

**OBSERVED GROUND DEFORMATION
DURING THE KRAFLA ERUPTION OF MARCH 16, 1980**

by

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Abstract

The Krafla volcano has been monitored with continuously recording tiltmeters and seismometers and frequent geodetic measurements since the beginning of the present episode of activity in 1975. The inflation-deflation sequence of the volcano showed striking regularity in 1977 and 1978 but it became more erratic in late 1979 with slow inflation interrupted by small deflations.

The eruption of March 16, 1980 was preceded by rapid deflation which started at 15:15 (GMT) and intense volcanic tremor started simultaneously. The subsidence became very rapid at about 16:00, about three times more rapid than had been seen in any previous subsidence event. The eruption was first seen at about 16:20, but it may have started 10 to 20 minutes earlier. It lasted until about 22^h that same night. The deflation of the volcano ceased at about 03^h next morning, March 17, and a new inflation started within a few hours. Tilt observations indicate that roughly $30 \times 10^6 \text{ m}^3$ of magma left the Krafla magma chamber, but only some 10% of this came to the surface as very fluid basaltic lava. New fissures extended through the Krafla volcano over a distance of about 21 km and the widening of the fissure zone was about 1.5 m.

Introduction

A period of volcanic and tectonic activity started in 1975 in North Iceland, and the center of activity is located in the Krafla Central Volcano and the associated fissure swarm (Björnsson et al. 1977). This activity has been characterized by alternating inflations and deflations of the volcano, and episodic widenings of the fissure swarm (Fig. 1). The inflation of the volcano progresses at a rate of 0.5 to 1.0 cm per day for one to seven months between deflations, which last from a few hours to 20 days. The rate of deflation varies greatly from one deflation event to another (Björnsson et al. 1979, Tryggvason 1980). Widening of the fissure swarm associated with opening of new and old fissures, vertical fault displacements, earthquake swarms in the fissure swarm, and sometimes outpouring of basaltic lava, occurs only during deflations of the Krafla volcano. Only a fraction of the fissure swarm widens during each deflation event, often about 20 km section, but the part of the fissure swarm which has widened during the sequence of events since 1975 extends from Axarfjörður in the north to the southern part of the Mývatn area in the south, or over a 80 km distance. The southernmost part of the fissure swarm has not been affected by the present activity as yet (Björnsson et al. 1979).

After the deflation event of May 13 to 18, 1979 (Tryggvason 1980) inflation proceeded at the usual rate, and in mid October 1979 the Krafla volcano had reached the same stage of inflation as immediately before the May deflation. The inflation rate in October and November 1979 was rather slow or only 1.0 to 1.5 mm per day, and in early December 1979 a small deflation of about 4.5 cm occurred and another small deflation of 10 to 12 cm occurred in early February 1980. The rate of inflation remained rather slow between these mini-deflations and also after the February 1980 deflation, and in mid March the ground surface in the central part of the Krafla volcano was about 12 cm higher than immediately before the May 1979 deflation.

