NORDIC VOLCANOLOGICAL INSTITUTE 8102
UNIVERSITY OF ICELAND

VERTICAL COMPONENT OF GROUND DEFORMATION IN SOUTHWEST- AND NORTH-ICELAND

Result of levelings in 1976 and 1980

by

Eysteinn Tryggvason

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ABSTRACT

Several profiles of precision leveling in the rift zones of Southwest Iceland and North Iceland were leveled in 1976 and 1980. These profiles had been leveled frequently in 1966-1973. The ground deformation observed by the two last levelings was much greater than had been observed previously. This apparent increase in tectonic activity is in North Iceland tied to the rifting episode which started in the Krafla fissure swarm in 1975.

The observations in Southwest Iceland show that the average rate of ground deformation over long periods is not obtained by measurements over only 5 to 10 years, and the variation in ground deformation from one period to another is apparently associated with variation in the seismic activity.

INTRODUCTION

Several lines, 2 to 10 km long, for precise levelings were established in the rift zones of Iceland in 1966-1967 in order to study the vertical component of ground deformation. The result of repeated levelings of these lines have been reported by Tryggvason (1974a) and significant deformation was observed. Two of these lines were releveled in 1976, and in 1980 two lines were also releveled, one of those had been leveled in 1976.

The principal result of the repeated precision levelings in 1966-1973 was that the central axis of each rift zone subsided and the tilt rate of the flanks of the rift zones was roughly 0.5 microradians per year. The rate of subsidence of the central axis of the North Iceland rift zone was crudely estimated as 1 cm per year (Tryggvason, 1974a). An episode of volcanic and tectonic activity in the North Iceland rift zone started in 1975 (Björnsson et al., 1977). This activity caused large scale ground deformation along the Krafla fissure swarm, and the Reykjaheidi leveling line, about 10 km west of this fissure swarm, was certainly within the region where measureable deformation had taken place. Therefore, this line was leveled in 1976 and again in 1980, and also three small tilt arrays which were constructed in 1970 in the vicinity of the Reykjaheidi leveling line.

The Vogar leveling profile on the Reykjanes peninsula showed clear subsidence of the southern part of the profile, relative to its northern part between 1966 and 1971, and also small displacement on a fault between measurements of 1966 and 1968. This fault displacement is believed to have occurred during a large earthquake swarm of late September 1967 (Tryggvason, 1970). Still greater earthquake swarm occurred in the region of this leveling profile in September 1973 and sizeable swarms in January 1972, September 1972, March 1974, December 1974, and December 1975 (Klein et al., 1973, P.D.E.). The high seismic activity of the Reykjanes peninsula after 1971 made it desirable to obtain new leveling data to see some of the effects of the earthquakes on the ground deformation. The Vogar profile was leveled in 1976, and the Búrfellshraun profile, southeast of Hafnarfjördur, was leveled in 1980, but this last profile was leveled every year from 1966 to 1970 without showing significant ground deformation, except a fault displacement of about 1.3 mm on one fault (Tryggvason, 1974b).

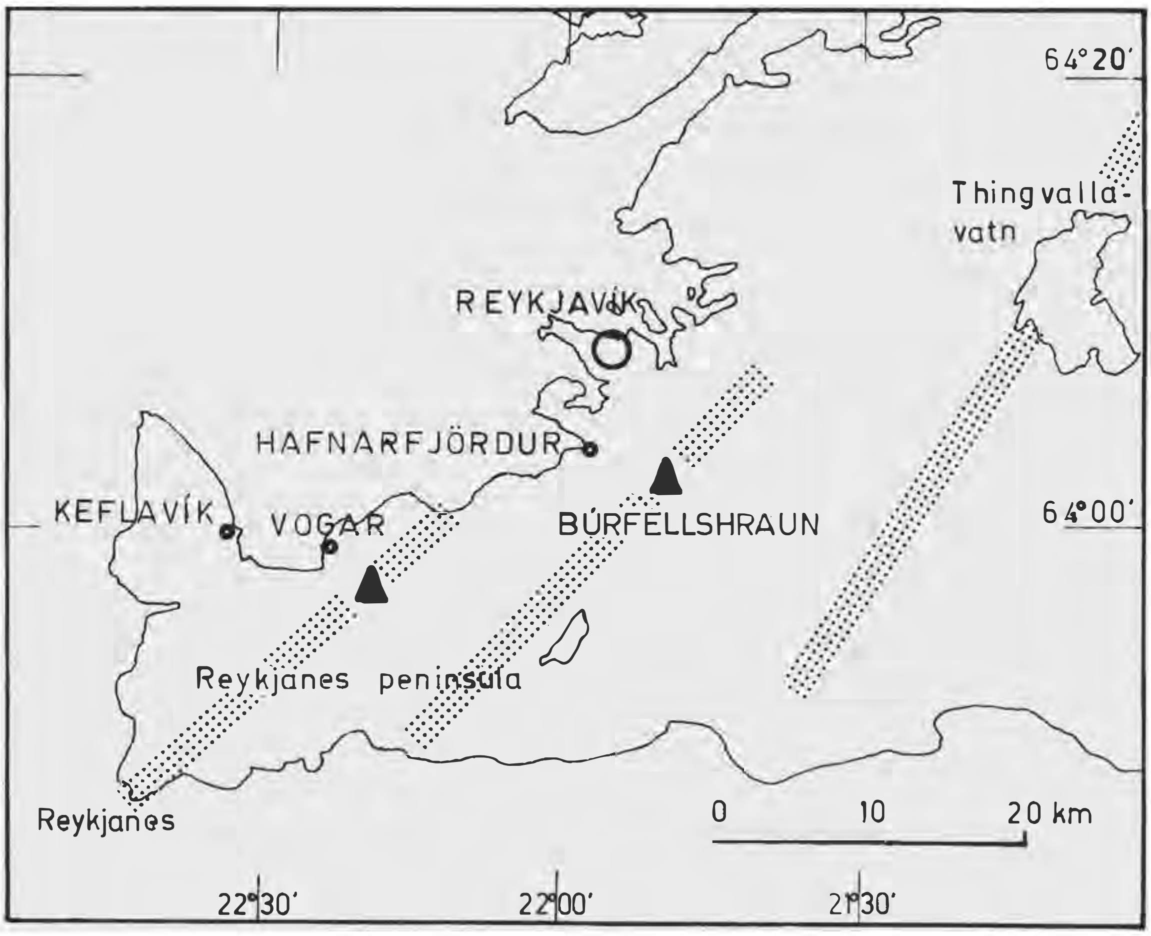

Fig. 1. Southwest Iceland. Filled triangles show the location of the Vogar and Búrfellshraun precision leveling profiles. The major fissure swarms are shaded.

