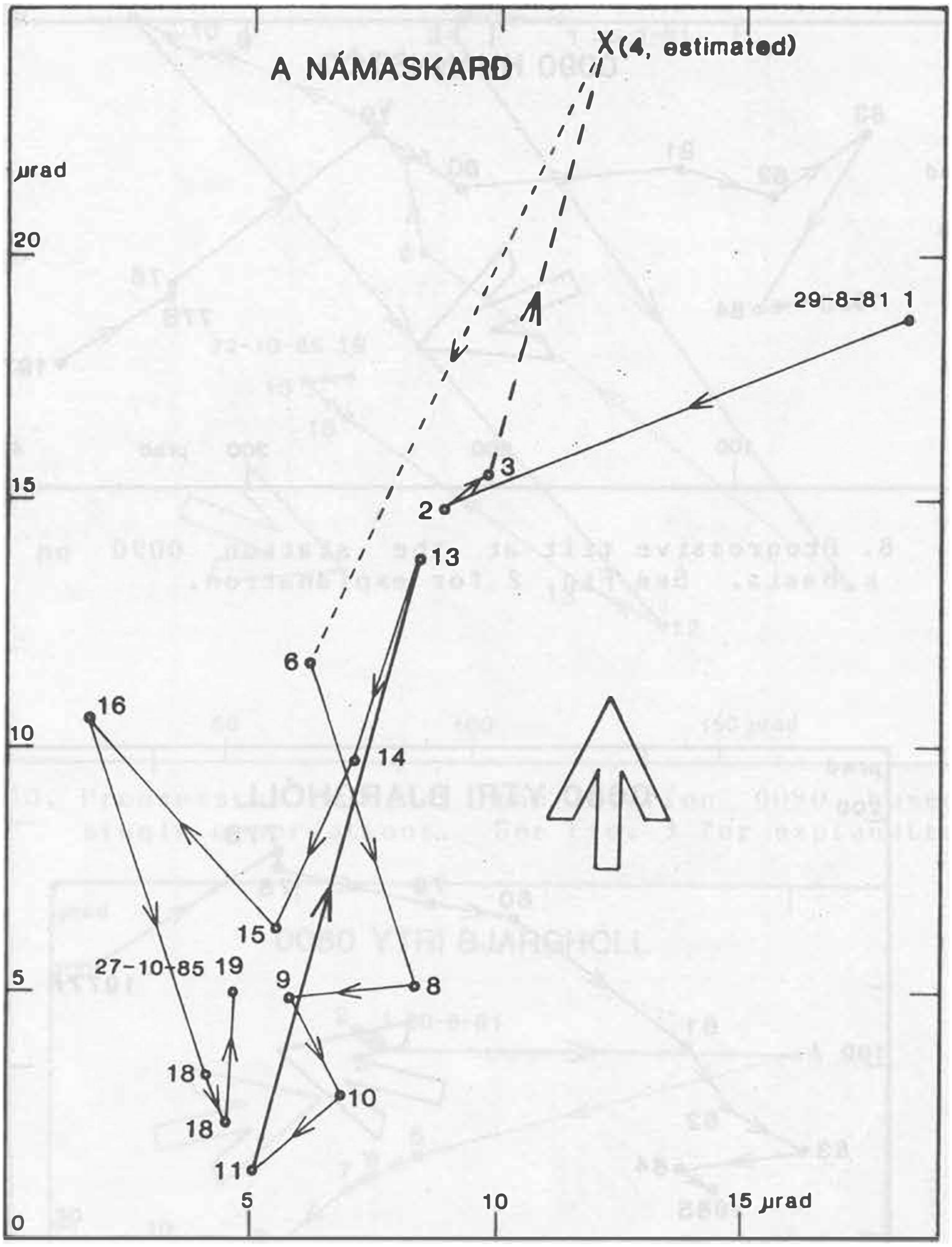


Fig. 7. Progressive tilt at the station A based on single observations. Tilt stage (4) is estimated at end of the November 1981 deflation. See Fig. 3 for explanation.

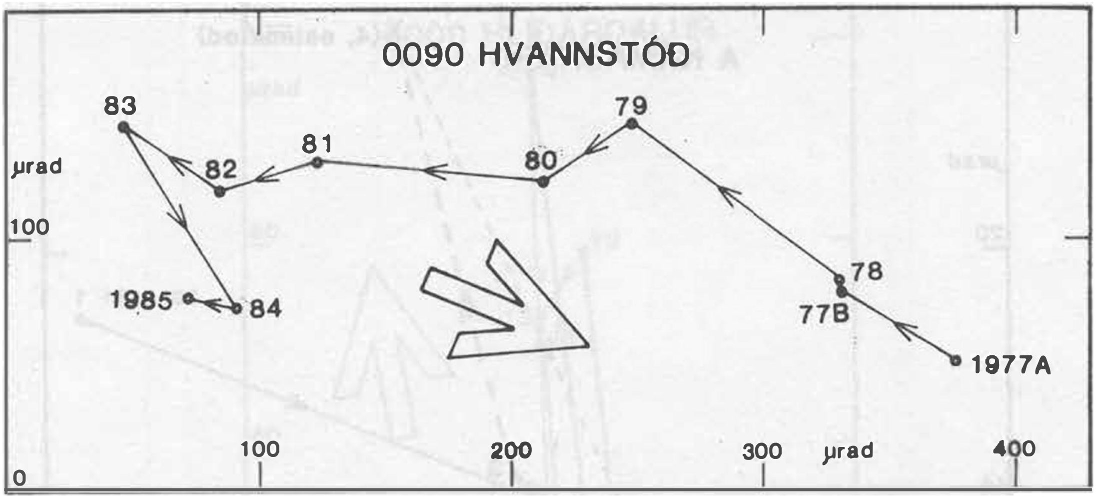


Fig. 8. Progressive tilt at the station 0090 on annual basis. See Fig. 2 for explanation.

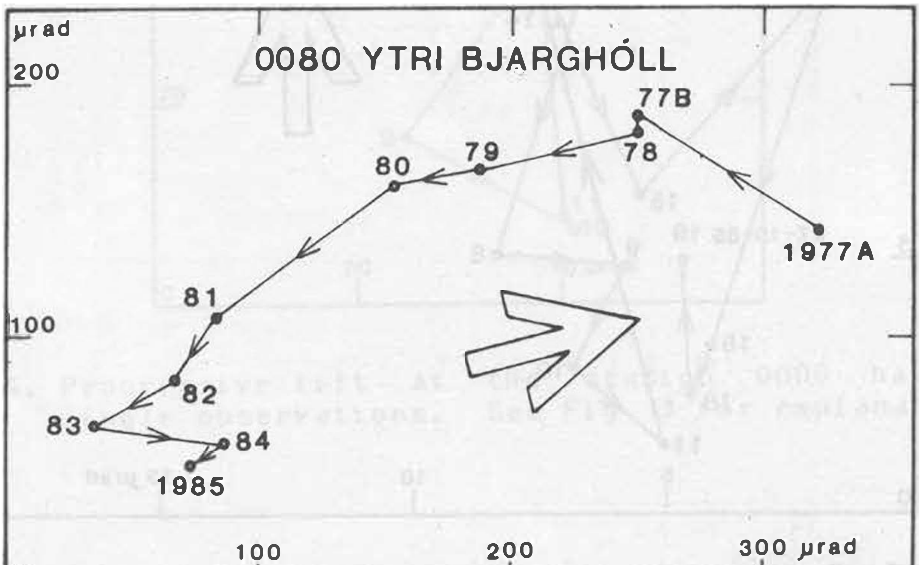


Fig. 9. Progressive tilt at the station 0080 on annual basis. See Fig. 2 for explanation.

