NORDIC VOLCANOLOGIAL INSTITUTE 9402

University of Iceland

SKORRADALSVATN

LAKE LEVEL MEASUREMENTS

1982-1993

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Abstract

Measurements of lake level of lake Skorradalsvatn, south-west Iceland, for the purpose of observing vertical component of ground deformation, were initiated in 1982. Permanent bench marks were established at six locations along the shore of the lake and the measurements determined the height of these bench marks above the surface of the lake. The measurements were originally made by using steel tape to measure the vertical distance from the marks to the lake surface. These measurements had to be made in calm weather, as otherwise excessive errors were experienced. A new and more accurate measuring technique was introduced in late 1984. Measurements were made 6 times in 1982-1984, using the tape, and 7 times in 1984-1993, using the more accurate measuring technique. The shape of the lake allows ground tilt in WNW-ESE direction to be observed with high degree of accuracy, while tilt perpendicular to this direction will not be detected, unless it is very large. The measurements suggest ground tilt of 0.1 μ-rad per year, up towards east or south-east at the western one-third of the lake and no ground tilt near the central part of the lake. Observations near the east end of the lake suggest unstable foundations of one or two bench marks.

Introduction

The lake Skorradalsvatn is a long and narrow lake in a glacially eroded valley in west Iceland. The length of the lake is about 15.8 km and the average width is slightly less than one km but the maximum width is 1.5 km, making the lake area 14.7 km^2 (Orkustofnun 1957). Its maximum depth is 48 m and the average depth 22.5 m. The general direction of the long axis of the lake is E24°S or almost perpendicular to the strike of the western volcanic and rift zone which lies 20 to 30 km south-east of the east end of the lake. The location of the lake, its shape and orientation relative to the western volcanic zone of Iceland makes it very promising for observing the vertical component of ground deformation associated with processes on the plate boundary in south Iceland. Measurements of ground deformation in the Þingvellir area, 20-30 km south-east of the east end of Skorradalsvatn have detected considerable ground deformation (Brander et al. 1976; Czubik 1988; Decker et al. 1976; Gerke 1969, 1974; Sundquist and Tryggvason 1982; Tryggvason 1968, 1973, 1990). The relatively uniform depth of the lake makes seiches prominent and persistent at times of rapid wind and air pressure changes. The first order wave on the long axis of the lake has a period of 20 to 25 minutes. Another adverse fact is that roads along the lake are not kept open during winters, but best lake level observations are generally obtained while ice covers the lake, eliminating wind waves and probably also seiches.

The first network of stations at lake Skorradalsvatn for the purpose of observing ground deformation was established on June 4 1982 by the construction of 5 stations for measurements of the lake level. The bench marks were identified as NE79008, NE79009, NE79010, NE79011 and NE79012 (Fig. 1). The measuring technique at that time was to use steel tape to measure the vertical distance from a permanent marker to the lake surface. This required the markers to be placed on the side of vertical cliff at the lake edge. The elevation of the marker above the lake should be less than 2 meter, but the marker should be above highest normal lake level, The lake depth at the cliff where the marker was placed should be sufficient for measurements to be made at lowest normal lake level. The methods required the lake to be very quiet during the time of measurements, with no disturbing seiches nor wind waves. Therefore, measurements could be made only in calm weather, and the calm weather should have prevailed for one or more days before the observations. This weather requirements were difficult to reach. On September 27, 1983 four new bench marks were constructed, one (NE79013) to replace an older marker (NE79009)which had been removed, two (NE79014 and NE7915) to duplicate markers, but experience had showed that they could disappear, either by vandalism or by natural forces. One station (NE79016) was established to shorten the distance between stations, about midways between older markers NE79011 and NE79012. All these stations had markers placed horizontally into near vertical rock surfaces.

In 1984 a new measuring technique was adopted. This method used a vertical measuring rod placed on permanent marker and another rod hanging on a tripod in the lake. The second rod was attached to a barrel reaching into the lake water during observations (Tryggvason 1987). A narrow opening into the barrel causes the water surface inside it to be at the same level as the average surface of the lake. Small wind

