NORDIC VOLCANOLOGICAL INSTITUTE 9502
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## 1985-1994

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## ABSTRACT

Precise measurements of Kleifarvatn lake level have been made about once each year since 1985. These measurements are made at seven locations (stations) around the lake, with the specific purpose of determining the vertical component of ground deformation in the area of the lake, which is located inside the seismic and volcanic zone of the Reykjanes Peninsula in south-west Iceland. The observations in 1985 to 1994 suggest that continuous deformation has been going on at a specific rate, but abrupt displacements can not be excluded. Absolute vertical displacements are not determined but relative movements are related to one of the lake level stations. A station on the north-west shore of the lake has been selected as reference station, and all other stations appear to have risen relative to this reference. This signifies that the reference station is subsiding at a faster rate than other stations, but previous deformation measurements in the area have shown that the seismic and volcanic zone on the Reykjanes peninsula is generally subsiding. Observed ground deformation in the southern part of the lake can be described as progressing tilt with uplift towards south or south-east at a rate of about 0.15 $\mu$rad per year.

## INTRODUCTION

The lake Kleifarvatn lies in a depression between two volcanic ridges in south-west Iceland. The mapped plate boundary between the American plate to the north-west and the European plate to the south-east lies under the lake. The area is volcanically active with numerous Holocene eruptive centers within 10 km distance from the lake, the last eruptions less than 800 years ago. The Holocene volcanism is characterised by extensive lava flows from eruptive fissures. Pleistocene volcanism has left ridges and irregular hills of 300 to 500 m elevation. The ridges are oriented in the direction NE-SW, and the same orientation is characteristic for eruptive and tectonic fissures. Seismic activity is high in the region of the lake with frequent swarms. An earthquake of Richter magnitude between 5 and 6 occurred in 1924 in the vicinity of the lake. Another earthquake of magnitude 6.3 in 1929 was located

