NORDIC VOLCANOLOGICAL INSTITUTE 8602
UNIVERSITY OF ICELAND

VERTICAL GROUND MOVEMENT IN THE KRAFLA REGION 1977-1986

BYPRODUCT OF DISTANCE MEASUREMENTS

by

EYSTEINN TRYGGVASON

REYKJAVÍK
December 1986

NORDIC VOLCANOLOGICAL INSTITUTE 8602
UNIVERSITY OF ICELAND

VERTICAL GROUND MOVEMENT IN THE KRAFLA REGION 1977-1986

BYPRODUCT OF DISTANCE MEASUREMENTS

by

EYSTEINN TRYGGVASON

REYKJAVÍK

December 1986

VERTICAL GROUND MOVEMENT IN THE KRAFLA REGION 1977-1986 BYPRODUCT OF DISTANCE MEASUREMENTS

Eysteinn Tryggvason

Abstract

The relative elevation of bench marks in the Krafla-Gjástykki geodimeter network has been observed repeatedly during 1977-1986. Many stations exhibit gradual change in the relative elevation, either uplift or subsidence. This change in elevation is best expressed in its rate, which amounts to about -10 to +3 cm/year in 1979-1986. The relative subsidence of peripheral stations is taken to indicate absolute uplift of the reference station, possibly 10-15 cm/year in 1979-1986. This means that the whole region of study is being uplifted. The maximum uplift, about 4 cm/year more than the reference, is observed along the east flank of the zone of maximum disturbance, 3-9 km north of Leirhnjúkur. The zone of maximum disturbance is roughly 1 km wide and strikes N13^{o}E through Leirhnjúkur. Stations in this zone have subsided 1 to 3 m, relative to near stations outside this zone, during the 9 years 1977-1986.

Introduction

An extensive program of repeated distance measurements in the Krafla region, North Iceland, was initiated by the Nordic Volcanological Institute in February 1977 (Tryggvason, 1978, 1980a, 1983). Although the aim of this program was to determine the horizontal component of ground deformation associated with the Krafla volcanic episode which commenced in 1975, the elevation difference of the stations was needed to reduce the distance from geodimeter and reflector to the bench marks. Therefore, the zenith angle from the geodimeter station to the reflector station was observed accurately with a theodolite, during almost every observation.

The elevation difference of geodimeter station and reflector station is calculated from the distance and the observed zenith angle. As the zenith angle is observed only at the geodimeter station, there is no observation which indicates the magnitude of the refraction of light on the path between the stations. This causes considerable uncertainities in the calculated elevation differences.

The present report is based on the calculated elevation differences of bench marks in the Krafla-Gjástykki region during each distance measurement coverage of the area (Fig. 1). First measurements were made in late February 1977 and then each year in February, March, or April till 1986. Additional measurements were made several times, especially in 1978 and 1979.

Although more than 50 stations have been occupied at one time or another during the years 1977-1986, these were not all occupied during any one year. Several stations have been destroyed by the lava flows of 1980-1984 and several stations were not established until 1981.

Obtaining bench mark elevations

The elevation difference of geodimeter station and reflector station is obtained from zenith angle measurement at the geodimeter station. A normal temperature gradient of 0.6°C per 100 m is assumed, giving a radius of curvature for horizontally travelling light rays approximately 35.000 km.

The radius of curvature of the earth's surface is assumed to be 6338.0 km. This is about the average radius of curvature of an N-S cut of the earth at 65°N latitude. An E-W cut will have a slightly greater radius of curvature, about 6396 km, and a careful calculation of elevation differences could assume a variable radius of curvature, depending on the azimuth of the observed line.

The main source of error in the calculated elevation difference is the refraction. The temperature gradient, and therefore the curvature of the light rays, can deviate greatly from the adopted average conditions. The one way measurements do not allow any precise estimate of the effect of refraction.

Each coverage of the Krafla-Gjástykki bench mark array, except that of 1977, included more elevation determinations than the number of stations occupied. This allowed a least squares treatment of the data to calculate the station elevations which gave the smallest standard deviation from the observed elevation differences. The calculated elevations thus obtained were checked for possible gross errors of individual computed elevations, and new model was constructed after eliminating these gross errors. The final calculated elevations are presented in Table 1. The standard deviation of calculated elevation differences from observed elevation differences is generally less than 5 cm.

The calculated elevations are all referred to station A012, whose elevation is taken as constant, 680.000 m. This reference elevation is believed to be correct to within 1.0 m.

Vertical ground movements during the inflation-deflation cycles of Krafla

The repeated inflations and deflations of Krafla in 1975-1984 have been studied in considerable details (Tryggvason, 1980b, 1984, 1986, Björnsson et al., 1977, 1979, and others). The center of inflation/deflation appears to have remained stationary, near the south end of Leirhnjúkur, according to unpublished studies by the present author. However, the shape of the inflation bulge has changed gradually during the inflation periods.

A model which agrees reasonably with observed ground deformation (tilt, vertical displacements, distance changes) during the deflations and relatively rapid inflations which follows, consists of a point source at 2.6 km depth below the south end of Leirhnjúkur (Tryggvason, 1986). The vertical displacement of a point on the earth's surface because of this model is given by

$$\Delta h = \Delta h_o \frac{H^3}{R^3} \qquad (1)$$

where Δh_o is the vertical displacement at the center of inflation/deflation, H is the depth to the point source below the earth's surface and R is the slant distance to the point source ($R = \sqrt{H^2 + r^2}$).

As the ground deformation in the Krafla area cannot altogether be explained by a process in a single point source, the above model is useful in separating the effect of the point source from deformation of other causes such as rifting and widening of the Krafla fissure swarm and secular deformation as of yet unexplained and not previously described.

A test of how well observed vertical displacements agree with the single point source model is given in Fig. 2. It shows determined elevation of stations near the center of inflation/deflation plotted against north component of tilt at the Krafla power house. This tilt component is found to represent quite well the inflation of Krafla (Björnsson et al., 1979). Only observations between September 1978 and

March 1980 are included in Fig. 2, but no eruptions occurred during this period, and also no noticeable ground rifting or widening in the near vicinity of Leirhnjúkur (Tryggvason, 1984).

It is noticeable on Fig. 2 that the three stations nearest to the center of inflation/deflation (A002, A003, A004) have been uplifted less than expected at highest stage of inflation, which occurred in late 1979. This indicates that the inflation bulge became flat-topped during this time, which is also a time of slow inflation. Otherwise the vertical displacements are as expected, within the observational errors.

The observed vertical displacement of 16 near stations is plotted against expected displacement (Fig. 3) to show if any of the stations show significant deviation. Two periods, one of relatively rapid inflation (March to June 1978) and another including large deflation (June to August 1978) are displayed. Neither shows any significant deviation from the point source model although some deviations are indicated, pointing towards irregular shape of the inflation bulge or deflation bowl.

The theoretical single point source model (Mogi model) predicts circular lines of equal vertical displacements. Figs. 4 and 5 show the predicted vertical displacements during the two periods of Fig. 3, and the observed displacements at several stations. The theoretical model is based on tilt at the Krafla power station for the magnitude of the displacement, and on numerous tilt stations for location of the source. Vertical displacements at individual stations are calculated relative to the station A012 (Fig. 1) on the northeastern caldera rim, and corrected for theoretical displacement of A012. The agreement between station displacements and model displacements is not very good. The inflation, March to June 1978, appear to be displaced eastwards in the northern part of the region mapped. Thus the eastern stations A006 and A007 show uplift of 24 and 23 cm respectively while the stations A010, A011, and NE77012 at about the same distance towards north or northwest from the center of inflation, were uplifted much less, or 1 to 5 cm.

Similar offset of the region of equal vertical displacements is not observed during the deflation in July 1978 (Fig. 5).

Secular vertical displacements

The calculated elevation of most of the geodetic stations is shown on Figs. 6 through 13 and in Table 1. The elevation is relative to station A012 which elevation is taken as constant, 680.00 m.

When the diagrams are studied, several facts should be kept in mind.

a. The measurements of February 1977 were made by traversing single zig-zag line, so no duplicate observations were made. Thus, if an error was made at one station interval, this error would be present at all succeeding (or preceding) stations. There appears to be an error in the elevation differences of stations A005 and A006 amounting to about 30 cm. If this is true, the elevation of stations A001 through A005 (Fig. 6 and 11) are too low by 30 cm in February of 1977.
b. Large oscillation in elevation of several stations in 1978 are caused by different inflation stage during the measurements. The measurements of March and August 1978, and also that of April 1980, were made shortly after deflations while the measurements of June 1978 and those of 1979 were made after inflation had reached high stage. These oscillations are noticeable at all stations within about 3 km distance from the center of inflation/deflation (A001, A004, A005 and A006 of Fig. 6, NE77012 of Fig. 9, A002 and A003 of Fig. 11).
c. A few individual elevations deviate greatly from others, indicating gross errors. This applies to the elevation of A014 in March 1984, A027 in February 1979, NE77008 in February 1979 and possibly several other.
d. Most stations outside the disturbed zone show near linear trend of elevation with time (Fig. 6 through 10). There are a few stations, especially A001, A004 and A005, where the rate of elevation change apparently changed around 1982-1983 in such a way that uplift relative to the reference station (A012) prevailed before 1981 while relative subsidence prevailed after 1982. Several

stations exhibit irregular elevation changes which are difficult to interpret (e.g. A023, A026, A035 and other).

e. Several stations show relative elevation changes which are greater and more irregular than at most of the stations. These are the stations in the disturbed zone, between the lines of Fig. 14 (Fig. 11 through 13). These stations have subsided relative to their surroundings, and the subsidence have occurred in several steps, coinciding with events of rifting and eruptions.

An estimate, although rather crude, of the rate of relative vertical movement of the stations is extracted from Figs. 6 through 10. This estimate is obtained by eye-ball estimate of the trend of a best fitted line for the period 1979-1986. The numerical values are shown on Fig. 14 where the relative vertical movement is expressed in cm per year.

