NORDIC VOLCANOLOGICAL INSTITUTE 8304
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THE WIDENING OF THE KRAFLA FISSURE SWARM DURING THE 1975 - 1981 VOLCANO-TECTONIC EPISODE

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ABSTRACT

Frequent distance measurements across the Krafla fissure swarm, North Iceland, show the amount of widening during the sequence of rifting events which started in December, 1975, and lasted for 6 years.

An 80 to 90 km long section of the fissure swarm has widened during this sequence of rifting and volcanic events. Maximum widening of about 8 m occurred 10 to 12 km north of the center of the Krafla magma reservoir, which is located below Leirhnjúkur. From that location, the widening decreases northwards, and is estimated to exceed 2 m where the seismicity indicates the northern termination of the present rifting, off the north coast, about 70 km north of Leirhnjúkur. The widening also decreases southwards and approaches zero at 15 to 20 km south of Leirhnjúkur.

The ground deformation associated with these rifting events can be described briefly as follows:

A narrow strip, usually one to two km wide, along the fissure swarm is heavily fractured with numerous open fissures parallel to the fissure swarm. This fractured strip has subsided some 2 to 3 m relative to the flanks of the rifted zone.

The flanks of the fractured zone have been uplifted relative to regions farther away. This uplift is not well determined, but tilt observations at several locations indicate about one meter uplift. The flanks of the rifted zone have been contracted, perpendicular to the fissure swarm. The maximum contractional strain exceeds 20 cm per km.

The total area of expansion (widening of the fissure swarm, times the length of the widened zone) during these rifting events is estimated as about 0.38 square kilometers. For individual events, the area of expansion has been roughly proportional to the volume of the subsidence bowl above the Krafla magma chamber.

The ratio of the volume of the subsidence bowl to the area of expansion for the best observed events, indicates a height of the hypothetical new dike as 2.4 to 2.8 km, if the width of the dike is equal widening of surface fissures. This ratio is significantly less for events of great lava production, but even in these events, majority of the magma leaving the magma reservoir was deposited in subsurface fissures.

INTRODUCTION

A major rifting episode on the plate boundary in north Iceland started in December 1975, and continued for about 6 years. This rifting episode affected one of the several fissure swarms which constitute the boundary between the European and the North American crustal plates in north Iceland (Saemundsson, 1978), the Krafla fissure swarm, between about 65° 34′ N and 66° 18′ N (Fig. 1). The two flanks of the Krafla fissure swarm have moved away from from each other in about 20 discrete rifting events, and each rifting event has affected only a portion of the 85 to 90 km length of the fissure swarm which was affected by this sequence of events (Björnsson et al., 1979, Tryggvason, 1980a). The clearly observable effect of these rifting events is opening of new and old fissures in the ground, and vertical displacements on a few faults. Most of the obvious fissure movements occurred along a 1 to 2 km wide zone within the 4 to 8 km wide Krafla fissure swarm, and the vertical displacements indicate relative subsidence of this zone of fissure widening.

Each of the rifting events is accompanied by subsidence or deflation of a roughly circular region centered near Leirhnjúkur, a small hill in the central area of the Krafla caldera. The subsidence bowl has a form that closely resembles that predicted by Mogi (1958) for pressure drop within a small spherical region at depth within an elastic half space. The depth to this hypothetical point source is about 3 km. (Björnsson et al., 1979, Tryggvason, 1980a).

The rifting events are also accompanied by sizable earthquake swarms, located within or near the section of the Krafla fissure swarm, where rifting occurs (Einarsson and Brandsdóttir, 1980), and basaltic lava eruptions occurred during several of these events (Björnsson et al., 1977, Grönvold and Saemundsson, 1981, 1982).

The present rifting episode resembles closely another episode 250 years earlier at the same location. This earlier episode started in May, 1724 and several rifting events occurred in 1725, 1727, 1728, and 1729. Contemporary records describe only events which were accompanied by strongly felt earthquakes or eruptions (Thoroddsen, 1925), but comparison with the present episode strongly suggest that several rifting events may have occurred without being recorded. The limited description of the ground fissuring during the 1724-1729 episode indicates that rifting extended somewhat farther towards south, than during the present episode, but probably not as far towards north.

Another similar episode occurred in 1874-1875 in the Askja fissure swarm (Fig. 1). The duration of that rifting episode is not known, but rifting of the northern part of the Askja fissure swarm is reported in the fall of 1874 (Gudmundsson, 1972) and lava eruptions occurred several times in February through August, 1875 (Thoroddsen, 1925). These lava eruptions were located 40 to 65 km north of the central volcano Askja, and rifting may have extended to about 80 km north of Askja. How far south the rifting extended is not known, but violent eruption occurred in Askja in March, 1875.

Still another rifting episode occurred in North Iceland in 1618, with frequent earthquakes on the north coast in the fall and early winter. Large ground fissures were observed, probably near 66° 10′N, 17° 0′W (Thoroddsen, 1925). No eruption was reported, but location of ground fissures indicates that rifting occurred on the northern part of

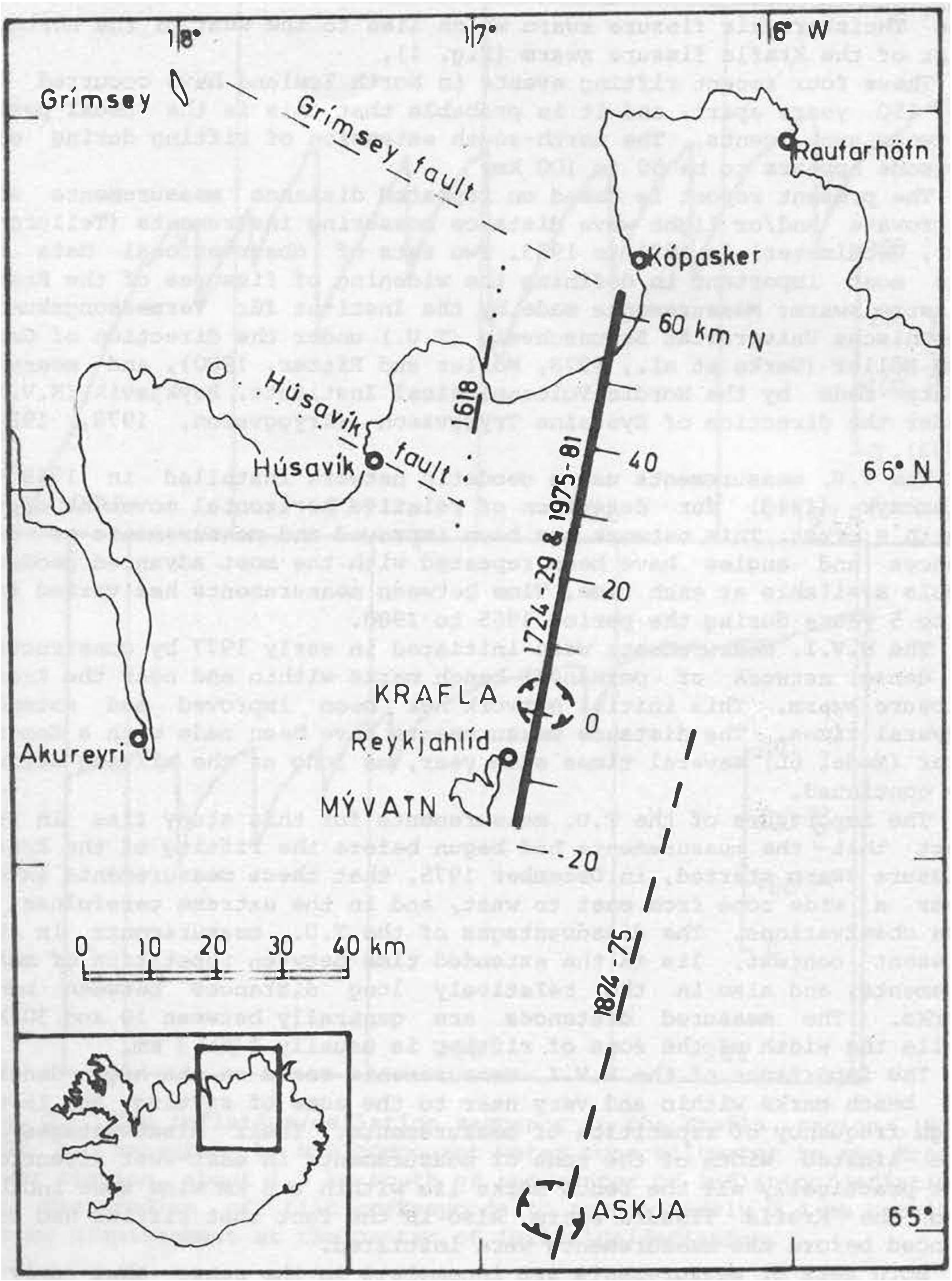

Fig. 1. Location map showing the Krafla fissure swarm, where rifting occurred in 1724-1729 and 1975-1981, the Askja fissure swarm where rifting occurred in 1874-1875, and the Theistareykir fissure swarm where rifting occurred in 1618. Also is shown the approximate location of the Grímsey fault and the Húsavík fault. Distance scale along the Krafla fissure swarm has its origin at the center of inflation/deflation near Leirhnjúkur, and it is identical to the distance scale of Figs 9 through 20.

the Theistareykir fissure swarm which lies to the west of the northern part of the Krafla fissure swarm (Fig. 1).

These four recent rifting events in North Iceland have occurred 100 to 150 years apart, and it is probable that this is the usual period between such events. The north-south extension of rifting during each episode appears to be 50 to 100 km.

The present report is based on repeated distance measurements with microwave and/or light wave distance measuring instruments (Tellurometer, Geodimeter) in 1971 to 1983. Two sets of observational data are the most important in defining the widening of fissures of the Krafla fissure swarm: Measurements made by the Institut für Vermessungskunde, Technische Universität Braunschweig (T.U.) under the direction of Gerke and Möller (Gerke et al., 1978, Möller and Ritter, 1980), and measurements made by the Nordic Volcanological Institute, Reykjavik (N.V.I.) under the direction of Eysteinn Tryggvason (Tryggvason, 1978, 1980b, 1983).

The T.U. measurements use a geodetic network installed in 1938 by Niemczyk (1943) for detection of relative horizontal movement of the earth's crust. This network has been improved and measurements of distances and angles have been repeated with the most advanced geodetic tools available at each time. Time between measurements has varied from 2 to 5 years during the period 1965 to 1980.

The N.V.I. measurements were initiated in early 1977 by constructing a dense network of permanent bench marks within and near the Krafla fissure swarm. This initial network has been improved and extended several times. The distance measurements have been made with a Geodimeter (Model 6L) several times each year, as long as the rifting activity continued.

The importance of the T.U. measurements for this study lies in the fact that the measurements had begun before the rifting of the Krafla fissure swarm started, in December 1975, that these measurements extend over a wide zone from east to west, and in the extreme carefulness of the observations. The disadvantages of the T.U. measurements in the present context, lie in the extended time between repetition of measurements, and also in the relatively long distances between bench marks. The measured distances are generally between 10 and 30 km, while the width of the zone of rifting is usually 1 to 3 km.

The importance of the N.V.I. measurements rests on the high density of bench marks within and very near to the zone of rifting, and in the high frequency of repetition of measurements. Their disadvantages is the limited width of the zone of measurements in east-west direction, but practically all the bench marks lie within a 8 km wide zone including the Krafla fissure swarm. Also in the fact that rifting had commenced before the measurements were initiated.

Both sets of measurements are incomplete in the sense that only a fraction of the north-south extent of the active zone of rifting is covered by the observations.

A few measurements of Orkustofnun (National Energy Authority), Reykjavik, made by geodimeter or tape measurements of new fissures (Björnsson et al., 1977, 1979, Sigurdsson, 1980) are incorporated into the present study, as they cover other localities or time spans than the T.U. and N.V.I. observations.

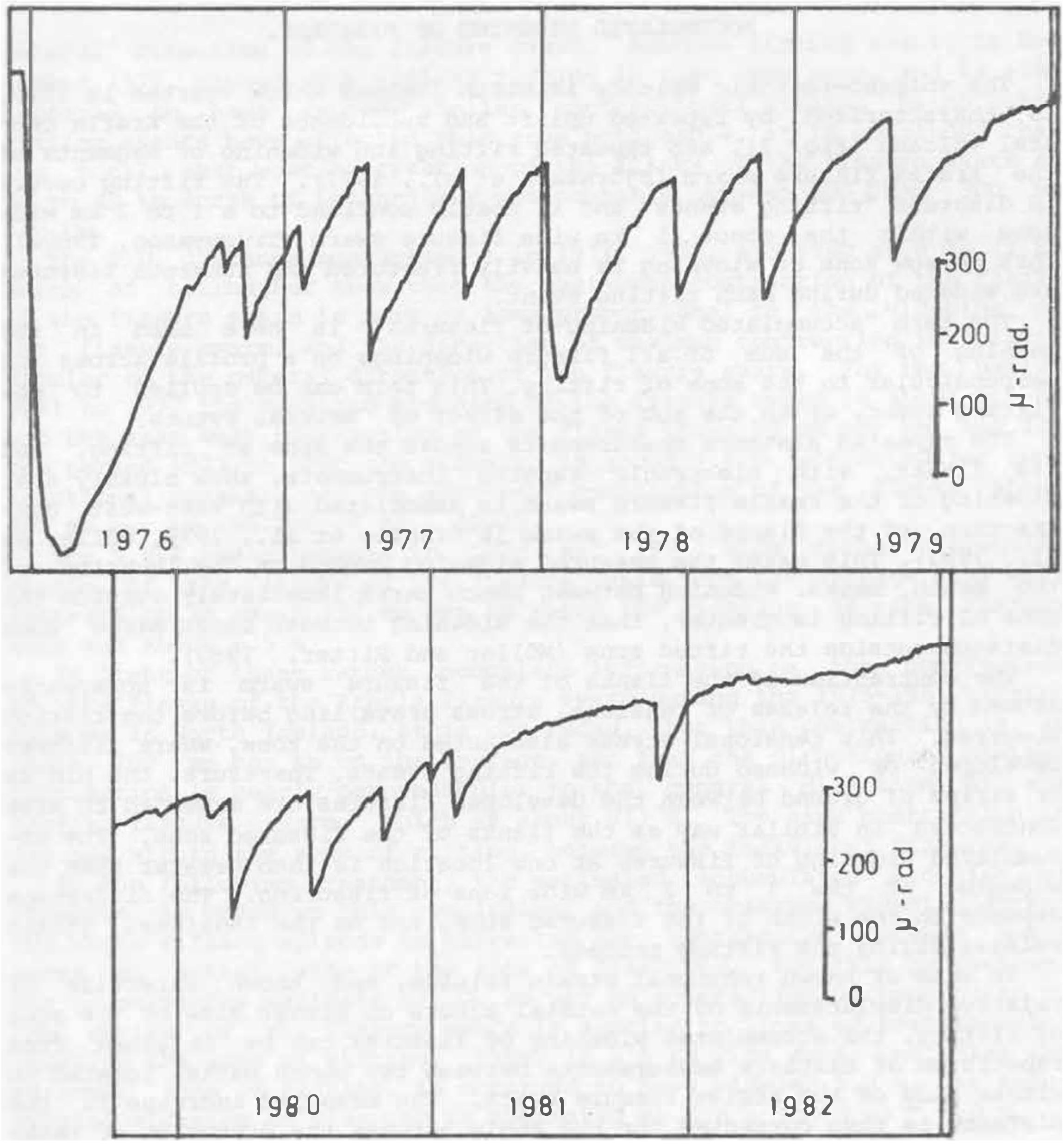

Fig. 2. The inflation/deflation sequence in the Krafla region 1975-1982 as measured by N-S component water tube tiltmeter in the Krafla power station, about 1.5 km south of the center of inflation/deflation. One microradian of tilt corresponds to approximately 3.4 mm vertical ground displacement at the center of inflation/deflation.

ACCUMULATED WIDENING OF FISSURES.

The volcano-tectonic episode in North Iceland which started in 1975, is characterized by repeated uplift and subsidence of the Krafla central volcano (Fig. 2), and repeated rifting and widening of segments of the Krafla fissure swarm (Björnsson et al., 1977). The rifting occurs in discrete "rifting events" and is mostly confined to a 1 to 2 km wide zone within the about 5 km wide fissure swarm (Tryggvason, 1980a). This narrow zone of widening is heavily fractured and numerous fissures are widened during each rifting event.

The term "accumulated widening of fissures" is here used in the meaning of the sum of all fissure widenings on a profile across and perpendicular to the zone of rifting. This term can be applied to one rifting event, or to the sum of the effect of several events.

The repeated distance measurements across the zone of rifting, and its flanks, with electronic ranging instruments, show clearly that widening of the Krafla fissure swarm is associated with east-west contraction of the flanks of the swarm (Björnsson et al., 1979, Möller et al., 1982). This makes the measured widening depend on the location of the bench marks. Widening between bench marks immediately outside the zone of rifting is greater, than the widening between bench marks some distance outside the rifted zone (Möller and Ritter, 1980).

The contraction of the flanks of the fissure swarm is apparently caused by the release of tensional stress prevailing before the rifting occurred. This tensional stress also acted on the zone, where fissures developed or widened during the rifting events. Therefore, the blocks or strips of ground between the developed fissures are expected to have contracted in similar way as the flanks of the fissured zone. The accumulated widening of fissures at one location is then greater than the widening of the 1 to 2 km wide zone of fissuring. The difference depends on the width of the fissured zone, and on the tensional strain release during the rifting process.