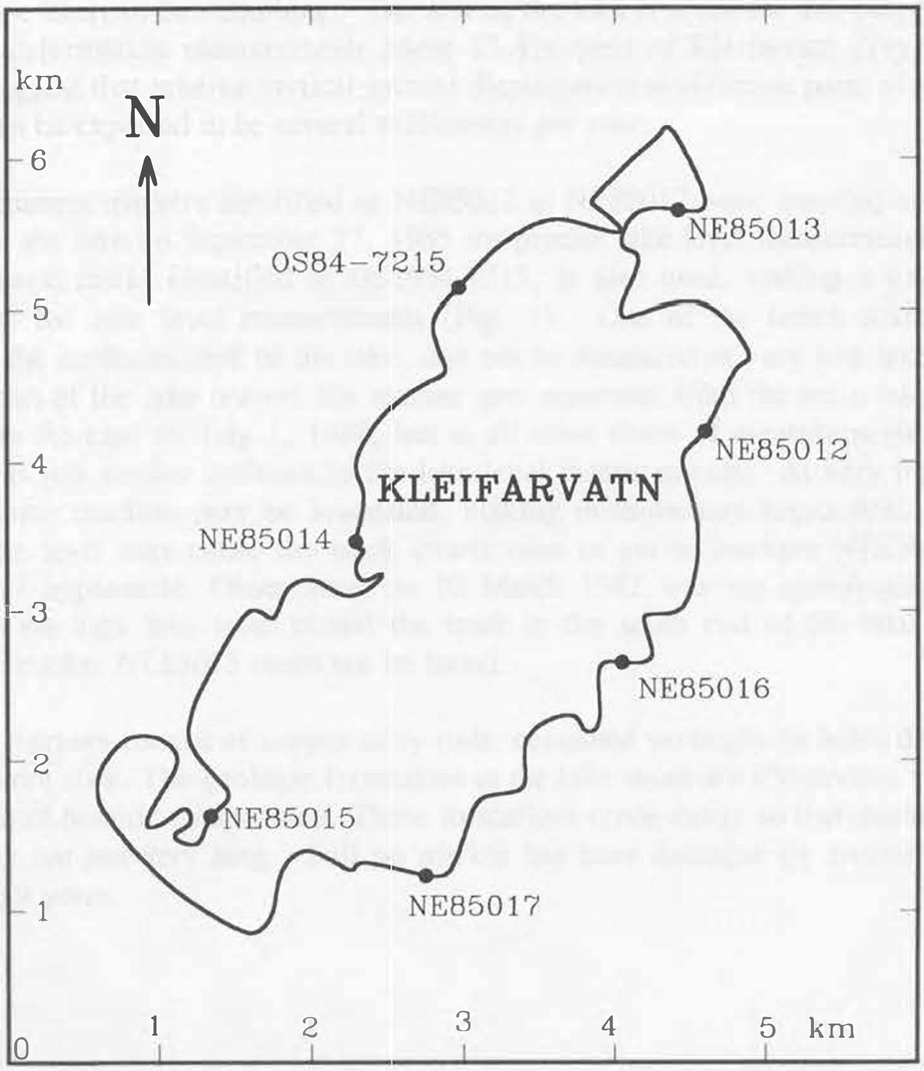


Fig. 1. Sketch map of lake Kleifarvatn, showing the stations used for lake lavel observations

about 10 km east of the lake (Ottósson, 1980). An earthquake of magnitude about 6.0 occurred in 1933 about 5 km west of the lake (Tryggvason 1978a), and another of magnitude 5.8 in 1968 about 10 km east of the lake. Several earthquakes of M4.5 to M5.5 have occurred in the immediate vicinity of the lake, including a quake of magnitude 4.8 below the southern part of the lake on March 19, 1990 (US Geol. Survey 1990). The lake Kleifarvatn has no surface drainage and its elevation varies by meters. Its length from north-east to south-west is about 6 km at high lake level, but both ends of the lake are shallow and at low lake level its length shrinks to about 5 km. The lake is about 2.5 km broad near the center. Its maximum depth is about 87 m (Hannesson 1941), and a 3 km long channel exceeds 40 m in depth.

The location of lake Kleifarvatn on the crustal plate boundary, in a region of considerable volcanic activity and within an area of intense seismic activity makes it ideal for study of crustal deformation by lake level measurements. The great average depth of the lake causes its surface to be level even in some wind, but wind waves are likely to be disturbing. The size of the lake is small for this purpose, but ground deformation measurements about 15 km west of Kleifarvatn (Tryggvason 1970) suggest that relative vertical ground displacement at different parts of the lake shore can be expected to be several millimeters per year.

Six permanent markers identified as NE85012 to NE85017 were installed along the shore of the lake on September 27, 1985 for precise lake level measurements. One older bench mark, identified as OS1984-7215, is also used, making a total of 7 locations for lake level measurements (Fig. 1). One of the bench marks, that nearest the north-east end of the lake, can not be measured at very low lake stage, as the part of the lake nearest this marker gets separated from the main lake body. This was the case on July 1, 1988, but at all other times of measurements 1985 - 1994 was this marker included in the lake level measurements. At very high lake level, some markers may be inundated, making measurement impractical. Also, high lake level may cause the track (road) used to get to markers NE85016 and NE85017 impassable. Observation on 10 March 1982 was not completed, partly because the high lake level closed the track at the south end of the lake, partly because marker NE85015 could not be found.

All the markers consist of copper alloy rods, cemented vertically in holes drilled in unfractured rock. The geologic formations at the lake shore are Pleistocene volcanic products of basaltic composition. These formations erode easily so that markers will probably not last very long. Still no marker has been damaged by erosion during the first 9 years.

## MEASUREMENTS

Measurements of the lake level have been made using the technique described by Tryggvason (1987). First measurement is normally at station identified as NE85012, then at NE85013, OS1984-7215, NE85014, NE85015, NE85017, NE85016, and NE85012, in this order. The large lake level variation with time requires modification of the lake level measurements as conducted at lake Myvatn and other lakes at near constant level. The measuring rod attached to the suspended cylinder (barrel) is about 2 m long, which requires a reference on land at less than 2 m above the lake surface. If the lake level is more than 2 m below the permanent marker, then a temporary reference is established, and conventional level survey determines height difference of this temporary reference and the permanent marker.