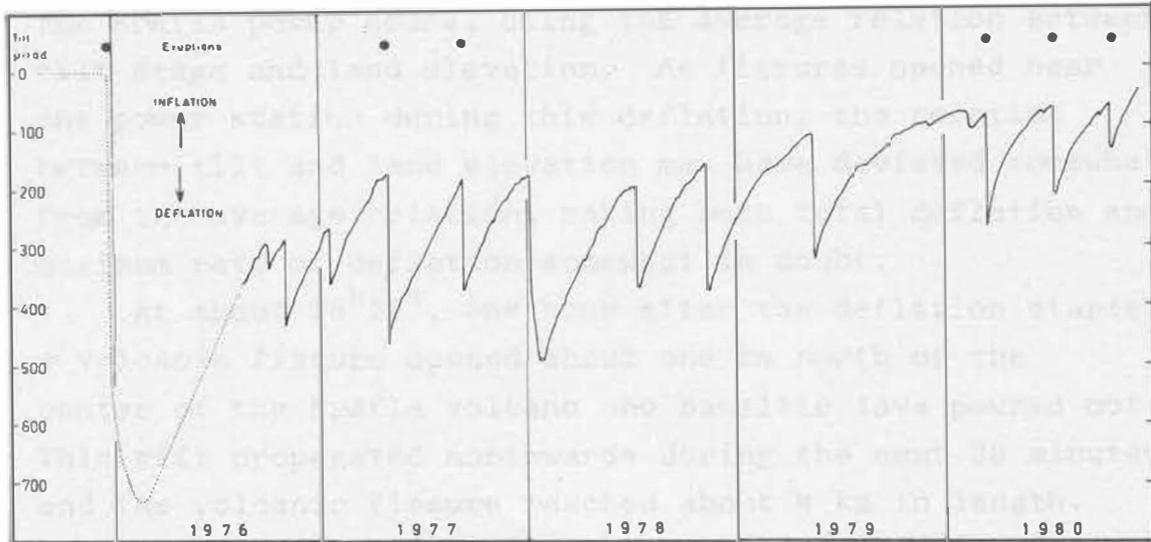


Fig. 1. North component of tilt at the Krafla power station. Before August 20, 1976 (dotted curve), no tiltmeter was operated, but several levelings give the approximate tilt values. Filled circles give the times of volcanic eruptions.

On March 16, at about 15^h15^m rapid deflation of the Krafla volcano started. The maximum rate of deflation of about 50 cm per hour occurred at 16^h30^m. This was faster deflation rate than in any previous deflation event. The deflation stopped at about 03^h on March 17. The total deflation amounted to about 61 cm according to tiltmeters in the Krafla power house, using the average relation between tilt stage and land elevation. As fissures opened near the power station during this deflation, the relation between tilt and land elevation may have deviated somewhat from the average relation, making both total deflation and maximum rate of deflation somewhat in doubt.

At about 16^h20^m, one hour after the deflation started, a volcanic fissure opened about one km north of the center of the Krafla volcano and basaltic lava poured out. This rift propagated northwards during the next 30 minutes and the volcanic fissure reached about 4 km in length. The eruption lasted only some 6 hours during which time an estimated amount of 3 million cubic meters of lava was formed.

Inflation of the Krafla volcano started in the morning of March 17, and the rate of inflation was very high during the following days, or about 2 cm per day.

The subsidence event of March 16-17, 1980 differs from all previous subsidence events in the Krafla volcano as the maximum rate of subsidence was about three times higher than had been observed before. The highest rate of deflation previously observed was on September 8, 1977, about 16.5 cm per hour and about 15.5 cm per hour on April 27, 1977. In all other subsidence events the maximum rate of deflation was observed as 5 cm per hour or less (Tryggvason 1980).

Two subsidence events have occurred since March 1980 until the writing of this paper in December 1980. Both events were accompanied by outpouring of basaltic lava in much greater quantity than in previous eruptions during the present sequence of events in the Krafla area.

Observed tilt

There were 4 recording tiltmeters in the Krafla area during the deflation event of March 16-17, 1980, in addition to one water tube tiltmeter where daily readings were made. Furthermore, 11 "dry tilt" stations were occupied about three months before the event and about two months after the event. These stations can rarely be occupied during winters because of snow cover. All these stations, with possibly one exception, showed clear indication of tilt during the deflation event.

At five of the "dry tilt" stations, which are located within 7 km from the center of deflation, good correlation is found between their tilt, and that of the water tube tiltmeter in the Krafla power house. This correlation is used to estimate the tilt stage immediately before and after the event. At the remaining six "dry tilt" stations no or very poor correlation is found with the water tube tiltmeter, and the observed tilt between the last observation before the event and the first observation after the event is taken as the tilt during the event. Errors in the event tilt due to this assumption are considerable or roughly 10μ -rad as judged from other observations at the same stations.

Fig. 2 shows the location and the observed tilt at all the tilt stations in the Krafla area during the deflation event of March 16-17, 1980. Tilt at stations less than 5 km away from the center of subsidence is primarily caused by the nearly circular subsidence bowl, while stations farther away are affected by deformation along the fissure swarm to the south of the center of subsidence.

Ground subsidence and volume of the subsidence bowl

Two methods are available to estimate the ground subsidence from observed tilt at the tilt stations. One method uses the relation between observed north component of tilt at the Krafla power station and land elevation determined by precise leveling, and the relation between