In case of known tensional strain release, and known direction of relative displacements of the crustal blocks on either side of the zone of rifting, the accumulated widening of fissures can be obtained from repetition of distance measurements between two bench marks, located on either side of the active fissure swarm. The measured increase in the distance is then corrected for the angle between the direction of relative displacements and the direction of the line connecting the bench marks, and also for the tensional strain release in the area between the bench marks.

CONTRACTION OF THE FLANKS OF THE FISSURE ZONE.

The magnitude of the contraction of the flanks of the Krafla fissure swarm during the 1975-1981 rifting episode, can be estimated from numerous repetitions of distance measurements. A few examples are given below.

Distance measurements before and after the January 1978 rifting event, at a location about 38 km north of Leirhnjúkur, show about 2.5 m widening of a 7.5 km wide zone, but contraction of 100 to 150 mm per km immediately outside this zone (Sigurdsson, 1980). This result is based on a single line of measurements, oriented nearly perpendicular to the general direction of the fissure swarm. Another rifting event, in December 1975, caused very similar rifting in that same area, and is also expected to have caused similar contractional strain. As no other rifting events have affected this area noticeable, it is concluded that the total east west contraction of the flanks of the fissure swarm at 30 to 40 km north of Leirhnjúkur was probably between 200 and 300 mm per km.

The T.U. distance measurements in 1971, 1977, and 1980 at 8 to 12 km north of Leirhnjúkur show that the east-west contraction of the flanks of the fissure swarm is more or less proportional to the widening of the fissure swarm, and the direction of maximum contraction is perpendicular to the general direction of the fissure swarm. For the period 1971 to 1977 the measured widening of the fissure swarm is about 2.5 m, and the east west contraction of the flanks about 50 mm per km, and for the period 1971 to 1980 the widening is about 7.8 m (corrected for contractional strain), and the east-west contraction of the flanks about 300 mm per km (Mōller et al., 1982).

The N.V.I. measurements in 1978 and 1981 show rather irregular strain of the flanks of the fissure swarm, but the average east-west contraction is about 150 mm per km where the widening of the fissure zone was about 5.5 m

In light of these rather incomplete information on the contraction of the flanks of the Krafla fissure swarm during the 1975-1981 rifting episode in North Iceland, it is concluded, that this contraction is at least 200 mm per km on the average, and that the direction of maximum contraction is nearly perpendicular to the general direction of the Krafla fissure swarm, which is about N11°E. The same contraction is assumed within the zone of rifting, between the individual fissures.

In the following treatment, the estimated accumulated widening of fissures is based on this conclusion, and the observed widening during the whole rifting episode is corrected for contraction between bench marks on either side of the zone of fissuring. For this correction, the conservative estimate of 200 mm per km contraction perpendicular to the strike of the fissure swarm is applied to lines of measurements, crossing the zone of rifting. Thus, if a 5 km wide zone, including the narrower zone of rifting, is observed to have widened 5.0 m, the accumulated widening of fissures is estimated as $5.0 + (5 \cdot 0.2) = 6.0$ m.

DIRECTION OF RELATIVE DISPLACEMENTS.

The direction of displacements of one flank of the zone of fissuring, relative to the other flank, has been estimated in several locations, and over several different periods. As lines of distance measurements, which are oriented parallel to the zone of rifting, have generally shown insignificant length changes (Tryggvason, 1983), it is assumed that these lines have also been stable with respect to orientation. This assumption is supported by the results of the T.U. measurements, which show no significant rotation of the flanks of the fissure swarm (Mōller et al., 1982).

This assumption was applied on the rifting event of March, 1980 (Tryggvason, 1982), and direction of relative movement of the flanks was found to be N 99° E at locations 8 to 12 km north of Leirhnjúkur, but about N 104° E at locations 0 to 3 km north of Leirhnjúkur. The

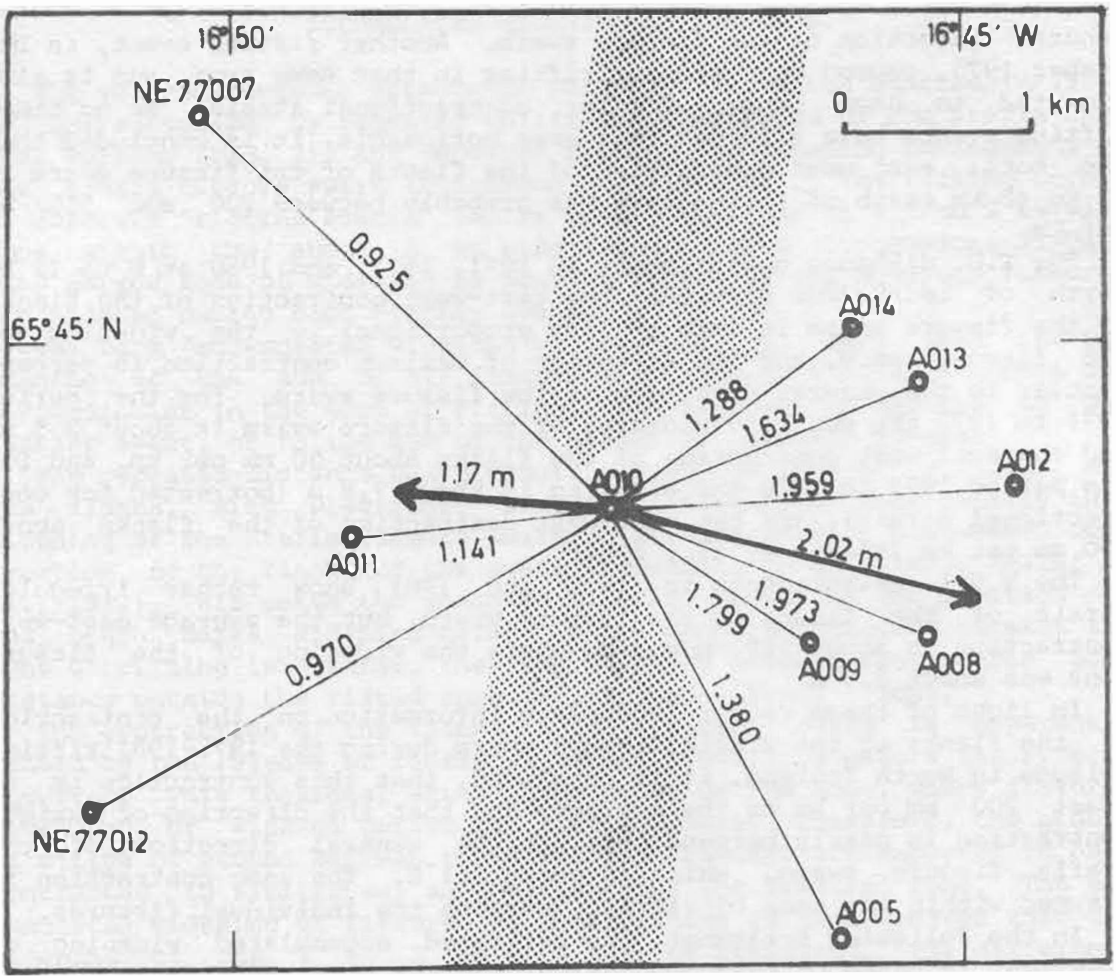

Fig. 3. Increase of distances between March 1978 and April 1981 from bench mark A010 (inside the zone of intense rifting and 2.7 km north of Leirhnjúkur) to several bench marks to the east and to the west of the zone of rifting. Thick arrows show the average displacements of the two crustal blocks relative to BM A010, assuming no rotation of either block. The zone of intense rifting is shaded. The increase of distances is in meter.

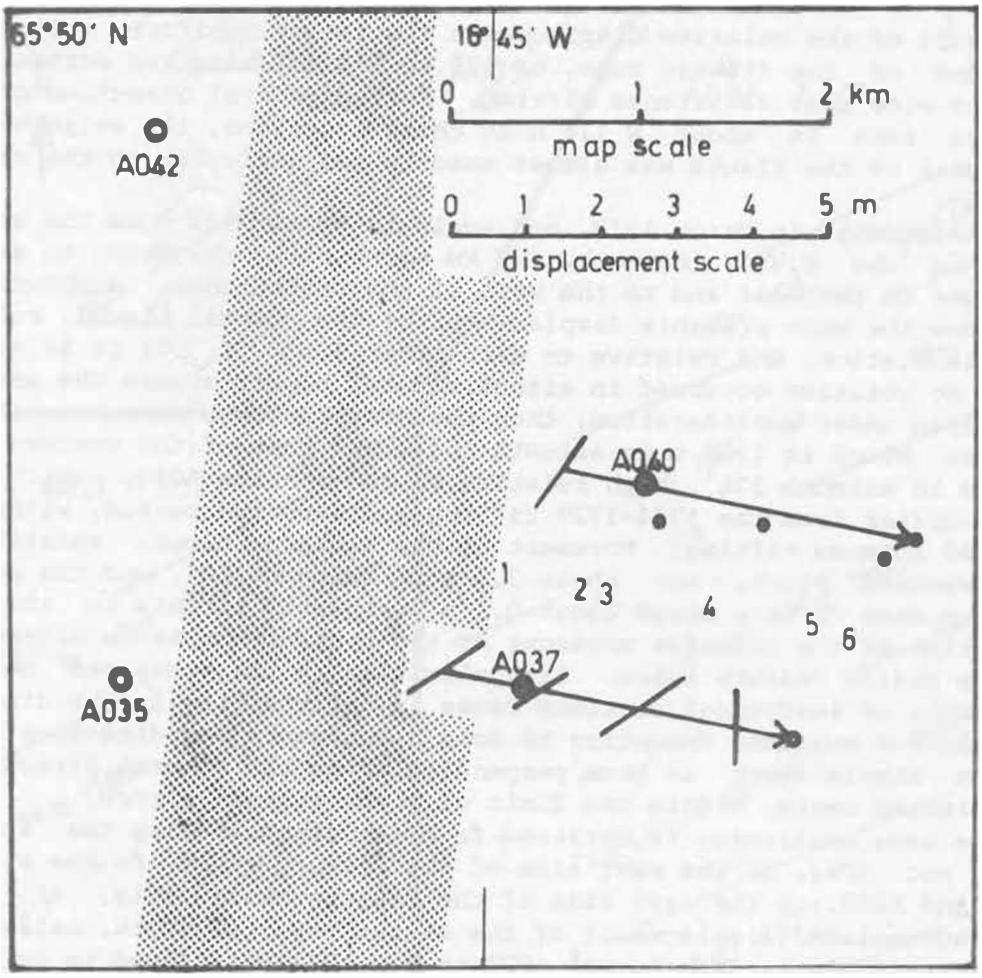

Fig. 4. Displacement of bench marks A037 and A040 (east of the Krafla fissure swarm), relative to bench marks A035 (9.3 km north of Leirhnjúkur) and A042 (12.2 km north of Leirhnjúkur) west of the fissure swarm. Large circles marked A037 and A040 show the map location of the respective bench marks and short lines or small circles show the relative location of the same bench marks at the times of distance measurements. The short lines indicate that distance was measured from only one of the stations A035 and A042. Times of measurements are: April 1978 (1), August 1978 (2), late May 1979 (3), April 1980 (4), September 1980 (5), and May 1982 (6). Arrows show the relative displacement from April 1978 to May 1982 assuming the direction of displacement being the same as from August 1978 to May 1982. The zone of intense rifting is shaded.

magnitude of the relative displacement was rather uniform over these sections of the fissure zone, or 123 to 165 cm, measured across the 1 to 2 km wide zone of intense rifting. As the general direction of the fissure zone is about N 11° E at these locations, the relative displacement of the flanks was almost exactly perpendicular to the zone of rifting.

Measurements in March 1978, and again in April 1981 from the station A010 in the N.V.I. network, 2.7 km north of Leirhnjúkur, to several stations to the east and to the west of the rifted zone, are analyzed to show the most probable displacement of the crustal blocks, relative to this station, and relative to each other (Fig. 3). If it is assumed that no rotation occurred in either crustal block, within the area and time span under consideration, then the most probable movement of the eastern block is 2.02 m in azimuth 104°, and that of the western block 1.17 m in azimuth 276°, both relative to the station A010, which lies on a crater from the 1724-1729 rifting and eruption period, within the zone of intense rifting. Movement of the eastern block, relative to the western block, was about 3.2 m in azimuth 100°, and the station A010 appears to have moved about 0.1 m northward, if this is the true direction of the relative movement of the crustal blocks on either side of the Krafla fissure swarm. Irregularities in the observed relative movements of individual stations cause an uncertainity in the direction of relative movement amounting to some 3 degrees. The direction of relative displacement is thus perpendicular to the general direction of the fissure swarm, within the limit of observational errors.

The same conclusion is obtained from measurements from the stations A035 and A042, on the west side of the fissure swarm, to the stations A037 and A040, on the east side of the fissure swarm (Fig. 4). Here the accumulated displacement of the eastern crustal block, relative to the western block, from August 1978 to May 1982, was found to be 3.8 m in direction N 101° E, or exactly perpendicular to the average strike of the fissure zone.

These few examples indicate strongly, that the relative displacement of the crustal blocks on either side of the zone of rifting has been exactly perpendicular to the zone of rifting.

DEFINING ACCUMULATED WIDENING OF FISSURES IN THE CENTRAL AREA OF INFLATION/DEFLATION

The central area of the Krafla volcano has been subject to repeated inflations and deflations during the 1975-1981 sequence of events (Fig. 2). Repeated distance and tilt measurements in addition to repeated precision leveling in that area show that the relation between horizontal strain and vertical displacements and tilt of the ground agrees quite well with that predicted by Mogi (1958) for pressure variations in a small spherical volume inside an elastic half space (Björnsson et al. 1979, Tryggvason, 1980a). The equivalent sphere of varying pressure is centered at a depth of 3.0 km below the geographic location: 65° 42.8′ N, 16° 47.3′ W in the immediate vicinity of the hill Leirhnjúkur and very near the center of the Krafla caldera. The probable error of this location is about 200 m. This location is the origin for the distance scale along the fissure swarm used on Figures in this report.

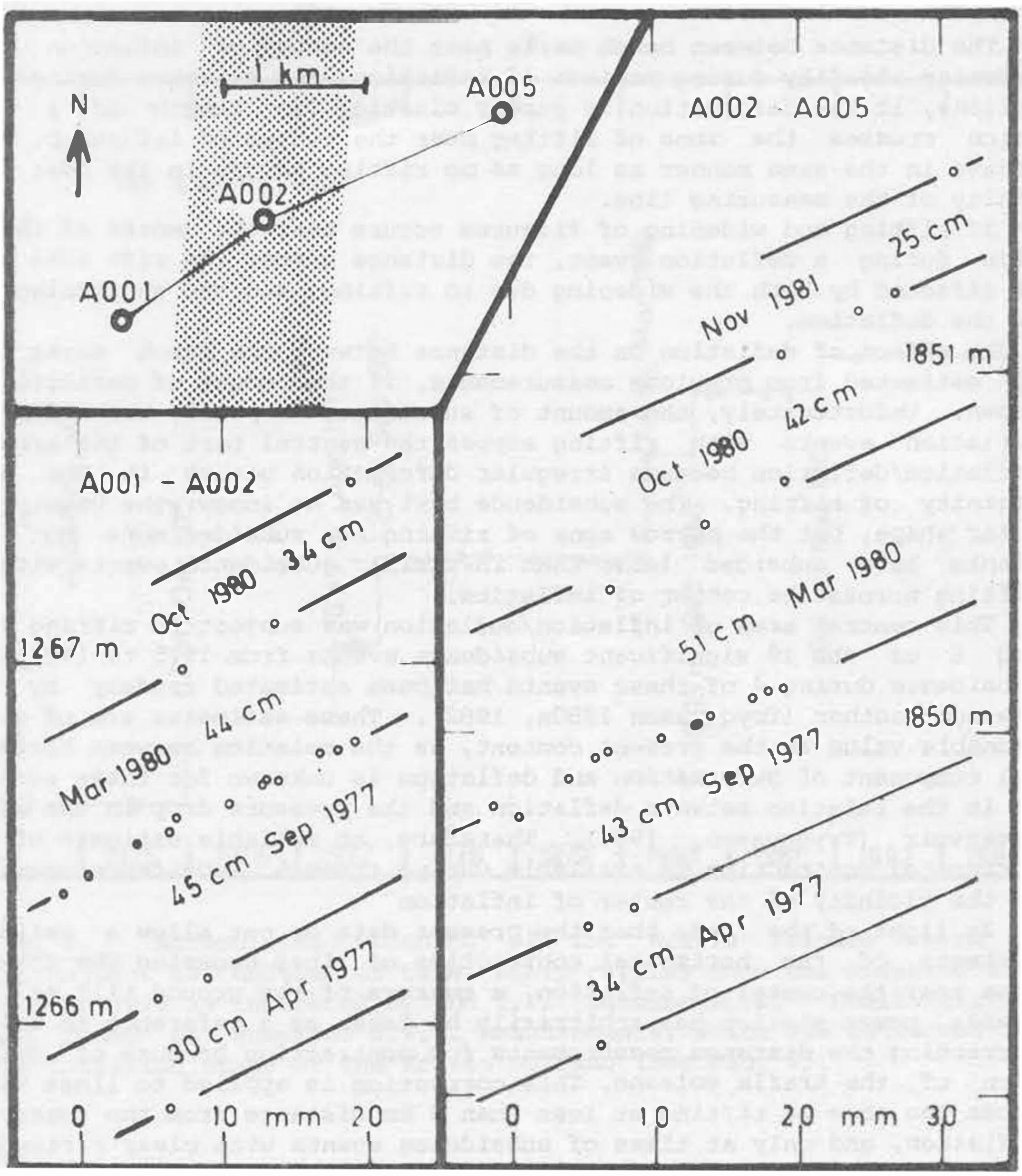

Fig. 5. Measured slope distance from bench mark A002 (on Leirhnjúkur) to A001 (west of the zone of intense rifting) and A005 (east of the zone of rifting). The horizontal coordinate is the reading of the 70 m N-S component water tube tiltmeter in the Krafla power station. Dates of rifting of this part of the fissure swarm, and length increase of the two lines caused by the riftings is given. Note that no rifting occurred between September 1977 and March 1980. Map in upper left corner shows the relative location of the bench marks.