The first lake level survey was made on 27 September, 1985 and subsequent measurements on 5 May, 1986, 21 May, 1987, 1 July 1988, 18 April 1991, 25 May 1992 and 3 October 1994. Incomplete measurements were made on 17 April 1991, but increasing wind prevented completion of the observation. Also on 10 March 1992, when only 3 stations were observed because of adverse conditions.

### TABLE 1

Measured height of permanent markers above lake level of lake Kleifarvatn in cm.

| Bench mark | 27 09 1985 | 05 05 1986 | 21 05 1987 | 01 07 1988 | 17 04 1991 |
|---|---|---|---|---|---|
| NE85012 | 167.602 | 206.828 | 225.221 | 265.161 | 144.130 |
| NE85013 | 129.741 | 168.984 | 187.708 | * | 105.431 |
| OS1984-7215 | 143.499 | 182.864 | 201.356 | 241.409 | 117.926 |
| NE85014 | 152.215 | 191.651 | 210.220 | 250.195 | 128.167 |
| NE85015 | 107.772 | 147.325 | 165.949 | 205.721 | ** |
| NE85016 | 153.729 | 193.163 | 211.572 | 251.502 | ** |
| NE85017 | 182.397 | 222.077 | 240.398 | 280.777 | ** |

| Bench mark | 18 04 1991 | 10 03 1992 | 25 05 1992 | 03 10 1994 |
|---|---|---|---|---|
| NE85012 | 143.986 | 95.825 | 98.729 | 133.671 |
| NE85013 | 106.193 | ** | 60.777 | 96.811 |
| OS1984-7215 | 119.092 | 71.987 | 73.964 | 109.710 |
| NE85014 | 128.488 | 80.347 | 83.325 | 119.081 |
| NE85015 | 84.692 | ** | 39.148 | 74.853 |
| NE85016 | 130.695 | ** | 85.399 | 121.335 |
| NE85017 | 160.403 | ** | 115.194 | 151.302 |

** Observation not possible because of low lake level.*
*** Observation not made because of adverse condition.*

The observed height of the markers above the lake level is given in Table 1 in cm with three decimal digits, suggesting an accuracy of 0.001 cm. This is a calculated value, and in fact, the precision of the observations is not this good. The reading of the lake level is attempted at an accuracy of 0.05 cm and several readings, usually 3 to 5, are made during each observation. More readings are taken if the scatter of readings suggest bad but tolerable conditions. The average value is calculated to the nearest 0.001 cm, but an error estimate is not made for each observation. If the observation is made in calm weather, the scatter of individual readings indicate standard deviation of each reading of about 0.1 cm, but wind waves may cause the standard deviation to be up to 0.5 cm. The wind during observation may tilt the suspended measuring rod causing considerable reading errors. Seiches have not been studied in lake Kleifarvatn, but they may cause observations to be erratic. Observations are terminated if errors in excess of about 0.5 cm are indicated. Judging all factors, the error in observed lake level, relative to the permanent bench marks, is assumed to be less than 0.2 cm if observations are made under reasonably good weather condition.

## OBSERVED VERTICAL DISPLACEMENTS

Comparison of two lake level observations will show if the bench marks have been displaced vertically between times of the observations. For the indicated vertical displacement to be certain or significant, it has to exceed the errors that may have occurred in the observations. Displacement of one marker may be observed relative to another marker only, but "absolute" displacement can only be inferred, because no place on the lake shore can be regarded as absolutely stable. It is convenient to select a reference station which is treated as if it was absolutely stable. This reference station must be observed at the same time and in the same way as the other stations, and thus it must be one of the lake level stations at lake Kleifarvatn. The reference station should be very stable in the sense that the marker is securely fastened into rock which does not move relative to the geologic formation of which it is a part.