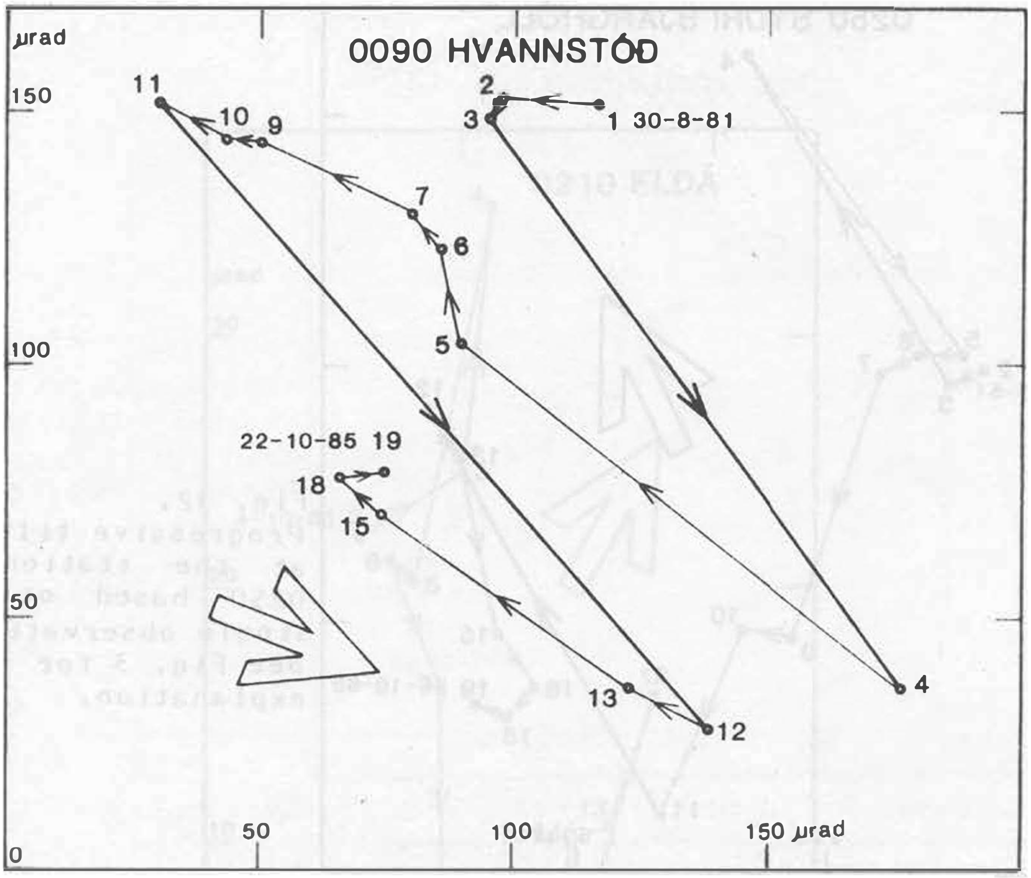


Fig. 10. Progressive tilt at the station 0090 based on single observations. See Fig. 3 for explanation.

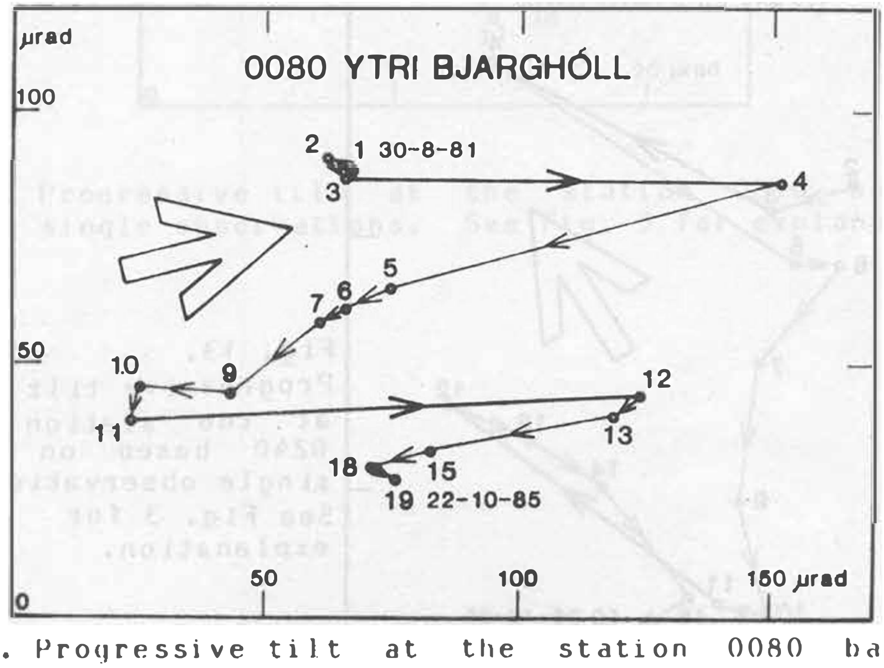
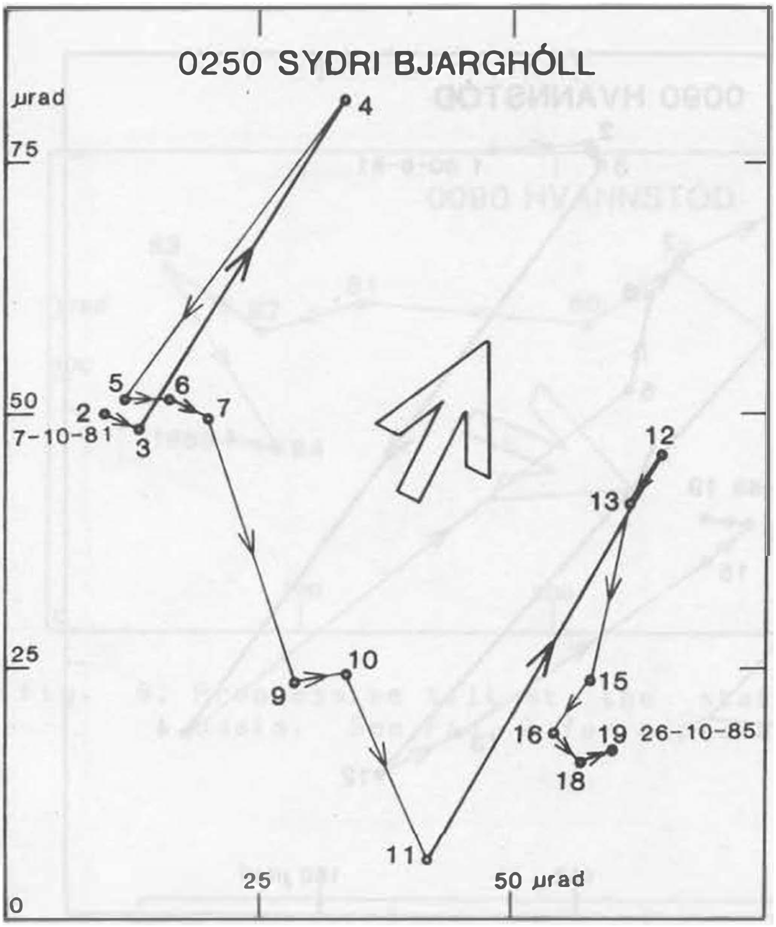


Fig. 11. Progressive tilt at the station 0080 based on single observations. See Fig. 3 for explanation.