The distance between bench marks near the center of inflation will increase steadily during periods of inflation, and decrease during deflations, if the deformation is purely elastic. The length of a line which crosses the zone of rifting near the center of inflation, will behave in the same manner as long as no rifting occurs in the near vicinity of the measuring line.

If rifting and widening of fissures occurs near the center of inflation during a deflation event, the distance across the rift zone will be affected by both the widening due to rifting, and the shortening due to the deflation.

The effect of deflation on the distance between the bench marks can be estimated from previous measurements, if the amount of deflation is known. Unfortunately, the amount of subsidence is poorly known for the deflation events with rifting across the central part of the area of inflation/deflation because irregular deformation occurs in the near vicinity of rifting. The subsidence bowl has no longer the usual circular shape, but the narrow zone of rifting has subsided more but its flanks have subsided less, than in similar subsidence events without rifting across the center of inflation.

This central area of inflation/deflation was subject to rifting during 6 of the 19 significant subsidence events from 1975 to 1981. The subsidence during 4 of these events has been estimated crudely by the present author (Tryggvason 1980a, 1982). These estimates are of questionable value in the present context, as the relation between horizontal component of deformation and deflation is unknown for these events, as is the relation between deflation and the pressure drop in the magma reservoir (Tryggvason, 1981). Therefore, no reliable estimate of the horizontal contraction is available during these 6 subsidence events, in the vicinity of the center of inflation

In light of the fact, that the present data do not allow a reliable estimate of the horizontal contraction of lines crossing the fissure zone near the center of inflation, a measure of the ground tilt at the Krafla power station has arbitrarily be taken as a reference to use in correcting the distance measurements for contraction because of deflation of the Krafla volcano. This correction is applied to lines which cross the zone of rifting at less than 3 km distance from the center of inflation, and only at times of subsidence events with clear rifting in the central area of the deflation.

The distance measurements before and after such rifting events are normalized to a common reading of the Krafla tiltmeter, and the difference of these normalized distances is taken as the change in distance as caused by the rifting (Fig. 5.)

The distance across the fissure swarm can be reduced to a fixed reading of the Krafla power house tiltmeter and then corrected for the angle between the measured line, and the direction of relative displacements of the crustal blocks, to obtain widening of the fissure swarm (Fig. 6, 7). Elsewhere along the fissure swarm, only correction for the angle between measured lines and relative displacements is applied (Fig. 8). The final accumulated widening of fissures is then obtained by adding to the widening of the fissure swarm, a correction for contraction of the flanks, and between the fissures. This contraction has not been estimated for individual rifting events, except in a few cases.

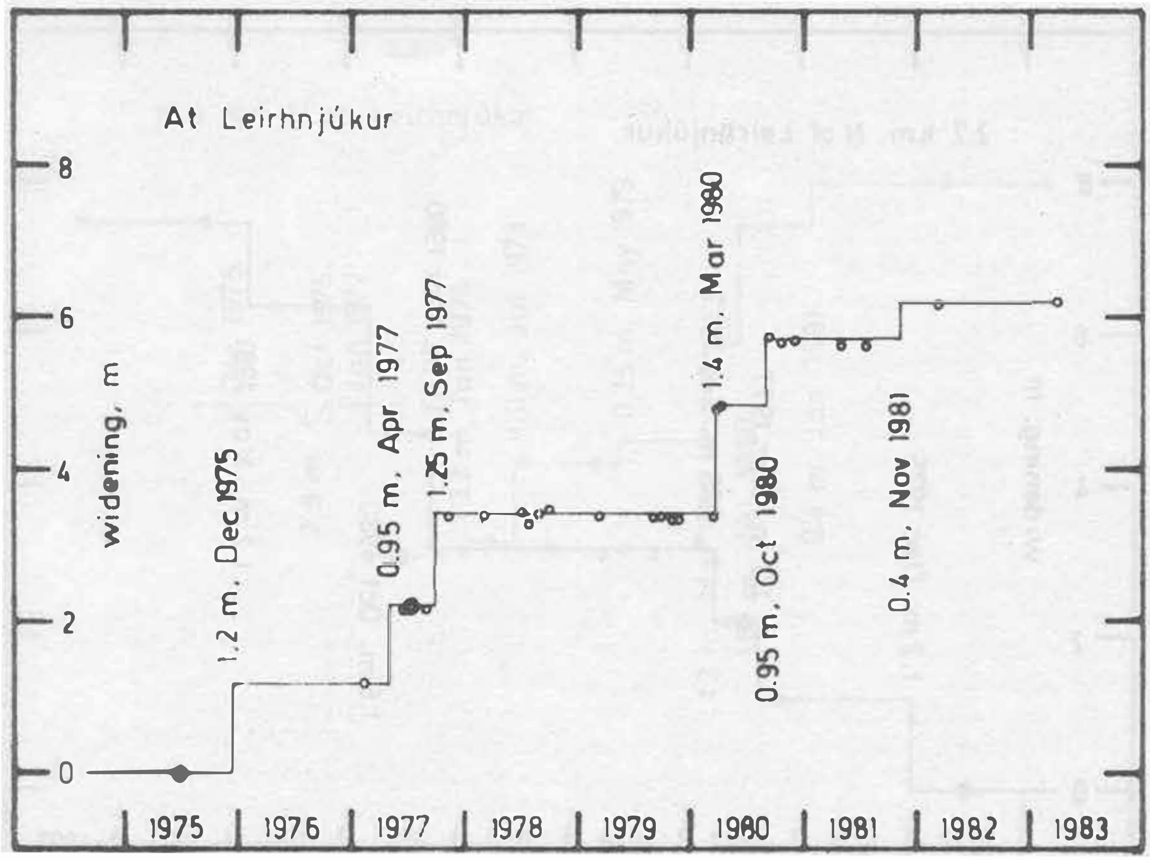

Fig. 6. Accumulated widening of the Krafla fissure swarm at Leirhnjúkur as function of time. Heavy circles show the widening from 1975 to 1977 as indicated by the T.U. measurements. Small circles are based on numerous N.V.I. measurements, which are corrected for the inflation stage of the Krafla volcano (see Fig. 5).

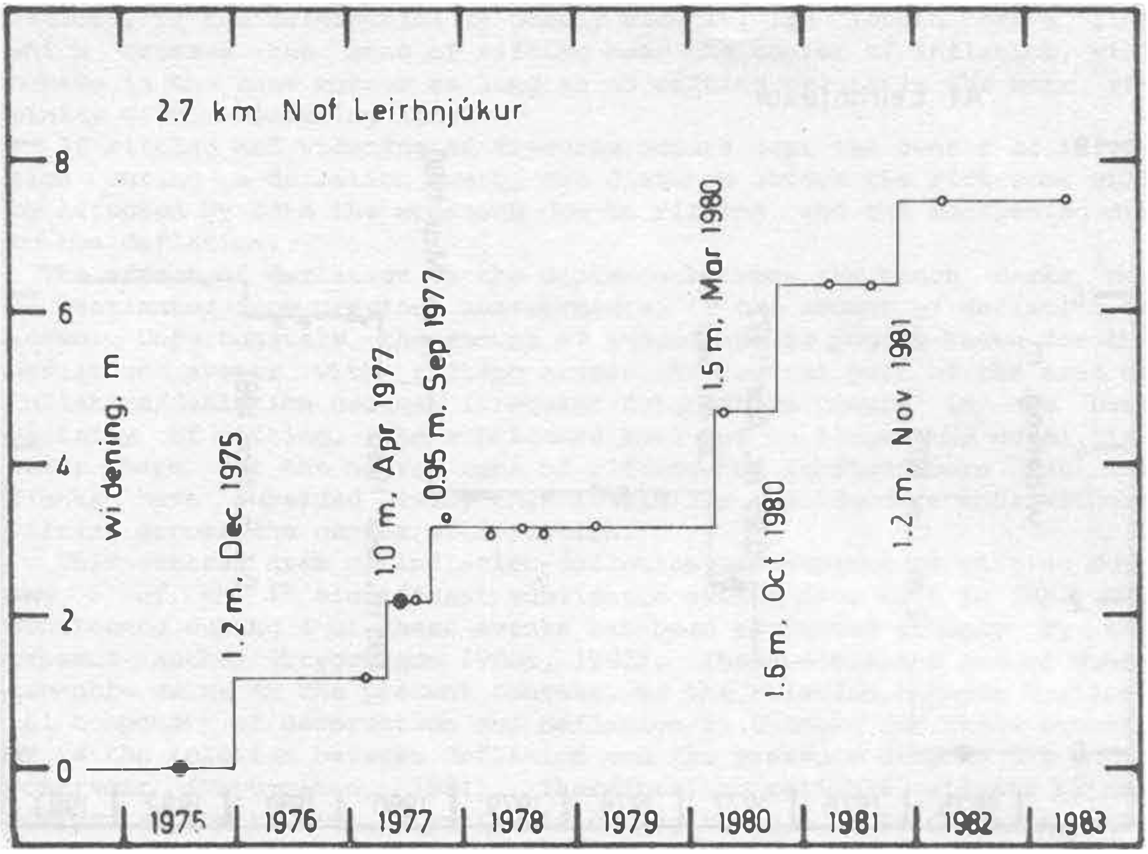

Fig. 7. Accumulated widening of the Krafla fissure swarm at 2.7 km north of Leirhnjúkur, based on measurements from BM A010 to A011 and NE77012 west of the fissured zone and to A009 and A012 east of the fissured zone (see Fig. 3). Heavy circles show widening from 1975 to 1977 as obtained from the T.U. measurements.

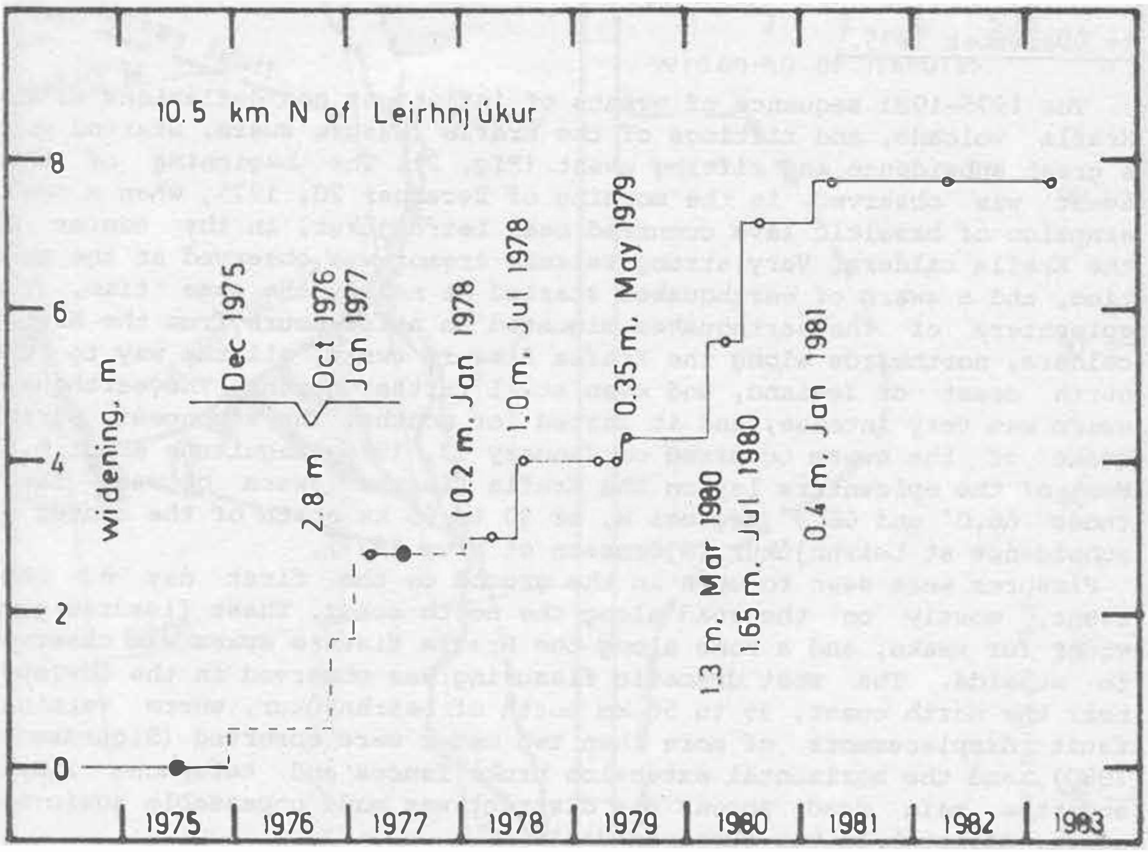

Fig. 8. Accumulated widening of the Krafla fissure swarm at 10 to 12 km north of Leirhnjúkur based on measurements between BM's A035, A037, A040, and A042, (see Fig. 4) Measurements in February 1977 are not wholly comparable to later measurements. Heavy circles show the widening from 1975 to 1977 according to the T.U. measurements. Widening during individual events before July 1978 are crudely estimated.

WIDENING IN INDIVIDUAL RIFTING EVENTS.

1: December 1975.

The 1975-1981 sequence of events of inflations and deflations of the Krafla volcano, and riftings of the Krafla fissure swarm, started with a great subsidence and rifting event (Fig. 2). The beginning of this event was observed in the morning of December 20, 1975, when a small eruption of basaltic lava occurred near Leirhnjúkur, in the center of the Krafla caldera. Very strong seismic tremor was observed at the same time, and a swarm of earthquakes started at nearly the same time. The epicenters of the earthquakes migrated in a few hours from the Krafla caldera, northwards along the Krafla fissure swarm, all the way to the north coast of Iceland, and even still farther north. The earthquake swarm was very intense, and it lasted for months. The strongest earthquake of the swarm occurred on January 13, 1976, magnitude about 6.2. Most of the epicenters lay on the Krafla fissure swarm between latitudes 66.0° and 66.3° degrees N, or 30 to 65 km north of the center of subsidence at Leirhnjúkur (Björnsson et al., 1977).

Fissures were seen to open in the ground on the first day of this event, mostly on the road along the north coast. These fissures grew wider for weeks, and a zone along the Krafla fissure swarm was observed to subside. The most dramatic fissuring was observed in the lowland, near the north coast, 35 to 50 km north of Leirhnjúkur, where vertical fault displacements of more than two meter were observed (Sigurdsson, 1980), and the horizontal extension broke fences and telephone lines, and the main road across the district was made unpassable again and again, although it was repaired daily

A few measurements of the width of new open fissures in snow or frozen ground indicated about 1.5 m accumulated widening of fissures along the coastal highway, 38 km north of Leirhnjúkur, about 0.7 m just south of the eruption fissure near Leirhnjúkur, and about 0.1 m near Mývatn, 10 km south of Leirhnjúkur (Björnsson et al., 1977).

An eruption fissure opened 0.5 to 2.5 km north of Leirhnjúkur and produced about 0.4 million cubic meter of lava (Grönvold 1978). Later experience shows that the fissure swarm widens generally at least 1.0 m where eruption occurs.

Leveling in the Krafla area showed that the central part of the Krafla caldera had subsided about 2.5 m since earlier leveling. This indicated that the volume of the subsidence bowl was approximately 150 million cubic meter (Tryggvason, 1980a).

In light of the fact, that the most intense earthquake swarm was located well north of the coastal highway, and that the most dramatic vertical fault displacements also occurred north of the highway, it is assumed that the greatest widening occurred in the coastal region, about 50 km north of Leirhnjúkur. Further, the long duration of the rifting process, made the measurements of width of new fissures somewhat dubious as fissures that formed in snow during the early part of the rifting period were partly destroyed before the fissuring ceased. Therefore, it is concluded, that the measured widening of fissures were on the low side.