If all stations in the network are observed at all observational times and are equally trustworthy with regard to stability, then the average elevation of all station may be taken as reference. This is practised in numerous ground tilt arrays (dry-tilt stations) and also at lake level networks (Tryggvason 1978b, Tryggvason et al. 1994). The Kleifarvatn lake level markers are not all occupied at all times of observation. The marker NE85013 is located near the north end of the lake. At extreme low level of the lake, this marker is so far away from the lake that measurements are not practical. Markers NE85016 and NE85017 are at locations which are difficult to reach at high lake level, and NE85015 may be inundated at extremely high lake level. This leaves only NE85012, NE85014 and OS1984-7215 as practical reference stations. Of these the station OS1984-7215 has been chosen as reference to which all observations of the lake level of lake Kleifarvatn are compared.

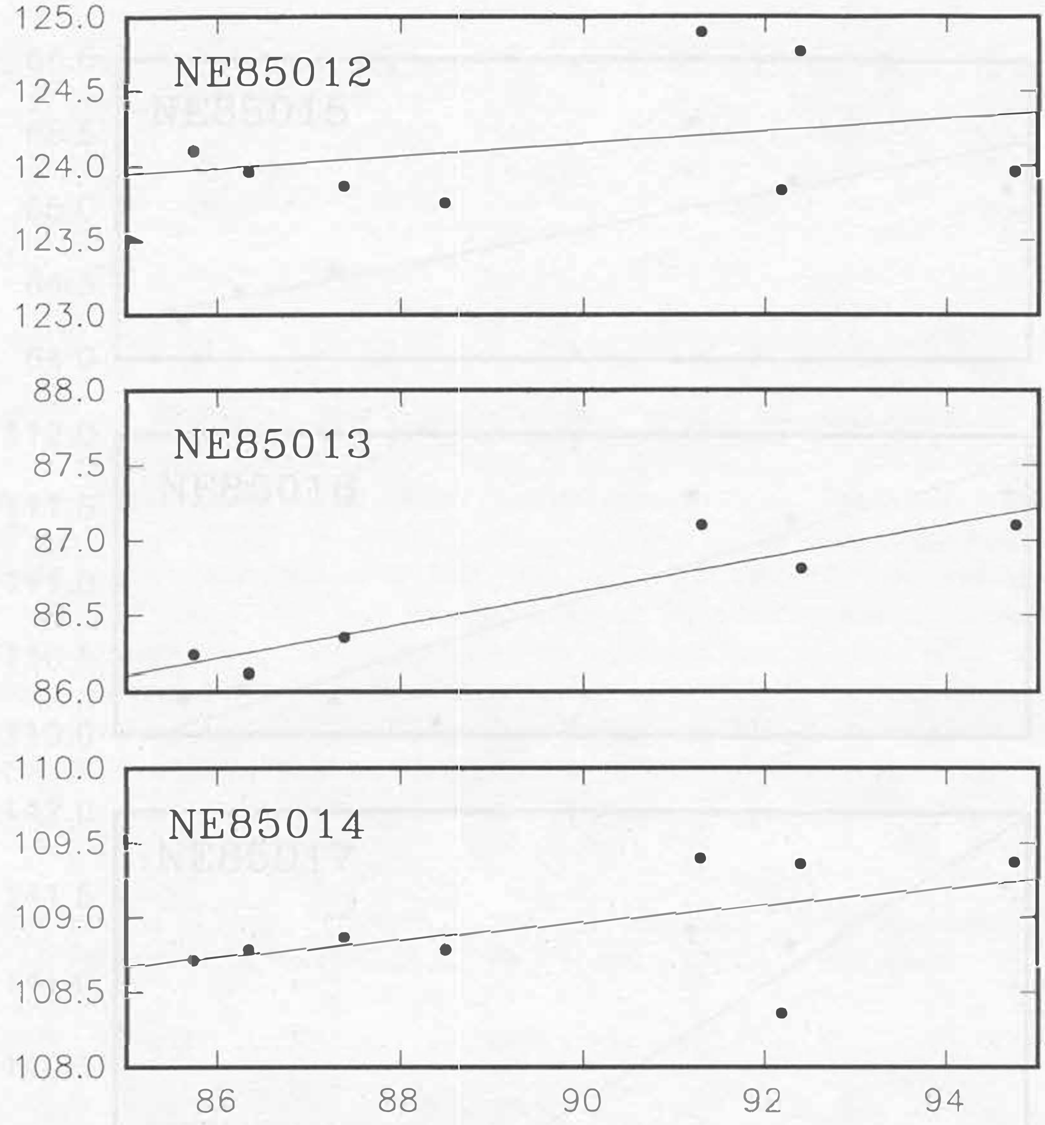


Fig. 2. Observed height of three northern lake level markers at Kleifarvatn, relative to height of marker OS1984-7215. Vertical scale is in cm above the lake surface, if the reference marker height is 100.000 cm. Horizontal scale is time in years. Drawn are regression lines of station heights versus time.