Fiq. 12. Progressive tilt at the station 0250 based on single observations. See Fiq. 3 for explanation.

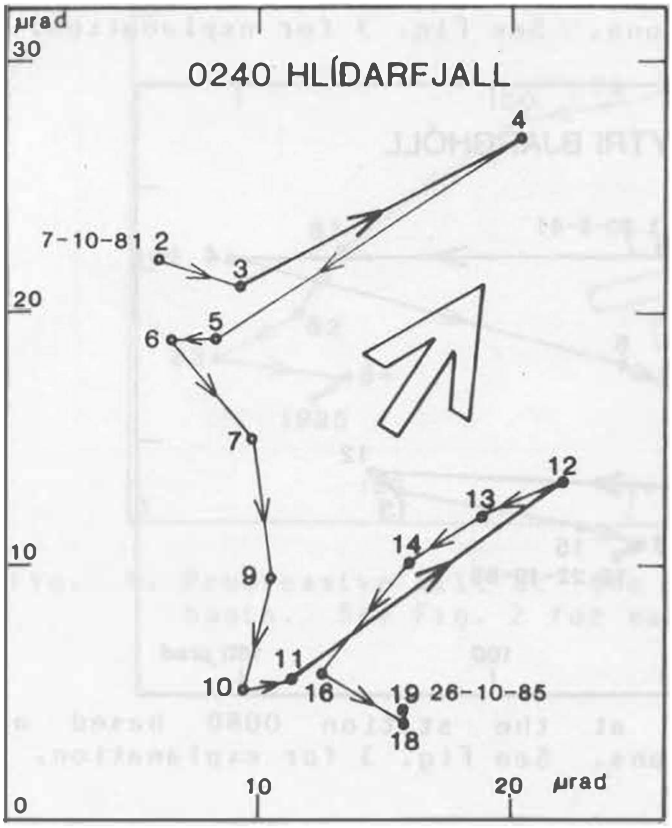


Fig. 13. Progressive tilt at the station 0240 based on single observation. See Fiq. 3 for explanation.

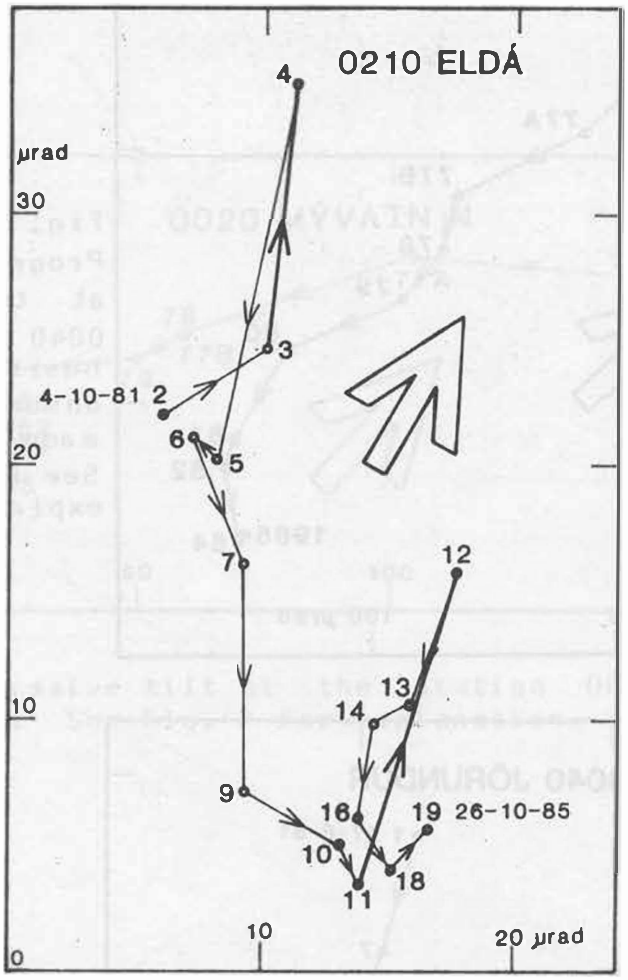


Fig. 14. Progressive tilt at the station 0210 based on single observations. See Fig. 3 for explanation.

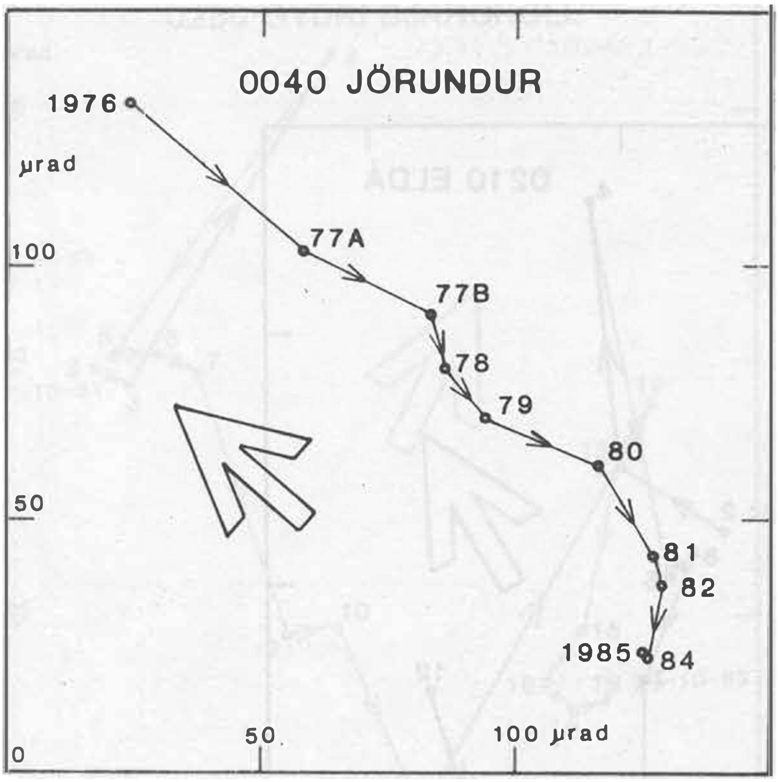


Fig. 15.
Progressive tilt at the station 0040 on annual basis. No tilt observation was made in 1983. See Fig. 2 for explanation.