Measurements of vertical ground displacements along the coastal highway (Sigurdsson, 1980) indicate that this event caused very similar vertical displacements as the event of January 1978, which is discussed

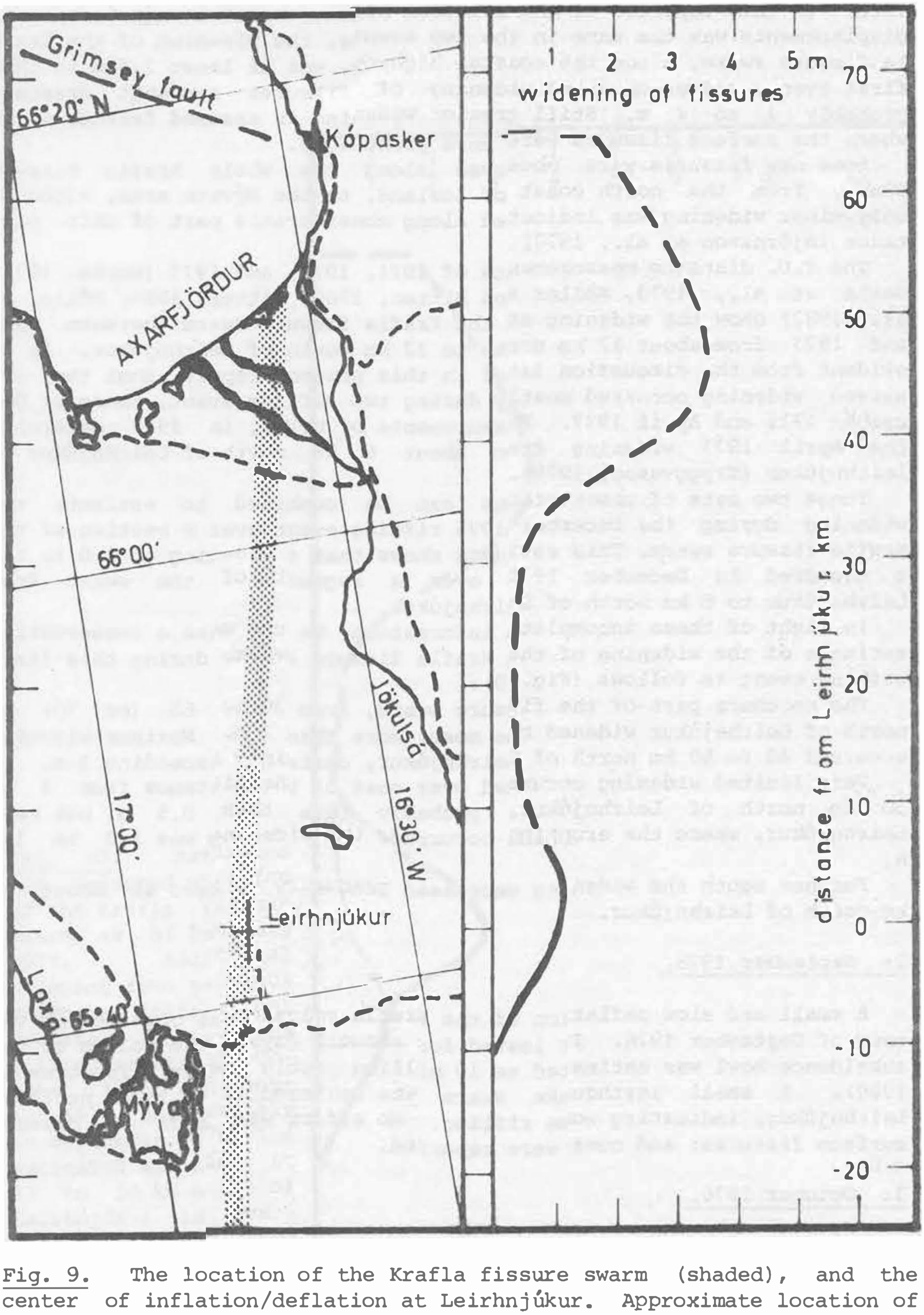

Fig. 9. The location of the Krafla fissure swarm (shaded), and the center of inflation/deflation at Leirhnjúkur. Approximate location of the Grímsey transform fault is also shown. A distance scale, in km from Leirhnjúkur, is shown at the right. This distance scale is shown on the following illustration, and on Fig. 1., and is used in the text. The right half of the figure shows estimated (dashed) or measured widening of the Krafla fissure swarm during the rifting event of December 1975.

later in this report. If the relation between vertical and horizontal displacements was the same in the two events, the widening of the Krafla fissure swarm, along the coastal highway, was at least 2.5 m in this first event, and accumulated widening of fissures somewhat greater, probably 3 to 4 m. Still greater widening is assumed farther north where the surface fissures were more pronounced.

Some new fissures were observed along the whole Krafla fissure swarm, from the north coast of Iceland, to the Mývatn area, although only minor widening was indicated along considerable part of this distance (Björnsson et al., 1977).

The T.U. distance measurements of 1971, 1975, and 1977 (Gerke, 1977, Gerke et al., 1978, Möller and Ritter, 1980, Ritter, 1982, Möller et al., 1982) show the widening of the Krafla fissure swarm between 1975 and 1977 from about 12 km north to 12 km south of Leirhnjúkur. It is evident from the discussion later in this present report, that the observed widening occurred mostly during two rifting event, those of December 1975 and April 1977. Measurements by N.V.I. in 1977 determine the April 1977 widening from about 6 km north of Leirhnjúkur to Leirhnjúkur (Tryggvason, 1978).

These two sets of observations can be combined to estimate the widening during the December 1975 rifting event over a section of the Krafla fissure swarm. This estimate shows that a widening of 1.0 to 1.2 m occurred in December 1975 over a segment of the swarm from Leirhnjúkur to 6 km north of Leirhnjúkur.

In light of these incomplete information, we can make a conservative estimate of the widening of the Krafla fissure swarm, during this first rifting event as follows (Fig. 9):

The northern part of the fissure swarm, from 30 to 65 (or 70) km north of Leirhnjúkur widened the most, more than 2 m. Maximum widening occurred 40 to 50 km north of Leirhnjúkur, certainly exceeding 3 m.

Very limited widening occurred over most of the distance from 5 to 30 km north of Leirhnjúkur, probably less than 0.5 m, but near Leirhnjúkur, where the eruption occurred, the widening was 1.0 to 1.2 m.

Farther south the widening decreased gradually to zero at about 10 km south of Leirhnjúkur.

2: September 1976.

A small and slow deflation of the Krafla volcano was observed at the end of September 1976. It lasted for about 5 days. The volume of the subsidence bowl was estimated as 10 million cubic meter (Tryggvason, 1980). A small earthquake swarm was centered 12 to 15 km north of Leirhnjúkur, indicating some rifting. No effort was made to observe surface fissures, and none were reported.

3: October 1976.

A rapid and large deflation of the Krafla volcano started on October 31, 1976 and lasted for less than 48 hours. The volume of the subsidence bowl was estimated as 32 million cubic meter (Tryggvason, 1980a). A sizable earthquake swarm accompanied this subsidence event, akd the majority of the epicenters were distributed along the Krafla fissure swarm, 5 to 25 km north of Leirhnjúkur, with highest concentra-

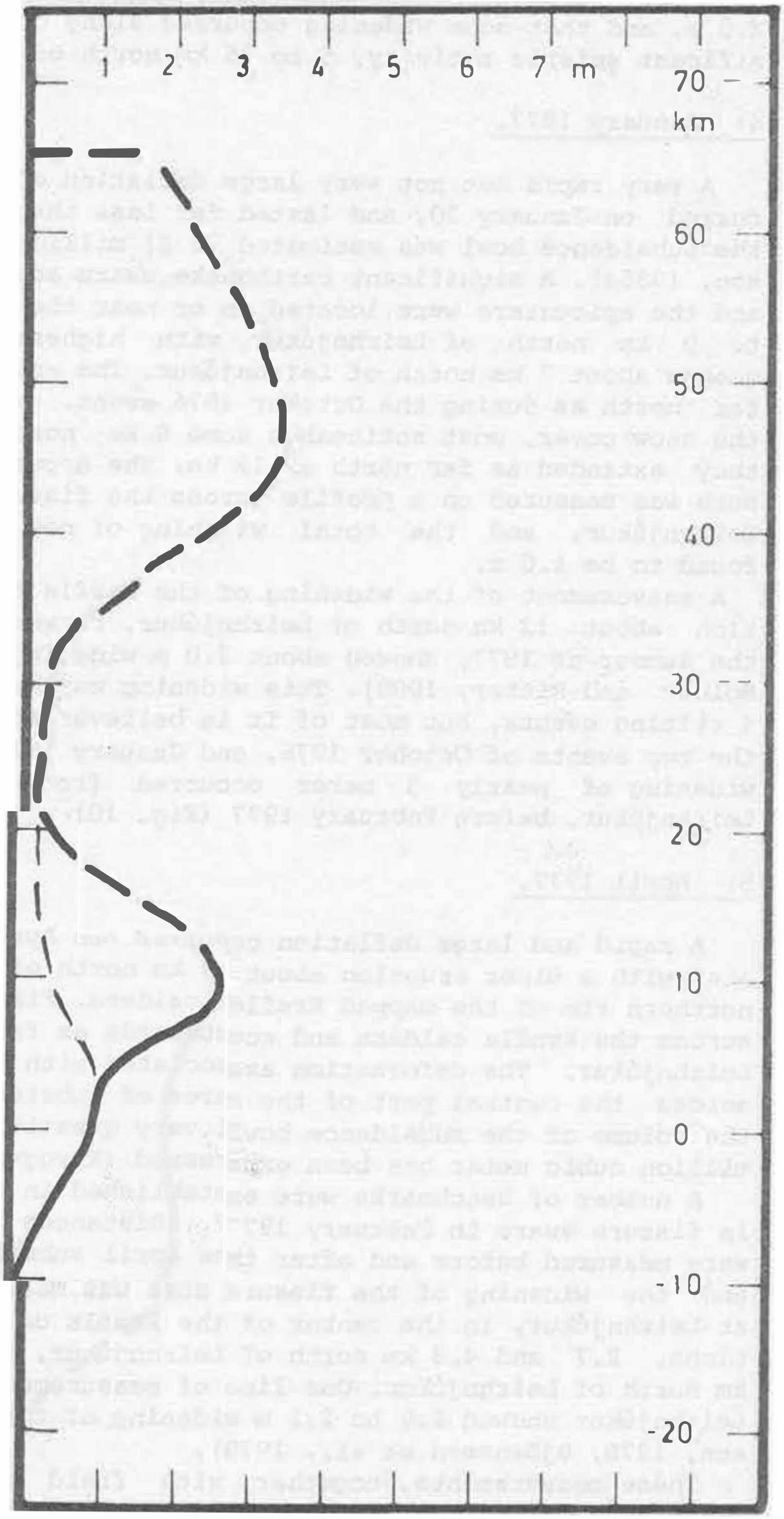

Fig. 10. Estimated and measured widening of the Krafla fissure swarm as of February 1977. Additional widening from previous estimate (thin line) occurred during the rifting events of October 1976, and January 1977, and possibly in September 1976. The estimated widening at 12 to 20 km north of Leirhnjúkur is very uncertain, and the present estimate of the widening in this region is intended to be very conservative.

tion of epicenters about 10 km north of Leirhnjúkur.

Fissures were seen to form in an area about 10 to 15 km north of Leirhnjúkur (Björnsson et al. 1979) but no measurements were made on the width of the fissures. Later experience can be used to estimate the maximum widening of the fissure swarm to have been between 1.0 and 2.0 m, and that some widening occurred along the whole stretch of significant seismic activity, 5 to 25 km north of Leirhnjúkur.

4: January 1977.

A very rapid but not very large deflation of the Krafla volcano occurred on January 20, and lasted for less than 24 hours. The volume of the subsidence bowl was estimated as 21 million cubic meter (Tryggvason, 1980a). A significant earthquake swarm accompanied this subsidence and the epicenters were located in or near the Krafla fissure swarm 2 to 9 km north of Leirhnjúkur, with highest concentration of earthquakes about 7 km north of Leirhnjúkur. The epicenters did not reach as far north as during the October 1976 event. New fissures were seen in the snow cover, most noticeable some 8 km north of Leirhnjúkur, but they extended as far north as 12 km. The accumulated width of the fissure was measured on a profile across the fissure swarm, 8 km north of Leirhnjúkur, and the total widening of new fissures in the snow was found to be 1.0 m.

A measurement of the widening of the Krafla fissure swarm at a location about 12 km north of Leirhnjúkur, between the summer of 1975 and the summer of 1977, showed about 2.8 m widening (Gerke et al., 1978, Möller and Ritter, 1980). This widening may have been accumulated over 4 rifting events, but most of it is believed to have occurred during the two events of October 1976, and January 1977. It is estimated, that widening of nearly 3 meter occurred from 7 to 12 km north of Leirhnjúkur, before February 1977 (Fig. 10).

5: April 1977.

A rapid and large deflation occurred on April 28 - 29, 1977 associated with a minor eruption about 3 km north of Leirhnjúkur, or near the northern rim of the mapped Krafla caldera. Fissures were seen to open across the Krafla caldera and southwards as far as 15 to 20 km south of Leirhnjúkur. The deformation associated with the opening of fissures across the central part of the area of subsidence made any estimate of the volume of the subsidence bowl very questionable, but a value of 46 million cubic meter has been expressed (Tryggvason, 1980a).

A number of benchmarks were established in the vicinity of the Krafla fissure swarm in February 1977. Distances between these bench marks were measured before and after the April subsidence and rifting event, and the widening of the fissure zone was measured to have been 0.95 m at Leirhnjúkur, in the center of the Krafla caldera, 1.0 m at two locations, 2.7 and 4.3 km north of Leirhnjúkur, but practically none at 7 km north of Leirhnjúkur. One line of measurements about 10 km south of Leirhnjúkur showed 2.0 to 2.1 m widening of the fissure swarm (Tryggvason, 1978, Björnsson et al., 1979).

These measurements, together with field observations, show that widening of the Krafla fissure swarm in the April 1977 event, extended from about 7 km north of Leirhnjúkur southwards to more than 15 km

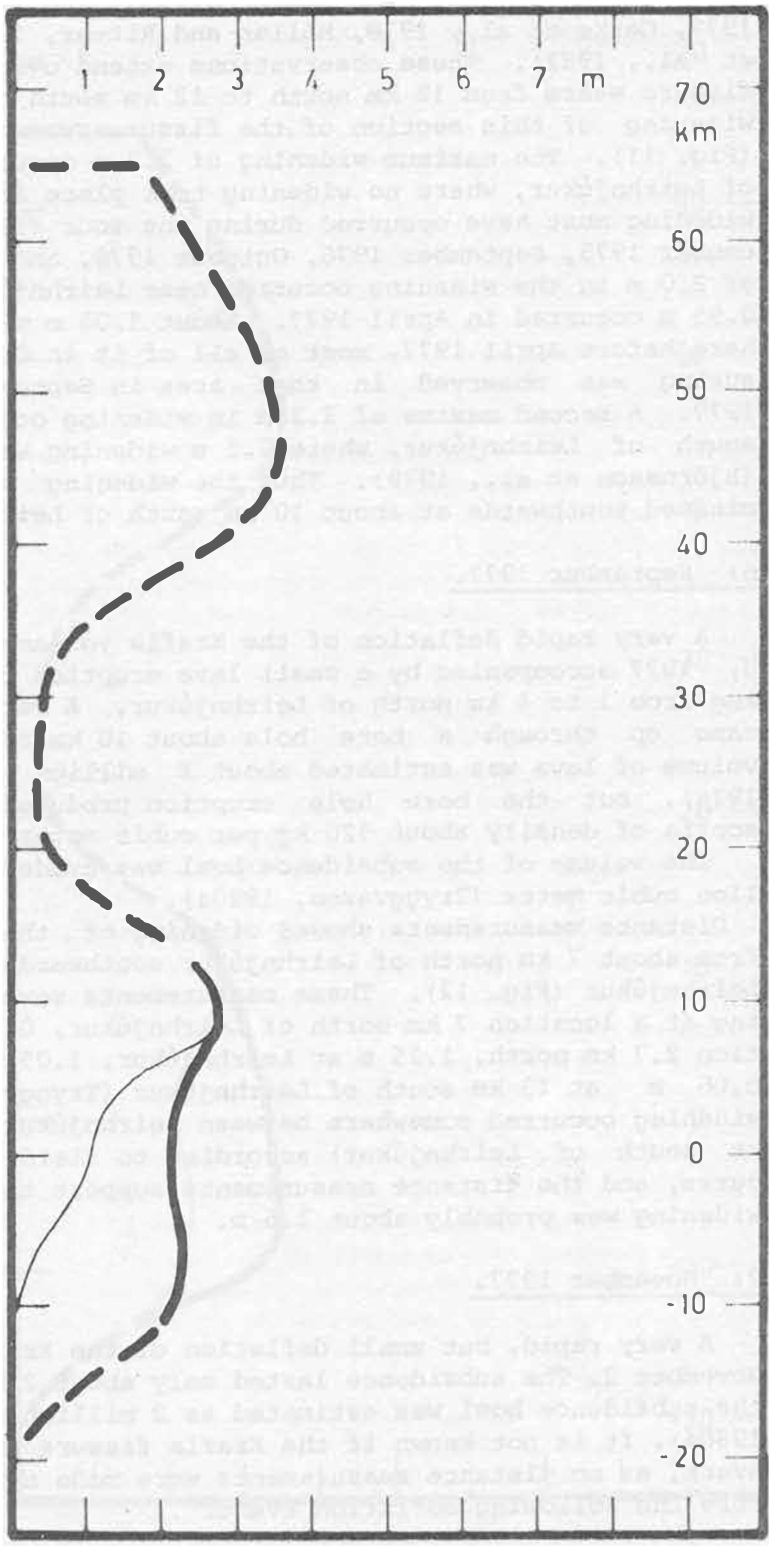

Fig. 11. Estimated and measured widening of the Krafla fissure swarm as of July or August 1977. The whole drawn thick curve shows the widening as obtained from Gerke et al. (1978), and the increase of widening since previous estimate (thin line) occurred during the event of April 1977, and is rather well determined by distance measurements in February 1977, and again in July and August 1977.

south of Leirhnjúkur. Maximum widening, of slightly more than 2 m, occurred somewhere between Leirhnjúkur and 12 km south of Leirhnjúkur, but the most dramatic surface fissuring was observed in that region.