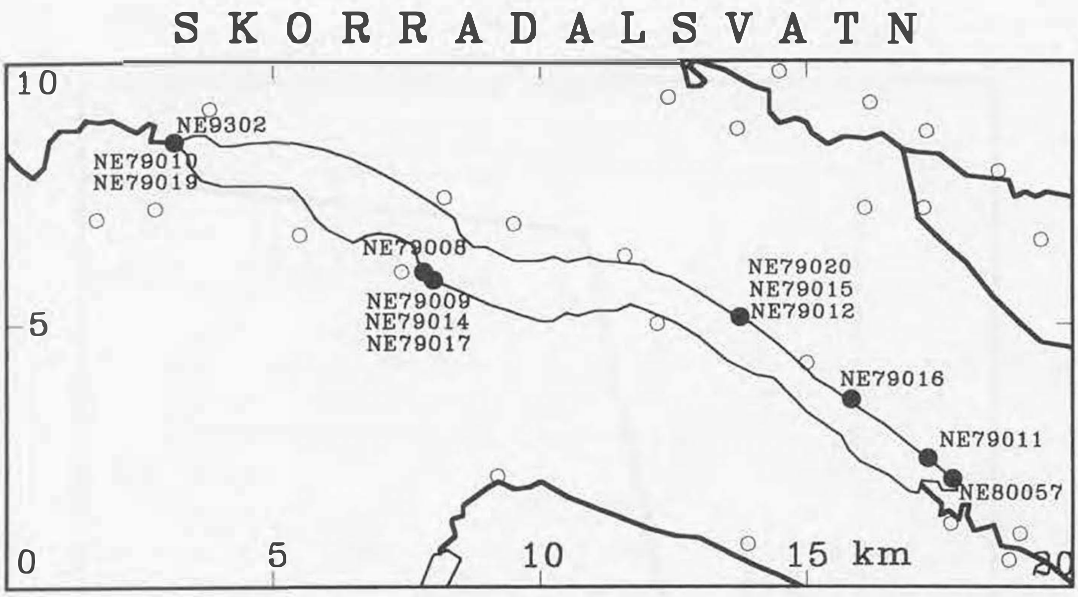

Fig. 1. Sketch map of lake Skorradalsvatn with lake level bench marks (filled circles), farms occupied or abandoned (open circles) and rivers (thick lines). North is up.

waves do not disturb the observation notably. A precision optical level is used to compare elevations of the two rods, that on the permanent marker and that hanging on the tripod in the lake. Water level in the barrel is read on the hanging measuring rod. This method allows a precision of about one millimeter in comparison of permanent marker and the lake level. This new method of observing the lake level required different bench marks than those previously used, preferably vertical nails in near horizontal rock surface. These marker may be located several meters from the lake shore, and their elevation should not be more than 1.5 m above lowest lake level to obtain optimum precision. Bench mark distance of more than about 30 m from the lake shore will cause the observations to be less precise, except unreasonable time is spent on precision levelling. The same is true if the marker is too high above the lake to make readings on both rods at same level installation. Four markers fitting these new requirements were installed on 5 June 1984, NE79017 near older marker NE79014 (and NE79009); NE79019 close to older marker NE79010; NE79020 close to older marker NE79012 and NE79015; and NE80057 about 0.6 km east of older marker NE79011. Efforts have been made to use the old bench marks, whenever weather and lake surface condition allows, to obtain comparison of the two observation methods. The tape measurements were made from an indentation in the center of the horizontal marker, method A (Fig. 2). When the new measuring technique was adopted in 1984, the measurements on the old markers were made by placing the rod on the top side of the markers (method B, Fig. 2). Measurements on the vertical markers of 1984 (and later markers) were originally made using a rod where hole, 0.82 cm deep, had been drilled into the bottom of the base plate, to stabilise the rod on the vertical marker. When the rod was placed on a horizontal marker, the base plate around the hole rested on the marker. This drilled rod was used from 1984 to 1987, but measurements of 1992 and 1993 (no measurements were made at Skorradalsvatn in 1988 to 1991) were