It is obvious that the data do not warrant an exact estimate of the uplift or subsidence rate, partly because the rate may have changed with time (stations A001, A004, A005), partly because of unexplained apparent movement, and partly because of too few observations. The vertical movement is estimated from data of Table 1 for several stations not shown on Figs. 6 through 10 (A034, NE80050, NE80051).

In spite of these uncertainities of the relative vertical movement, it is obvious that there is very significant difference between different stations. Clear relative uplift is observed at A009 (Fig. 6), A014 and A019 (Fig. 7) while very definite subsidence is observed at A020 (Fig. 7), NE77006 (Fig. 9) and NE79078 (Fig. 10) and several others. The difference in rate of vertical movement between e.g. A014 and NE79078 is almost 15 cm/year for the period 1979-1986.

Contours of Fig. 14 are drawn approximately to show how rate of vertical movement varies within the region of the map. This illustration indicates that the reference station (A012) has moved upwards at a rate of roughly 10 cm/year based on the assumption that stations farthest away from the region of maximum movement (uplift) have been about stationary.

Subsidence of the "disturbed zone"

Several stations (Figs. 11 to 13) have subsided at irregular rate and very differently from most near-by stations. They are all located in near vicinity of the volcanic fissures which have erupted in 1975 through 1984, and within zone of large fault movement, the "disturbed zone", or "fissure zone".

The subsidence of these stations appears to be associated with rifting and/or eruptions near the stations. Thus the southern stations A002 and A003 subsided during events of April and September 1977, March and October 1980, November 1981 and possibly September 1984. The subsidence of A002 was roughly twice that of A003, and total relative subsidence of A002, from early 1977 to early 1986, amounted to about 2.75 m.

The stations A015 and A017 also subsided during the same events, and their total relative subsidence amounted to about 2.5 m. The 1985 observation of A017 (Fig. 12) is suspicious and further observations are needed before this is judged as correct or incorrect.

There has not been made any effort to occupy the stations within the disturbed zone, and several of these stations have been destroyed by the eruptions (A010, A016, A022). The stations A032, A036 and A038 have not been occupied since before 1981, and the two first were probably buried below lava in 1980. The station A031 has not been visited after 1984 and are believed to have been destroyed by the September 1984 lava.

The stations which obviously have been disturbed (A002, A003, A010, A015, A016, A017, A022, A030, and A038) all lie within about 1 km wide zone, the disturbed zone (Fig. 14). This zone is poorly defined by the present data, althouqh all stations outside the zone marked on Fig. 14 are not disturbed by the stepwise subsidence characterized by all stations within the disturbed zone.

Discussion

The vertical component of ground deformation of the Krafla area, as reflected by the vertical angle observations during geodimeter measurements, can be grouped into three classes:

1. Inflations and deflations centered near Leirhnjúkur.
2. Severe disturbance, mainly subsidence of a narrow zone striking about N13°E through Leirhnjúkur.
3. Secular (gradual) vertical displacement, mostly uplift, of an N-S elongated area centered about 6 km NNE of Leirhnúkur.

Deformation of group 1 has been discussed by several authors (Tryggvason, 1980b and 1986, Johnsen et al., 1980) and the present observations do not add significantly to the previous ones.

Deformation of group 2 is not sufficiently well observed by the measurements discussed here, that a clear picture can be obtained. The outlines of the disturbed zone are poorly defined. It appears that a zone, roughly one kilometer wide, subsided 2 to 3 m relative to its surroundings. This zone of subsidence coincides with the zone of fissure widening (Tryggvason, 1984).

Deformation of group 3 is here described for the first time (Fig. 14) although uplift of the flanks of the fissure zone has been described previously. The reference station, A012, is probably uplifted about 10 cm per year in 1979-1986, and the southern stations (NE80048, NE80050, NE80051, and NE80052) and also the northwestern stations (A034, NE77006, NE77007, and NE77008) are considered as relatively stable. This assumed stability of the relatively remote stations is not confirmed by other measurements, and repeated leveling indicates gradual uplift, although at gradually reduced rate, of the region of the southern stations (Björnsson et al., 1985). The average uplift of these southern stations in 1979-1985 can be about 7 cm/year (Björnsson et al., 1985). If this is true, the area of maximum uplift (stations A014, A018, and A023) have been uplifted at an average annual rate of 20 cm/year approximately.

The elongated uplifted region has an axis of maximum uplift along the eastern edge of the disturbed zone, and points at equal distance east of this zone have been uplifted 6 cm/year more than west of the zone. Also the uplift drops off more rapidly with distance to the west, than to the east (Fig. 14).

This elongated bulge is well separated from the previously observed inflation bulge centered immediately south of Leirhnjúkur. Its elongated shape and steep drop off to the west, differs greatly from a single point source inflation (Fig. 4). Its long axis is parallel to the greatly disturbed fissure zone, indicating a genetic relation between the disturbed zone and the secular uplift of the elongated region.

The cause or physical nature of this uplift is still not clear. A cross section, east west, across the uplift near its center (Fig. 15), can be interpreted in terms of flank uplift. The widening of the fissure zone (Tryggvason, 1984) caused E-W contraction and elastic thickening of the flank zones. This type of uplift is expected to be symmetrical about the disturbed zone. The non-symmetry could possibly be caused by slope of the fissures below the fissure zone, but this is quite dubious. Also, the flank uplift would be expected to vary along the fissure zone similarly to the widening, and the flank uplift should occur only during events of widening. The uplift of the elongated bulge appears to have continued at relatively constant rate for several years. The flank uplift is thus not a convincing explanation of the elongated bulge.

Another explanation is that this uplift is caused by advection of magma at depth, and thus of similar nature as the frequently described Krafla inflation bulge centered near Leirhnjúkur. This would require that magma was collected in rather irregular, but mostly narrow and elongated chamber below but slightly to the east of the fissure zone. This chamber would then receive the influx of magma after the shallow Krafla magma reservoir is filled and thus correspond to reservoir I and reservoir II in the model developed after the 1984 eruption (Tryggvason, 1986).

References

Björnsson, A., Sæmundsson, K., Einarsson, P., Tryggvason, E., and Grönvold, K., 1977. Current rifting episode in north Iceland. Nature, 266:318-323.

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

Björnsson, A., Björnsson, G., Gunnarsson, A., and Þorbergsson, G., 1985. Breytingar á landhæð við Kröflu 1974-1984 (in Icelandic). Orkustofnun, OS-85019/SHD-05:1-67.

Johnsen, G.V., Björnsson, A., and Sigurdsson, S., 1980. Gravity and elevation changes caused by magma movement beneath the Krafla caldera, northeast Iceland. J. Geophys., 47:132-140.

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

Tryggvason, E., 1980a. Distance measurements in the Krafla-Gjástykki geodimeter network, March 1978 to May 1979. Nordic Volcanological Institute 8002:1-42.

Tryggvason, E., 1980b. Subsidence events in the Krafla area, North Iceland, 1975-1979. J. Geophys., 47:141-153.

Tryggvason, E., 1983. Distance measurements in the Gjástykki-Krafla-Mývatn area 1979-1982, progress report. Nordic Volcanological Institute 8301:1-48.

Tryggvason, E., 1984. Widening of the Krafla fissure swarm during the 1975-1981 volcano-tectonic episode. Bull. Volcanol. 47:47-69.

Tryggvason, E., 1986. Multiple magma reservoirs in a rift zone volcano: Ground deformation and magma transport during the September 1984 eruption of Krafla Iceland. J. Volcanol. Geothermal Res., 28:1-44.

Table 1a

Computed relative elevation of geodimeter stations in the Krafla region, February 1977 - February 1979

	Feb 77	Mar 78	Jun 78	Aug 78 I	Aug 78 II	Feb 79
A001	542.222	542.412	542.670	542.304	542.572	542.693
A002	592.502	591.393	591.850	591.512	591.742	591.812
A003	594.421	593.946	594.360	593.986	594.228	594.289
A004	549.619	549.723	549.990	549.711	549.954	549.928
A005	563.736	562.966	563.132	562.916	563.117	563.146
A006	681.368	681.290	681.443	681.213	681.345	681.316
A007	728.308	728.258	728.399	728.293	728.359	728.327
A008	581.025	581.066	581.013	580.998	581.054	581.022
A009	576.523	576.580	576.658	576.473	576.569	576.628
A010	600.697	599.900	599.857	599.755	599.804	599.759
A011	539.427	539.460	539.407	539.278	-	539.293
A012	680.000	680.000	680.000	680.000	680.000	680.000
A013	625.758	625.740	625.774	625.743	-	625.692
A014	605.436	605.439	605.494	605.422	-	605.449
A015	546.054	545.095	545.108	545.077	-	545.049
A016	522.162	522.029	521.920	521.869	-	521.829
A017	555.979	555.158	-	555.044	-	555.012
A018	608.815	608.716	-	608.726	-	608.715
A019	637.911	637.730	-	637.780	-	637.865
A020	674.878	674.654	-	674.660	-	-
A021	713.728	713.509	-	713.480	-	-
A022	523.813	523.444	-	523.316	-	523.297
A023	576.173	575.964	-	575.943	-	575.885
A024	645.844	645.648	-	645.638	-	645.674
A025	561.994	561.789	-	561.759	-	-
A026	639.059	638.789	-	638.819	-	-
A027	533.385	533.169	-	533.189	-	533.405
A028	527.851	527.601	-	527.652	-	527.665
A029	550.530	550.316	-	550.351	-	550.305
A030	543.070	542.804	-	542.509	-	542.405
A031	513.740	513.558	-	513.449	-	513.475
A033	523.638	523.337	-	523.506	-	-
A034	512.547	512.409	-	512.403	-	512.302
A035	509.316	508.943	-	509.126	-	508.963
A036	481.656	481.189	-	481.358	abandoned	-
A037	-	498.599	-	498.758	-	498.645
A038	485.466	485.149	-	484.742	-	-
A040	-	487.979	-	487.987	-	487.922
A042	-	488.849	-	489.058	-	488.842
77006	-	446.699	-	446.642	-	446.702
77007	-	513.344	-	513.177	-	513.139
77008	-	490.455	-	490.248	-	490.934
77012	-	546.460	546.380	546.161	546.398	546.419
79077	-	-	-	-	-	-
79078	-	-	-	-	-	-
80048	-	-	-	-	-	-
80049	-	-	-	-	-	-
80050	-	-	-	-	-	-
80051	-	-	-	-	-	-
80052	-	-	-	-	-	-