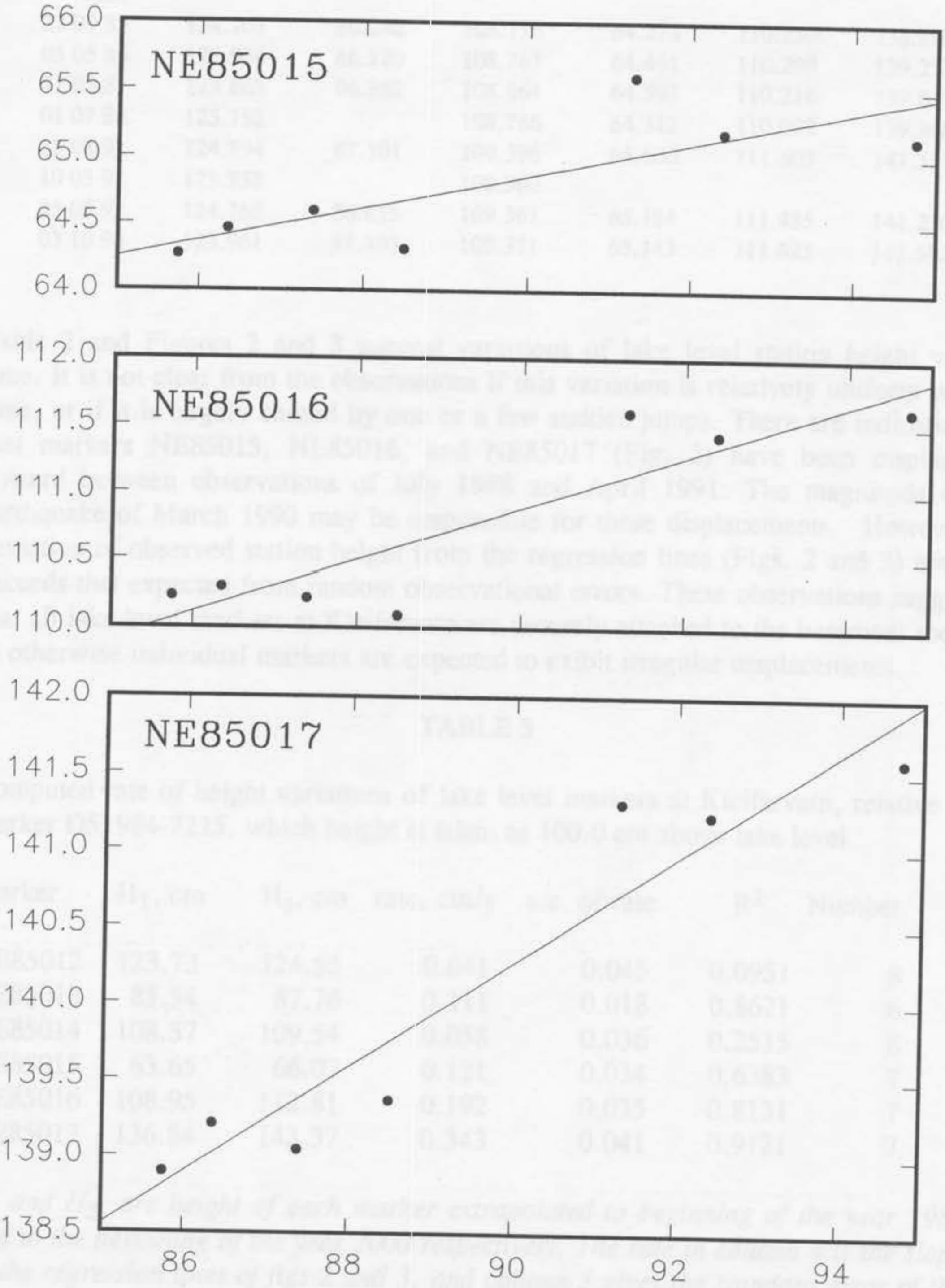


**Fig. 3. Observed heights of three southern lake level markers at Kleifarvatn, relative to marker OS1984-7215. See Fig. 2 for explanation.**

TABLE 2

Height of lake level markers at lake Kleifarvatn relative to marker OS1984-7215 in cm if height of marker OS1984-7215 is 100.000 cm.

| Time | NE85012 | NE85013 | NE85014 | NE85015 | NE85016 | NE85017 |
|---|---|---|---|---|---|---|
| 27 09 85 | 124.103 | 86.242 | 108.716 | 64.273 | 110.230 | 138.898 |
| 05 05 86 | 123.964 | 86.120 | 108.787 | 64.461 | 110.299 | 139.213 |
| 21 05 87 | 123.865 | 86.352 | 108.864 | 64.593 | 110.216 | 139.042 |
| 01 07 88 | 123.752 | | 108.786 | 64.312 | 110.093 | 139.368 |
| 18 04 91 | 124.894 | 87.101 | 109.396 | 65.600 | 111.603 | 141.311 |
| 10 03 92 | 123.838 | | 108.360 | | | |
| 25 05 92 | 124.765 | 86.813 | 109.361 | 65.184 | 111.435 | 141.230 |
| 03 10 94 | 123.961 | 87.101 | 109.371 | 65.143 | 111.625 | 141.592 |

Table 2 and Figures 2 and 3 suggest variations of lake level station height with time. It is not clear from the observations if this variation is relatively uniform with time, or if it is largely caused by one or a few sudden jumps. There are indications that markers NE85015, NE85016, and NE85017 (Fig. 3) have been displaced upward between observations of July 1988 and April 1991. The magnitude 4.8 earthquake of March 1990 may be responsible for these displacements. However, deviation of observed station height from the regression lines (Figs. 2 and 3) never exceeds that expected from random observational errors. These observations suggest that all lake level markers at Kleifarvatn are securely attached to the basement rock, as otherwise individual markers are expected to exibit irregular displacements.

TABLE 3