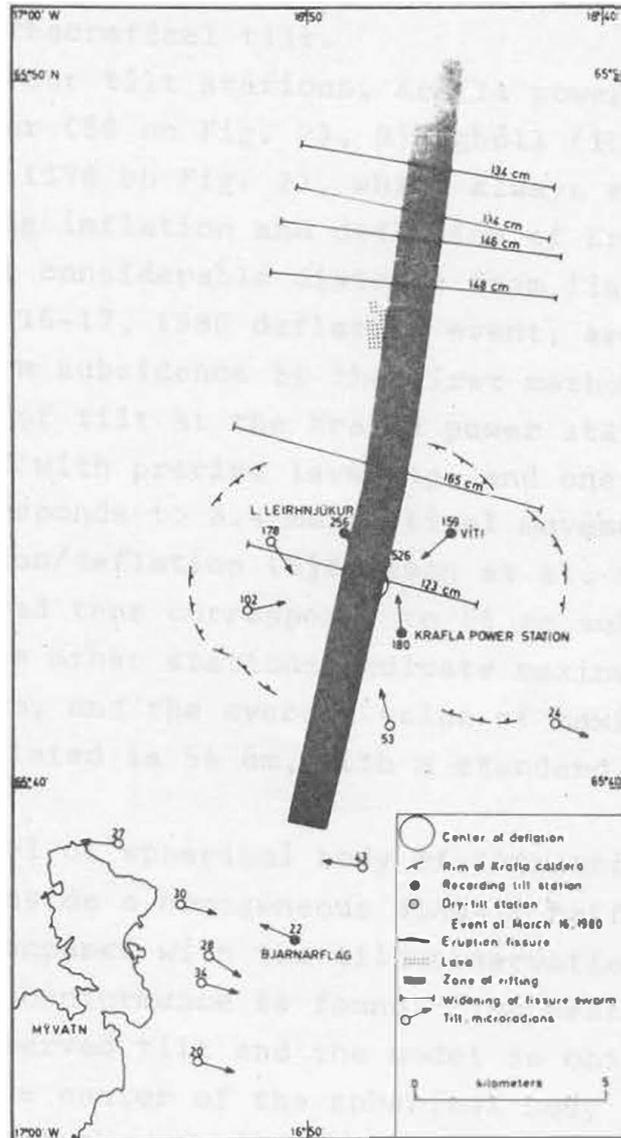


Fig. 2. Map of the Krafla area showing tilt stations with observed tilt during the subsidence event of March 16-17, 1980. Bars show displacements of one side of the rift zone relative to the other during this event. The center of deflation is shown with an open circle and the size of this circle indicates the uncertainty of location of this center. All geodimeter lines which crossed the rift zone (stippled) or extended into it in E-W direction increased in length by more than 20 cm during the event.

tilt at different tilt stations. The other method uses a deformation model and seeks the best fit between observed tilt and theoretical tilt.

The four tilt stations, Krafla power station, Hlidardalur (53 on Fig. 2), Bjarghóll (102 on Fig. 2), and Hvannstód (178 on Fig. 2), which always show considerable tilt during inflation and deflation of Krafla, and are located at considerable distance from fissures formed during the March 16-17, 1980 deflation event, are used to estimate the maximum subsidence by the first method. The north component of tilt at the Krafla power station has been correlated with precise leveling, and one microradian of tilt corresponds to 3.4 mm vertical movement in the center of inflation/deflation (Björnsson et al. 1979). The tilt of 180 μ -rad thus corresponds to 61 cm subsidence. The tilt at the other stations indicate maximum subsidence of 43 to 62 cm, and the average value of maximum subsidence thus calculated is 55 cm, with a standard error of about 5 cm.

A model of spherical body of increasing or decreasing pressure inside a homogeneous elastic halfspace (Mogi 1958) has been compared with the tilt observations and a reasonable conformance is found. The best correlation between observed tilt and the model is obtained if the depth to the center of the spherical body is 2.9 ± 0.1 km, the volume of the subsidence bowl 35 ± 2 million m^3 , and the maximum subsidence 65 ± 5 cm.

The discrepancy between the empirical value for maximum subsidence of 55 ± 5 cm, and the theoretical value of 65 ± 5 cm is not significant and the theoretical model seems not to deviate greatly from the actual condition. However, one obvious error in the model is the assumption of homogeneous elastic halfspace, while the geology of the Krafla area is rather chaotic, and increasing temperature and pressure with depth causes vertical gradient in the elastic properties. It is also very unlikely that the inflating and deflating body is spherical, and its diameter is probably large compared with its depth, but the theory accounts for a small body relative to its depth below the surface of the halfspace.

The conclusion of this discussion is that the subsidence bowl formed during the March 16-17 deflation of the Krafla volcano had a maximum depth of 60 ± 10 cm, and its volume was probably between 30 and 40 million m^3 . The shape of the bowl can be roughly approximated by a theoretical model of decreasing pressure in a spherical body centered at 2.9 km depth. This is taken as indication of removal of material (magma) at approximately this depth. The volume of material removed is probably somewhat greater than the volume of the subsidence bowl as the decreased stress causes increase in volume. However, the stress change is not known, and the volume of material removed from below the area of subsidence can best be estimated as 30 to 40 million m^3 . Tilt in the Mývatn area, 7 to 13 km south of the center of deflation (Fig. 1) is mostly towards the Krafla fissure swarm, 20 to 40 microradians. This shows that the fissure swarm subsided to the south of the region where surface rifting was observed. One station, off the north coast of the lake Mývatn, shows tilt away from the fissure swarm. This may indicate uplift of the flanks of the fissure swarm in the region where surface rifting occurred, similar as observed during the subsidence events of April 1977 and January 1978 (Björnsson et al. 1979, Sigurdsson 1980).