Table 1b

Computed relative elevation of geodimeter stations in the Krafla region, August 1979 - July 1981

	Aug 79 I	Aug 79 II	Nov 79	Apr 80	Apr 81	Jul 81
A001	542.708	542.641	542.772	542.575	542.623	542.522
A002	591.858	591.830	591.903	590.853	590.481	590.444
A003	594.375	594.379	594.411	593.765	593.714	593.684
A004	549.996	549.990	550.048	549.764	549.992	549.987
A005	563.227	563.200	563.225	563.100	563.204	563.244
A006	681.430	681.365	681.330	681.240	681.259	681.214
A007	728.477	728.320	728.255	728.359	728.170	728.184
A008	581.046	581.034	580.958	581.064	581.107	581.064
A009	576.671	576.594	576.553	576.644	576.741	576.707
A010	599.821	599.729	599.833	599.188	598.908	598.848
A011	-	-	-	539.410	539.376	539.338
A012	680.000	680.000	680.000	680.000	680.000	680.000
A013	-	-	-	625.789	625.809	625.799
A014	-	-	-	605.538	605.589	605.559
A015	-	-	-	544.438	543.829	543.814
A016	-	-	-	buried beneth lava		-
A017	-	-	-	554.371	553.706	-
A018	-	-	-	608.780	608.762	-
A019	-	-	-	637.802	637.744	-
A020	-	-	-	674.601	674.475	-
A021	-	-	-	713.521	713.245	-
A022	-	-	-	523.115	522.944	-
A023	-	-	-	575.944	576.083	-
A024	-	-	-	645.761	645.693	-
A025	-	-	-	561.740	561.629	-
A026	-	-	-	-	638.634	-
A027	-	-	-	533.160	533.089	-
A028	-	-	-	527.780	-	-
A029	-	-	-	550.420	-	-
A030	-	-	-	542.420	542.360	-
A031	-	-	-	513.426	513.239	-
A033	-	-	-	523.450	523.354	-
A034	-	-	-	512.220	512.131	-
A035	-	-	-	509.065	508.974	-
A036	-	-	-	-	-	-
A037	-	-	-	498.755	498.784	-
A038	-	-	-	484.140	-	-
A040	-	-	-	488.110	487.934	-
A042	-	-	-	488.865	488.826	-
77006	-	-	-	446.495	446.383	-
77007	-	-	-	513.202	513.075	-
77008	-	-	-	490.267	490.024	-
77012	546.495	546.409	-	546.309	546.175	-
79077	558.330	558.343	558.400	558.091	558.327	558.277
79078	494.980	495.003	494.920	494.871	494.744	494.650
80048	-	-	-	-	537.073	537.011
80049	-	-	-	-	572.543	572.231
80050	-	-	-	-	621.731	621.606
80051	-	-	-	-	552.865	552.783
80052	-	-	-	-	516.050	515.951

Table 1c

Computed relative elevation of geodimeter stations in the Krafla region, April 1982 - March 1986

	Apr 82	Apr 83	Mar 84	Mar 85	Mar 86
A001	542.582	542.618	542.475	542.356	542.312
A002	590.198	590.212	590.088	589.864	589.741
A003	593.563	593.609	593.498	593.257	593.244
A004	550.063	550.104	550.057	549.977	549.975
A005	563.283	563.314	563.234	563.214	563.175
A006	681.256	681.228	681.197	681.121	681.182
A007	728.196	728.197	728.172	728.159	728.194
A008	581.111	581.107	581.107	581.130	581.078
A009	576.758	576.763	576.755	576.823	576.809
A010	buried beneath tephra -			-	-
A011	539.382	539.205	539.246	-	539.174
A012	680.000	680.000	680.000	680.000	680.000
A013	625.857	625.810	625.823	625.792	625.912
A014	605.600	605.604	605.770	605.666	605.711
A015	543.410	543.480	543.390	-	-
A016	-	-	-	-	-
A017	553.480	553.375	553.340	553.789	-
A018	608.850	608.774	608.716	609.008	608.930
A019	637.740	637.664	637.676	637.811	637.815
A020	674.520	674.427	674.433	674.411	674.336
A021	713.220	713.102	713.118	713.251	713.243
A022	buried beneath lava		-	-	-
A023	-	575.975	575.946	576.151	576.081
A024	645.756	645.650	645.642	645.810	645.762
A025	-	561.572	561.567	-	561.577
A026	-	638.374	638.447	638.631	638.579
A027	-	532.937	533.012	-	532.973
A028	-	527.685	527.677	527.831	527.712
A029	-	-	-	-	-
A030	-	542.343	542.363	-	542.489
A031	-	513.273	513.503	buried beneath lava	
A033	-	-	-	-	-
A034	-	-	-	-	-
A035	508.766	508.647	508.743	508.801	508.581
A036	-	-	-	-	-
A037	498.651	498.609	498.637	498.750	498.620
A038	-	-	-	-	-
A040	487.849	487.804	487.800	487.783	487.715
A042	488.519	488.504	488.510	488.503	488.494
77006	-	446.153	446.053	446.032	445.970
77007	512.971	512.752	512.739	buried beneath lava	
77008	-	489.826	489.865	489.866	489.604
77012	546.181	546.185	546.012	546.020	545.986
79077	558.283	558.279	558.212	558.015	558.023
79078	494.543	494.515	494.441	494.220	494.246
80048	536.790	536.840	536.642	536.486	536.592
80049	572.335	572.305	572.192	572.257	572.060
80050	621.477	621.420	621.361	621.276	-
80051	552.646	552.630	552.606	552.358	-
80052	515.819	515.770	515.601	515.498	515.472

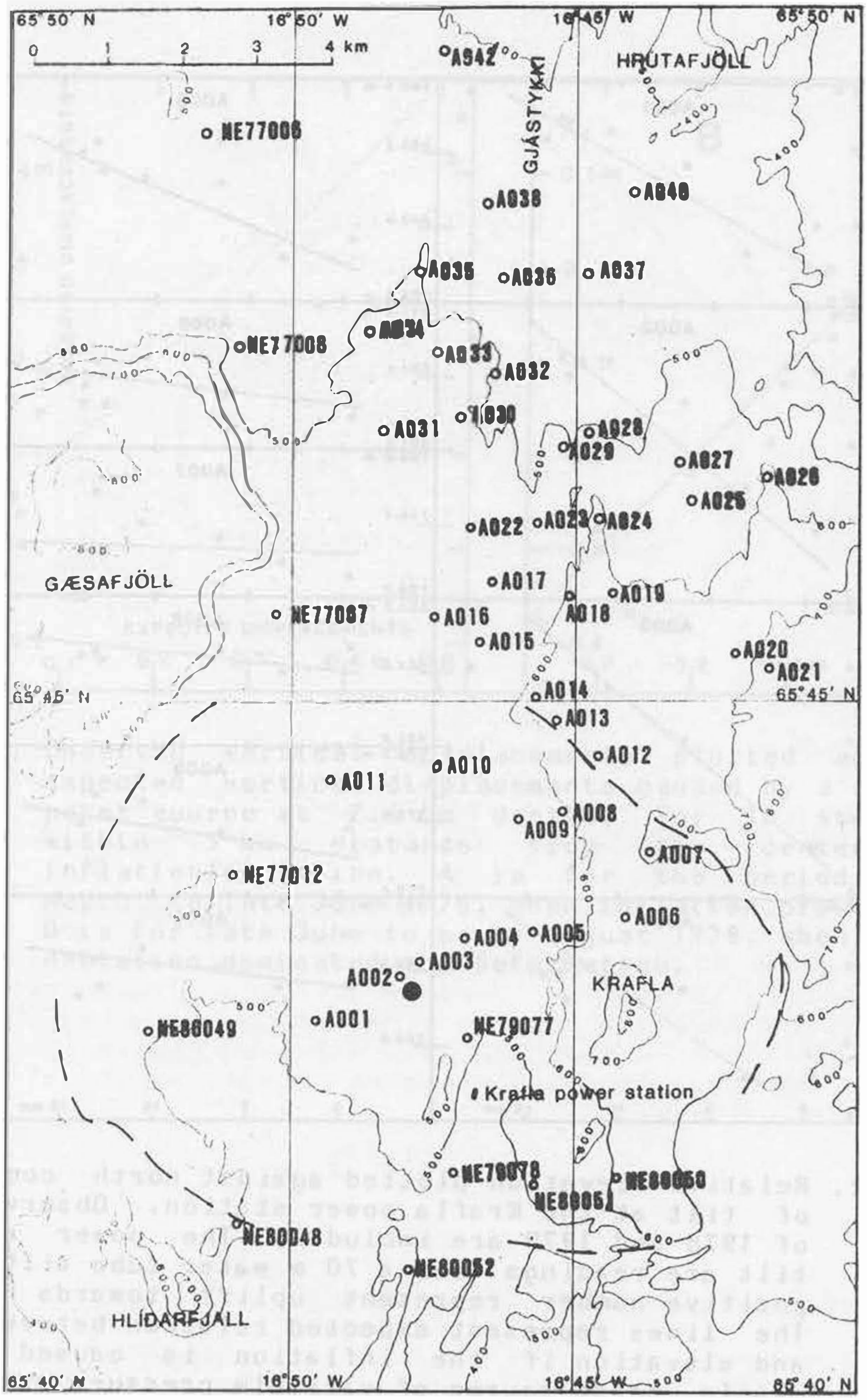

Fig. 1. Stations of the Krafla-Gjástykki geodimeter network. The Krafla caldera rim is indicated by heavy dashed lines and the center of inflation/deflation is marked by filled circle. The reference station A012 lies near the NE section of the caldera rim.