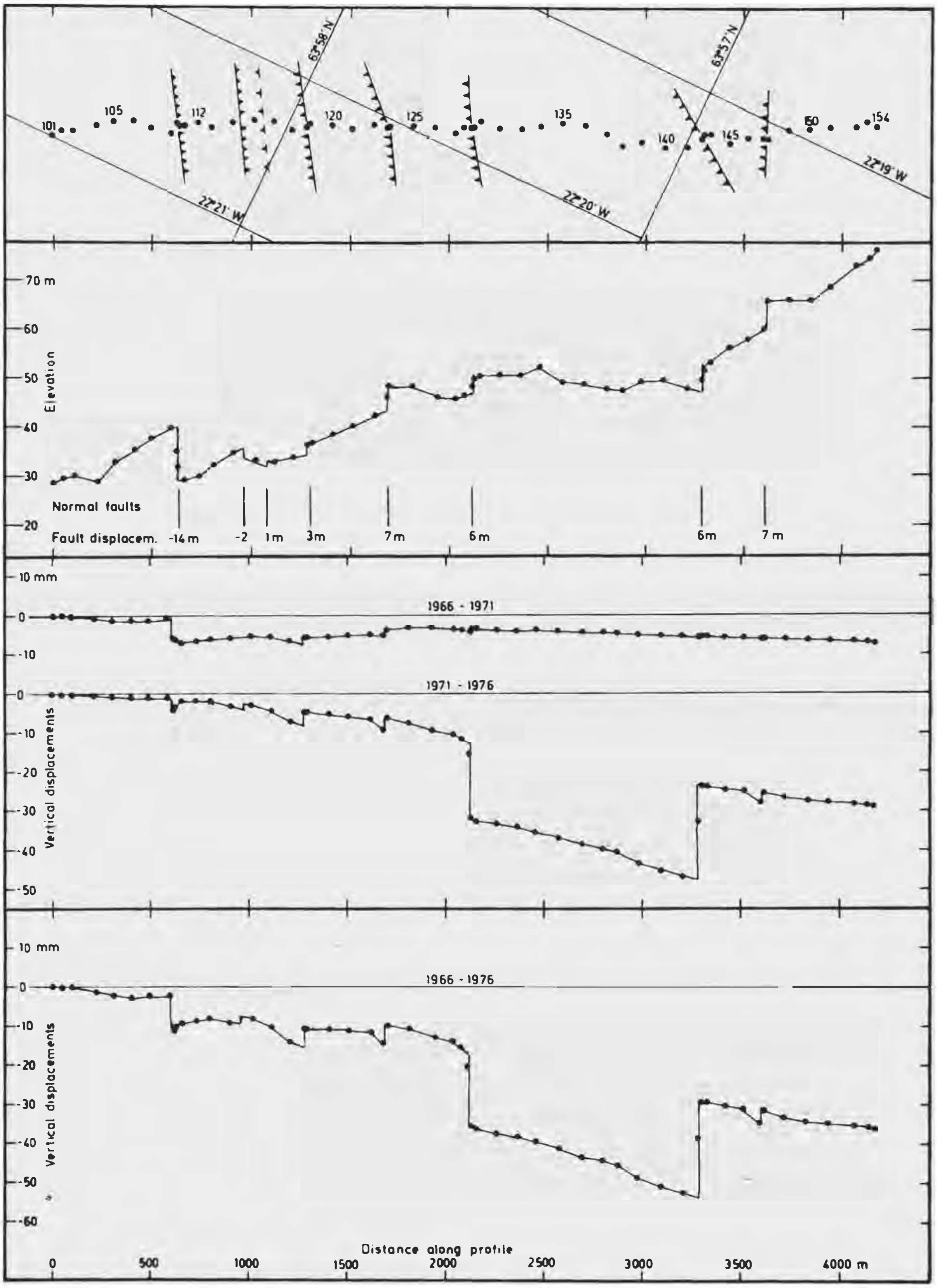

Fig. 2. The Vogar leveling profile. The top part of the illustration shows a map of the profile and elevation above sea level along the profile. The three graphs in the lower part show changes in elevation along the profile for three periods as indicated.

THE VOGAR PROFILE

This precision leveling profile is about 4.5 km long and lies on the Strandarheidi lava to the south of Vogar on the Reykjanes peninsula (Fig. 1). It is near linear and begins with bench mark 101, near the Reykjanes highway about 200 m east of the road to Vogar. From there it lies in direction S25°E. There are 54 permanent markers in the profile (Fig. 2). The first leveling was made in June 1966 and the profile was releveled in June 1968, and July 1971, and a part of the profile was leveled in August 1969. A final leveling was made in June 1976. The results of the four first levelings have been reported in several papers (Tryggvason, 1968, 1970, 1974a, 1974b) but the results of the last leveling has not been reported previously.

The results of the 1966-1971 levelings can be summarized as follows (Tryggvason, 1974b):

(1) A regional tilt occurred which caused the southern part of the profile to subside relative to its northern part. The direction of this tilt is not known, only the tilt component which is parallel to the profile. Tilt rate in this direction was about 0.2 microradians per year during the 1966-1971 period.

(2) Vertical displacement of one fault amounting to about 6.8 mm was observed between levelings of 1966 and 1968.

(3) The immediate area of the displaced fault subsided about 8.7 mm between the 1966 and 1968 levelings.

(4) The area of the displaced fault was again uplifted over a period of a few years after it subsided, and minor displacements were observed on several faults during this relaxation period.

The leveling of 1976 shows the following deformation since 1971 (Fig. 2):

(1) The south end of the profile has subsided about 30 mm relative to the north end, which indicates a regilnal tilt component of about 6.5 microradians in 5 years parallel to the profile, about 6 times higher tilt rate than observed 1967-1971.

(2) Vertical displacement of about 20 mm was observed on two faults, and the 1200 m wide zone between these faults had subsided.

(3) Vertical displacements of 2 to 4 mm was observed on 5 other faults, most of which had shown indication of minor movements before 1971.

All the observed vertical fault displacements can be correlated with fault scarps in the lava. The minor displacements appear to be caused by subsidence of one side of the fault and bending of the down warped block, and the direction of present displacements agrees with the past displacements as indicated by the fault scarps. There is however, one important exception to this rule. The fault at 2100 m (measured from bench mark 101 along the general direction of the profile, Fig. 2) has a definite fault scarp facing NNE in the topography, about 6 m high, but in 1971-1976 the region to the south of this fault subsided about 20 mm.

There is significant difference between the observed deformation 1971-1976 and 1966-1971. The great difference in apparent regional tilt is mentioned above. The area of the displaced faults in 1971-1976 has not subsided noticeable during this last period as was the case in September 1967. This may indicate that tensional movement on the displaced faults was smaller in 1971-1976 than in 1967.