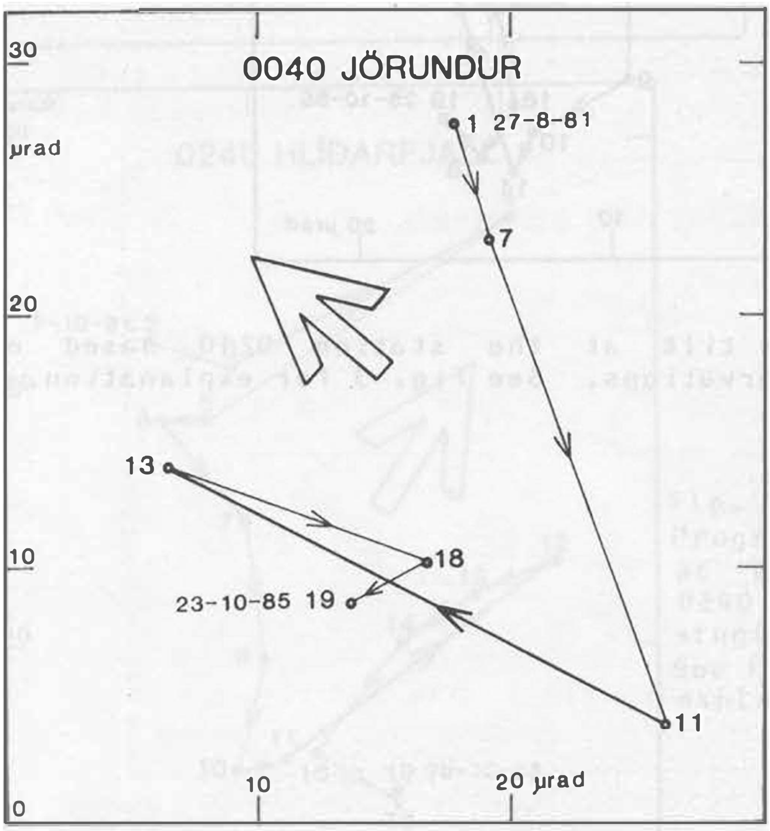


Fig. 16.
Progressive tilt at the station 0040 based on single observations. See Fig. 3 for explanation.

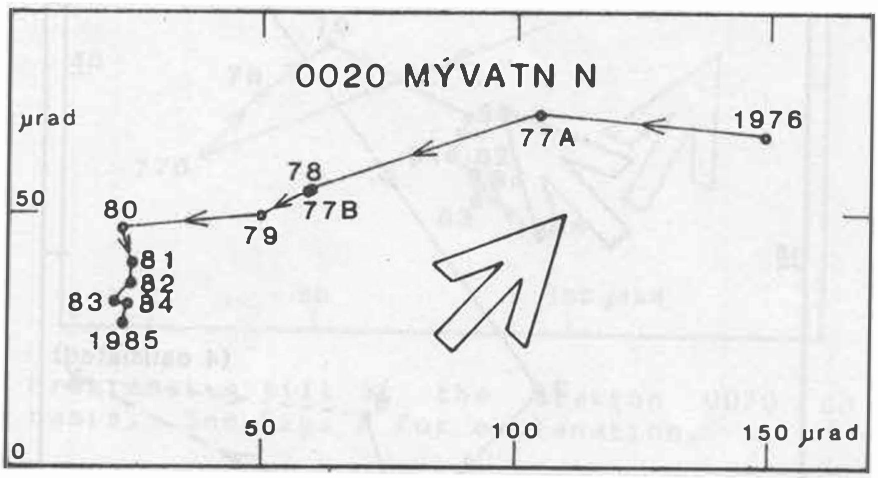


Fig. 17. Progressive tilt at the station 0020 on annual basis. See Fig. 2 for explanation.

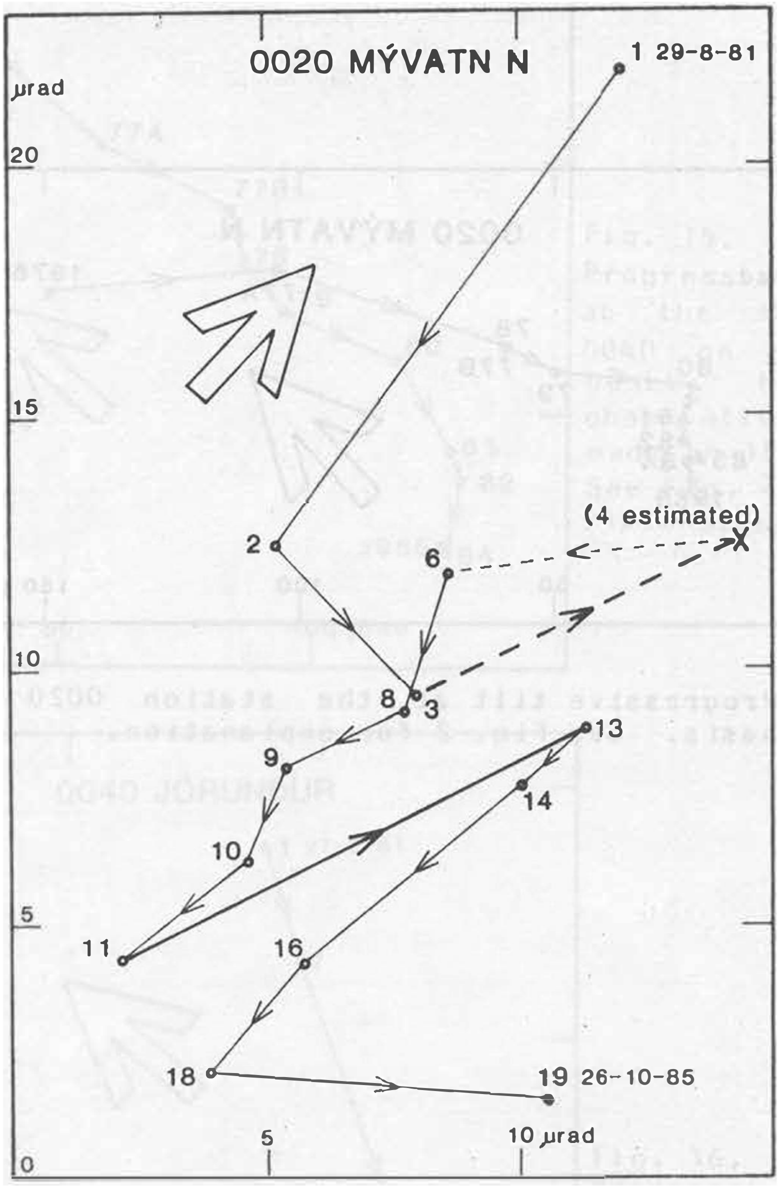


Fig. 18. Progressive tilt at the station 0020 based on single observations. See Fig. 3 for explanation.

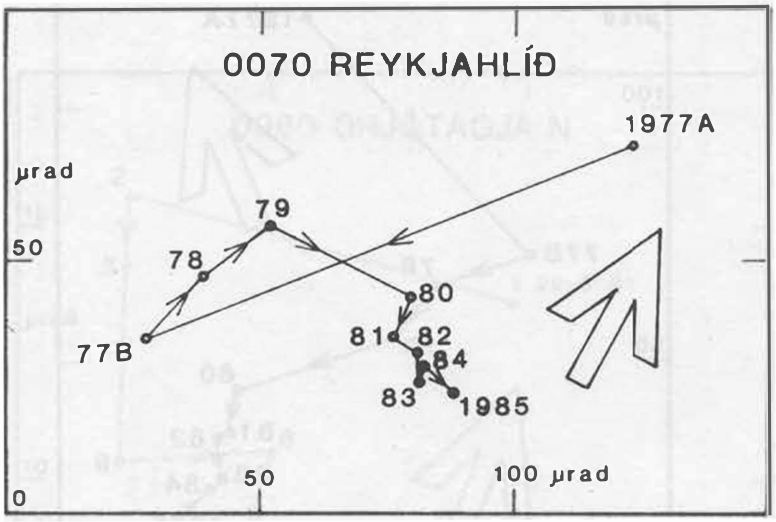


Fig. 19. Progressive tilt at the station 0070 on annual basis. See Fig. 2 for explanation.