The T.U. measurements of 1977 showed the widening of the Krafla fissure swarm between the summer of 1975 and the summer of 1977 (Gerke, 1977, Gerke et al., 1978, Möller and Ritter, 1980, Ritter, 1982, Möller et al., 1982). These observations extend over a segment of the Krafla fissure swarm from 12 km north to 12 km south of Leirhnjúkur, and the widening of this section of the fissure swarm ranged from 2.0 to 2.8 m (Fig. 11). The maximum widening of 2.8 m occurred at 10 to 12 km north of Leirhnjúkur, where no widening took place in April 1977, so all this widening must have occurred during the four first rifting events (December 1975, September 1976, October 1976, and January 1977). A minima of 2.0 m in the widening occurred near Leirhnjúkur, where a widening of 0.95 m occurred in April 1977. About 1.05 m widening has thus occurred here before April 1977, most or all of it in December 1975, as no fissuring was observed in that area in September 1976 through January 1977. A second maxima of 2.2 m in widening occurred at 8 to 10 km south of Leirhnjúkur, where 2.1 m widening was observed in April 1977 (Björnsson et al., 1979). Thus the widening before April 1977 terminated southwards at about 10 km south of Leirhnjúkur.

6: September 1977.

A very rapid deflation of the Krafla volcano occurred on September 8, 1977 accompanied by a small lava eruption through a fissure extending from 1 to 4 km north of Leirhnjúkur. A very small eruption also came up through a bore hole about 10 km south of Leirhnjúkur. The volume of lava was estimated about 2 million cubic meter (Grönvold, 1978), but the bore hole eruption produced about 26 cubic meter of scoria of density about 120 kg per cubic meter (Larsen et al. 1979).

The volume of the subsidence bowl was crudely estimated as 20 million cubic meter (Tryggvason, 1980a).

Distance measurements showed widening of the Krafla fissure swarm from about 7 km north of Leirhnjúkur southwards to about 13 km south of Leirhnjúkur (Fig. 12). These measurements sowed practically no widening at a location 7 km north of Leirhnjúkur, 0.95 m widening at a location 2.7 km north, 1.25 m at Leirhnjúkur, 1.05 m at 10 km south and 0.06 m at 13 km south of Leirhnjúkur (Tryggvason, 1978). The maximum widening occurred somewhere between Leirhnjúkur and Bjarnarflag (0 - 10 km south of Leirhnjúkur) according to field observations of new fissures, and the distance measurements support that view. This maximum widening was probably about 1.5 m.

7: November 1977.

A very rapid, but small deflation of the Krafla volcano occurred on November 2. The subsidence lasted only about 2 hours, and the volume of the subsidence bowl was estimated as 2 million cubic meter (Tryggvason, 1980a). It is not known if the Krafla fissure swarm widened during this event, as no distance measurements were made after this event, and before the following deflation event.

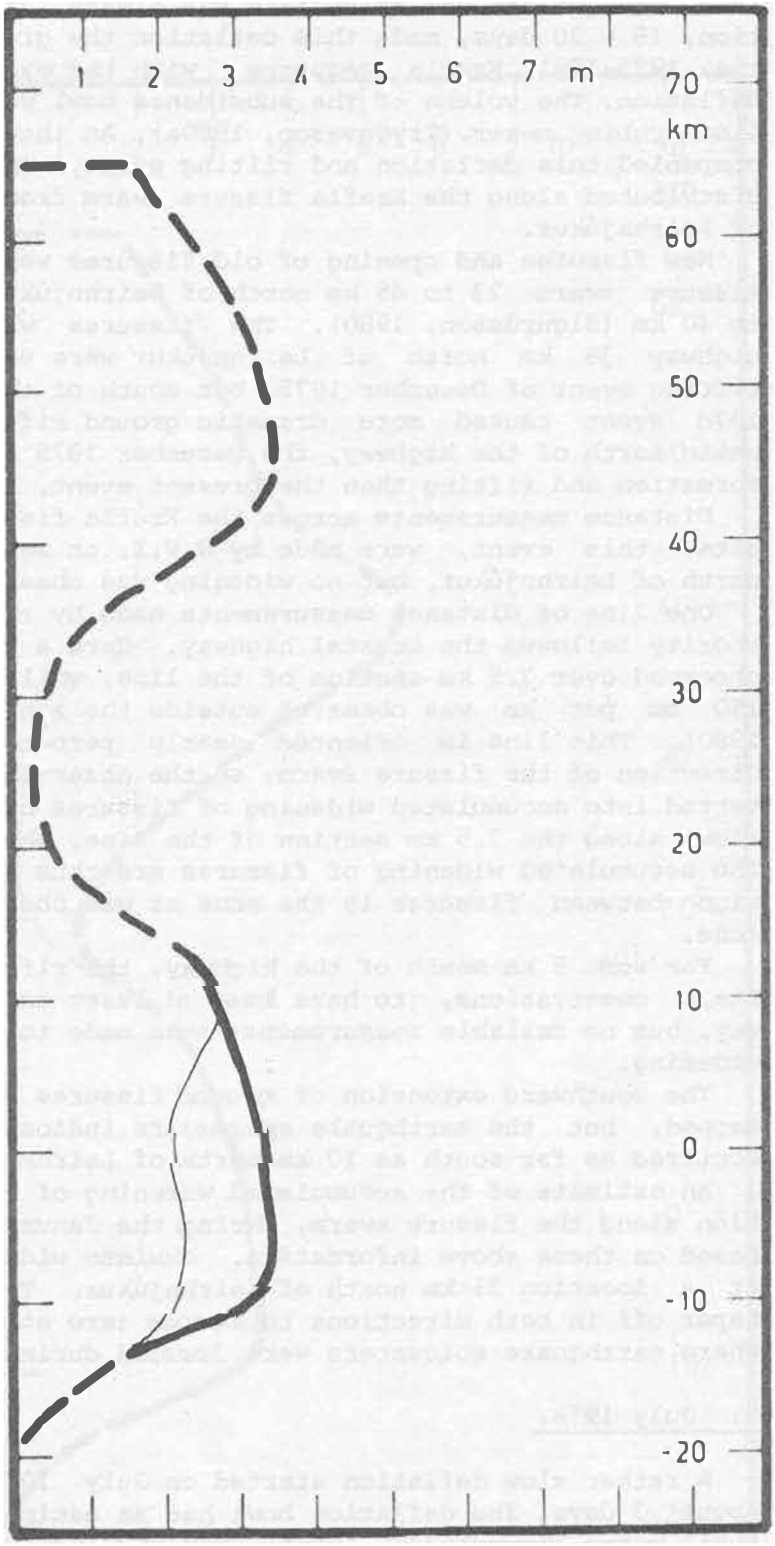

Fig. 12. Estimated and measured widening of the Krafla fissure swarm after the September 1977 rifting event. Addition from previous estimate (thin line) occurred in September 1977, and it is well determined by distance measurements in July to November 1977.

8: January 1978.

A slow deflation of the Krafla volcano started on January 7, 1978. Even though the deflation rate was always rather slow, the long duration, 18 - 20 days, made this deflation the greatest in the history of the 1975-1981 Krafla sequence, with the exception of the very first deflation. The volume of the subsidence bowl was estimated as 74 million cubic meter.(Tryggvason, 1980a). An intense earthquake swarm accompanied this deflation and rifting event, and the epicenters were distributed along the Krafla fissure swarm from about 10 to 45 km north of Leirhnjúkur.

New fissures and opening of old fissures were observed in the Krafla fissure swarm 23 to 45 km north of Leirhnjúkur, most pronounced at 30 to 40 km (Sigurdsson, 1980). The fissures which cross the coastal highway 38 km north of Leirhnjúkur were very similar as during the rifting event of December 1975, but south of the highway the January 1978 event caused more dramatic ground rifting than the 1975 event, while north of the highway, the December 1975 event caused greater deformation and rifting than the present event.

Distance measurements across the Krafla fissure swarm, before and after this event, were made by N.V.I. at several locations 0 to 8 km north of Leirhnjúkur, but no widening was observed.

One line of distance measurements made by the National Energy Authority followed the coastal highway. Here a lengthening of 2.66 m was observed over 7.5 km section of the line, while contraction of 100 to 150 mm per km was observed outside the zone of rifting (Sigurdsson, 1980). This line is oriented nearly perpendicular to the general direction of the fissure swarm, so the observed lengthening can be converted into accumulated widening of fissures by correcting for contraction along the 7.5 km section of the line, where lengthening occurred. The accumulated widening of fissures are thus 3.4 to 3.7 m if contraction between fissures is the same as was observed outside the fissure zone.

For some 5 km south of the highway, the rifting appeared, from crude field observations, to have been at least as great as along the highway, but no reliable measurements were made to determine the amount of widening.

The southward extension of ground fissures during this event was not mapped, but the earthquake epicenters indicate that widening may have occurred as far south as 10 km north of Leirhnjúkur.

An estimate of the accumulated widening of fissures, and its variation along the fissure swarm, during the January 1978 rifting event, is based on these above information. Maximum widening is assumed as 3.5 m at a location 35 km north of Leirhnjúkur. The widening is assumed to taper off in both directions to become zero at both ends of the zone, where earthquake epicenters were located during this event (Fig. 13).

9: July 1978.

A rather slow deflation started on July 10, 1978 and lasted for about 3 days. The deflation bowl had an estimated volume of 37 million cubic meter (Tryggvason, 1980a), and thus became one of the larger deflations. The accompanying earthquake swarm migrated northwards from 2 to 30 km north of Leirhnjúkur, at a velocity of about 5 km per hour,

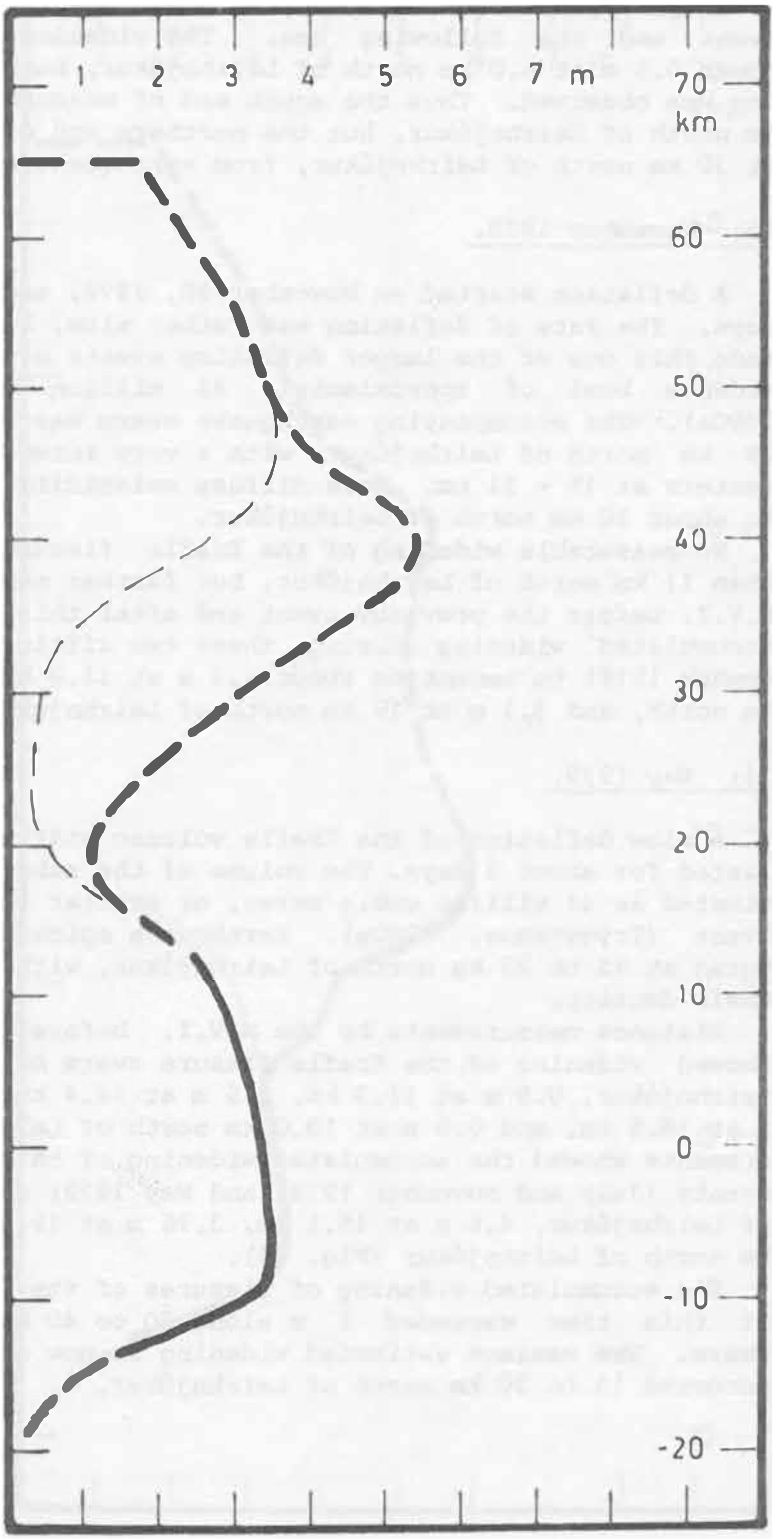

Fig. 13. Estimated and measured widening of the Krafla fissure swarm as of March 1978. The addition from previous estimate (thin line) is the widening of the rifting event of January 1978. The estimated widening in January 1978 is based on distance measurements at one location, 38 km north of Leirhnjúkur (see distance scale to the right), and on extension of observed ground fissures and earthquake epicenters. This estimate is rather crude, and the apparent minima in the widening at 20 km north of Leirhnjúkur may be the artifact of this estimate, and of the estimated widening of October 1976 and January 1977 (Fig. 10).

and the maximum density of epicenters was observed at the northern end of the seismic zone, 25 to 30 km north of Leirhnjúkur (Einarsson and Brandsdóttir, 1980).

Distance measurements by the N.V.I. before and after this event showed about 1.0 m widening of the fissure swarm at 8 to 11 km north of Leirhnjúkur, but farther north, no measurements were made between this event and the following one. The widening of the fissure zone was about 0.5 m at 6.0 km north of Leirhnjúkur, but farther south no widening was observed. Thus the south end of measurable widening was 5 to 6 km north of Leirhnjúkur, but the northern end of widening is estimated at 30 km north of Leirhnjúkur, from earthquake epicenters.

10: November 1978.

A deflation started on November 10, 1978, and lasted for about 5 days. The rate of deflation was rather slow, but the extended duration made this one of the larger deflation events of Krafla, forming a subsidence bowl of approximately 45 million cubic meter (Tryggvason, 1980a). The accompanying earthquake swarm was mostly located at 18 to 28 km north of Leirhnjúkur, with a very intense concentration of epicenters at 19 - 21 km. Some diffuse seismicity extended farther south, to about 10 km north of Leirhnjúkur.

No measurable widening of the Krafla fissure swarm occurred less than 11 km north of Leirhnjúkur, but farther north, measurements by the N.V.I. before the previous event and after this present event showed accumulated widening during these two rifting event (in July and November 1978) to amount to about 1.3 m at 11.3 km north, 3.2 m at 15.1 km north, and 3.1 m at 19 km north of Leirhnjúkur.

11: May 1979.

A slow deflation of the Krafla volcano started on May 13, 1979, and lasted for about 5 days. The volume of the subsidence bowl has been estimated as 44 million cubic meter, or similar to that of the preceding event (Tryggvason, 1980a). Earthquake epicenters were mostly distributed at 12 to 23 km north of Leirhnjúkur, with no pronounced maxima in their density.

Distance measurements by the N.V.I. before and after this event showed widening of the Krafla fissure swarm of 0.1 m at 10 km north of Leirhnjúkur, 0.5 m at 11.3 km, 1.5 m at 14.4 km, 1.5 m at 16.6 km, 0.8 m at 18.5 km, and 0.5 m at 19.0 km north of Leirhnjúkur. Further measurements showed the accumulated widening of this, and the two preceding events (July and November 1978, and May 1979) as 1.9 m at 11.3 km north of Leirhnjúkur, 4.6 m at 15.1 km, 3.76 m at 19.0 km, and 4.3 m at 21.4 km north of Leirhnjúkur (Fig. 14).

The accumulated widening of fissures of the Krafla fissure swarm has at this time exceeded 5 m along 30 to 40 km segment of the fissure swarm. The maximum estimated widening is now about 6.0 m, and this has occurred 15 to 20 km north of Leirhnjúkur.