THE BÚRFELLSHRAUN PROFILE

This profile is about 2.0 km long and lies in the lava from the volcano Búrfell, about 7 km southeast of Hafnarfjördur, Southwest Iceland (Fig. 1). The age of the lava Búrfellshraun has been estimated as about 7000 years by C^{14} dating of peat immediately below it (Kjartansson, 1973). The profile follows a lava channel, Búrfellsgjá, and consists of three roughly linear sections (Fig. 3). The direction between the two ends of the profile (BM 259 and 222) is S27°E. The northern part, from BM 259 to 207 (about 900 m) has a direction of roughly S45°E, the central part, from BM 207 to 216 (about 800 m) has a direction of about S8°W and the southern end from BM 216 to 222 (about 200 m) has a direction roughly S60°E.

This profile was leveled in 1966, 1967, 1968, 1969, 1970, and finally in 1980. All levelings were made in the summer, usually in June or July. The results of the levelings in 1966 through 1970 have been reported elsewhere (Tryggvason, 1968, 1974a, 1974b). These results can be summarized as follows:

(1) Between 1966 and 1968 no ground deformation was observed, but individual bench marks moved erratically up to 1.4 mm, indicating imperfect foundations.

(2) A fault displacement of about 1.3 mm occurred between levelings of 1978 and 1979, probably during an earthquake of December 5, 1978 (Tryggvason, 1974b). Furthermore, the south end of the profile subsided about 1.6 mm relative to the north end between levelings of 1978 and 1979.

(3) The south end of the profile was uplifted some 1.7 mm relative to the north end between levelings of 1969 and 1970 so the total deformation between 1968 and 1970 was a small fault displacement on one fault and bending of the ground surface south of the fault, but no movement of the south end of the profile relative to tis north end.

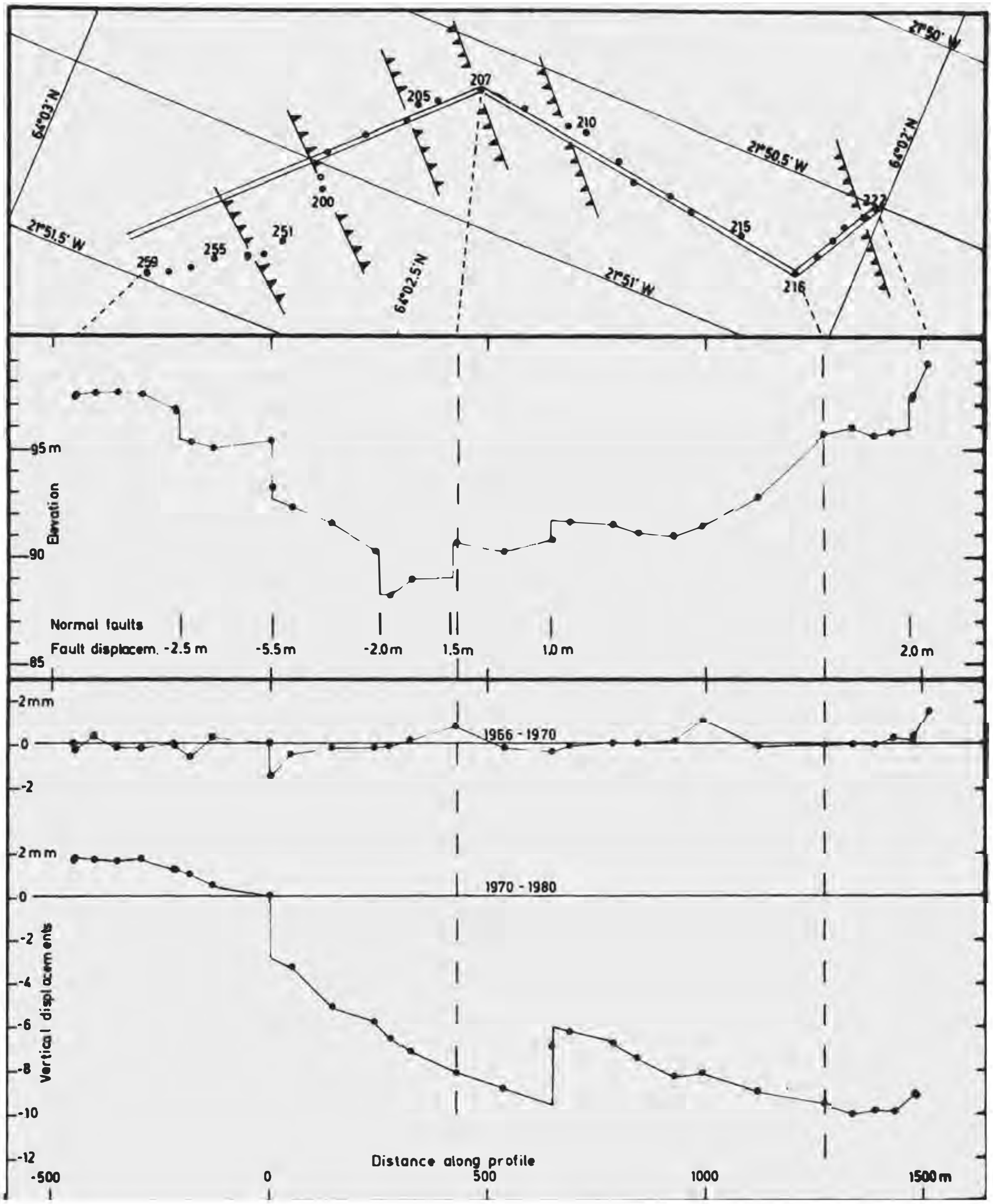

Fig. 3. The Búrfellshraun leveling profile. See Fig. 2 for explanation.

The observed deformation between levelings of 1970 and 1980 (Fig. 3) was a tilt in southerly direction and fault displacement on two faults. The south end of the profile subsided about 11 mm relative to its north end, but this represents an average tilt component in direction S27°E of about 7 microradians. The tilt varies significantly along the profile and the fault displacements make it of no significance to calculate the apparent mean tilt by statistical methods. The fault displacement amounts to about 3 mm on each displaced fault and the 650 m wide zone between these faults has subsided this much relative to the regions outside these faults. No bending of the ground surface near these faults is indicated in these measurements.

There is thus a great difference between the small ground deformation between 1966 and 1970 and the very significant deformation between 1970 and 1980. The average rate of deformation, if this is an acceptable term, is much faster in the last period than in the first period.

THE REYKJAHEIDI PROFILE

This profile is about 3.3 km long in direction W8°N from bench mark 301 at the east end of the profile to 330 at its west end (Fig. 4 and 5). It is located near the old road across Reykjaheidi and the E-W segment of the track from the Reykjaheidi road to Theistareykir. This profile crosses a part of the Theystareykir fissure swarm which is the farthest west of the several fissure swarms in the North Iceland rift zone (Björnsson et al., 1977).