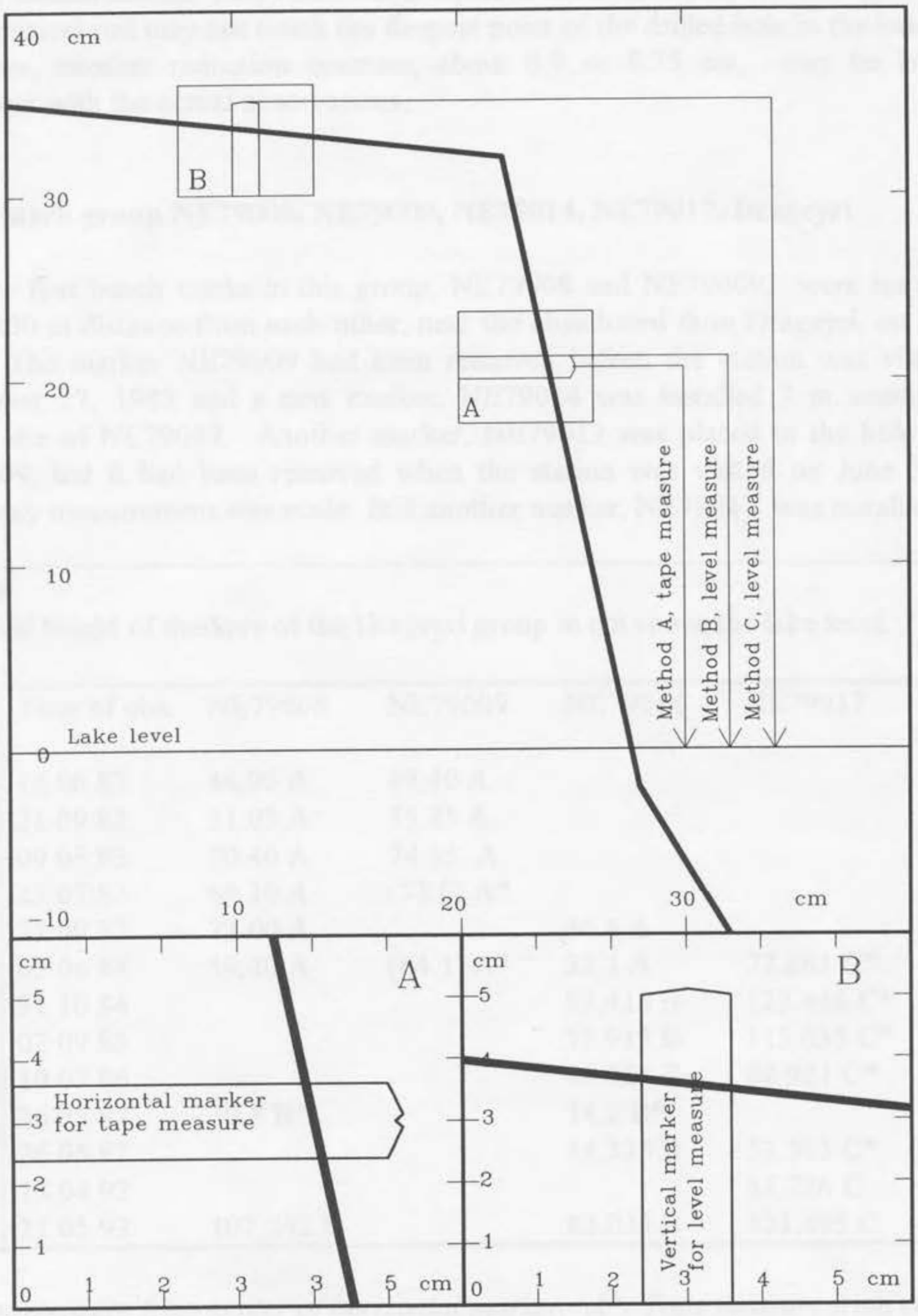

Fig. 2. Sketch of bench marks installations. Thick lines indicate the rock surface near the lake shore. Bench marks of 1982 were installed horizontally into near vertical cliffs (A) but bench marks of 1984 and later were installed vertically into relatively flat rock surface (B). Tape measurements were made from the center of horizontal markers but level measurements of 1984 and later were made from top of vertical marker or from the top side of horizontal marker. All markers are made of 12.7 mm diameter rods of copper alloy.

made using a rod with flat base plate. When elevation of vertical and horizontal markers are compared, the measurements of 1984 to 1987 on vertical markers are reduced to equivalent of measurements with flat base rods by adding 0.82 cm to the original measurements. This reduction is equal to the hole depth, but the highest point of the vertical rod may not touch the deepest point of the drilled hole in the base plate. Therefore, another reduction constant, about 0.7 or 0.75 cm, may be in better agreement with the actual observations.

Bench mark group NE79008, NE79009, NE79014, NE79017, Drageyri

The two first bench marks in this group, NE79008 and NE79009, were installed at about 200 m distance from each other, near the abandoned farm Drageyri, on June 4, 1982. The marker NE79009 had been removed before the station was visited on September 27, 1983 and a new marker, NE79014 was installed 3 m south of the former site of NE79009. Another marker, NE79013 was placed in the hole left by NE79009, but it had been removed when the station was visited on June 5 1984, before any measurement was made. Still another marker, NE79017, was installed on

Table 1
Measured height of markers of the Drageyri group in cm above the lake level.

Time of obs.	NE79008	NE79009	NE79014	NE79017
14 06 82	44.95 A	49.40 A		
21 09 82	31.05 A	35.75 A		
09 05 83	70.40 A	74.95 A		
23 07 83	69.10 A	(73.0) A*		
27 09 83	73.00 A		46.8 A	
05 06 84	59.40 A	(64.1) A*	33.1 A	72.881 C*
31 10 84			83.416 B	122.446 C*
02 09 85			75.915 B	115.035 C*
10 07 86			49.824 B	88.921 C*
26 05 87	39.8 B*		14.2 B*	
26 05 87			14.335 B	53.505 C*
13 04 92				81.726 C
21 05 93	107.242 B		82.035 B	121.695 C