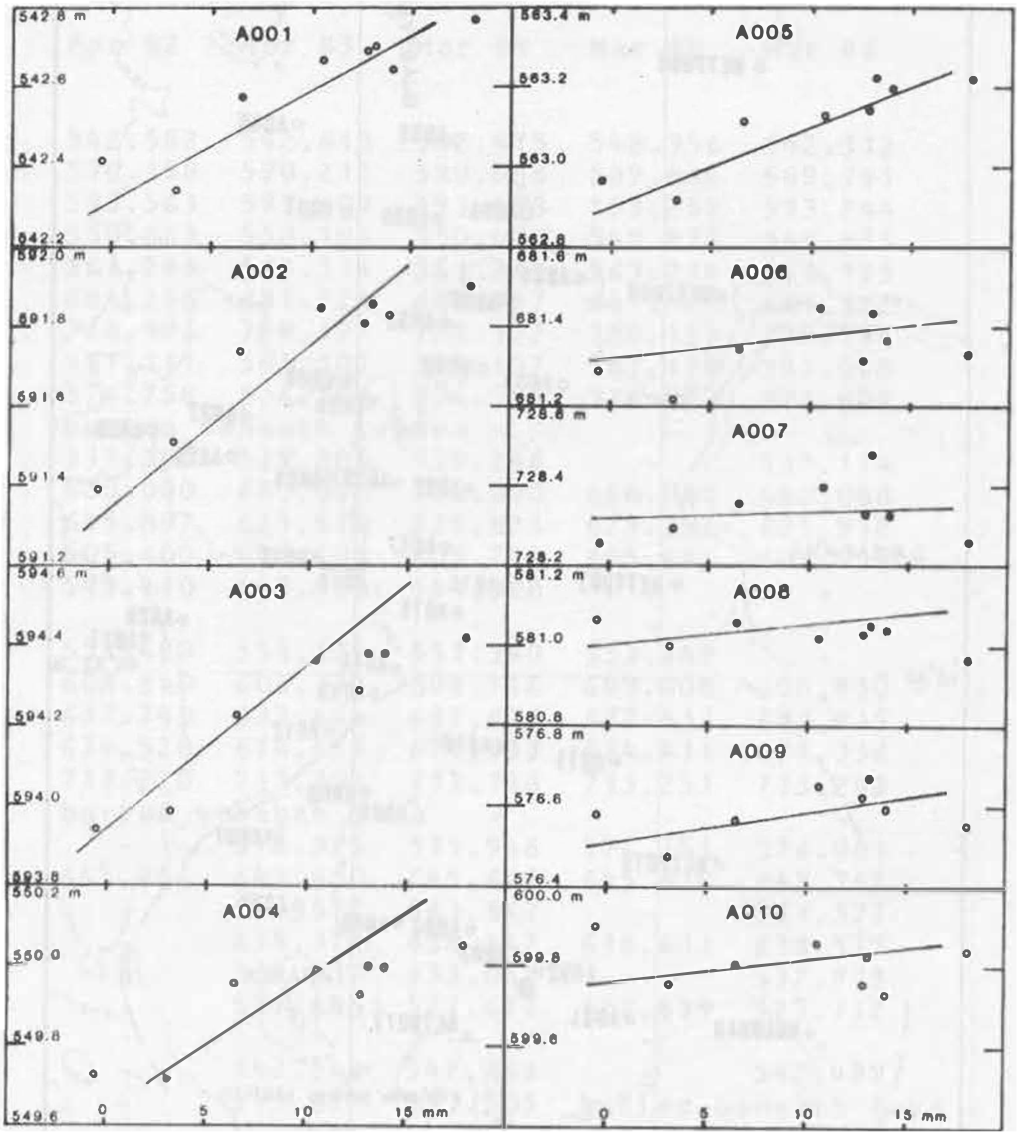

Fig. 2. Relative elevation plotted against north component of tilt at the Krafla power station. Observations of 1978 and 1979 are included. The power station tilt are readings from a 70 m water tube tiltmeter, positive number represent uplift towards N13°E. The lines represent expected relation between tilt and elevation if the inflation is caused by a single point source of variable pressure at 2.6 km depth below the point indicated on Fig. 1.

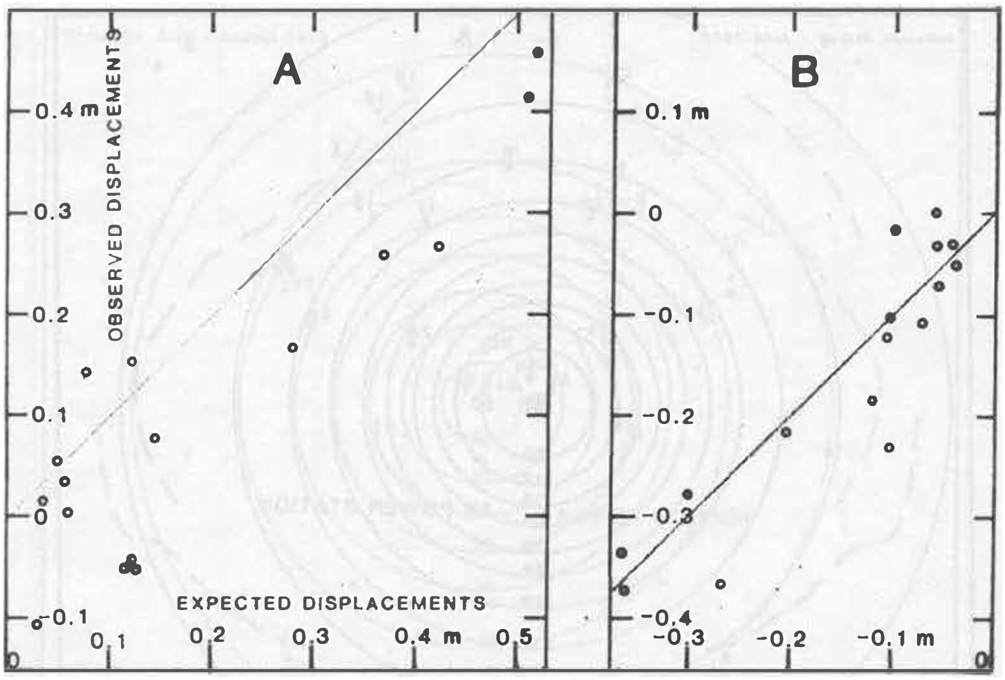

Fig. 3. Observed vertical displacements plotted against expected vertical displacements caused by a single point source at 2.6 km depths, for 16 stations within 5 km distance from the center of inflation/deflation. A is for the period late March to late June 1978, when inflation prevailed. B is for late June to early August 1978, when large deflation dominated the deformation.

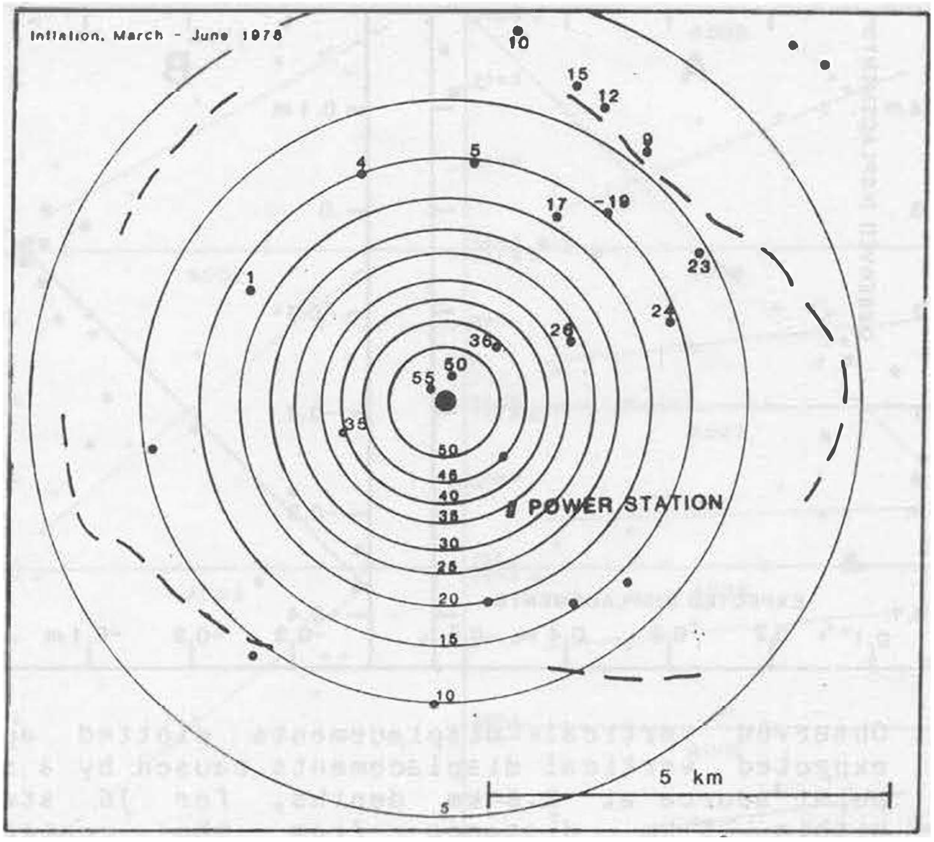

Fig. 4. Map of the expected vertical displacement in cm around the center of inflation during the March-June 1978 period. The Krafla caldera rim is shown for location. Observed vertical displacements of the near stations is given in cm, assuming that the reference station A012 has been displaced 9 cm to agree with the expected displacement at that location.