The Reykjaheidi profile was leveled in 1966, 1968, 1970, 1972, 1976, and 1980. The results of the first four levelings were presented by Tryggvason (1974a), and they can be summarized as follows:

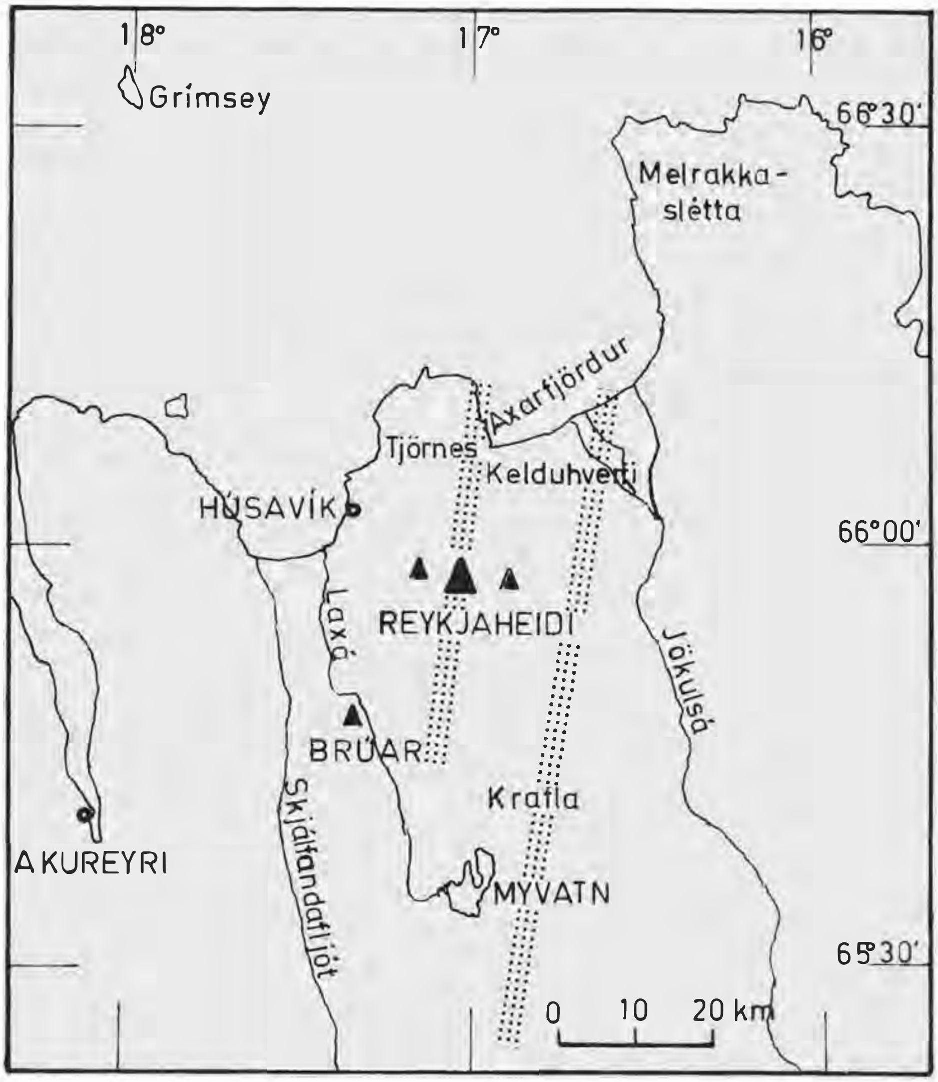

Fig. 4. Eastern North Iceland. Large filled triangle shows the location of the Reykjaheidi precision leveling profile and small triangles show the short tilt profiles on Reykjaheidi and Brúar. The Theistareykir fissure swarm and the Krafla fissure swarm are shaded.

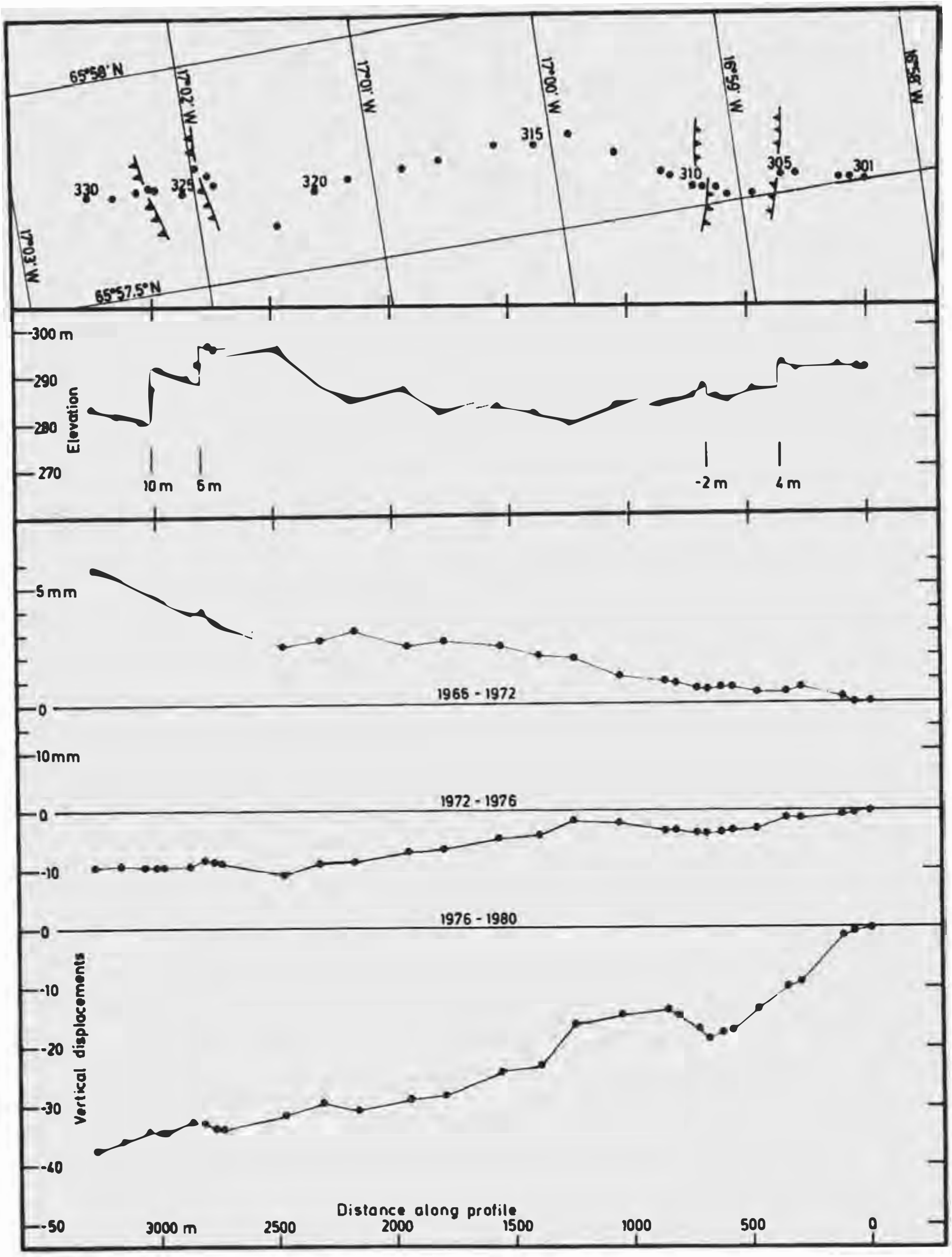

Fig. 5. The Reykjaheidi leveling profile (Reykjaheidi I). See Fig. 2 for explanation. Note that the scale of elevation change 1966-1972 differs by a factor of 4 from the scale of elevation change after 1972.