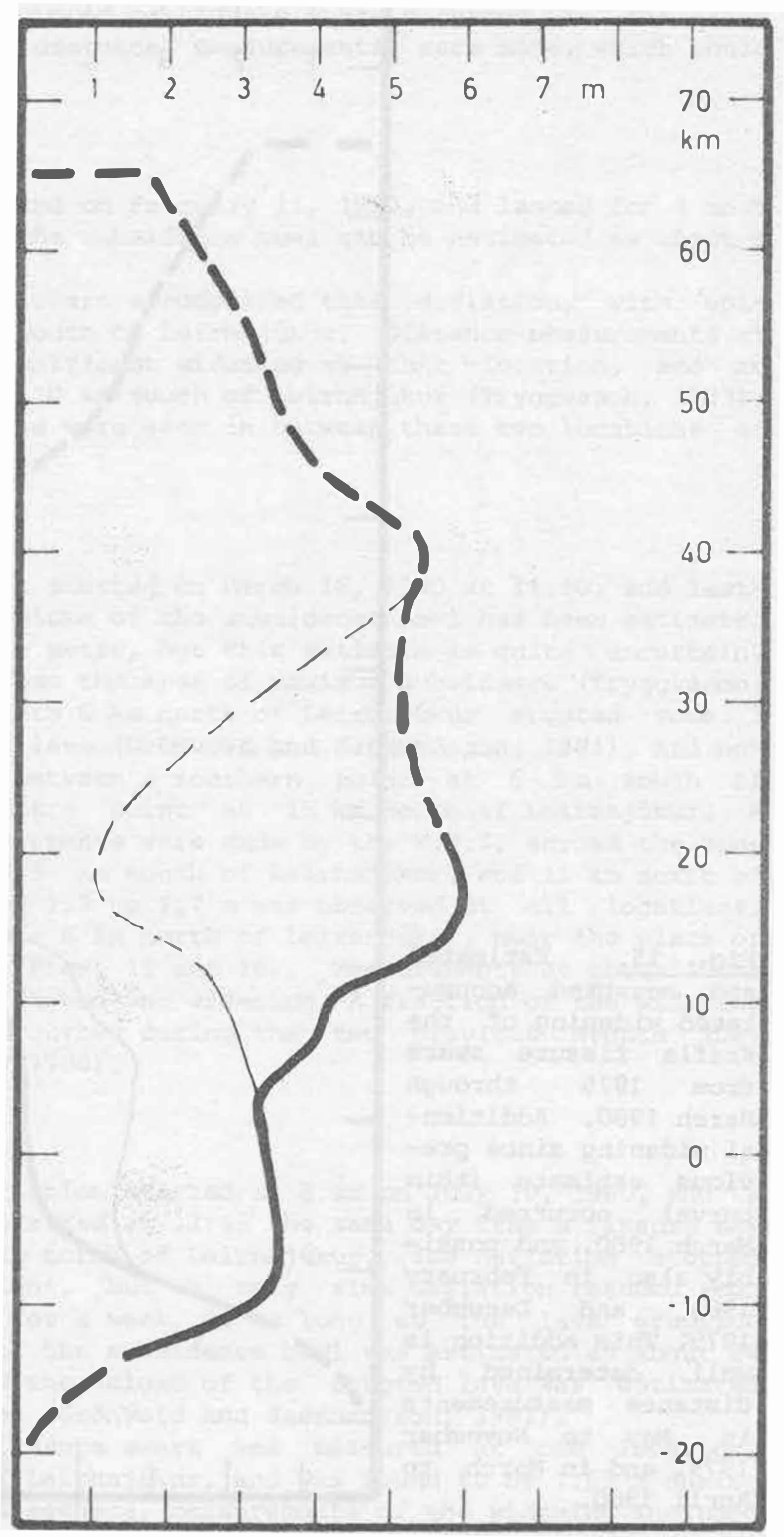

Fig. 14. Estimated and measured widening of the Krafla fissure swarm as of late May 1979. Additional widening since previous estimate (thin curve) occurred during the three rifting events of July 1978, November 1978, and May 1979. This addition is well determined as far north as 20 km north of Leirhnjúkur, but farther north only crude estimates are available, based on distribution of earthquake epicenters.

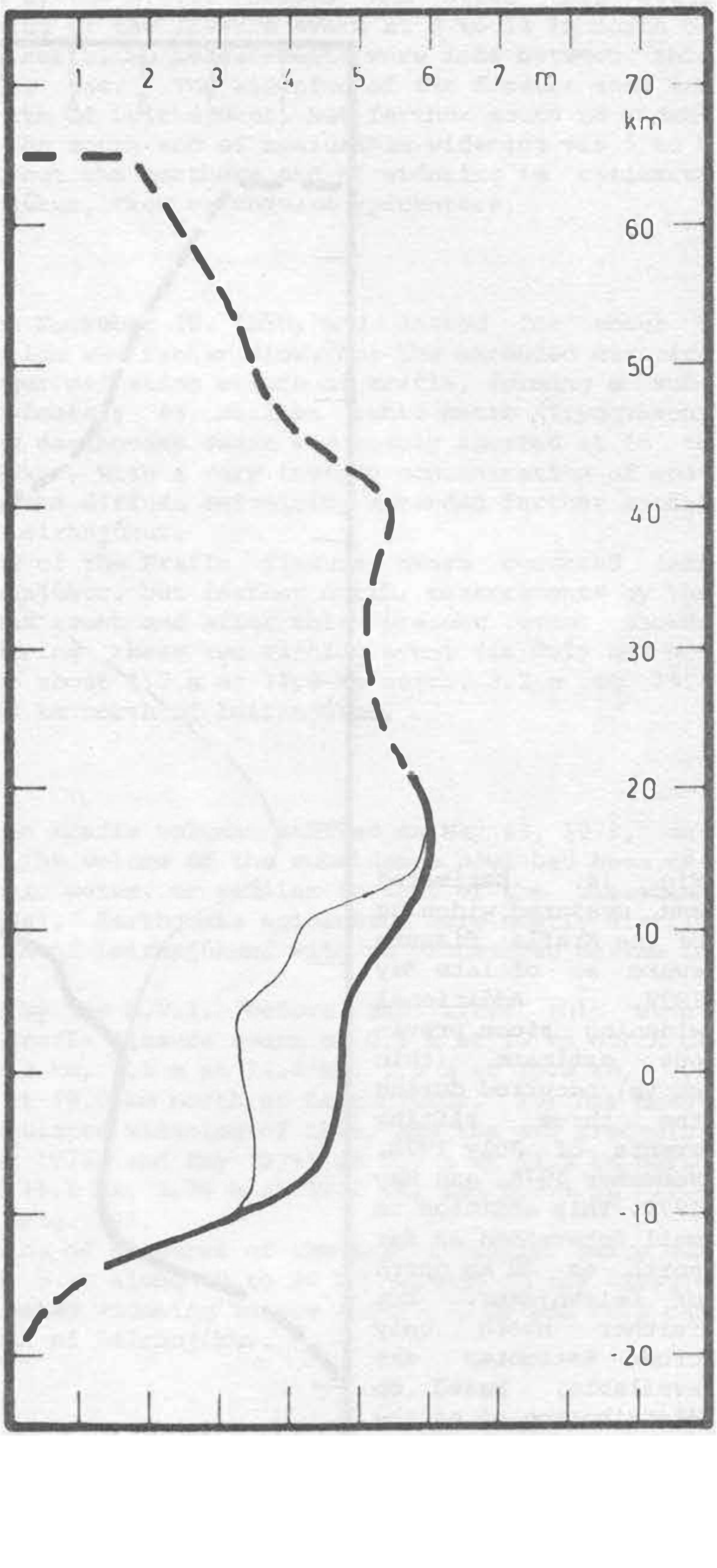

Fig. 15. Estimated and measured accumulated widening of the Krafla fissure swarm from 1975 through March 1980. Additional widening since previous estimate (thin curve) occurred in March 1980, and possibly also in February 1980 and December 1979. This addition is well determined by distance measurements in May to November 1979, and in March to April 1980.

12: December 1979.

A minor deflation started on December 3, 1979, and continued for 4 to 6 days. The volume of the subsidence bowl was less than 3 million cubic meter, and no pronounced earthquake swarm occurred. No fissuring was observed, and no distance measurements were made, which could detect any widening.

13: February 1980.

A slow deflation started on February 11, 1980, and lasted for 4 to 5 days. The volume of the subsidence bowl can be estimated as about 6 million cubic meter.

An intense earthquake swarm accompanied this deflation, with epicenters 3 to 10 km south of Leirhnjúkur. Distance measurements at Leirhnjúkur showed no significant widening at that location, and no widening was measured 10 km south of Leirhnjúkur (Tryggvason, 1983), but minor surface fissures were seen in between these two locations of distance measurements.

14: March 1980.

A very rapid deflation started on March 16, 1980 at 15:10, and lasted about 12 hours. The volume of the subsidence bowl has been estimated as 30 to 40 million cubic meter, but this estimate is quite uncertain, as rifting occurred across the area of maximum subsidence (Tryggvason, 1982). A fissure from 1 to 6 km north of Leirhnjúkur erupted some 3 million cubic meter of lava (Grönvold and Saemundsson, 1981), and new open fissures were seen between a southern point at 6 km south of Leirhnjúkur to a northern point at 15 km north of Leirhnjúkur. A number of distance measurements were made by the N.V.I. across the zone of rifting, between 0.5 km south of Leirhnjúkur, and 11 km north of Leirhnjúkur. Widening of 1.2 to 1.7 m was observed at all locations, with maximum widening 4 - 6 km north of Leirhnjúkur, near the place of maximum lava production (Figs. 15 and 16). Measurements at about 10 km south of Leirhnjúkur showed no widening. A fraction of the widening here reported may have occurred during the two previous events (December 1979 and February 1980).

15: July 1980.

A moderately fast deflation started at 8 am on July 10, 1980, and a voluminous lava flow started at 12:45 the same day from a fissure extending from 6.5 to 11 km north of Leirhnjúkur. The deflation stopped temporarily near midnight, but a very slow deflation resumed soon thereafter, to continue for a week, or as long as the lava eruption continued. The volume of the subsidence bowl was estimated as about 24 million cubic meter, and the volume of the erupted lava was estimated as 23 million cubic meter (Grönvold and Saemundsson, 1981).

The widening of the fissure swarm was measured at one location, about 10.5 km north of Leirhnjúkur, and was found to be 1.65 m during this event (Fig. 16). Elsewhere, measurements of the widening included some other events of rifting, either the March 1980 event, or one or more of the following events.

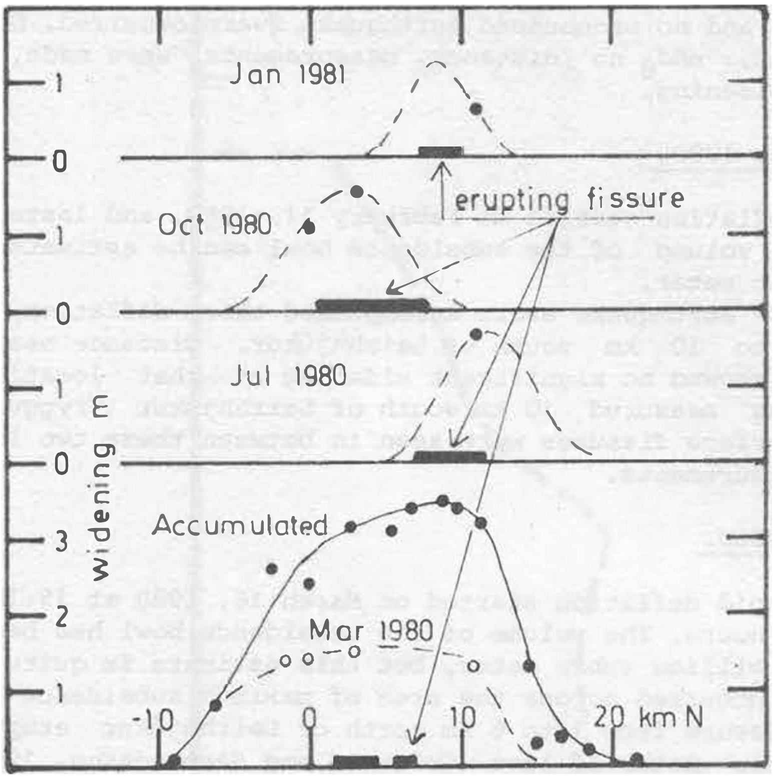

Fig. 16. Measured widening of the Krafla fissure swarm in March 1980 through January 1981 (bottom) and in individual rifting events during the same period. Measurements are shown by solid dots or open circles (March 1980). Dashed curves show how estimated widening varies along the fissure swarm during each event. Distance scale at the bottom is the same as on Figs 9 through 15.

16: October 1980.

An extremely rapid deflation started at about 21:00 on October 18, 1980, and lasted only 8 hours. A 7 km long eruption fissure started erupting about one hour later and the eruption lasted for about 5 days. The south end of this eruption fissure was at Leirhnjúkur. Some slight deflation was observed on and off during the eruption, but a rather rapid inflation started as soon as the eruption ceased. The volume of the deflation bowl was crudely estimated as 16 million cubic meter, but the volume of the erupted lava was estimated as 35 million cubic meter (Grōnvold and Saemundsson, 1981).

The widening of the fissure swarm was measured at Leirhnjúkur, where it was found to be 0.95 m, and 2.7 km north of Leirhnjúkur, the widening between April 1980 and April 1981 was measured as 1.6 m (Tryggvason, 1983), probably all occurring during the October 1980 rifting event, as the July 1980 event and the January 1981 event produced no noticeable fissures at this location (Fig. 16).

17: December 1980.

A small and slow deflation of the Krafla volcano occurred on December 25 to 28, 1980. The volume of the subsidence bowl can be estimated as about 5 million cubic meter. No eruption occurred and no ground fissures were observed. Any possible widening of the Krafla fissure swarm during this event is included in the observed widening during the preceding and following events.

18: January 1981.

A rapid deflation of the Krafla volcano started at about 7:00 on January 30, 1981, and lasted until the afternoon of February 1. Very slow deflation continued for two more days. An eruption fissure from 6 to 8 km north of Leirhnjúkur started erupting at 14:10 on January 30 and the eruption continued until February 4. The volume of the subsidence bowl was estimated as 25 million cubic meter, and the volume of the erupted lava as 32 million cubic meter (Grōnvold and Saemundsson, 1981).

The widening of the fissure swarm was measured by the N.V.I. as 0.4 m at a location 10.5 km north of Leirhnjúkur, but elsewhere, the measurements of the widening included one or more other rifting events (Fig. 16).

A rather detailed picture of the accumulated widening of the Krafla fissure swarm between August 1979 and April 1981 is available from extensive distance measurements by the N.V.I. at these dates (Tryggvason, 1983). This period includes events 12 through 18. Widening of the Krafla fissure swarm during these events extends from 9 km south of Leirhnjúkur to 20 km north of Leirhnjúkur. The maximum accumulated widening is 3.5 m at 8 to 10 km north of Leirhnjúkur (Figs. 16 and 17).

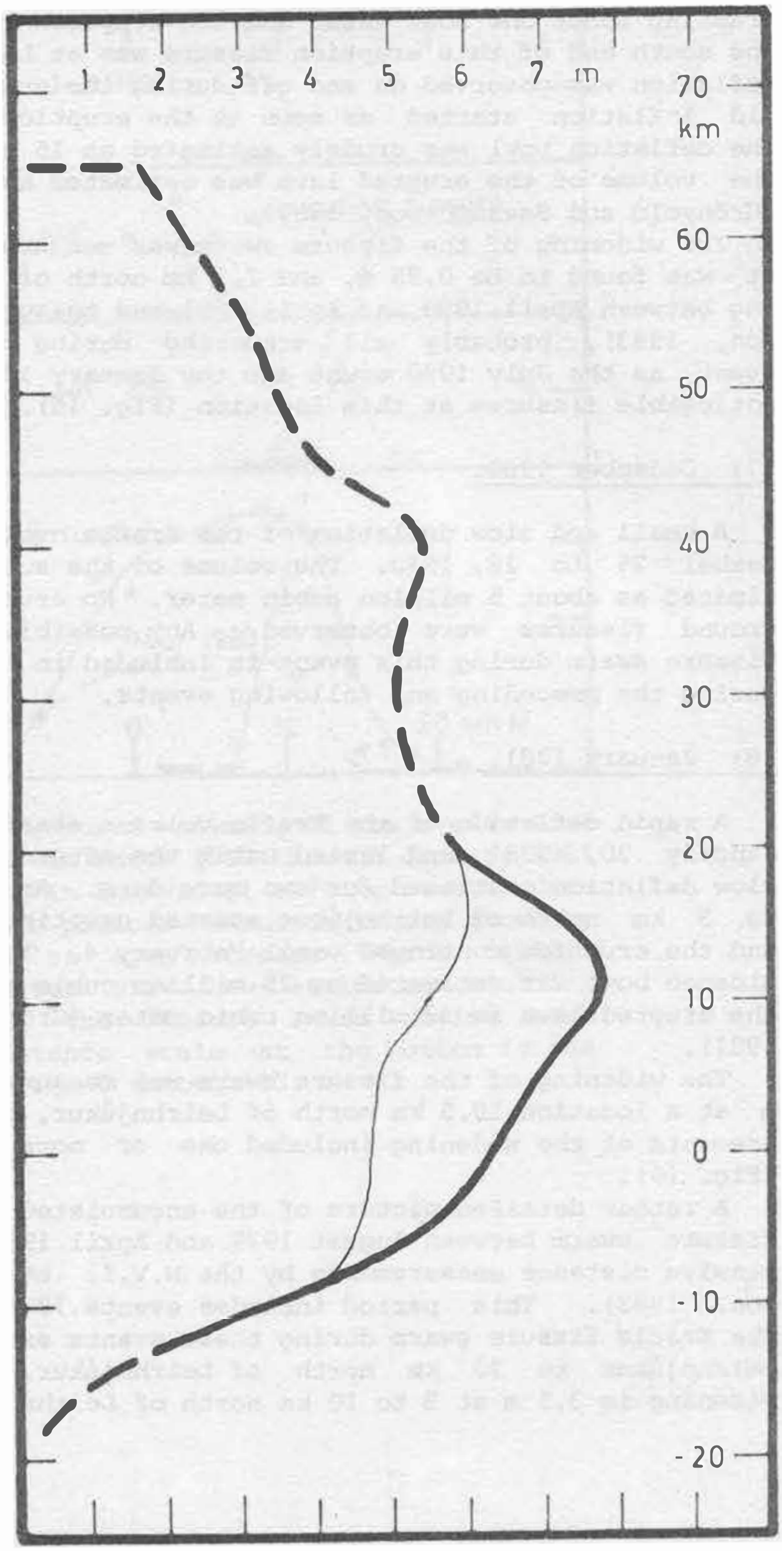

Fig. 17. Estimated and measured accumulated widening of the Krafla fissure swarm from 1975 through April 1981. Additional widening since previous estimate (thin curve) occurred in three rifting events, July and October 1980, and January 1981 (see Fig. 16), and possibly also in December 1980. This addition is well determined by distance measurements of April 1980, and April 1981.