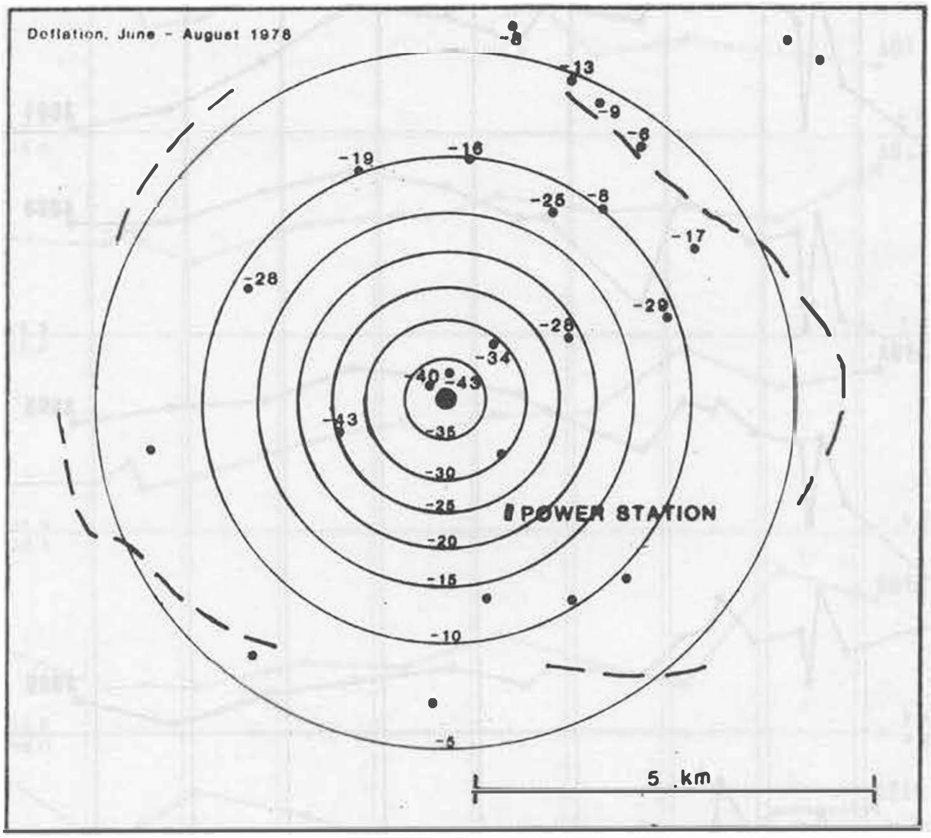

Fig. 5. Same as Fig. 4, except that the period is June to August 1978, when deflation dominated.

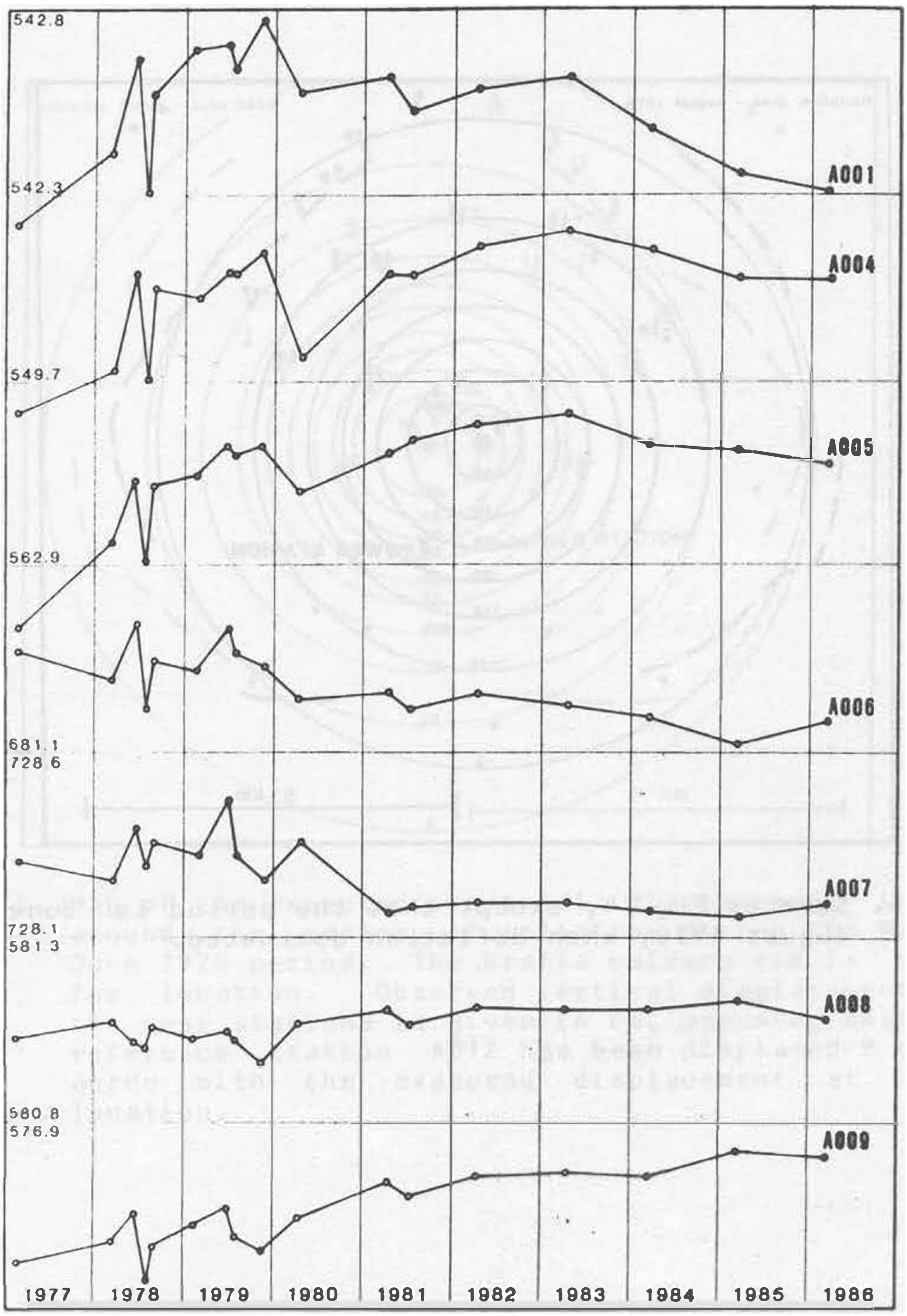

Fig. 6. Variation of observed relative elevation with time from 1977 to 1986 of seven stations which all lie outside the "disturbed zone". Large oscillations in 1978 at the stations A001, A004, A005, A006 and A009 reflect the inflation-deflation cycles near the center of inflation/deflation. The station A006 is apparently subsiding at a rate of about 2 cm/year during the whole period of observation while the station A009 is similarly rising about 3 cm/year.

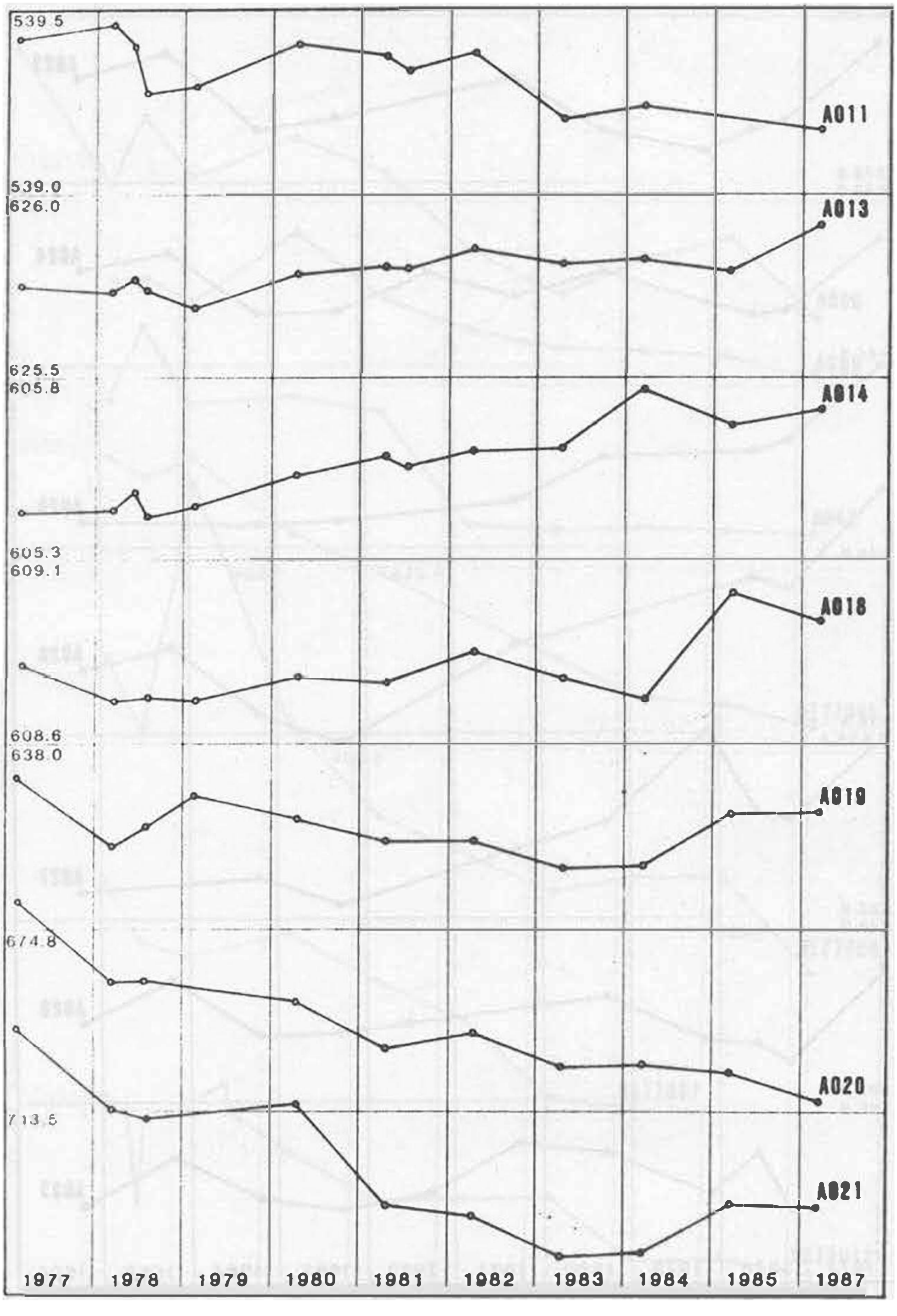

Fig. 7. Same as Fig. 6, but 7 additional stations are displayed. The stations A013, A014 and A018 are being uplifted while A020 and A021 are subsiding throughout the whole period of observations.