Horizontal deformation

Distance measurements in the Krafla area have been made many times since early 1977, and an effort has been made to cover the area with measurements during every inflation period. These measurements have shown that inside the Krafla caldera the distances between bench marks vary regularly with the stage of inflation, and each distance varies linearly with the observed tilt at the Krafla power station. This linear relation is broken only during deflation events with rifting across the caldera. This allows us to estimate the length of each measured line immediately before and after the March 16 to 17, 1980

deflation event, and to estimate further how much of the observed length difference is due to the deflation and how much is due to permanent deformation in form of rifting.

A total of 79 lines were measured with a geodimeter at times before and after the March event which allowed estimate of the length change during the event. Of these, 41 had increased in length by more than 20 cm. All these 41 lines cross the rift zone shown on Fig. 2, or extend into this zone. No line which lies wholly outside the rift zone had increased in length by more than 10 cm.

Where two or more lines crossed the rift zone at different angles, the total displacement of one side of the zone relative to the other can be determined. Six such determinations of displacements across the rift zone are shown on Fig. 2. One line, about one km south of the southernmost such determination, gave increase in length of 142 cm, but the exact direction of displacement was not obtained.

The direction of displacement is found to be nearly perpendicular to the rift zone. In the northern part of the area, this direction is 99 ± 3 degrees and in the southern part is about 104 degrees. Thus a slight change in the direction of the rift zone is reflected in the direction of displacements.

The north and south ends of the zone where rifting occurred during the March 1980 event were not determined with the geodimeter measurements, but open fissures were observed in the snow as far north and south as shown on Fig. 2.

Fig. 2 shows that the observed widening of the rift zone during the March 16-17 deflation event ranged between 123 and 165 cm. The average widening of the rift zone over the 13 km of length, where it was measured is about 140 cm. The length of the zone where surface rifting was seen is about 21 km, and it may be assumed that the widening was less towards the end of the rifted zone, than in the central part. If it is assumed that the 8 km length of the fissured zone, which lays outside the region of distance measurements was widened 70 cm on the average, the increase in area of the rift zone was 23800 m^2 . The

increase in area of the Krafla fissure swarm during all rifting events since December 1975, is probably more than 300000 m^2 (Björnsson et al. 1979).

The volume of the subsidence bowl formed during the March 16-17 deflation event is estimated as $30-40 \times 10^6 \text{ m}^3$, and less than 10 per cent of that volume was erupted. Therefore, it is estimated that some 30 million cubic meters of magma were deposited in a dike of horizontal cross section similar to the areal increase of the rift zone of 23800 m^2 . This gives the average vertical extension of the dike about 1.3 km.

Conclusion

The subsidence event in the Krafla area, North Iceland, on March 16-17, 1980, is one of 13 similar events since December 1975 (Fig. 1) (Björnsson et al. 1979, Einarsson & Brandsdóttir 1980). Common features of all these subsidence events are

1. Rapid subsidence of the Krafla area, with center of subsidence about 1.5 km north or northwest of the Krafla geothermal power station.
2. Rifting and widening of a section of the Krafla fissure swarm.
3. Swarm of earthquakes with epicenters in the area of rifting.
4. Continuous tremor on local seismometers.

In six of the subsidence events, basaltic lava has reached the surface, but in only small amounts as compared with the volume of the subsidence bowl, until in July and October 1980, when the volume of lava was similar to the volume of the subsidence bowl.

It is assumed that the subsidence in the Krafla area is caused by removal of magma from beneath that area, and depositing it in fissure or fissures in the elastic crust below the zone which developed surface rifting (Björnsson

et al. 1977). The areal increase of this zone is considered to reflect the horizontal cross sectional area of the dike or dikes formed and the average height of the dike is calculated as 1.3 km by equating the volume of the subsidence bowl and the volume of the dike. The depth to the top of the dike is zero along the eruption fissure, but elsewhere the depth of the dike can be roughly estimated as equal the width of the fissured zone (Tryggvason 1980), or about one km. Thus the bottom of the dike should be at somewhat less than 3 km depth.

Acknowledgements

The National Energy Authority operates the water tube tiltmeter at the Krafla power station, which is the most important single measurements made to monitor the tectonic events in the Krafla area.

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