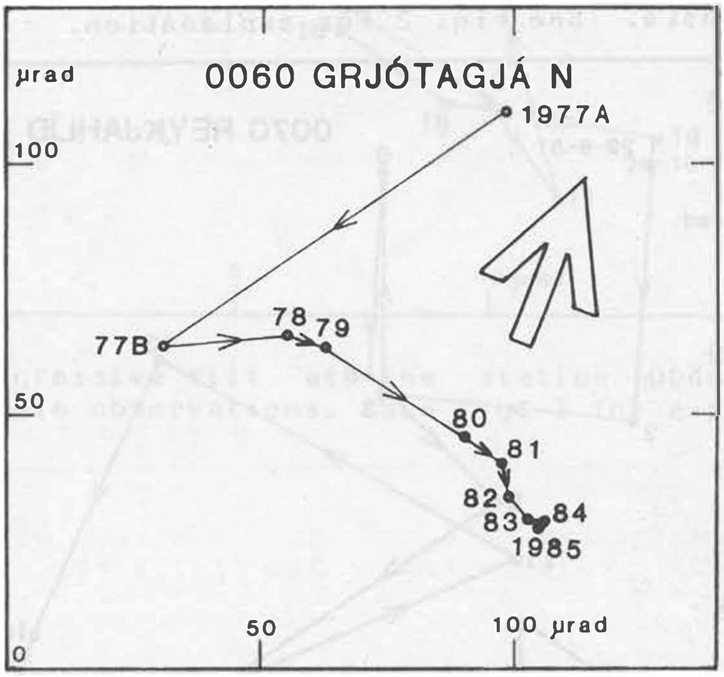


Fig. 20. Progressive tilt at the station 0060 on annual basis. See Fig. 2 for explanation.

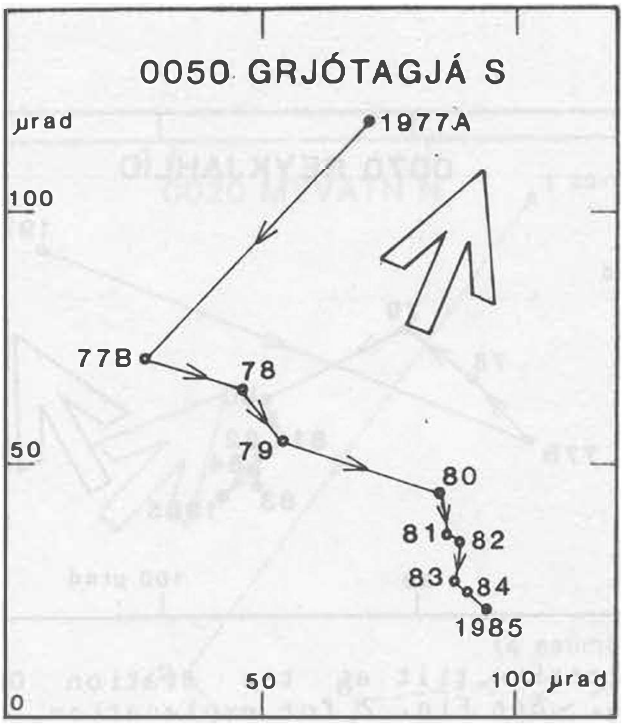


Fig. 21. Progressive tilt at the station 0050 on annual basis. See Fig. 2 for explanation.

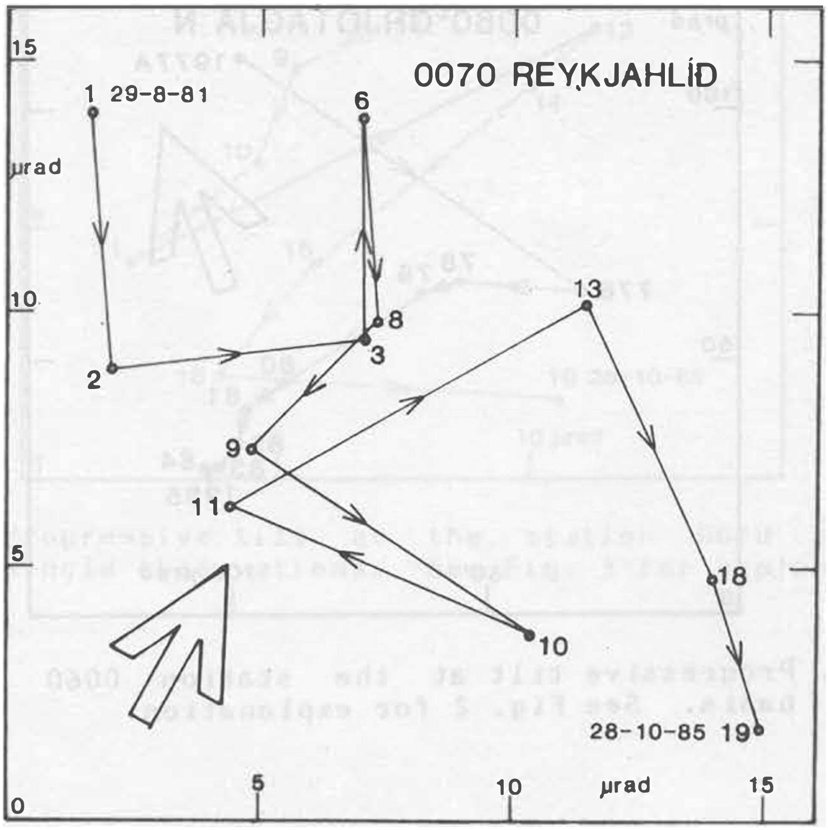


Fig. 22. Progressive tilt at the station 0070 based on single observations. See Fig. 3 for explanation.