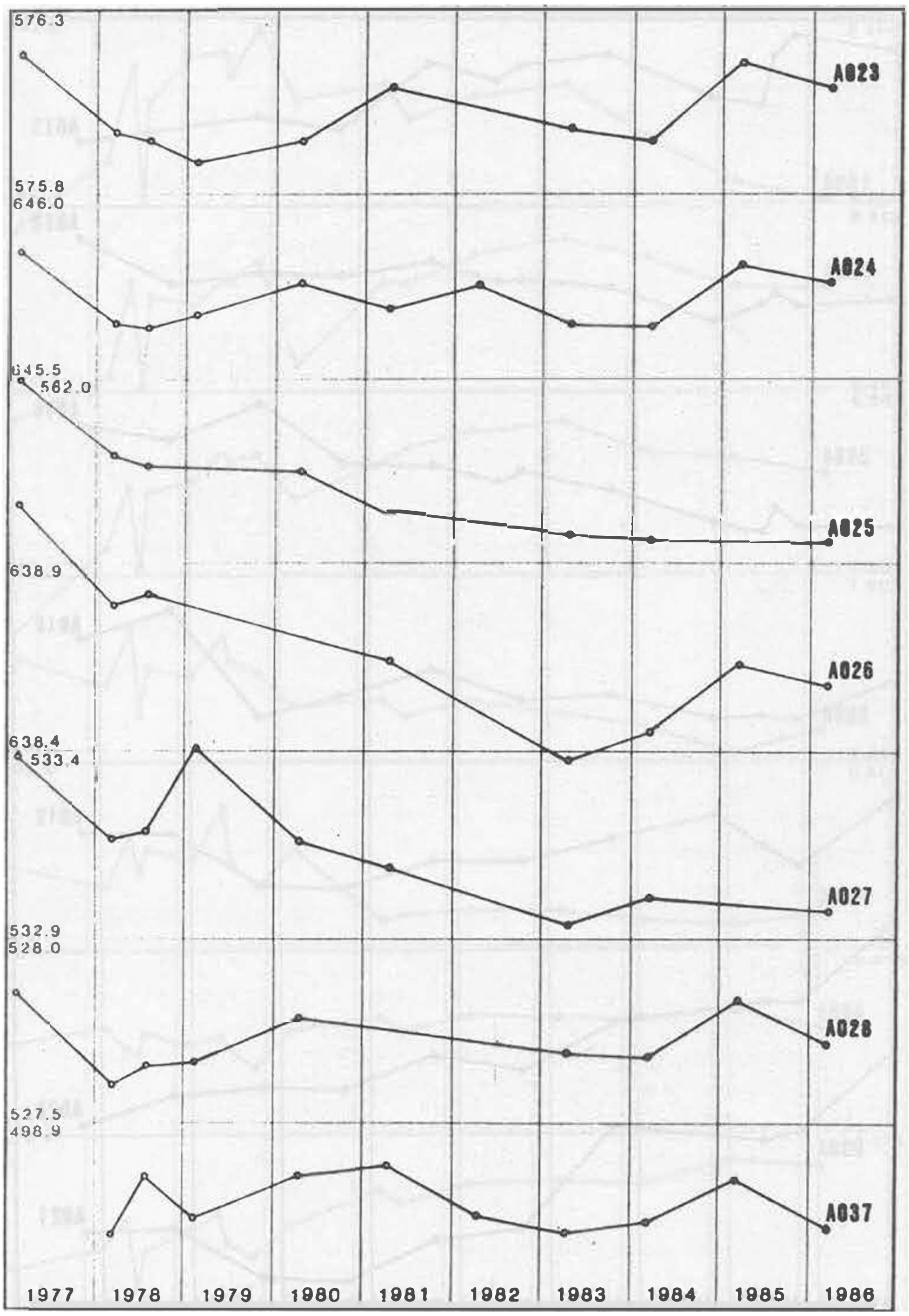

Fig. 8. Same as Fig. 6 and 7, but 7 additional stations are included.

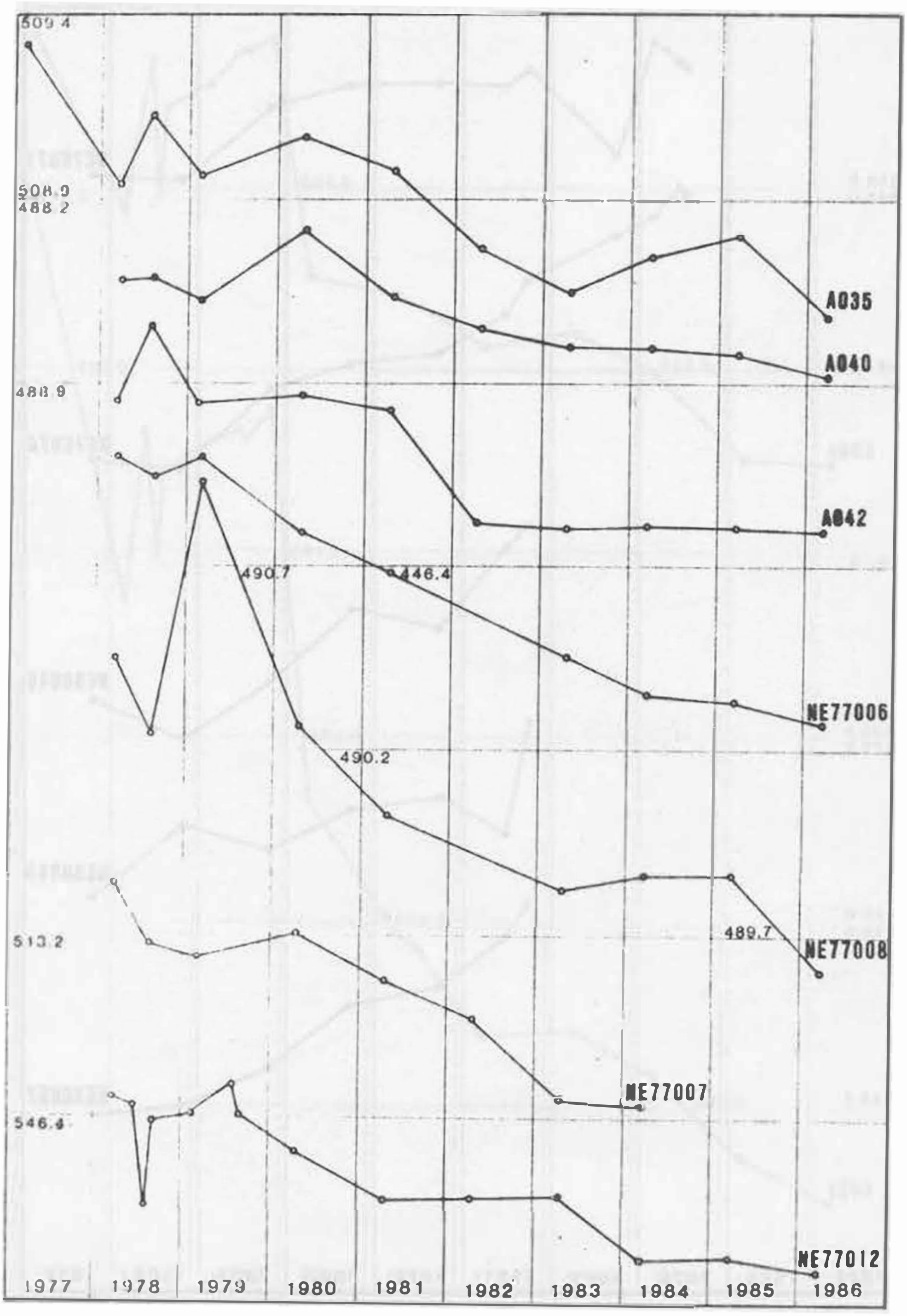

Fig. 9. Further seven stations displayed in the same way as on Figs. 6 through 8. Very pronounced relative subsidence is observed at most stations although the 1979 observations of NE77008 must be regarded as erroneous. The near linear relation with time is spectacular, especially at NE77006.