A: Tape measure from center of horizontal marker. ***A*:*** *Tape measure from center of hole left by marker rod NE79009.* ***B:*** *Level measure with rod on top side of horizontal marker, method B of Fig. 2.* ***B*:*** *Tape measure from the center of the horizontal marker, reduced to the top side of the marker,* ***C:*** *Level measure with flat base plate rod on top of vertical marker,* ***C*:*** *Level measure with drilled base plate rod on top of vertical marker, the drilled hole is 0.82 cm deep.*

June 5 1984 about 8 m south-west of NE79014. The bench mark NE79008 is at a location where measurements are difficult at high lake level. The four markers, NE79008, NE79009, NE79014, and NE79017, are considered as a single station when comparison with other stations along the lake shore are made. They are all placed in the same low cliff. Table 1 gives the observed height of each marker in the Drageyri group at each time of observation. Relative elevation of the four benchmarks of this group are given in Table 2.

Table 2
Average observed elevation difference of bench marks in the 79008 group. The standard deviation of the elevation difference suggests about 3 mm standard error of each lake level observation.

Station A	Station B	elevation difference cm	standard deviation cm	number of simult. obs
79008	79009	-4.567	0.10	3
79008	79014	25.504	0.31	3
79008	79017	-14.437*	0.07	2
79009	79014	31.00	-	1
79014	79017	-39.871*	0.12	5

**: Observations of 1984 to 1987 were made with drilled base plate rod but measurements of 1992 and 1993 used flat base plate rod. Measurements of 1984 to 1987 on the vertical marker NE79017 were reduced to equivalent of plane base plate rod measurements by adding 0.82 cm to original observations before comparison with markers NE79008 and NE79014 were made.*

Table 3
Accepted elevation of each marker in the Drageyri group relative to NE79017

Station	Elevation, cm
79008	-14.43
79009	-9.66
79014	-39.89
79017	0.00

The values of Table 3 are based on values of Table 2 when they have been weighted according to number of simultaneous observations and apparent standard deviation.

Bench mark group NE79010, NE79019, NE9302 (The Dam group)

These bench marks are at the west end of lake Skorradalsvatn where a low dam was built to control flow out of the lake in connection with a hydroelectric plant. Marker NE79010, a horizontal marker, was installed on 4 June 1982 in the near vertical side of the dam and NE79019, a vertical marker, was installed on 5 June 1984 on top of the low dam. Because of plans to rebuild the dam in 1993, a vertical marker, NE9302, was constructed in early 1993, and first measured on 21 May 1993. It is located some 200 m north-east of markers NE79010 and NE79019 which were subsequently destroyed.

Table 4
Measured height of markers of the Dam group in cm above the lake level.

Time of obs.	NE79010	NE79019	NE9302
04 06 82	47.2 A		
02 09 82	33.35 A		
09 05 83	75.40 A		
23 07 83	71.9 A		
27 09 83	74.9 A*		
05 06 84	61.9 A	69.69 C*	
31 10 84	112.093 B	118.814 C*	
02 09 85	104.682 B	111.365 C*	
10 07 86	78.675 B	85.453 C*	
26 05 87	43.244 B	49.903 C*	
13 04 92	70.363 B	-	
21 05 93	110.224 B	117.536 C	147.768 C
			147.564 C

A: *Tape measurements to the center of marker,* ***A*:*** *A particularly unreliable measurement because of wind waves on the lake.* ***B:*** *Level measurements with rod standing on the top side of horizontal marker.* ***C:*** *Level measurement with flat base plate rod standing on top of marker,* ***C*:*** *Level measurement with drilled base plate rod on vertical marker, drill hole 0.82 cm deep.*

Table 5 shows comparison of height of the markers in the dam bench mark group. Correction for the hole depth in the drilled base plate, 0.82 cm, is added to measurements marked C* in the table above.

Table 5
Observed elevation differences of bench marks of the Dam group

Station A	Station B	Elevation difference cm	Standard deviation cm	Number of simult obs
NE79010	NE79019	7.487	0.096	5
NE79010	NE9302	37.442	0.102	2
NE79019	NE9302	30.130	0.102	2

Comparison of NE9302 and the other two markers is based on two lake level observations, both made on the same day.

Level measure between markers NE79019 and NE9302 on 21 May 1993 gave height difference of 29.367 (± 0.024) cm. This differs from what lake level measurements gave by about 0.7 cm, indicating an error in the levelling far exceeding the estimated error margin.

Table 6
Accepted elevation of bench marks in the Dam group relative to bench mark NE79019

Marker	Relative elevation cm
NE79010	-7.49
NE79019	0.00
NE9302	30.00

Bench mark group 79012, 79015 and 79020.

Bench mark NE79012 was constructed on 4 June 1982 about midways between the Drageyri bench mark group and the east end of the lake in solid bedrock. Another

Table 7
Height of bench marks NE79012, NE79015, and NE79020 in cm above the lake level.