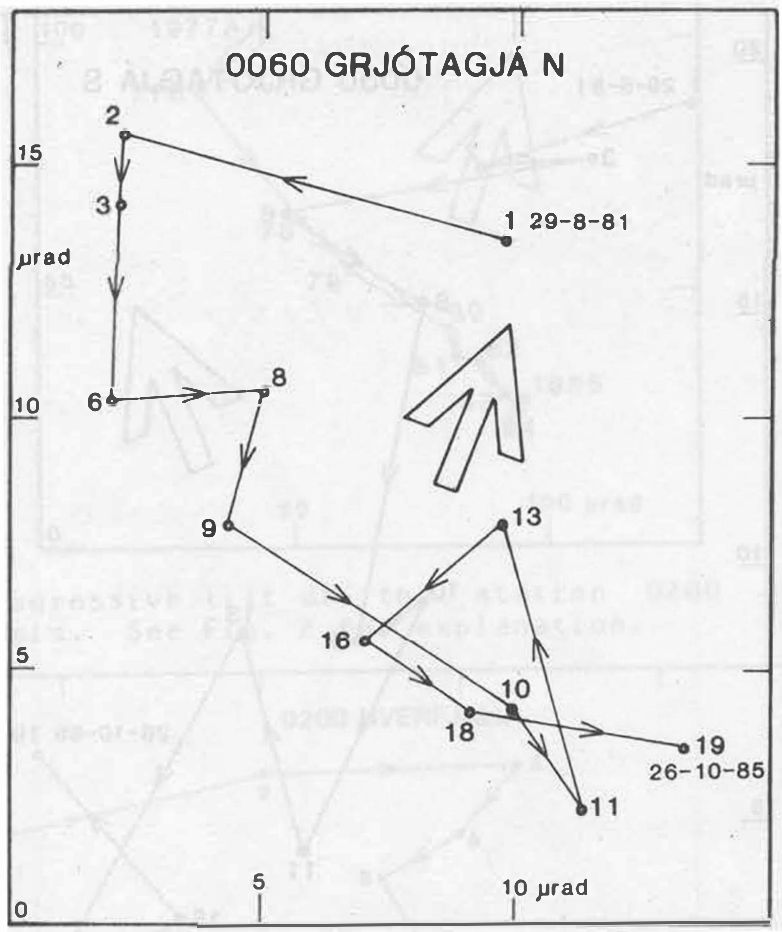


Fig. 23. Progressive tilt at the station 0060 based on single observations. See Fig. 3 for explanation.

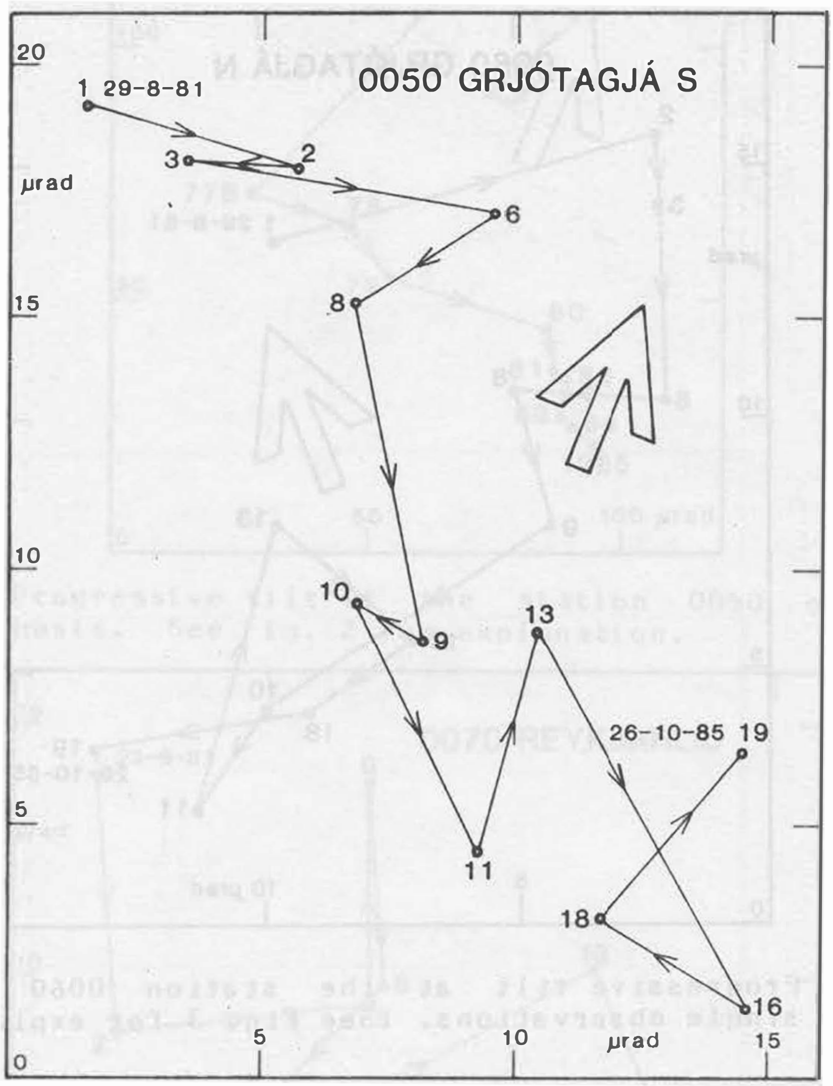


Fig. 24. Progressive tilt at the station 0050 based on single observations. See Fig. 3 for explanation.

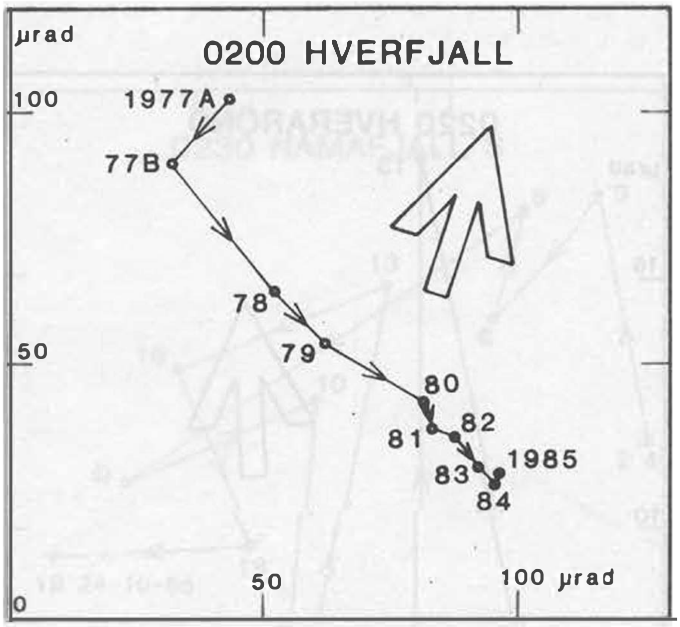


Fig. 25. Progressive tilt at the station 0200 on annual basis. See Fig. 2 for explanation.