An eastward tilt dominated although the rate of tilt varied from one two-year period to another. The total tilt over a six-year period was about 2 microradians along the general direction of the profile, or about 0.3 microradians per year on the average. The western part of the profile showed steeper tilt than its central and eastern part.

The leveling of 1976 was made in July, about 7 months after the beginning of the Krafla rifting episode (Björnsson et al., 1977). This rifting episode affects the Krafla fissure swarm (Fig. 4), which is centered about 11 km east of the eastern end of the Reykjaheidi profile. The 1976 leveling showed that the rifting episode of the Krafla fissure swarm had reversed the tilt at the Reykjaheidi leveling profile, and a westward tilt of roughly 3 microradians had occurred since 1972 (Fig. 5). If we assume that the eastward tilt continued until 1975 at the same rate as 1966-1972, 0.3 microradians per year, then the westward tilt from 1975 to 1976 was about 4 microradians.

The rifting episode in the Krafla fissure swarm continued after the 1976 leveling. Distance measurements with a geodimeter showed that the Krafla fissure swarm was widened 3 to 3.5 m in the region east of the Reykjaheidi fissure swarm between April 1978, and late May 1979 (Tryggvason, 1980a). The leveling of the Reykjaheidi profile in July 1980 showed great deformation, obviously associated with the rifting of the Krafla fissure swarm. From 1976 to 1980 the profile showed westward tilt of roughly 13 microradians (Fig. 5). The tilt varied greatly along the profile, as if the earth surface had been wrinkled, but no clear evidence of any fault displacement was seen. This irregularity in the tilt along the profile appears to be caused by the same processes as the tilt, and the greater the observed tilt, the greater are these irregular ground movements, and also the error in the calculated average tilt.

The total westward tilt from 1975 to 1980 is roughly 17 microradians. This much eastward tilt will be observed over a period of 50 years, if tilt rate is as observed 1966-1972.

SHORT TILT PROFILES ON REYKJAHEIDI AND VICINITY

Several short tilt profiles were constructed in 1970 in and near the North Iceland rift zone (Fig. 4). Precise leveling of these profiles was made in 1970 and the first releveling in 1972 and 1973 (Tryggvason, 1974a). Three of these profiles were leveled in 1976 and 1980.

One of these short profiles, Reykjaheidi III, lies about 4 km east of the east end of the Reykjaheidi leveling profile, and some 7 km west of the central axis of the Krafla fissure swarm, near 65°57.7´N, 16°54´W. This is a linear profile, 320 m long in direction E10°N consisting of 5 bench marks (Fig. 6).

Releveling of the profile in 1972 showed no significant tilt in two years. A tilt of 0.8 µ-rad towards west was indicated, but an estimated standard error of tilt on this short profile is about 0.5 to 1.0 µ-rad depending on the average stability of the bench marks.

The 1976 releveling showed significant tilt towards west of about 17 µ-rad since 1972 and the 1980 releveling showed a tilt component of about 75 µ-rad in direction of the profile towards W10°S since 1972.

Another profile, Reykjaheidi II, lies about 4.5 km west of the west end of the Reykjaheidi leveling profile and 18.5 km west of the central axis of the Krafla fissure swarm, near 65°58.2´N, 17°09´W (Fig. 7). This is an irregular leveling profile consisting of 6 bench marks.

The releveling in 1972 showed tilt towards east of about 1 µ-rad in two years, which indicates similar tilt as on the Reykjaheidi leveling profile. The 1976 leveling

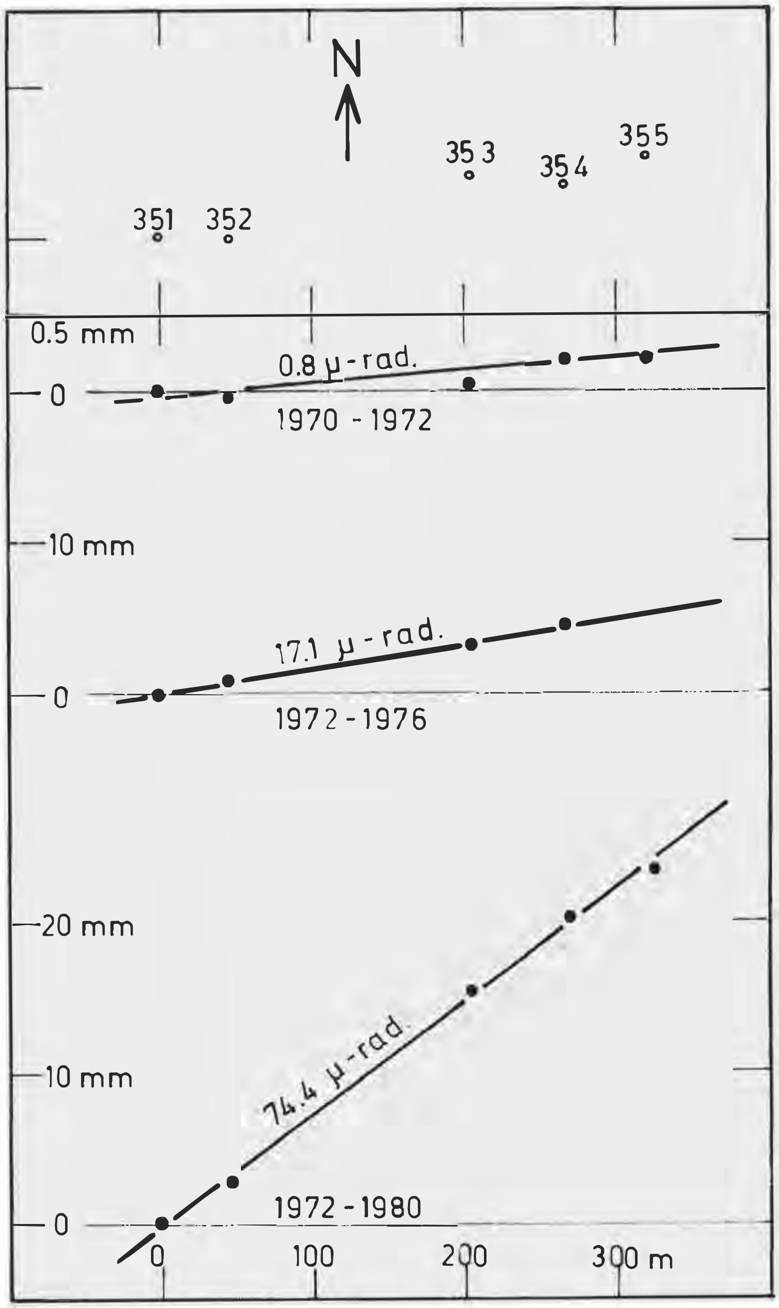

Fig. 6. The Reykjaheidi III short tilt profile at 65°57.7´N, 16°54´W. Top: Map of the profile. Bottom: Vertical displacements relative to bench mark 351. Note that the scale of vertical displacements 1970-1972 differs by a factor of 5 from the scale of displacements after 1972.