Time of obs	NE79012	NE79015	NE79020
14 06 82	33.00 A		
21 09 82	18.50 A		
27 09 83	60,8 A**	36.9 A	
05 06 84	-	21.2 A**	55.55 C*
31 10 84	97.635 B	73.177 B	105.353 C*
02 09 85	90.168 B	65.730 B	97.846 C*
10 07 86	63.947 B	39.363 B	71.651 C*
25 06 87	28.876 B	4.316 B	36.512 C*
13 04 92	-	31.201 B	64.422 C
21 05 93	-	71.476 B	104.274 C

: Observations of 27 09 83 and 05 06 84 were very inaccurate at the site of these markers because of wind and waves.* ***A: *Tape measurements to the center of horizontal marker.* ***B:*** *Level measurements with rod standing on top side of horizontal markers.* ***C:*** *Level measurements with flat base rod standing on top of vertical marker.* ***C*:*** *Level measurements with drilled base plate rods standing on vertical marker with the marker inside the drilled hole, hole depth 0.82 cm.*

bench mark, NE79015, was constructed on 27 September 1983 about 10 m east of NE79012 to secure measurements at this location if one marker would be destroyed or lost, keeping in mind that very few locations along the lake shore had reliable bedrock outcrops. When a new measuring technique was introduced in late 1984, a new bench mark, NE79020 was constructed about 20 m east of NE79012. Several simultaneous measurements of 79012, 79015 and 79020 were made to determine the relative elevation of these three markers. The marker NE79012 was not found in 1992 and

1993 and is presumed lost. Table 7 gives the height of markers NE79012, NE79015, and NE79020 as obtained by measurements of 1982 to 1993.

Table 8
Observed average elevation differences of bench marks in the NE79012, NE79015, NE79020 group

Station A	Station B	Elevation difference cm	Standard deviation cm	Number of simult obs
79012	79015	24.510	0.063	4
79012	79020	-8.504	0.031	4
79015	79020	-33.012	0.130	6

Observation of 27 09 83 is not included in the comparison of Table 8 because it was considered inaccurate due to wind and waves. Comparison of NE79015 and NE79020 is based on all observations but observations of 1984 to 1987 were reduced to plane base plate rod by adding 0.82 cm because of the hole in the base plate of the rod used at that time.

Table 9
Accepted elevation of the markers NE79012, NE79015, NE79020 relative to marker 79020.

Marker	Relative elevation cm
79012	-8.502
79015	-33.013
79020	0.000

Bench mark group NE79011, NE79016, NE80057

These bench marks are not in a close group, but lie near the east end of lake Skorradalsvatn. The distance between NE79016 and NE80057 is about 2.5 km and NE79011 is in between these two stations.

Table 10
Measured height of bench marks NE79011, NE79016, NE80057 in cm above lake level of lake Skorradalsvatn.

Time of obs	NE79011	NE79016	NE80057
04 06 82	45.8 A		
21 09 82	31.05 A		
09 05 83	69.85 A		
23 07 83	68.45 A		
27 09 83	72.8 A	72.8 A	
05 06 84	57.5 A	-	96.68 C*
31 10 84	-	108.956 B	147.554 C*
02 09 85	-	100.652 B	139.402 C*
10 07 86	-	74.500 B	115.255 C*
26 05 87	-	39.051 B	81.453 C*
13 04 92	-	-	110.929 C
21 05 93	109.022 B	105.215 B	150.946 C

***A:** Tape measurement to the center of horizontal marker. **B:** Level measurement with rod standing on top side of horizontal marker. **C:** Level measurement with flat base plate rod standing on vertical marker. **C*:** Level measurement with drilled base plate rod standing on vertical marker, drilled hole 0.82 cm deep.*

Observed lake level

The lake level observations at lake Skorradalsvatn are confused by the number of bench marks at each location. This can be simplified by taking one marker of each bench mark group as representative for that group. Bench mark NE79017 is taken to represent the Drageyri bench mark group and observations of bench marks NE79008, NE79009, and NE79014 are reduced to equivalent of observation of bench mark NE79017 by the constants of Table 3. When two or more of these bench marks were observed at the same time, a weighted average of the reduced observations was found. The tape measurements were given weight 1 while level measurements with the improved technique of 1984 were given weight 3.

The same procedure was applied on the Dam benchmark group where observations were reduced to those of bench mark NE79019 using constants of Table 6 and also of the 79012-79015-79020 bench mark group where all observations were reduced to those of bench mark NE79020 using constants of Table 9. Observations of bench marks NE79011, NE79016 and NE80057 are treated separately as these markers can not be considered equivalent to each other, both because they are placed at considerable distance from each other, and also because the observational results differ significantly.