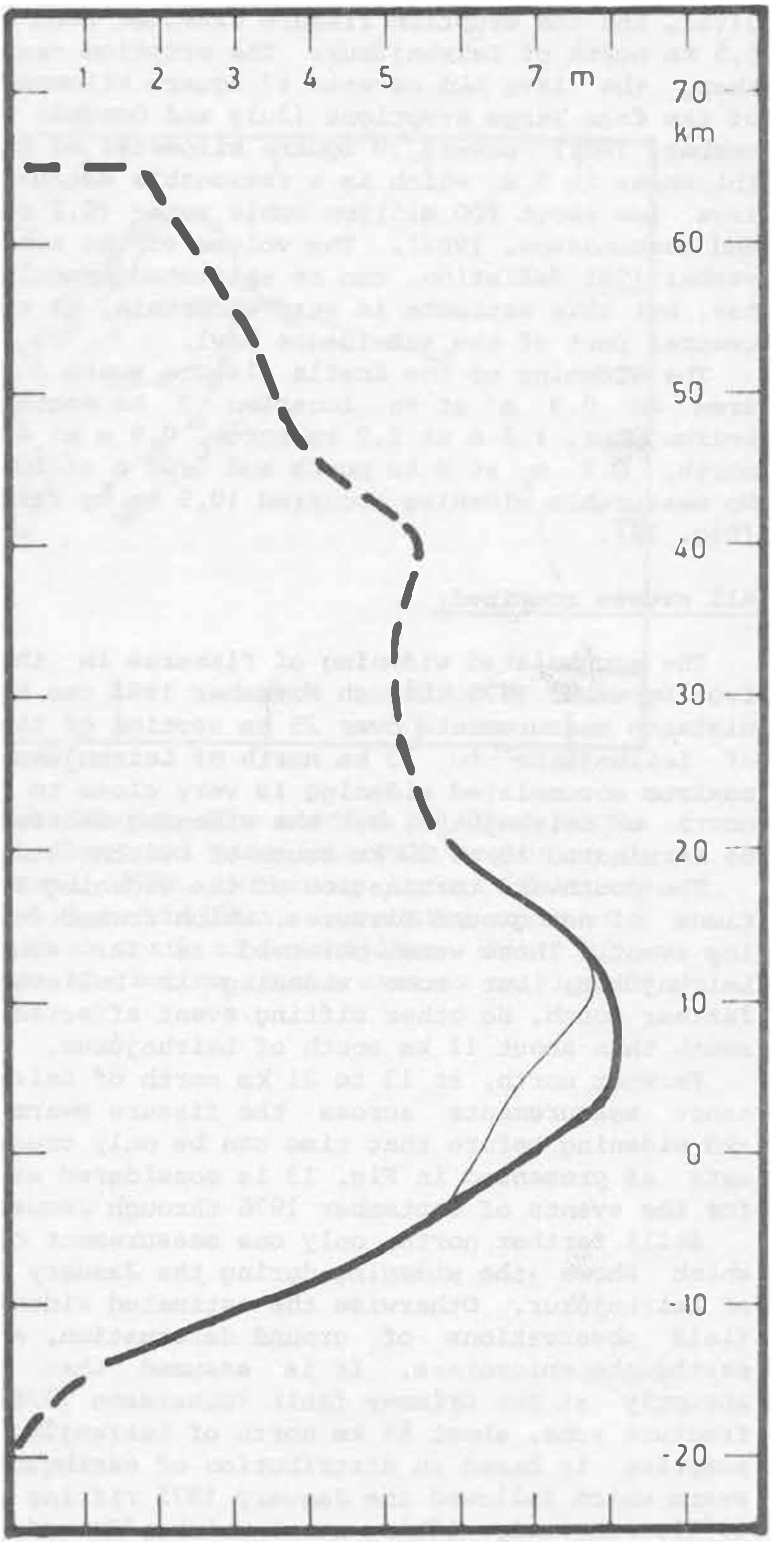

Fig. 18. Estimated and measured accumulated widening of fissures of the Krafla fissure swarm 1975 to 1982. Additional widening since previous estimate (thin curve) occurred in November 1981, and is rather well determined by measurements at several locations. The total estimated widening is obtained by summing the estimated or measured widening of individual rifting events, or a few consecutive events.

19: November 1981.

A very rapid deflation of the Krafla volcano started at 00:40 on November 18, 1981, and the deflation had practically ceased two hours later. Minor deflation lasted for about 5 days. An eruption started at 01:52, and the eruption fissure extended from Leirhnjúkur northwards to 6.5 km north of Leirhnjúkur. The eruption ceased on November 23 and by then, the lava had covered 17 square kilometer of flat land. The lava of the four large eruptions (July and October 1980, and January and November 1981) cover 30 square kilometer of ground, and if the average thickness is 7 m, which is a reasonable estimate, the total volume of lava is about 200 million cubic meter (0.2 cubic kilometer) (Grönvold and Saemundsson, 1982). The volume of the subsidence bowl of the November 1981 deflation, can be estimated crudely as 20 million cubic meter, but this estimate is very uncertain, as rifting passed through the central part of the subsidence bowl.

The widening of the Krafla fissure swarm during this event was measured as 0.3 m at a location 3 km south of Leirhnjúkur, 0.5 m at Leirhnjúkur, 1.2 m at 2.7 km north, 0.9 m at 6 km north, 0.6 m at 7 km north, 0.2 m at 8 km north and 0.05 m at 10 km north of Leirhnjúkur. No measurable widening occurred 10.5 km or farther north of Leirhnjúkur (Fig. 18).

All events combined:

The accumulated widening of fissures in the Krafla fissure swarm from December 1975 through November 1981 can be estimated from numerous distance measurements over 25 km section of the swarm from 12 km south of Leirhnjúkur to 13 km north of Leirhnjúkur (Figs. 10 and 19). The maximum accumulated widening is very close to 8.0 m, at 4 to 12 km north of Leirhnjúkur, but the widening decreases rapidly southwards to be terminated 15 to 20 km south of Leirhnjúkur.

The southward termination of the widening is estimated from observations of new ground fissures, which formed during the April 1977 rifting event. These were observed as far south as 15 km south of Leirhnjúkur, but some widening is believed to have occurred still farther south. No other rifting event affected the fissure zone farther south than about 12 km south of Leirhnjúkur.

Farther north, at 13 to 21 km north of Leirhnjúkur, the first distance measurements across the fissure swarm were made in April 1978, akd widening before that time can be only crudely estimated. The estimate as presented in Fig. 13 is considered as conservative, especially for the events of September 1976 through January 1977.

Still farther north, only one measurement of the widening exists, which shows the widening during the January 1978 event at 38 km north of Leirhnjúkur. Otherwise the estimated widening is based on crude field observations of ground deformation, and on the distribution of earthquake epicenters. It is assumed that the widening terminates abruptly at the Grímsey fault (Einarsson 1976),a branch of the Tjörnes fracture zone, about 65 km north of Leirhnjúkur (Fig. 10). This assumption is based on distribution of earthquökes during the earthquake swarm which followed the January 1975 rifting event (Björnsson et al. 1977), the only rifting event which affected the northern most part of the Krafla fissure swarm.

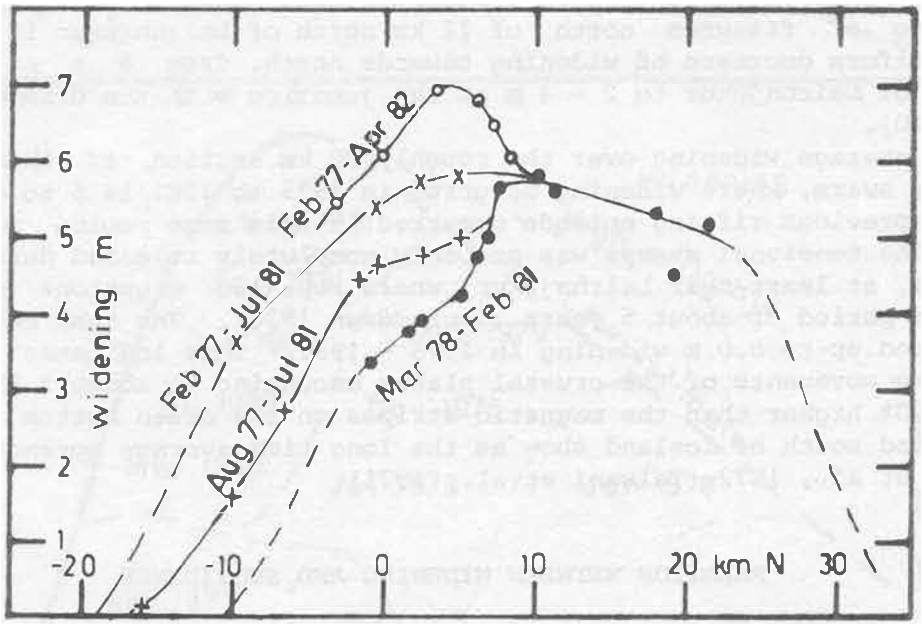

Fig. 19. Measured widening of a portion of the Krafla fissure swarm over several time intervals beginning in February 1977 to April 1978. Widening before February 1977 is about 1.0 m at Leirhnjúkur, increasing northwards to about 2.8 m at 10 km north of Leirhnjúkur (Fig. 10). Distance scale at the bottom is the same as on Figs. 9 through 18.

In view of the great uncertainties in the estimated accumulated widening of fissures of the Krafla fissure swarm between 13 and 65 km north of Leirhnjúkur, the irregularities in the curve as shown in Fig. 17 are most likely artifacts of the method of estimation. The peak in the widening at about 40 km north of Leirhnjúkur gives a value which is partly based on exact measurements, and is more reliable than other estimates of the widening. It is probable that the estimates elsewhere are rather too low than too high in general.

In view of this, the most probable distribution of accumulated widening of fissures north of 12 km north of Leirhnjúkur is more or less uniform decrease of widening towards north, from 8 m at 12 km north of Leirhnjúkur to 2 - 4 m at the junction with the Grímsey fault (Fig. 20).

The average widening over the roughly 80 km section of the Krafla fissure swarm, where widening occurred in 1975 to 1981 is 5 to 6 m.

The previous rifting episode occurred in this same region in 1724-1729. The tensional stress was probably completely released during that episode, at least near Leirhnjúkur, where repeated eruptions occurred over a period of about 5 years (Thoroddsen 1925). The same region experienced up to 8.0 m widening in 1975 - 1981. This indicates average relative movements of the crustal plates amounting to about 3.25 cm per year, 60% higher than the magnetic stripes on the ocean bottom to the north and south of Iceland show as the long time average spreading rate (Meyer et al., 1972, Talwani et al., 1971).

RELATION BETWEEN WIDENING AND SUBSIDENCE

The widening of fissures in the Krafla fissure swarm coincides in time with rapid subsidence of the Krafla central volcano. The events, or brief periods, of rifting and subsidence, are in this paper called "rifting events", but elsewhere, they may be named "subsidence events", or "deflation events", or named after the seismic signature, the subsurface magma transport, or even the eruptions, although not all rifting events are associated with volcanic eruptions.

The processes at work during these rifting events have been described by several authors (Björnsson et al., 1977, 1979, Tryggvason, 1980a, 1981, Einarsson and Brandsdóttir, 1980), and a brief summary of these descriptions is as follows:

A magma reservoir, centered at about 3 km depth below the central part of the Krafla caldera, receives a steady inflow of magma. The pressure of the magma reservoir increases correspondingly, until it reaches a critical value needed to rupture the walls of the reservoir. This rupture is the beginning of a rifting event. The magma flows rapidly out of the reservoir, into vertical fissures below the Krafla fissure swarm, and may reach the surface. Most of the magma is deposited in the vertical fissures, to form dike or dikes as it cools. Formation of a sill is not considered as a possibility, because of the observed ground deformation, which favors a dike.

The accumulated widening of fissures indicates the width of the dike which is being formed. The dike width may differ from the fissure widening, because of vertical gradient of the elastic parameters, but as a first approximation, we can assume these two measures to be the same.

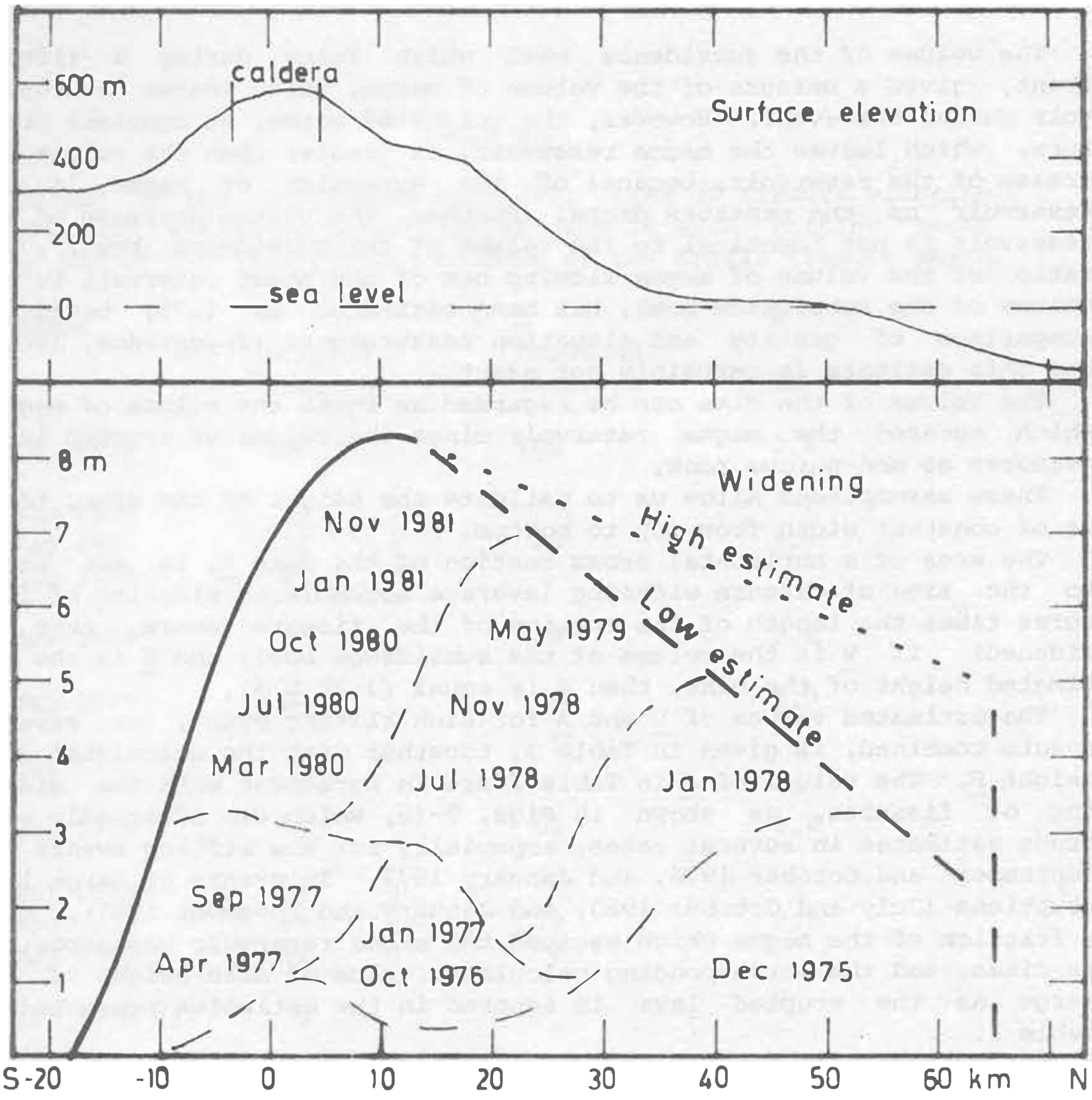

Fig. 20. A simplified estimate of the accumulated widening of fissures of the Krafla fissure swarm between 1975 and 1982, with crude estimate of the contribution of certain time intervals to this widening. This diagram is based on Fig. 18, but irregularities of that curve are evened out, as they are believed to be caused by errors of the estimated widening of individual rifting events. Land elevation along the Krafla fissure swarm is also shown (top). The distance scale (bottom) is the same as in Figs. 9 through 19.