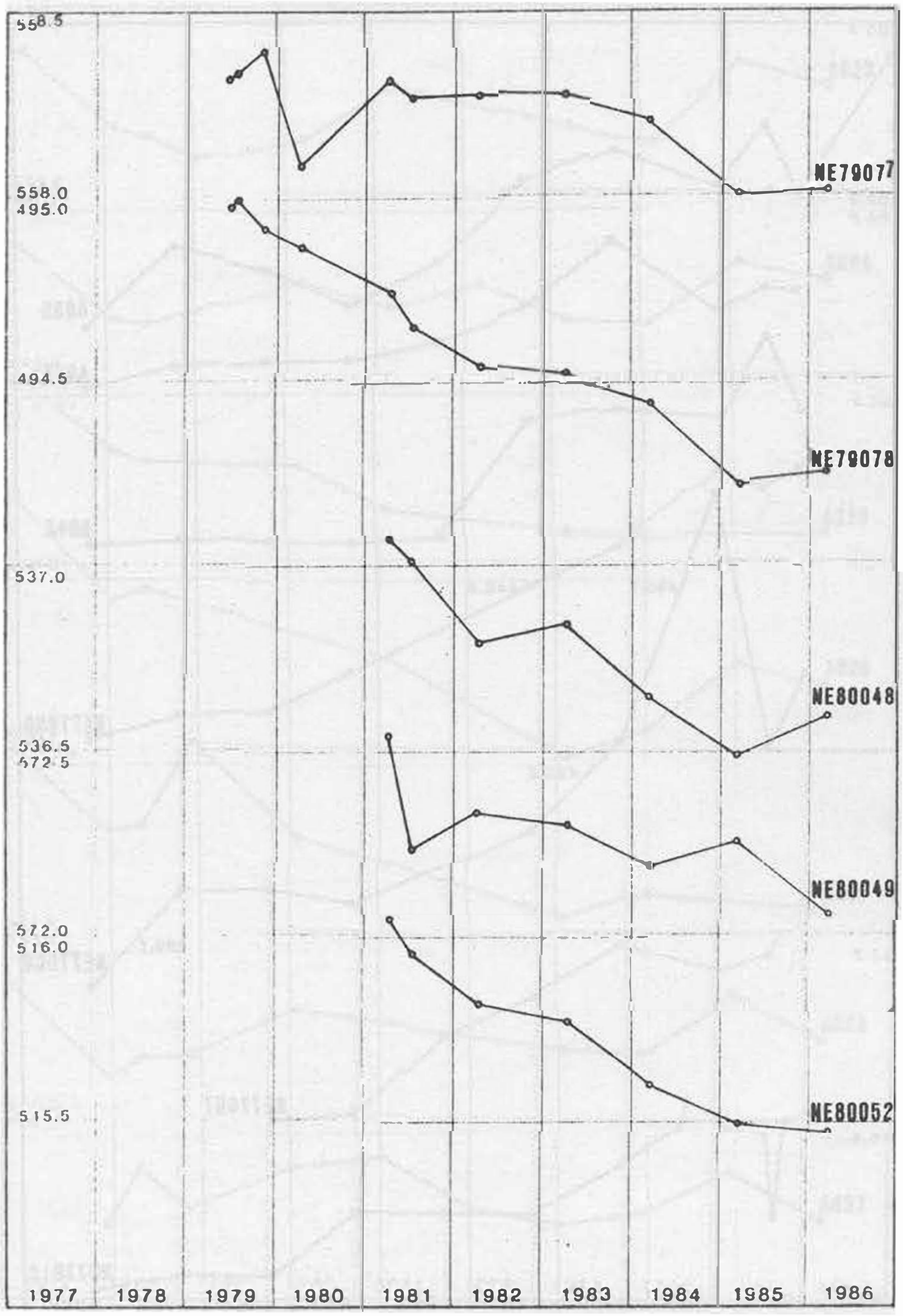

Fig. 10. The change of relative elevation with time of several stations established in 1979 and 1981. The near linear subsidence is very noticeable, especially at NE79078 and NE80052.

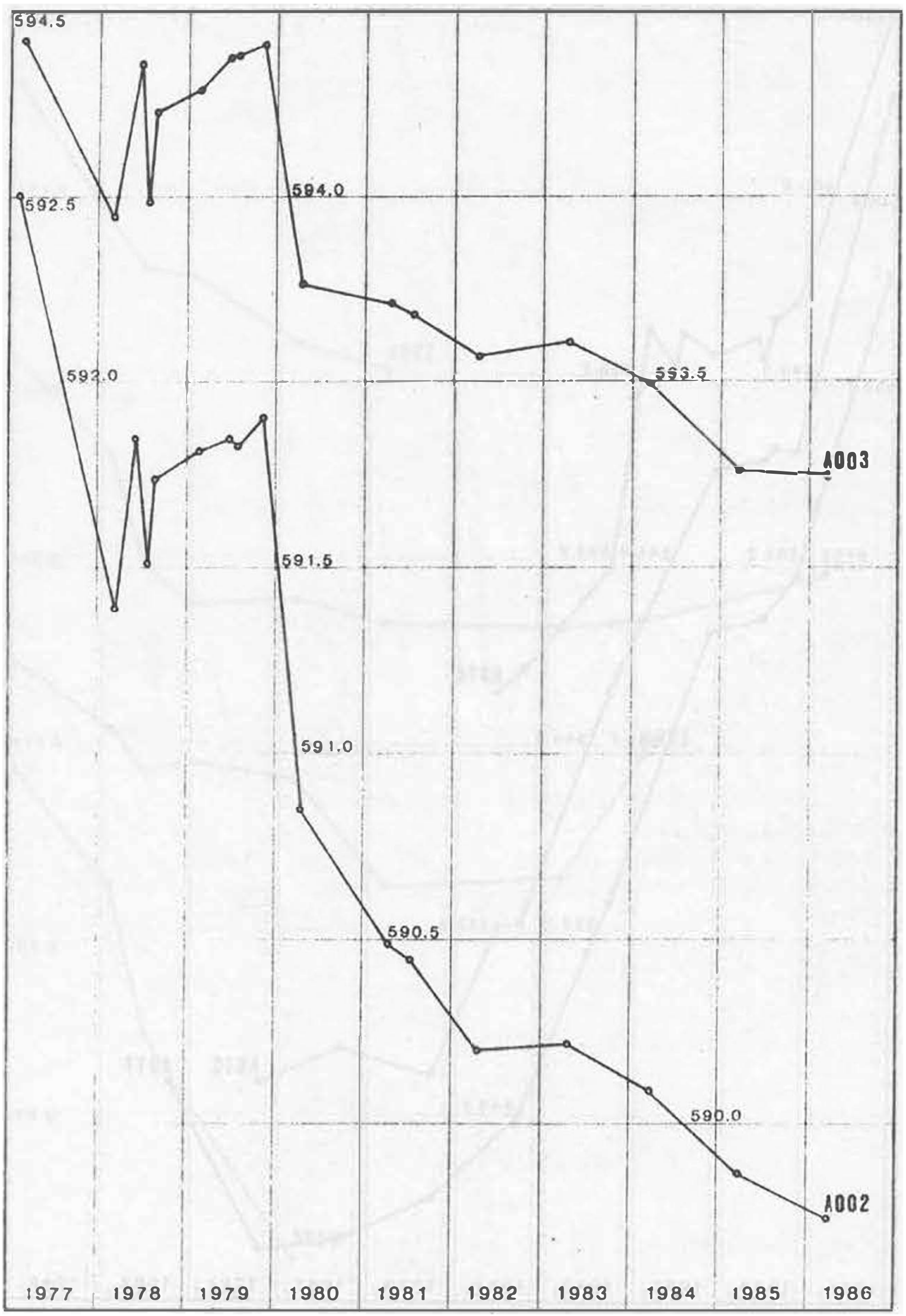

Fig. 11. Relative elevation and its change with time from 1977 to 1986 of two stations on Leirhnjúkur, within the "disturbed zone". These stations show irregular displacements, mostly relative subsidence, in steps which coincide with major rifting events of 1977, 1980 and 1981.

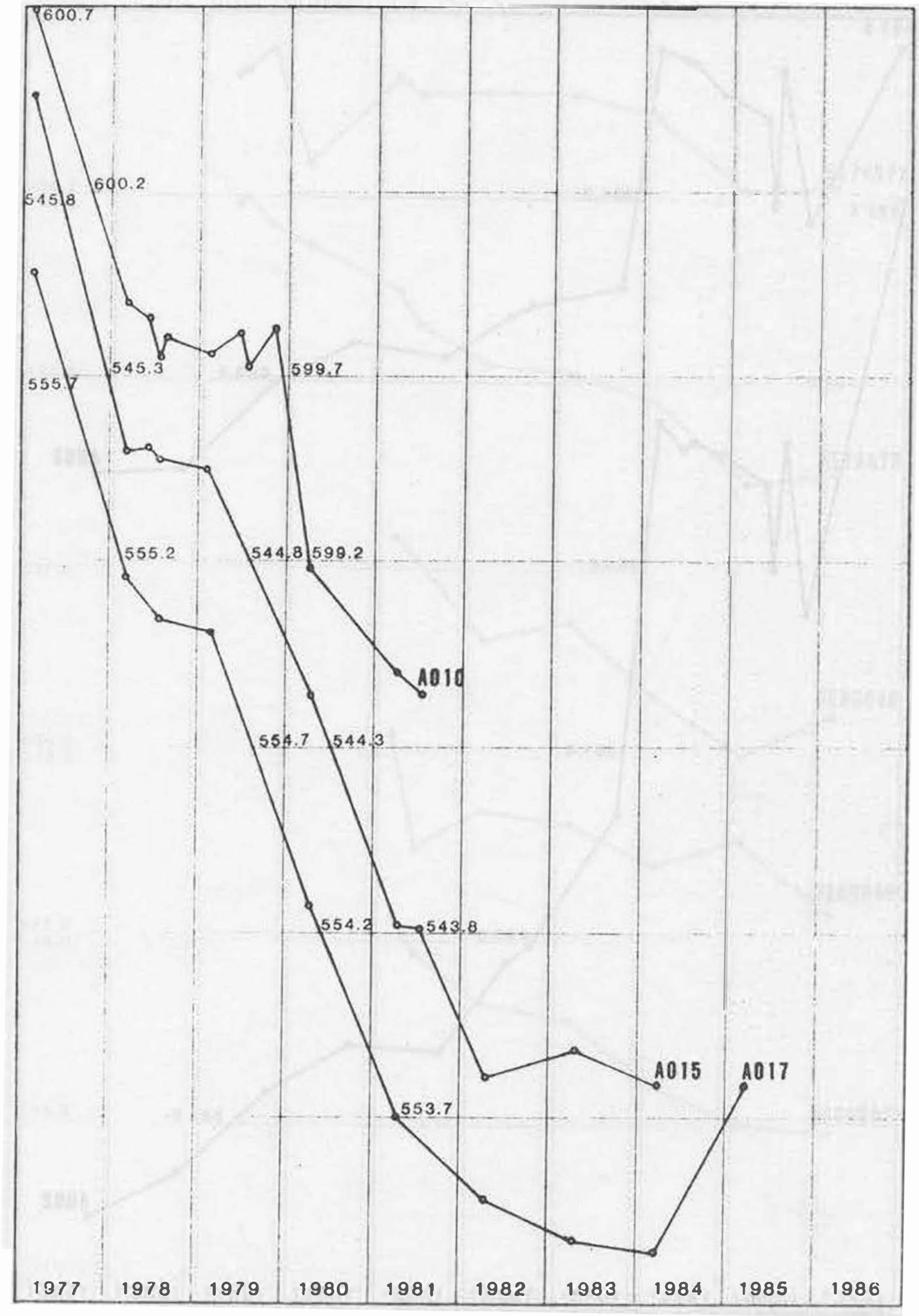

Fig. 12. Same as Fig. 11, but 3 additional stations displayed. The station A010 was buried by tephra from near eruption in November 1981. The stations were not observed in 1986, and the 1985 observation of A017 is suspicious.