Table 11 presents the bench mark height above the lake level at each time of measurements of the Skorradalsvatn lake level. Values for bench marks NE79017,

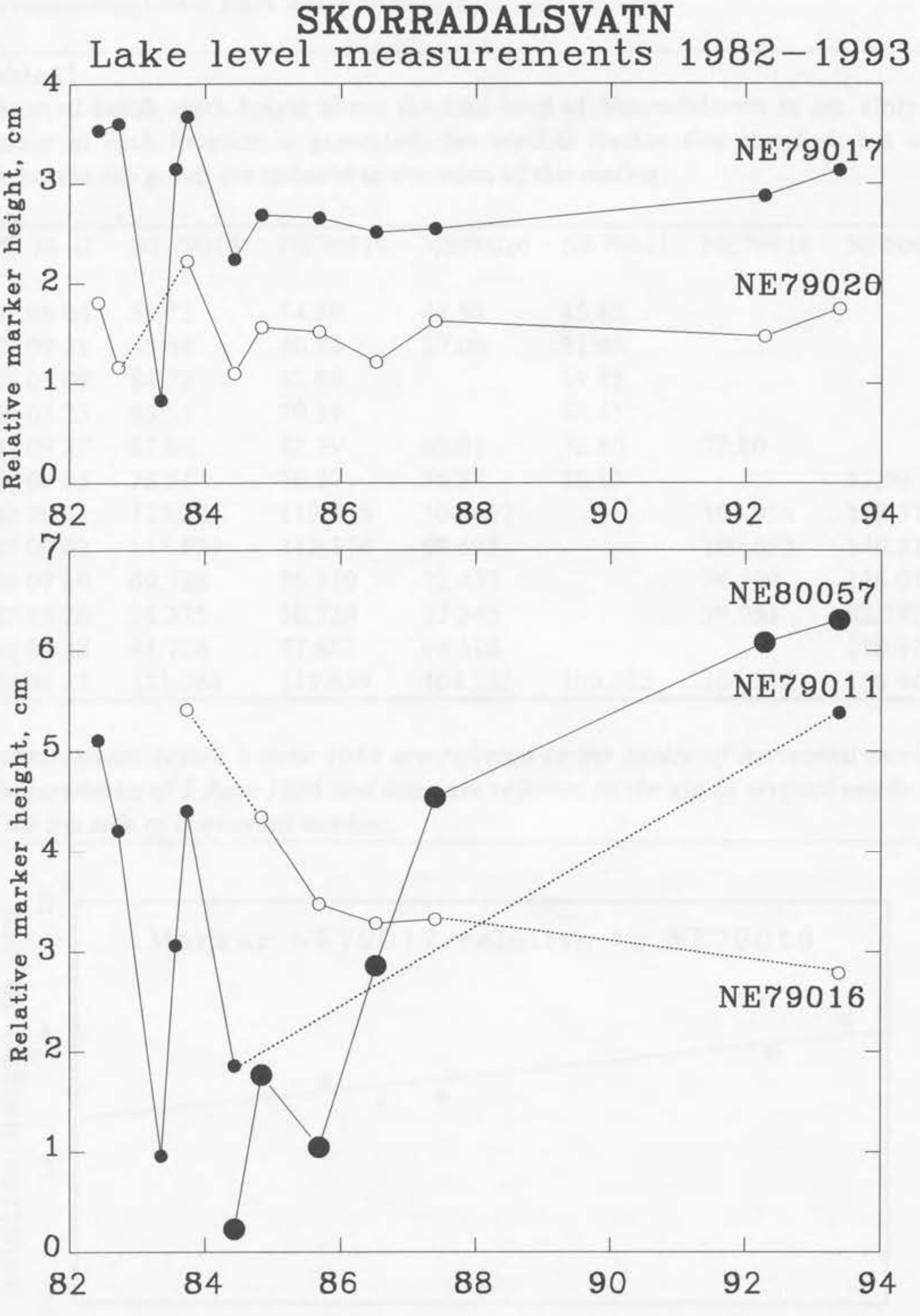

Fig. 3. Height above the lake level of one bench mark in each bench mark group relative to bench marks NE79010 and NE79019. Measurements before 1984 show large fluctuations, supposedly because of inaccurate measurements. Markers NE79017 and NE79020 (top) appear to have been uplifted less than 0.5 cm in 9 years while marker NE79016 appear to have subsided about 1.5 cm. Marker NE79011 and NE80057 near the east end of the lake have been uplifted 3.5 and 6.1 cm respectively in 9 years, 1984-1993. See also Table 12.

NE79019, and NE79020 are based on reduction of all observations in the corresponding bench mark group to these reference markers.

Table 11
Observed bench mark height above the lake level of Skorradalsvatn in cm. Only one marker at each location is presented, the vertical marker first installed, but other markers in the group are reduced to elevation of this marker.