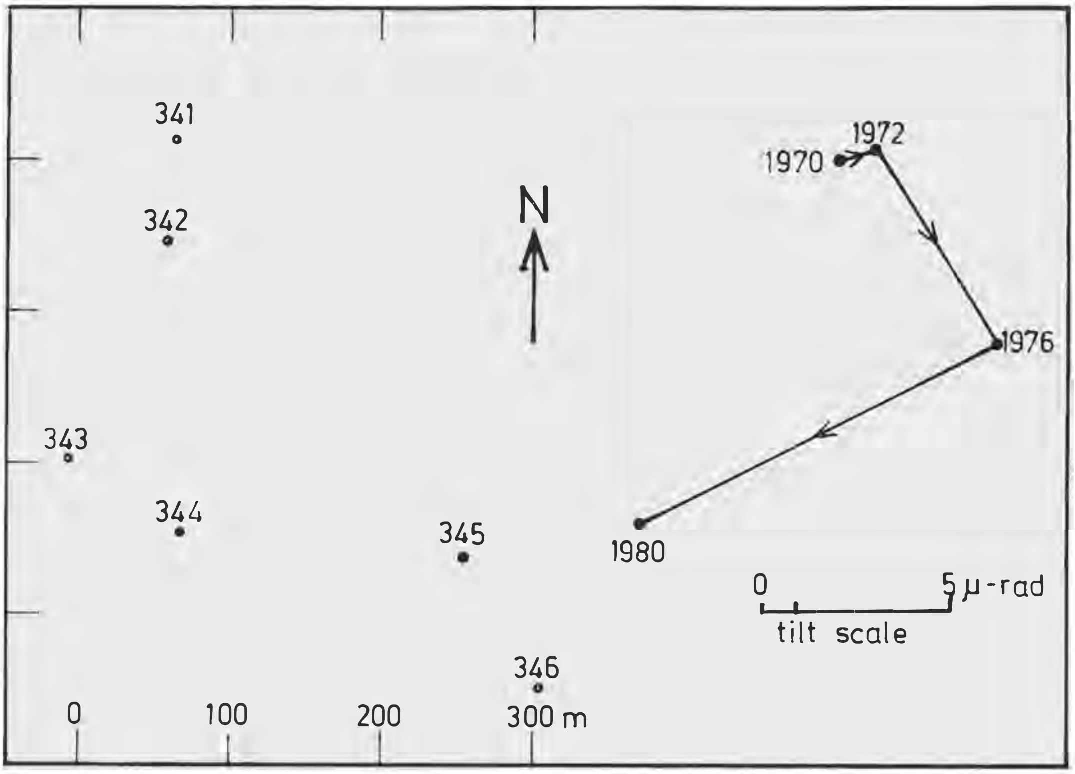

Fig. 7. The Reykjaheidi II short tilt profile at 65°52.8´N, 17°09´W. The left part of the illustration shows a map of the profile and the right part shows observed tilt vectors between observations.

showed a tilt of 6 µ-rad towards SSE between 1972 and 1976, but erratic movement of individual bench marks causes some doubt about the result.

The 1980 leveling showed a tilt of about 10.6 µ-rad towards WSW between 1976 and 1980 and about 11.8 µ-rad towards SW between 1972 and 1980. The standard error of tilt at this station between 1972 and later levelings, is about 1.0 µ-rad, mostly caused by apparently erratic movement of the bench marks amounting to up to 0.5 mm.

A third short tilt profile, Brúar, was leveled in 1970, 1973, 1976, and 1980. This profile was constructed with 13 bench marks (Tryggvason, 1974a), but a portion of it was destroyed by road construction and in 1976 and 1980 only 7 bench marks were observed. Only that part of

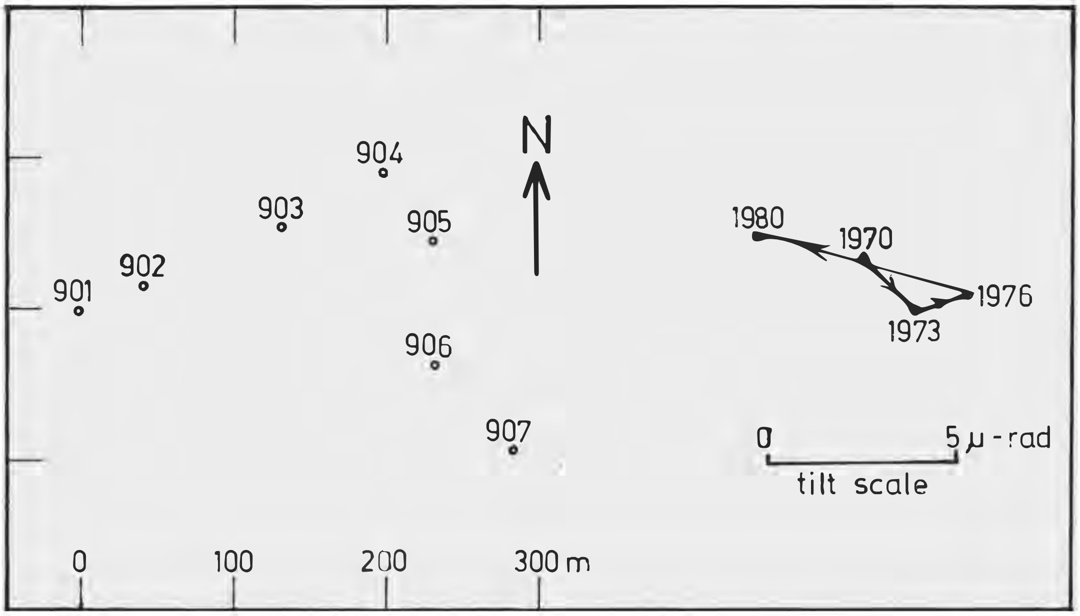

Fig. 8. The short leveling profile Brúar at 65°49.2´N, 17°21´W. See Fig. 7 for explanations.

the profile is considered here (Fig. 8). This profile lies near Laxá at 65°49.2´N, 17°21´W, about 26 km west of the central axis of the Krafla fissure swarm.

The observed tilt between 1970 and 1973 was about 2.1 μ-rad towards southeast and a further eastward tilt of 1.3 μ-rad was observed between 1973 and 1976. Thus the rifting episode in the Krafla fissure swarm appears not to have affected this profile measurably before the summer of 1976.