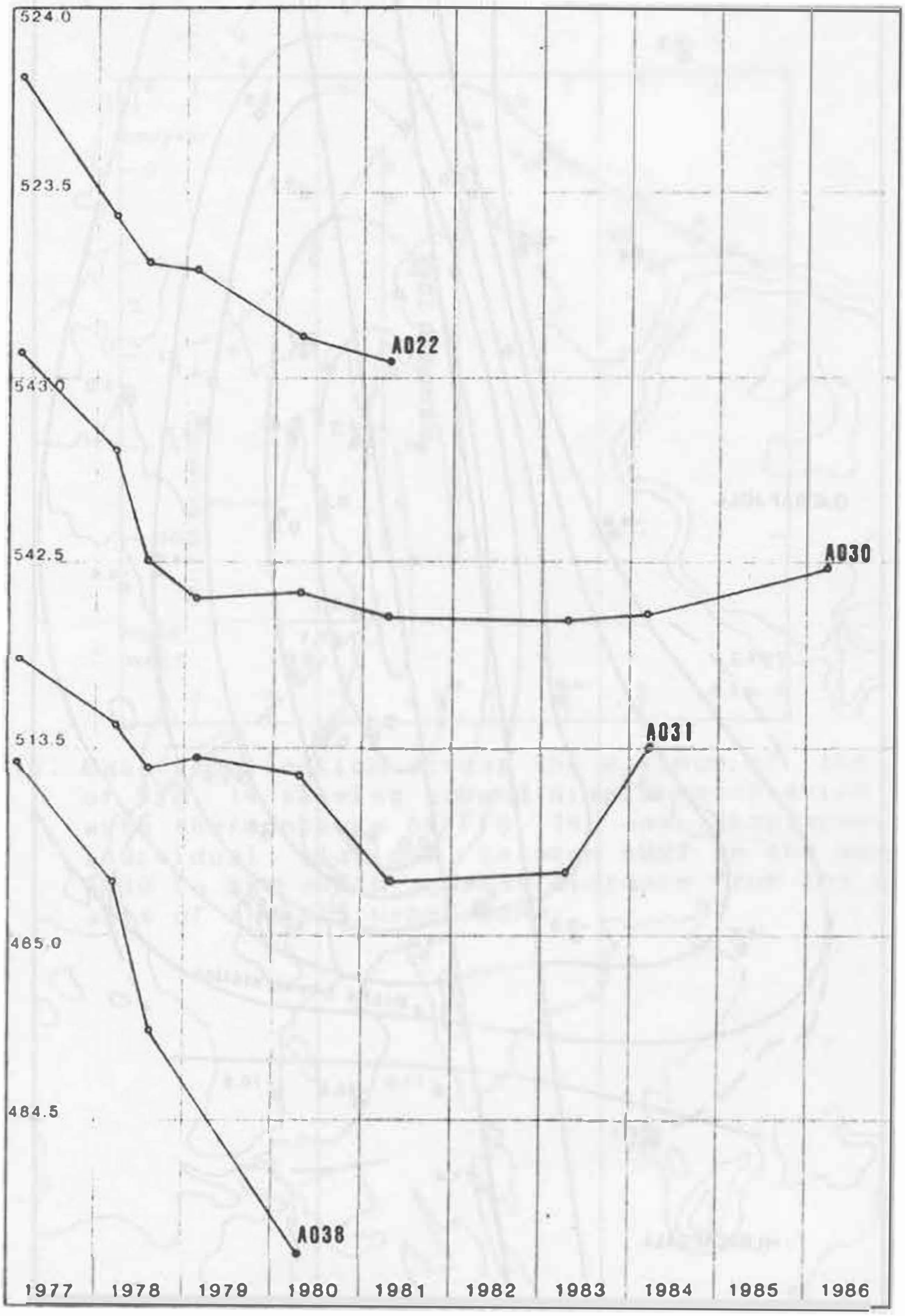

Fig. 13. Same as Fig. 11 and 12, but four additional stations displayed. The station A031 is probably outside the disturbed zone. It was probably destroyed by a lava flow of September 1984. The station A022 was destroyed by the eruption of November 1981, but A038 has not been observed since early 1980.

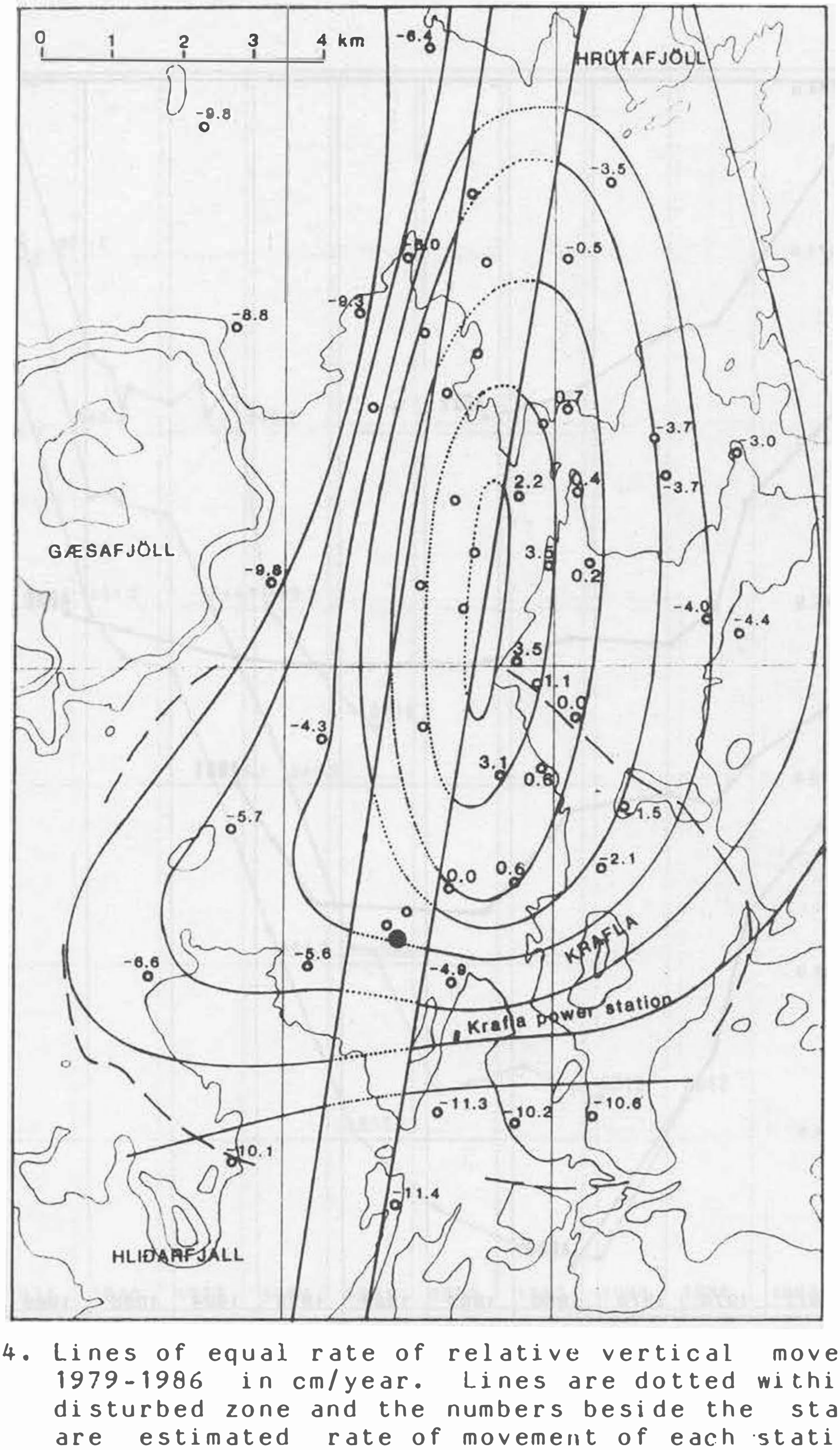

Fig. 14. Lines of equal rate of relative vertical movements 1979-1986 in cm/year. Lines are dotted within the disturbed zone and the numbers beside the stations are estimated rate of movement of each station in cm/year, derived from the data of Figs. 6 through 10. A few stations not displayed on Figs. 6 through 10 are given displacement rates from data of Table 1. Thick lines striking N13^{o}E outline roughly a zone of large and irregular ground movement, the disturbed zone. The rim of the Krafla caldera is shown by heavy dashed lines.

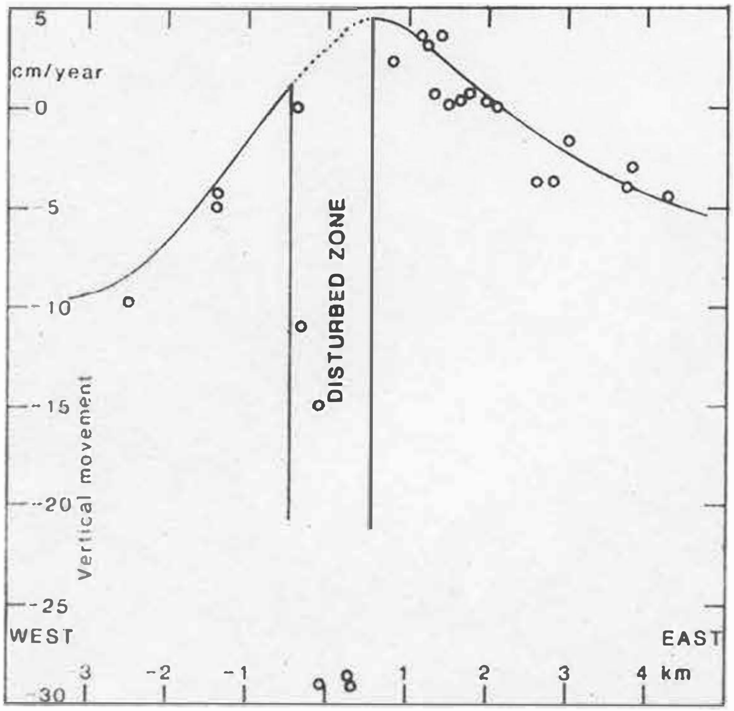

Fig. 15. East-west section across the maximum of the bulge of Fig. 14 showing ground displacement which agrees with the contours of Fig. 14, and displacement of individual stations between A009 in the south and A030 in the north against distance from the central axis of the disturbed zone.