Computed rate of height variations of lake level markers at Kleifarvatn, relative to marker OS1984-7215, which height is taken as 100.0 cm above lake level.

| Marker | $H_1$, cm | $H_2$, cm | rate, cm/y | s.e. of rate | $R^2$ | Number |
|---|---|---|---|---|---|---|
| NE85012 | 123.73 | 124.55 | 0.041 | 0.045 | 0.0951 | 8 |
| NE85013 | 85.54 | 87.76 | 0.111 | 0.018 | 0.8621 | 6 |
| NE85014 | 108.37 | 109.54 | 0.058 | 0.036 | 0.2515 | 8 |
| NE85015 | 63.65 | 66.07 | 0.121 | 0.034 | 0.6383 | 7 |
| NE85016 | 108.95 | 112.81 | 0.192 | 0.035 | 0.8131 | 7 |
| NE85017 | 136.84 | 143.37 | 0.343 | 0.041 | 0.9121 | 7 |

*$H_1$ and $H_2$ are height of each marker extrapolated to beginning of the year 1980 and to the beginning of the year 2000 respectively. The rate in column 4 is the slope of the regression lines of figs 2 and 3, and column 5 gives the standard error of the slope. R is the coefficient of correlation of relative height versus time and N is number of lake level observation at each station.*

It is clear from Table 3 that the four lake level stations NE85013, NE85015, NE85016 and NE85017 have been uplifted significantly relative to the reference station. At these stations the computed rate of relative uplift is more than three times the computed standard error of this rate, and thus the uplift rate is certainly significant at the 95% to 99% confidence level (Fig. 4). The computed relative uplift of the stations NE85012 and NE85014 is similar as the computed standard error, and thus the observed vertical displacement of these stations is not significant. This lack of significance is also clear from the value of the coefficient of correlation. The values of Table 3 suggest that a lake level observations, as those at lake Kleifarvatn, are capable to detect relative vertical movement of a rate of 0.1 cm per year if observations are made over a period of more than 5 years.