The leveling of 1980 showed definite tilt of about 5.8 μ-rad towards WNW since 1976 and 4.7 μ-rad towards WNW since 1973. This shows that the uplift of the flanks of the Krafla fissure swarm, associated with the rifting which started in 1975, is observed in this leveling profile.

DISCUSSION OF THE OBSERVED DEFORMATION ON THE REYKJAHEIDI TILT AND LEVELING PROFILES

The eastward tilt observed in this area before 1973 (Tryggvason, 1974a) can be interpreted in terms of subsidence along the central axis of the North Iceland rift zone. If we take this central axis to follow the Krafla fissure swarm in this region, then the maximum tilt rate of roughly 0.5 μ-rad/year is observed 10 to 15 km west of the axis of subsidence. This distance is quite uncertain as the axis of subsidence may not follow the Krafla fissure swarm, and the fact that no tilt was recorded at the short tilt profile Reykjaheidi III, some 7 km west of the Krafla fissure swarm may be taken to indicate that the axis of subsidence is west of the Krafla fissure swarm, and that maximum tilt rate is found 5 to 10 km west of the axis of subsidence.

A model which accounts for this subsidence could possibly be as follows:

The earth´s crust is pulled in east-west direction by forces acting on the bottom of the crust. The effect of this stretching on the vertical component of surface deformation is considered to be approximately the same as if the pressure decreases in a horizontal tube laying near the bottom of the elastic crust, in the direction of the rift zone. This deformation can be crudely estimated by integrating the "Mogi equation" (Mogi, 1958) for surface deformation caused by pressure variation in a point source within an elastic half space. The vertical displacement Δh is then a function of the tube depth H, and the horizontal distance from the tube X, as follows

$$\Delta h = \Delta h_o \frac{H^2}{H^2+X^2} \qquad (1)$$

where Δh_o is the vertical displacement of the ground surface vertically above the tube.

The tilt τ of the ground surface is then given by:

$$\frac{d(\Delta h)}{dX} = \tau = 2\Delta h_o \, H^2 \, \frac{X}{(H^2+X^2)^2} \qquad (2)$$

The maximum tilt rate is found at a horizontal distance from the tube of $H/\sqrt{3}$. If the maximum tilt rate is found at horizontal distance somewhere between 5 and 15 km from the tube, the depth of the tube should lie between 9 and 26 km.

Taking the maximum tilt rate to be 0.5 μ-rad/year, the maximum subsidence rate can be obtained from equations (1) and (2), and also the rate of increase of the cross sectional area of the subsidence trough.

If the depth H is 10 km, the maximum rate of subsidence is 7.7 mm/year and cross sectional area of the subsidence trough is 242 m^2 per year.

If the depth H is 15 km, the maximum rate of subsidence is 8.7 mm/year and cross sectional area of the subsidence trough is 544 m^2 per year.

If the depth H is 20 km, the maximum subsidence rate is 11.5 mm/year and the cross sectional area of the subsidence trough is 967 m^2 per year.

Thus the tilt observed before 1973 on Reykjaheidi indicates that the axis of the North Iceland rift zone subsided at a rate of 7 to 12 mm per year and the increase of the cross sectional area of the subsidence trough was 200 to 1000 m per year.

Consider the annual cross sectional area of the subsidence trough to be equal the product of the thickness of the elastic crust and the annual rate of spreading at the plate boundary. The average spreading rate as determined from magnetic stripes to the north and south of Iceland is 1.0 cm per year (Talwani et al., 1971, Meyer et al., 1972). This means that the widening of the rift zone is 2.0 cm/year as a long time average. The thickness of the elastic crust in the rift zone of Iceland is poorly known but magnetotelluric observations show a low resistivity layer at roughly 10 km depth (Beblo & Björnsson, 1980). This low resistivity layer is interpreted as partially molten basalt below the elastic crust.

The product of the thickness of the elastic crust (about 10000 m) and the average annual widening of the rift zone (0.02 m) is then about 200 m^2.

If the cross sectional area of the annual subsidence trough is also about 200 m^2, and the equations (1) and (2) above are approximately correct, the average subsidence rate in the axis of subsidence is most likely 7 to 8 mm/year, and maximum tilt is found 4 to 7 km outside the axis of the subsidence zone. This would require the central axis of the subsidence zone in 1966-1972 to be located no more than 2 km east of the east end of the Reykjaheidi profile.

Levelings of 1976 and 1980 show that the tilt in the area of the Reykjaheidi profiles and Brúar, associated with the rifting episode which started in 1975, was towards west, or uplift towards the active Krafla fissure swarm. The very steep tilt at the short tilt profile Reykjaheidi III, which lies closest to the active fissure swarm, shows that the source of this deformation lies at much shallower depth than the source of previous deformation.

If we accept the same model as above, with a horizontal tube of changing volume, located below the central axis of the Krafla fissure swarm, the best correlation between calculated and observed tilt it found if the depth of the tube is about 4.5 km. This correlation does not deteriorate significantly if we move the hypothetical tube one km up or down, but larger shift will make the correlation significantly worse.

The increase of cross sectional area of this hypothetical tube, which accounts for the observed tilt between 1975 and 1980 is between 15000 and 20000 m^2.

As observations are made at distances of 7 to 26 km from the axis of the active fissure swarm, the observational restrains of the model are very limited. A model of expanded vertical plate (dike) of about the same cross sectional area and centered at the depth of 4.5±1 km will give very similar tilt at the observed locations.

It has been postulated that the magma which has escaped from the Krafla magma chamber since 1975 has been deposited in a dike along the Krafla fissure swarm (Björnsson et al., 1979). The thickness of this dike is probably similar to the widening of the fissure swarm. This widening is observed as about 3.5 m between April 1978 and May 1979 in the vicinity of the Reykjaheidi leveling and tilt profiles (Tryggvason, 1980a), and additional widenings occurred in this area in December 1975, and January 1978. It is therefore sensible to estimate the width of the dike as 4 to 5 m. The height of the dike to make a cross sectional area of 15000 to 20000 m^2 is then 3 to 5 km. As this dike is centered at 4.5±1 km depth, the top of the dike should lie between 1 and 4 km depth.

If the cross sectional area of the dike of 15000 to 20000 m^2 can be accepted as an average for the whole length of the presently active part of the Krafla fissure swarm of about 80 km, the total volume of the dike formed in 1975-1980 is about 1.2 to 1.6 km^3. This should also be an approximate value for the volume of magma which has flowed out of the Krafla magma chamber during the present episode of activity. This volume estimate is roughly twice as high as earlier estimates which were based on the subsidence bowl formed in the Krafla area during each subsidence event (Tryggvason, 1980b).

Several observations support the assumption that the Reykaheidi observations are representative for the whole length of the active part of the Krafla fissure swarm, as repeated levelings across the fissure swarm in Kelduhverfi about 15 km north of the Reykjaheidi profiles (Sigurdsson, 1980) as well as in the Mývatn area 35 km south of the Reykjaheidi profiles (Spickernagel, 1980).