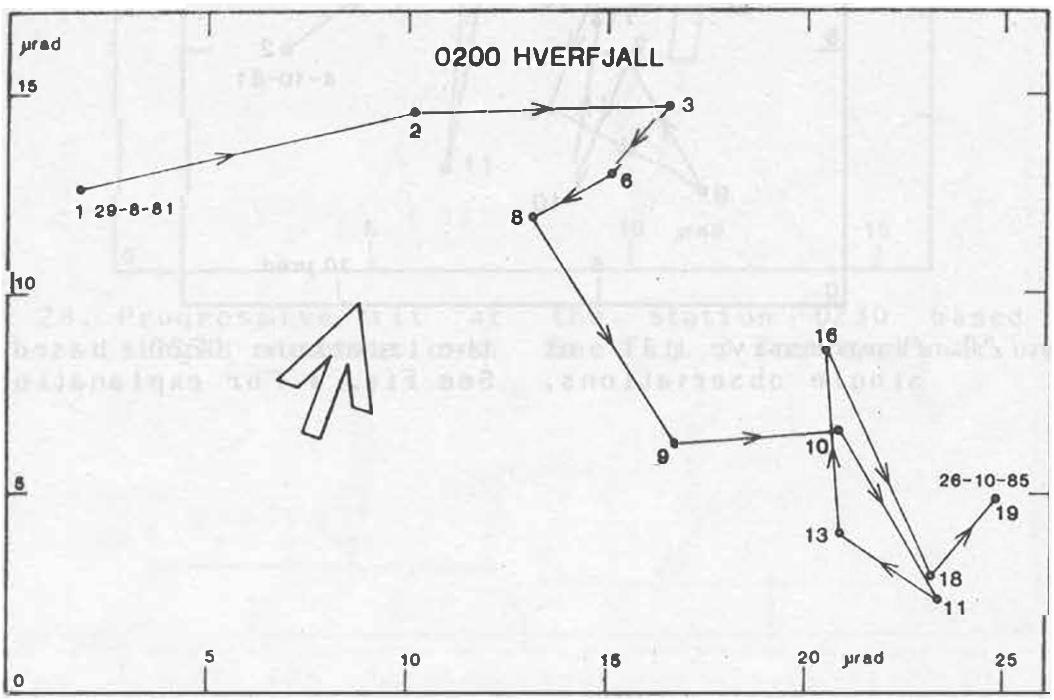


Fig. 26. Progressive tilt at the station 0200 based on single observations. See Fig. 3 for explanation.

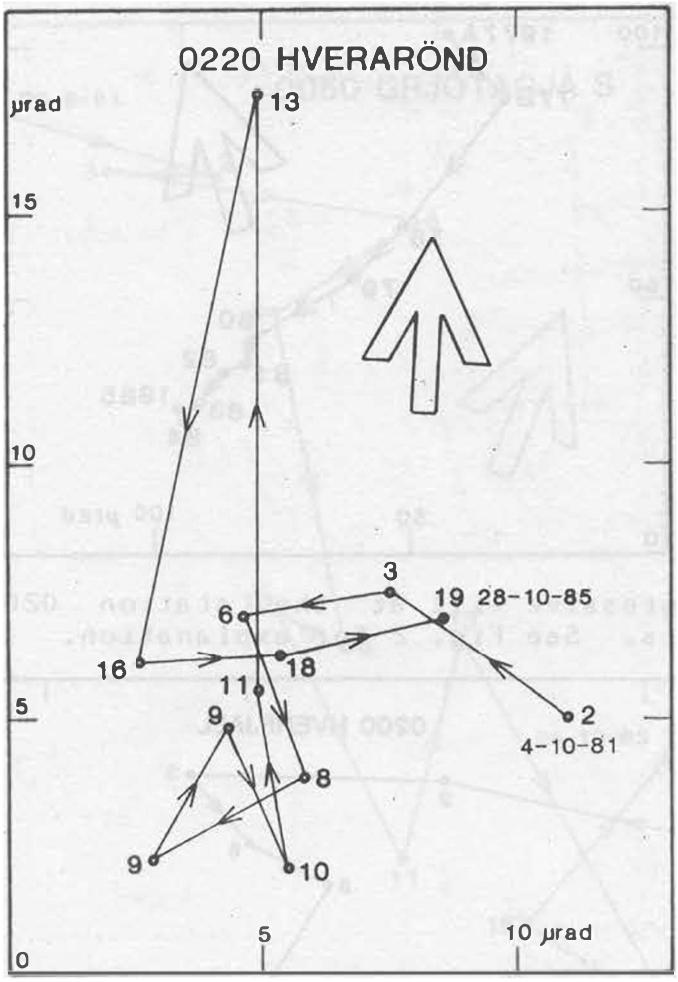


Fig. 27. Progressive tilt at the station 0220 based on single observations. See Fig. 3 for explanation.

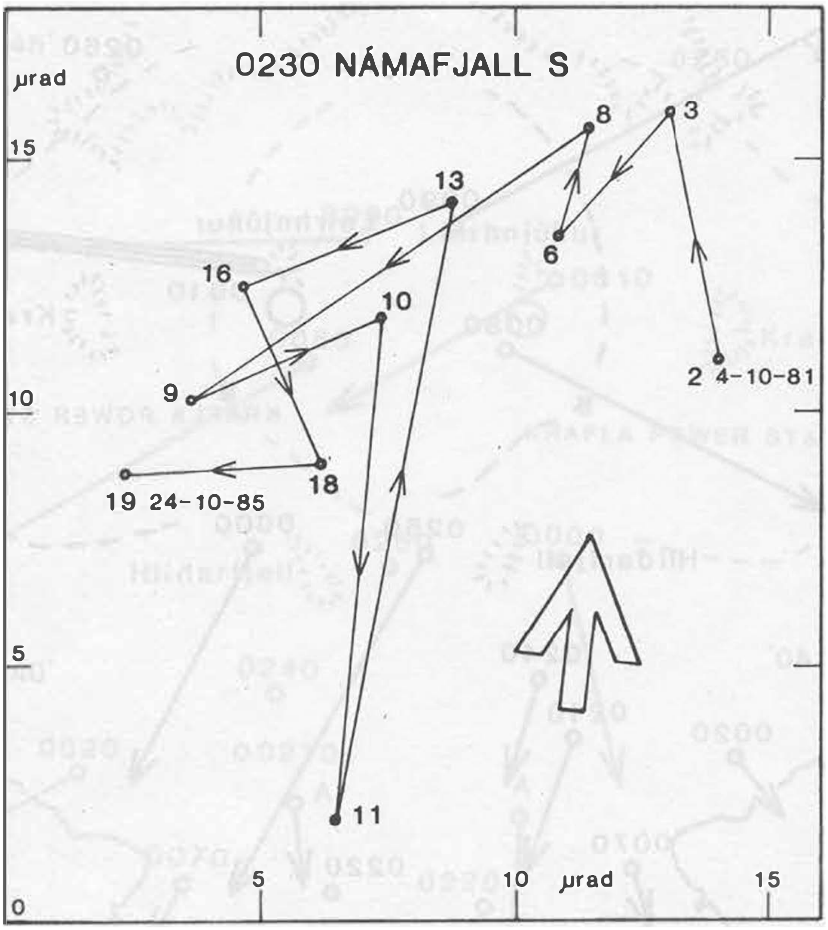


Fig. 28. Progressive tilt at the station 0230 based on single observations. See Fig. 3 for explanation.