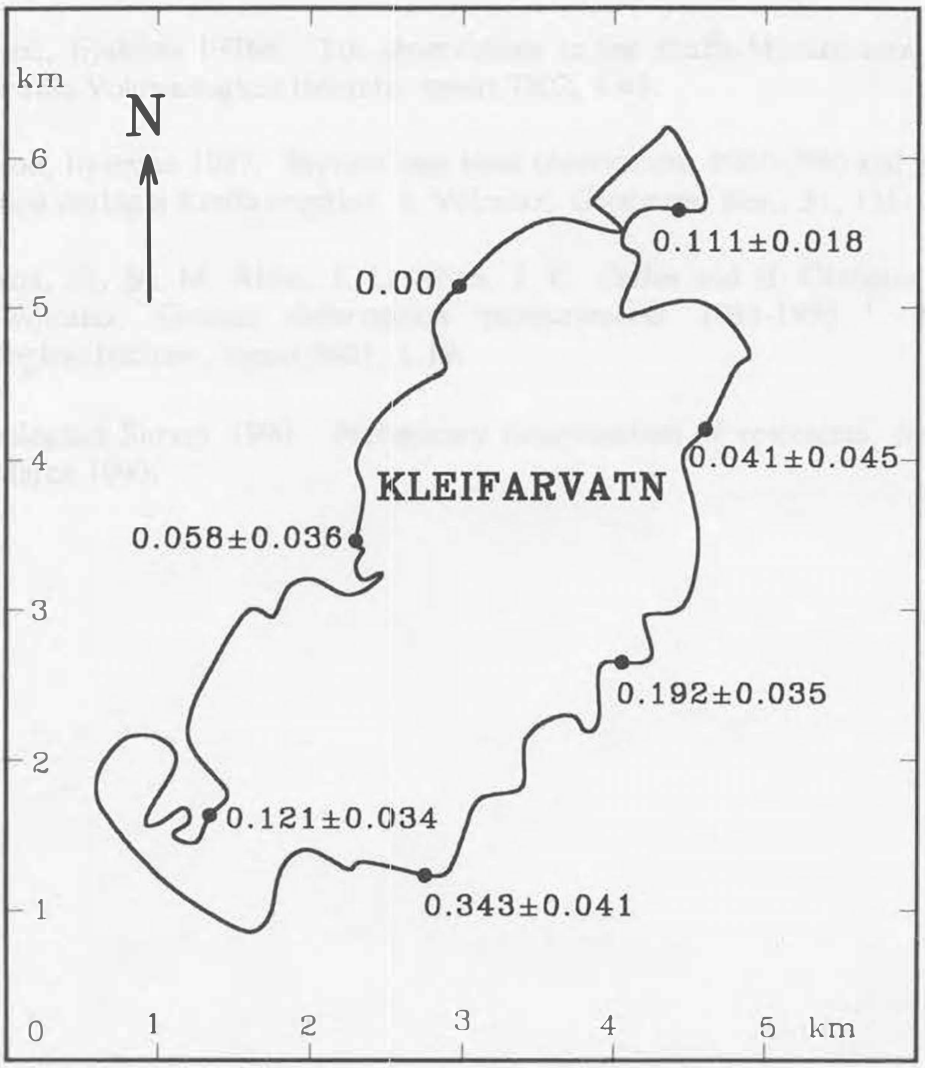


Fig. 4. Sketch map of lake Kleifarvatn showing the observed rate of relative height change, assuming uniform change of heights with time. The reference station OS1984-7215 is given the rate 0.00. Values are in cm per year and standard errors of computed rates are shown.

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