The present indication that the total volume of the newly formed dikes is about twice as much as the cumulative volume of the subsidence bowls formed during the

Krafla subsidence events is supported by the relation between gravity variations and height variation above the magma chamber. This relation shows that the mass added to or taken from the Krafla area is considerably greater than the added or decreased volume multiplied by the rock density (Johnsen et al., 1980). This means that the volume of magma which leaves the Krafla magma chamber is greater by a factor of possible 2 than the volume change of the magma chamber. Thus pressure changes is the magma chamber and associated contraction and expansion of the magma accounts for roughly 50% of the moving magma. If the bulk modulus of the magma is known and also pressure change associated with certain volume change the total volume of the Krafla magma chamber can be crudely estimated.

The variation in pressure in the magma reservoir during inflation and deflation of the Krafla volcano has been estimated as 0.44 MPa for 10^6 m^3 increase or decrease of the inflation bulge (Tryggvason, unpublished). Taking the volume increase of the magma reservoir to be equal the volume increase of the inflation bulge, and the bulk modulus of the magma 14 GPa (Blake, 1981), then the volume V of the magma reservoir is given by:

$$V = \frac{14\cdot 10^9}{0.44\cdot 10^6} \cdot 10^6 \text{ m}^3 = 3.2\cdot 10^{10} \text{ m}^3 \; (= 32 \text{ km}^3) \qquad (3)$$

if $2\text{x}10^6$ m^3 of magma injection is required to increase the volume of the magma by 10^6 m^3.

DISCUSSION OF GROUND DEFORMATION IN SOUTHWEST ICELAND

The observed deformation of the Vogar profile on the Reykjanes peninsula 1971-1976 and the Búrfellshraun profile southeast of Hafnarfjördur 1970-1980 is much greater than had been observed 1966-1971 and 1966-1970, respectively. This shows that the rate of ground deformation varies greatly from one period to another, and that measurements over a period of 5 to 10 years may not at all indicate what is the average rate of deformation over longer periods.

The fault displacements observed on these profiles in 1971-1976 and 1970-1980 respectively, differs greatly from the fault displacements observed before 1970. During the earlier period only one fault on each profile had been displaced significantly, and the downwarped side of the fault was bended in such a way that the displacement was only observed on a short segment (∿1 km) of each profile. During the latter period two faults on each profile had been displaced and a narrow strip (1.2 km and 0.6 km respectively) between the faults had subsided without noticeable bending of the ground surface.

It has been argued (Tryggvason, 1970, 1974b) that the observed fault displacements before 1970 were associated with earthquakes, the Reykjanes earthquake swarm of September 1967, and an earthquake of December 5, 1968. The fault displacements after 1970 are most certainly also associated with earthquakes. As the displacements observed after 1970 are much greater than those observed before 1970, the associated earthquakes or earthquake swarms were probably greater also.

A number of significant earthquake swarms occurred on the Reykjanes peninsula between 1970 and 1980 but the largest earthquakes occurred in the swarm of September 1973, with two earthquakes exceeding magnitude 5 (P.D.E.) Swarms of November 1970, November 1971, January 1972, March 1974, December 1974, December 1975, and May 1977 had largest earthquake of magnitude 4.5 to 4.8 according to the same source. Although any of these earthquake swarms can possibly be responsible for fault displacements on one or both leveling profiles, and possibly also other swarms as that of September 1972 (Klein et al., 1977), the earthquake swarm of September 1973 is the most likely cause of fault displacement on both leveling profiles, because of the size of the largest earthquakes. However, the earthquake swarm of December 1975 originated near Kleifarvatn (Páll Einarsson, pers.comm.) on the fissure swarm which goes through the Búrfellshraun profile. Therefore, this swarm may possibly have caused the observed fault displacement on the Búrfellshraun profile.

It is clear, that more frequent levelings are needed to obtain with certainty which ground deformation is caused by each earthquake or earthquake swarm on the leveling profiles in Southwest Iceland.

CONCLUSIONS

The precision leveling of several leveling and tilt profiles on Reykjaheidi and vicinity in 1976 and 1980 show that the ground deformation associated with the present Krafla rifting episode can be observed up to a distance of 26 km from the central axis of the Krafla fissure swarm. The ground tilt during this episode is roughly opposite in direction to that observed over several years before the rifting episode, and the magnitude of tilt from 1975 to 1980 is approximately equal to that expected over 50 years period before the episode, if observations 1966-1972 give representative tilt rate.

Tilt observations in Southwest Iceland show, however, that tilt observations over a few years do not give representative tilt rates, and the rate over two consecutive periods of 5 to 10 years each may differ by a factor of 5 or more.

ACKNOWLEDGEMENTS

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REFERENCES

Beblo, M., and A. Björnsson, A model of electrical resistivity beneath NE-Iceland, correlation with temperature, J. Geophys. 47, 184-190, 1980.

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

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

Blake, S., Volcanism and the dynamics of open magna chambers, Nature 289, 783-785, 1981.

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

Kjartansson, G., The Búrfellshraun lava flow and its age, Náttúrufraedingurinn 42, 159-183, 1973.

Klein, F.W., P. Einarsson, and M. Wyss, The Reykjanes peninsula, Iceland, earthquake swarm of September 1972 and its tectonic significance, J. Geophys. Res. 82, 865-888, 1977.

Meyer, O., D. Voppel, U. Fleischer, H. Closs, and K. Gerke, Results of bathymetric, magnetic and gravimetric measurements between Iceland and 70°N, Deutsche Hydrograph. Zeitsch. 25, 193-201, 1972.

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

P.D.E., Preliminary determination of epicenters, U.S. Department of the Interior, Geological Survey.

Sigurdsson, O., Surface deformation of the Krafla fissure swarm in two rifting events, J. Geophys. 47, 154-159, 1980.

Spickernagel, H., Results of height measurements in northern Iceland 1965-1977, J. Geophys. 47, 120-124, 1980.

Talwani, M., C.C. Windisch, and M.C. Langseth, Jr., Reykjanes ridge crest: A detailed geophysical study, J. Geophys. Res. 76, 473-517, 1971.

Tryggvason, E., Measurement of surface deformation in Iceland by precision leveling, J. Geophys. Res. 73, 7039-7050, 1968.

Tryggvason, E., Surface deformation and fault displacement associated with an earthquake swarm in Iceland, J. Geophys. Res. 75, 4407-4422.

Tryggvason, E., Vertical crustal movement in Iceland, in: Kristjansson (ed.), Geodynamics of Iceland and the North Atlantic area, 241-262, D. Reidel Publ. Co., Dordrecht-Holland, 1974a.

Tryggvason, E., Fault displacement and ground tilt during small earthquakes, in: Thoft-Christensen (ed.), Continuum Mechanics Aspects of Geodynamics and Rock Fracture Mechanics, 255-269, D. Reidel Publ. Co., Dordrecht-Holland, 1974b.

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

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