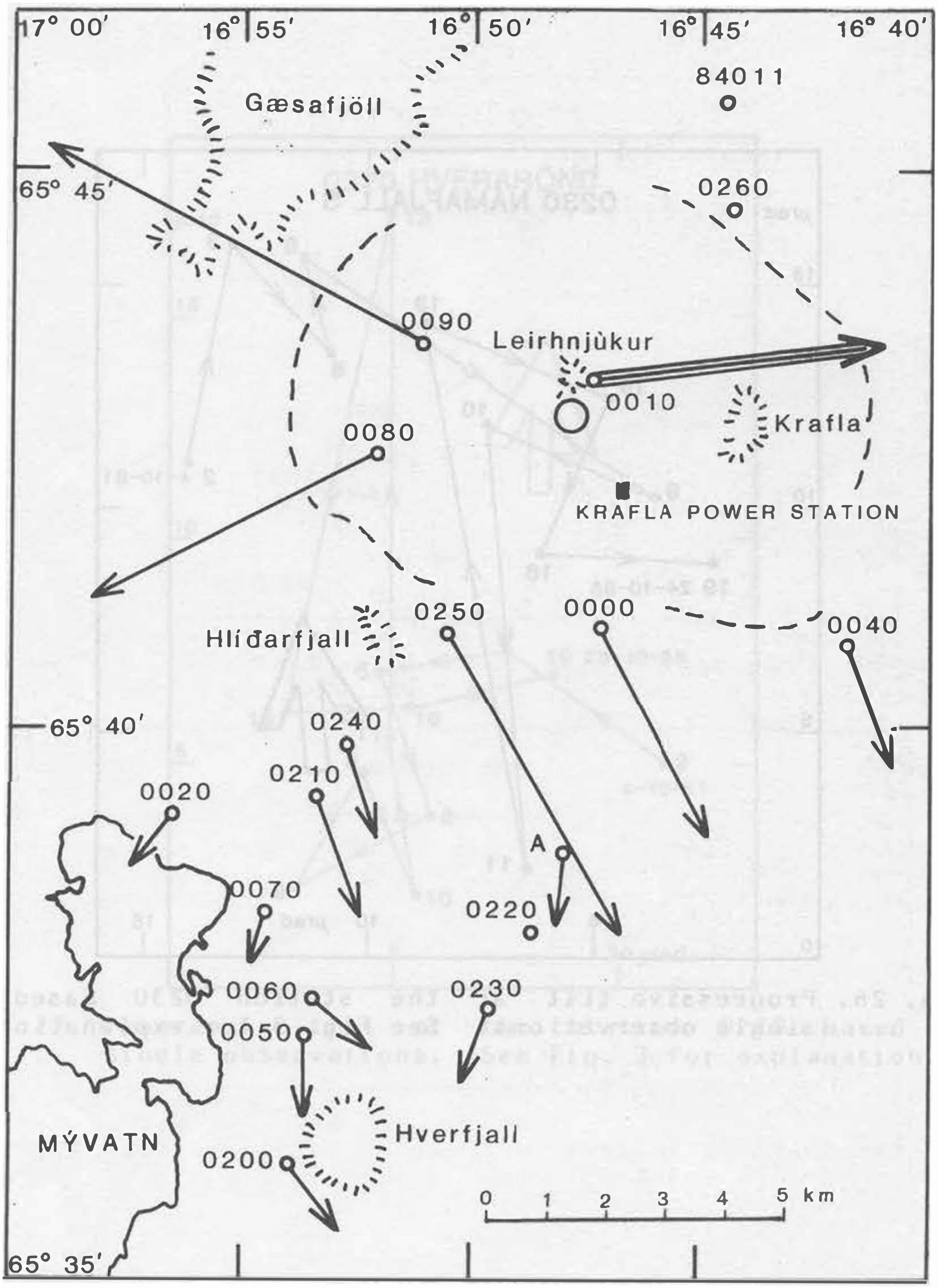


Fig. 29. Tilt during slow inflation of the Krafla volcano from May 1982 to June 1984. The arrow lengths are proportional to tilt except at station 0010 where the length of the arrow should be 4 times greater than shown.

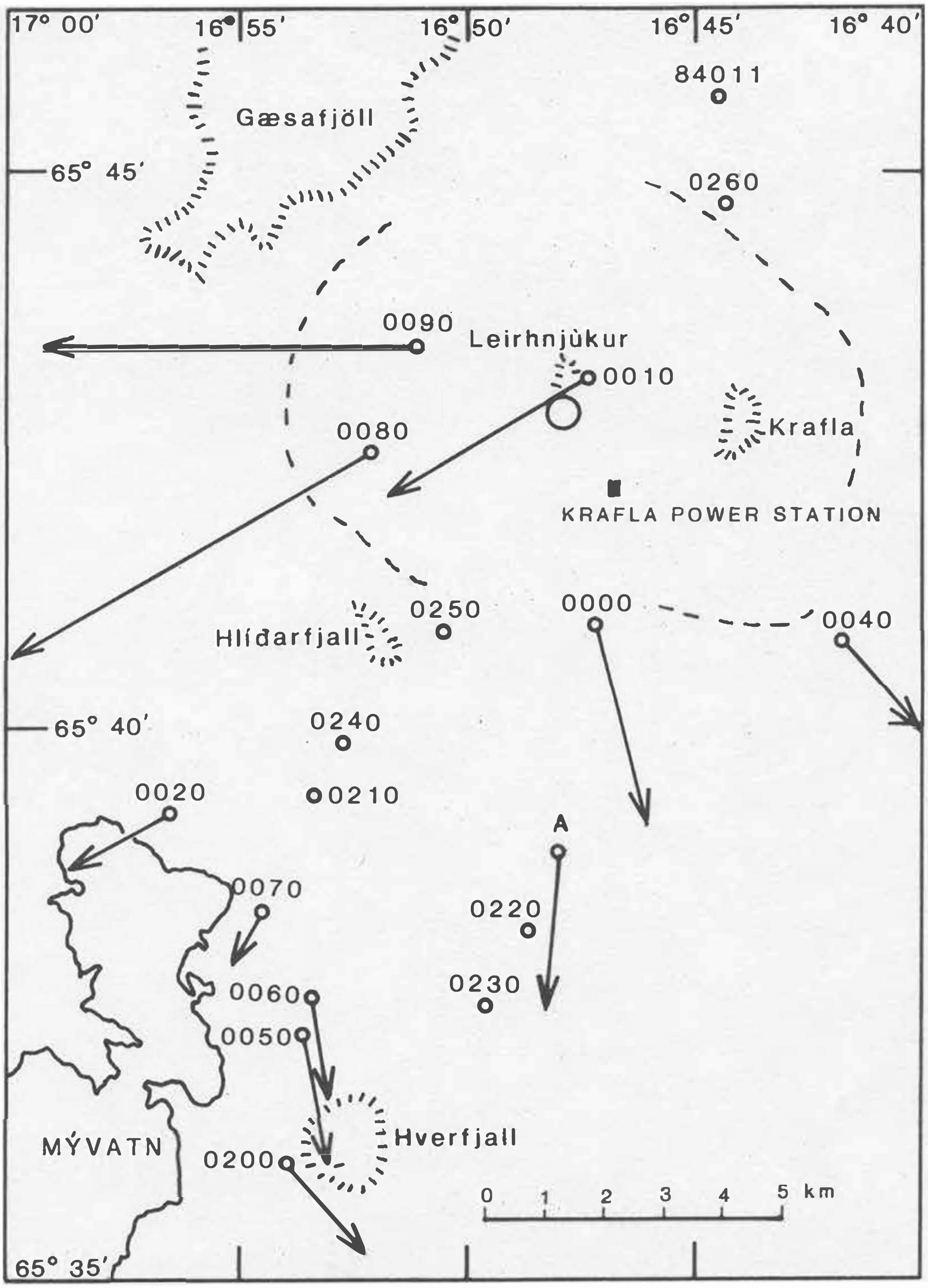


Fig. 30. Relative secular tilt at the optical leveling tilt stations in the Krafla-Mývatn area based on observations in 1979 and 1984. Station 0010 is anomalous because of extreme movement during several subsidence events, especially in March 1980.