Y M D	NE79017	NE79019	NE79020	NE79011	NE79016	NE80057
82 06 04	59.22	54.69	41.50	45.80		
82 09 21	45.44	40.84	27.00	31.05		
83 05 09	84.72	82.89		69.85		
83 07 23	83.53	79.39		68.45		
83 09 27	87.06	82.39	69.61	72.80	72.80	
84 06 05	73.51	70.27	56.37	58.13		97,50
84 10 31	123.286	119.608	106.167		108.956	148.374
85 09 02	115.830	112.178	98.693		100.652	140.222
86 07 10	89.728	86.219	72.432		74.500	116.075
87 05 26	54.275	50.728	37.346		39.051	82.273
92 04 13	81.726	77.853	64.318			110.929
93 05 21	121.764	117.639	104.382	109.022	105.215	150.946

Measurements before 5 June 1984 are referred to the center of horizontal markers. Measurements of 5 June 1984 and later are referred to the top of vertical markers or to the top side of horizontal markers.

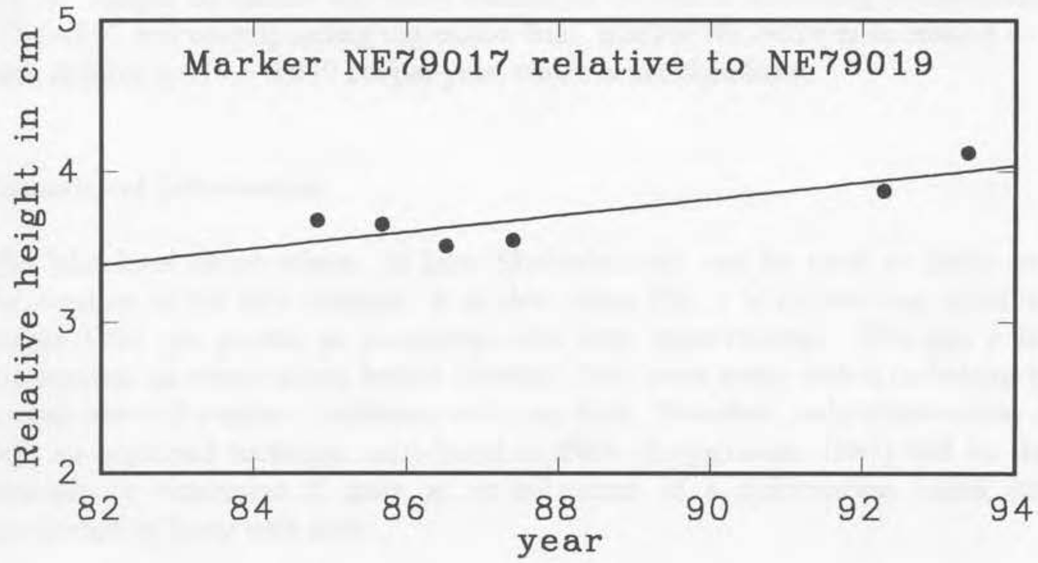

Fig. 4. Height of marker NE79017 relative to NE79019 according to measurements 1984-1993 and corresponding regression line. Marker NE79017 appear to have been uplifted 0.054 ± 0.014 cm per year. The presented error is the standard error of the slope of the regression line. The probability that the uplift is real is more than 99%.

It is clear from Table 11 that The actual lake level has varied by about 80 cm between lowest measured level of 31 October 1984 and the highest measured level of 21 September 1982. This variable lake height has to be removed from the measurements if the observations are used to investigate ground deformation in the region of the lake. This can be done by accepting one of the bench marks as reference. This reference marker can not be regarded as absolutely stable, but the following treatment takes the bench mark NE79019 as reference, and it is tentatively assumed to be absolutely stable and its height (elevation) is taken as 0.0 (cm). Table 12 gives observed elevation of each bench mark at each time of observation relative to NE79019. As in Table 11, only one marker of each bench mark group is presented.