The volume of the subsidence bowl which forms during a rifting event, gives a measure of the volume of magma, which leaves the reservoir during the event. However, the volume of magma, at constant pressure, which leaves the magma reservoir, is greater than the volume decrease of the reservoir, because of the expansion of magma in the reservoir as the pressure drops. Further, the volume decrease of the reservoir is not identical to the volume of the subsidence bowl. The ratio of the volume of magma flowing out of the magma reservoir to the volume of the subsidence bowl, has been estimated as 1.75, based on comparison of gravity and elevation measurements (Tryggvason, 1981), but this estimate is certainly not exact.

The volume of the dike can be regarded as equal the volume of magma, which escaped the magma reservoir minus the volume of erupted lava, measures as non-porous rock.

These assumptions allow us to estimate the height of the dike, if it is of constant width from top to bottom.

The area of a horizontal cross section of the dike A, is set equal to the area of fissure widening (average accumulated widening of fissures times the length of the section of the fissure swarm, that is widened) If V is the volume of the subsidence bowl, and H is the estimated height of the dike, then H is equal (1.75 V/A).

The estimated values of V and A for each rifting event, or several events combined, is given in Table I, together with the calculated dike height H. The values of A in Table I are in agreement with the widening of fissures, as shown in Figs. 9-18, which are admittedly only crude estimates in several cases, especially for the rifting events of September and October 1976, and January 1977. In events of large lava eruptions (July and October 1980, and January and November 1981), only a fraction of the magma which escaped the magma reservoir was deposited as dikes, and the corresponding calculated value of dike height is too large as the erupted lava is ignored in the estimates presented in Table I.

The calculated height of the dikes is 2.4 to 2.8 km for the best recorded events. If this value is in fact nearly the same for all events, the combined widening of the three events of September 1976 through January 1977, is underestimated by a factor of approximately 2. In the event of September 1977, rifting occurred through the center of the subsidence bowl, making the estimated volume of the bowl very uncertain. This has been underestimated by a factor of approximately 1.4 if above assumptions hold.

The events of July 1980 through November 1981 produced large lava flows, while all other events produced no or insignificant lava as compared to the volume of magma which escaped out of the magma reservoir. The estimated volume of lava produced during these first events is 200 million cubic meter (Grönvold and Saemundsson, 1982). This estimate far exceeds the estimated volume of magma which flowed out of the magma reservoir during the same events. The estimated accumulated volume of the subsidence bowl for the four events of great lava production (July and October 1980 and January and November 1981) is 85 million cubic meter (Table I). This corresponds to about 150 million cubic meter of magma flowing out of the reservoir, if the volume ratio of magma to subsidence bowl is 1.75, as assumed above.

The accumulated area (A) of fissure widening during the same events is about 43 thousand square meter (Table I), which indicates consider-

Table I

Volume of the subsidence bowl (V), area of fissure widening (A), and estimated height (H) of dike in each rifting event of the 1975 - 1981 rifting episode of the Krafla fissure swarm

Event	V million cubic m	A thousand square m	km
Dec 1975	150	108	2.4
Sep 1976	10		
Oct 1976	32	20	5.5
Jan 1977	21		
Apr 1977	46	29	2.8
Sep 1977	20	18	1.9
Nov 1977 (1)	2		
Jan 1978	74	55	2.4
Jul 1978	37		
Nov 1978	45	79	2.8
May 1979	44		
Dec 1979 (1)	3		
Feb 1980 (1)	6		
Mar 1980	35	25	2.5
Jul 1980	24		
Oct 1980	16	35	3.2
Dec 1980 (1)	5		
Jan 1981	25		
Nov 1981	20	8	4.4
Total	615	377	2.8

(1) events with no known fissure widening.

able dike formation. If the dike height (H) is 2.4 km, as indicated for other events above, about 100 million cubic meter of magma has been deposited in dikes. This leads to an estimate of roughly 50 million cubic meter of magma to have reached the earth's surface to form the lava.

This discrepancy between estimated volume of lava (200 million cubic meter), and estimated volume of magma used to form this lava (50 million cubic meter) indicates that one or both of these volumes is wrongly estimated by great amount. If the volume of magma which leaves the magma chamber is greatly underestimated (by a factor of 2?), the dike height of Table I is similarly underestimated.

The sum of estimated volumes of the subsidence bowl for all 19 events is 615 million cubic meter (Table I). This corresponds to about 1.08 cubic kilometer of magma, at constant pressure, to have escaped the Krafla magma reservoir during the 6 year period of activity, December 1975 through November 1981 if the ratio of magma volume to subsidence bowl volume is 1.75 as accepted above.

THE CAUSE OF THE SOUTHWARD TERMINATION OF WIDENING

The rapid decrease of widening towards the southern end of the zone of rifting, within the Krafla fissure swarm, during the 1975 to 1981 rifting episode (Fig. 20) invites an attempt to explain the reason for this rapid decrease.

Descriptions of the 1724 to 1729 rifting episode indicate that rifting extended some 20 km farther south, than during the present episode (Thoroddsen, 1925). Recent ground fissures and fault scarps also show recent activity of the Krafla fissure swarm more than 20 km farther south than the 1975-1981 widening. Therefore, the southward termination of widening during the 1975-1981 episode is not controlled by the termination of the fissure swarm, and does not coincide with the southward termination of widening during the preceding rifting episode of the same fissure swarm.

The several fissure swarms in the North Iceland spreading zone form an en echelon pattern in such a way, that the western fissure swarms extend farther towards north, while the eastern fissure swarms extend farther towards south (Tryggvason, 1973, Saemundsson, 1978). This may be explained by a model, where the axis of least crustal strength is not oriented perpendicular to the direction of relative plate movement, but individual tensional fissures tend to be oriented perpendicular to the displacements. Fissure swarm will then form through points of least crustal strength, and their orientation will be parallel to the maximum horizontal stress, and thus perpendicular to the direction of relative plate displacements. The points of least crustal strength supposedly develop into central volcanoes.

Widening of one fissure swarm will release tensional stress in a wide zone, including other parallel fissure swarms. This will prevent rifting in these "other" fissure swarms, or parts thereof, for a period of time sufficient to bring the tensional stress again to a high value, near the critical limit needed for rifting.

The 1874-1875 rifting event in the Askja fissure swarm (Sigurdsson and Sparks, 1978 and Fig 1.), about 25 km east of the Krafla fissure swarm, extended about as far north as Leirhnjúkur. The northern termination of that rifting is, however, poorly known, and the widening is unknown, although description of fissures, hard to pass on a horse, indicates meters of widening. The region where tensional stress was released during the 1874-1875 event must have included the southern part of the Krafla fissure swarm, which lies due west of that part of the Askja fissure swarm, which erupted during the 1874-1875 episode. The reduction of E-W tensile stress during the 1874-1874 rifting event affected the southern part of the Krafla fissure swarm to such an extend, that now, 100 years later, the tensional stress is still below the critical limit required for renewed rifting.

THE CAUSE OF NORTHWARD DECREASE IN WIDENING

The data and estimates presented here on total accumulated widening of fissures of the Krafla fissure swarm (Fig. 20) show a more or less steady decrease of widening from 12 km north of Leirhnjúkur to the northern termination of widening at the Grímsey transform fault. Even though the estimates of widening are rather uncertain in this range, there seems to be no doubt that considerably less widening occurred in the northern part of this region, than the 8.0 m widening at 4 to 12 km north of Leirhnjúkur. The abrupt termination of widening at the Grímsey fault is, however, quite uncertain

If the tensional stress was released as far towards north in 1724-1729, as in 1975-1981, then the same tensional stress is expected to have been built up throughout the whole fissure swarm before the present event started. Other processes, especially large earthquakes, may have modified the stress.

A large earthquake in 1872 (Thoroddsen, 1925) caused some visible displacements on the Húsavík fault, a southern branch of the Tjörnes fracture zone. The eastern termination of the Húsavík fault lies approximately 10 km west of the Krafla fissure swarm, but its extrapolation eastwards would cut the Krafla fissure swarm at about 20 km north of Leirhnjúkur. The most probable focal mechanism of this earthquake is a left lateral displacement on the WNW-ESE trending Húsavík fault. Such displacement would decrease the tensional stress across the northern part of the Krafla fissure swarm.

Another strong earthquake, struck the coastal area near the Krafla fissure swarm in 1885, and produced some sand craters in the coastal alluvium. a few km west of the Krafla fissure swarm (Thoroddsen, 1925). This indicates that some fissuring occurred in that area, which must have modified somewhat the stress condition in the Krafla fissure swarm about 45 km north of Leirhnjúkur.

A third earthquake which may have affected the stress within the northern part of the Krafla fissure swarm was a 7.1 magnitude earthquake in 1910 off the north coast of Iceland (Gutenberg and Richter 1954), possibly on the Grímsey fault.

Further, the numerous smaller earthquakes and earthquake swarms in the Tjörnes fracture zone (Tryggvason, 1973) are likely to have reduced the tensional stress near the north end of the Krafla fissure swarm.

These arguments strongly indicate, that the 1975-1981 widening of the northern part of the Krafla fissure swarm must have been less, than the accumulated relative crustal plate displacements since the end of the 1724-1729 rifting event. Thus the maximum widening of 8.0 m (Fig

20) is the best estimate of the magnitude of relative plate movement in the vicinity of the Krafla fissure swarm between about 1729 and 1981, or in about 250 years.

DURATION OF THE RIFTING EPISODE

The duration of the 1975-1981 Krafla rifting episode is much longer than the one-event rifting of the lake Asal rift zone in 1978 (Abdallah et al., 1979, Tarantola et al., 1979), and also longer than the 1874-1875 Askja rifting, which apparently lasted for less than one year (Thoroddsen, 1925). The 1724-1729 rifting and volcanic episode of the Krafla fissure swarm lasted for 5 years and 4 months, rather similar to the duration of the 1975-1981 rifting episode of 5 years and 11 months. Although very little is known of how rifting occurs along the mid ocean ridges, the 5 - 6 year duration of the Krafla rifting episodes appear to be anomalous.

It would seem natural, that rifting of the earth's crust, caused by gradually increasing tensional stress, would release all the accumulated stress in one event, as apparently happened in the Asal rift zone in 1978. The extended period of rifting with numerous rifting events in the Krafla fissure swarm thus requires an explanation.

In case of the 1975-1981 rifting of the Krafla fissure swarm, only a fraction of the tensional strain present in 1975 was released during the first rifting event. Other rifting events followed in rapid succession for 6 years, without giving the general rate of plate movement any time to increase the tensional strain significantly between rifting events. The reason for this succession of events must lie in some process, which prevents all the tensional strain to be released in one instant, or delays the strain release after it has started. Two models, which possibly can cause this delayed strain release will be briefly discussed.

(I) The supply of magma from the Krafla magma reservoir is required to fill the void created in the crust during the rifting, and this supply is limited at any instant, but is replenished over a period of weeks or months.

(II) The brittle crust lies on a plastic layer of high apparent viscosity, which is incapable of holding shear stress over extended periods, but will not yield significantly over a period of a few days.

In the first case, the Krafla magma reservoir has developed an overpressure before the first rifting event commenced on December 20, 1975. This magma overpressure, or pressure in excess of that caused by the weight of the overlying crust, will result in a greater tensile stress above the magma reservoir, than elsewhere along the fissure swarm. This overpressure, together with the regional tensile stress, will start rifting at the reservoir boundary. The high pressure magma will enter the rift, and extend it, as long as the pressure of the magma reservoir remains above a critical value, needed to continue the rifting, but the magma pressure will decrease in proportion to the amount of magma which leaves the original magma reservoir. The process which originally caused the magma overpressure continues, and the pressure of the magma reservoir gradually increases until new rifting starts, but at this time the crust is veaker than before as the recent rifting has not healed completely. The factors which control the amount of rifting in each rifting event is the amount of high pressure magma which is available to flow into the new rifts, but this is again controlled by the volume of the magma reservoir. Other factors which control the amount of rifting in each event are the regional stress field, the tensile strength of the crust, the thickness of the brittle crust and others. The factors which control the duration of quiescence between rifting events, include the rate of pressure increase in the magma reservoir, which is more or less proportional to the rate of magma flow into the reservoir from an unknown region of magma generation, presumably below the magma reservoir.

In the second case the regional tension of the crust is responsible for the rifting of the thin brittle crust, but a shallow layer of plastic material prevents the build up of shear stress below the brittle layer. The rifting will produce a temporary shear stress in the plastic layer at the bottom of the rifting, which prevents the surface rifting of each event to exceed a critical value which is partly controlled by the depth to the plastic layer and the duration of the rifting event. A gradual release of the shear strain in the plastic layer will, over a period of weeks or months, recreate a tensional stress in the surface layer, which has now a lower tensile strength than before, because of the recent rifting. The period between rifting events is now largely controlled by the apparent viscosity of the presumed plastic layer.

The observed sequence of rifting and fissure widening (Figs 2 and 20) can to some extend support both the above models. although the first case is favored. The first, and also the greatest rifting event was most pronounced at the northern end of the Krafla fissure swarm. This is also the part of the fissure swarm, where the surface elevation is lowest. If potential was equalized along the magma conduit from the Krafla magma chamber to the northern end of the Krafla fissure swarm, the magma pressure in excess of overburden pressure was the greatest at the north end of the zone of rifting. Therefore, the first batch of magma to leave the Krafla magma reservoir was most naturally deposited below the north end of the Krafla fissure swarm.

The next three events affected a higher lying section of the fissure swarm, not in good agreement with case I, but the following events affected the low south end of the rifted zone, followed by events near the north end of the widened zone, to gradually approach the part of the Krafla fissure swarm where the land elevation is highest.

The fact that the events of December 1975 and January 1978 produced greater widening of sections of the fissure swarm, than any of the other events, and that these events lasted much longer than any other events, may indicate that plasticity at the bottom of the brittle crust (case II) may partly control the magnitude of widening in a single event. Events of short duration (less than 2 days) seem not to produce widenings in excess of about 2 m, while these two events of 3 to 8 weeks duration produced maximum widening in excess of 3.5 m.

Although high pressure within the Krafla magma reservoir appear to be the principal cause of the beginning of rifting in 1975, the reason for this elevated pressure is unknown. Distance measurements by T.U. in 1967, 1971, and 1975 show that some surface expansion occurred in the Krafla area between 1971 and 1975, while no such expansion is seen between 1967 and 1971 (Gerke et al., 1978) This indicates that excess pressure started to develop in the Krafla magma reservoir between 1971 and 1975. This process, although largely unknown, causes fluid magma to enter the Krafla magma reservoir. The rate of inflow of magma is controlled by the magma pressure in the reservoir, and periodic rifting occurs as long as the maximum attainable reservoir pressure exceeds the compressional crustal stress by an amount equal to or greater than the tensile strength of the crust. This tensile strength has apparently been lowered greatly by the repeated rifting.

CONCLUSIONS

Rifting of the Krafla fissure swarm in North Iceland commenced in December 1975, after nearly 250 years of quiescence. Repeated rifting of 80 km segment of the fissure swarm lasted for 6 years, and individual events of rifting approached 20.

The maximum widening of fissures, accumulated across the fissure swarm, reached 8.0 m, or possibly slightly more (Fig. 20), at locations 4 to 8 km north of Leirhnjúkur, a small hill in the center of the old Krafla caldera. Widening decreased southward from that location, to terminate 15 to 20 km south of Leirhnjúkur. The widening also decreased northward from the region of maximum widening, but more slowly, and terminated apparently at the Grímsey fault, a branch of the Tjörnes fracture zone, off the north coast of Iceland, about 65 km north of Leirhnjúkur.

The average widening along the 80 km section of the Krafla fissure swarm is estimated as 5 to 6 m, which is considered as a conservative estimate, but very few exact measurements were made of the widening of the northern half of the zone of rifting.

During this episode of rifting, magma from the Krafla magma reservoir (beneath Leirhnjúkur) was repeatedly injected into dikes below the Krafla fissure swarm. several lava eruptions also occurred.

A total of 19 significant events of magma injections were recorded, and the total volume of magma, which flowed out of the Krafla magma reservoir during these injections is estimated as 1.08 cubic kilometer (1080 million cubic meter). Of this volume, 1.03 cubic kilometer is estimated to have been deposited as dikes below the Krafla fissure swarm, which leaves 0.05 cubic kilometer to be erupted to form basaltic lava. The estimated volume of lava on the surface is, however, much greater, or 0.2 cubic kilometer.

The 1975-1981 Krafla rifting episode was initiated by overpressure of magma within the Krafla magma reservoir. This overpressure was developed over a period of less than 4 years, as indicated by repeated precise distance measurements.

The succession of rifting events over a period of 6 years was primarily controlled by the pressure in the Krafla magma reservoir. This pressure was steadily increased between the rifting events, but it dropped during the events. The rate of pressure increase in the Krafla magma reservoir was controlled by the volume of the reservoir, the rate of inflow of new magma, and the elastic properties of the surrounding crust.

The rifting episode was initiated by a stress anomaly, which had been created by 250 years of no rifting, while the general plate movement had continually increased the tensile stress in the affected region. The maximum widening of about 8.0 m is believed to be approximately equal the relative plate movement during these 250 years. This indicates that the present spreading rate is 1.6 cm per year in either direction, or about 60% higher than the spreading rate as deduced from the magnetic stripes to the north or south of Iceland.

The southward termination of rifting was controlled by the stress anomaly created by the 1874-1875 rifting of the Askja fissure swarm, and the northward termination coincided with the Grímsey fault, a branch of the Tjörnes fracture zone.

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