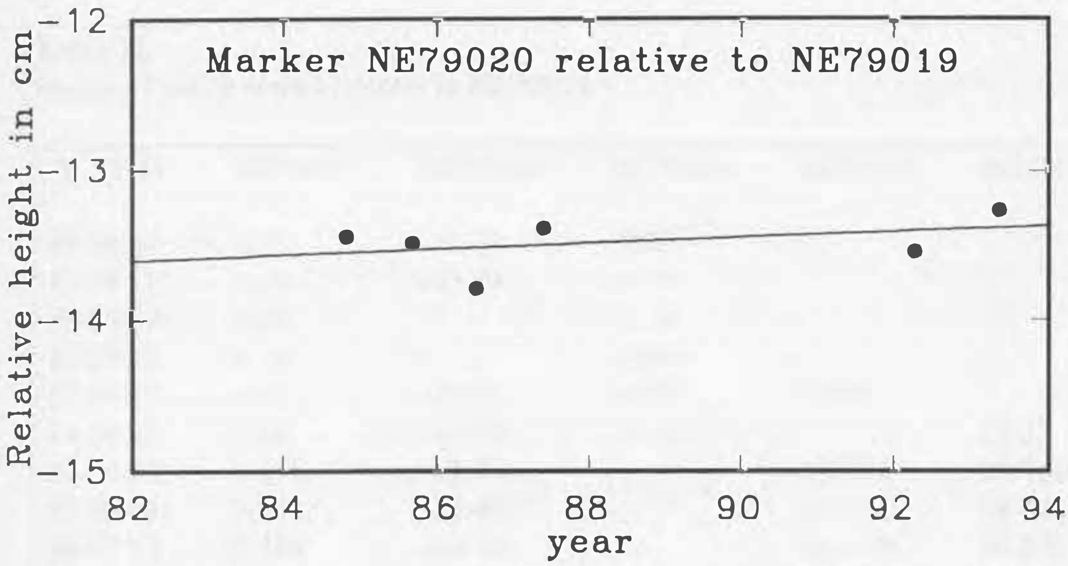

Fig. 5. Height of marker NE79020 relative to NE79019 according to measurements 1984-1993 and corresponding regression line. Marker NE79020 is calculated to have been uplifted 0.019 ± 0.019 cm per year, which is not significant.

Linearity of deformation

The lake level observations at lake Skorradalsvatn can be used to study ground deformation at the lake location. It is clear when Fig. 3 is viewed that observations before 1984 are erratic as compared with later observations. This has a logical explanation, as observations before October 1984 were made with a technique which invited errors if weather conditions were not ideal. Therefore, only observations made with an improved technique introduced in 1984 (Tryggvason, 1987) will be studied critically to determine if there is an indication of a deformation which can be considered as linear with time.

Fig. 4 shows the observed elevation of bench mark NE79017 in the Drageyri group, relative to bench mark NE79010 in the Dam group. Only observations made with the improved measuring technique of 1984 are shown, and the regression line which gives the best linear fit between elevation and time. The observations never deviate more than 2 mm from the regression line which suggests that the error in the lake level observations is generally less than this amount. It also suggests that elevation of NE79017 relative to NE79019 varies linearly with time if it varies at all. The slope of the regression line of 0.054 cm per year shows that NE79017 has been uplifted relative to NE79019. The standard error of the slope of the regression line is computed as 0.014 cm per year. This is certainly not a very reliable measure of the precision of the observations as it is based on six observations only, a small sample for statistical treatment. Still it suggests that the relative uplift is reliable at a confidence level higher than 99%. The Drageyri bench mark group, which includes bench mark NE79017, is considered to be very stable as the markers are placed in solid bedrock. The reference bench mark NE79019 is placed in massive concrete of a low dam. This is also considered to be very stable, although the stability relative to the underlying bedrock may be subject to some doubt.

Table 12
Height of bench marks relative to NE79019

Y M D	NE79017	NE79020	NE79011	NE79016	NE80057
82 06 04	4.53	-13.19	-8.89		
82 09 21	4.60	-13.84	-9.79		
83 05 09	1.83		-13.04		
83 07 23	4.14		-10.94		
83 09 27	4.67	-12.78	-9.59	-9.59	
84 06 05	3.24	-13.90	-12.14		27.23
84 10 31	3.678	-13.441		-10.652	28.766
85 09 02	3.652	-13.485		-11.526	28.044
86 07 10	3.509	-13.787		-11.719	29.856
87 05 26	3.547	-13.382		-11.677	31.545
92 04 13	3.873	-13.535			33.076
93 05 21	4.125	-13.257	-8.617	-12.215	33.307

Relative elevation of bench mark NE79020 is shown on Fig. 5. The slope of the regression line is 0.019 cm per year, considerably less than that of NE79017. The computed standard error of the slope of the regression line is 0.019 cm per year, equal to the computed slope. The upward slope of the regression line is not significant, but the small standard error of the slope suggest similar precision of measurements as at NE79017. As Bench mark NE79020 together with bench marks NE79012 and NE79015 of the same group are all placed in solid bedrock, they are considered as very stable. The fact that no significant displacement of the stable marker NE79020 relative to NE79019 has been observed, demonstrates that NE79019 is stable within the precision of the present observations. It also demonstrates that NE79020 has subsided relative to NE79017 at an average rate of 0.035 ± 0.02 cm per year.

Bench mark NE79016 near the east end of the lake was not observed in 1992, so only 5 observations have been made there with the improved technique introduced in 1984. Fig. 6 shows the observed relative elevation and the regression line. Observation of October 31 1984 deviates considerably from the regression line, suggesting inaccurate

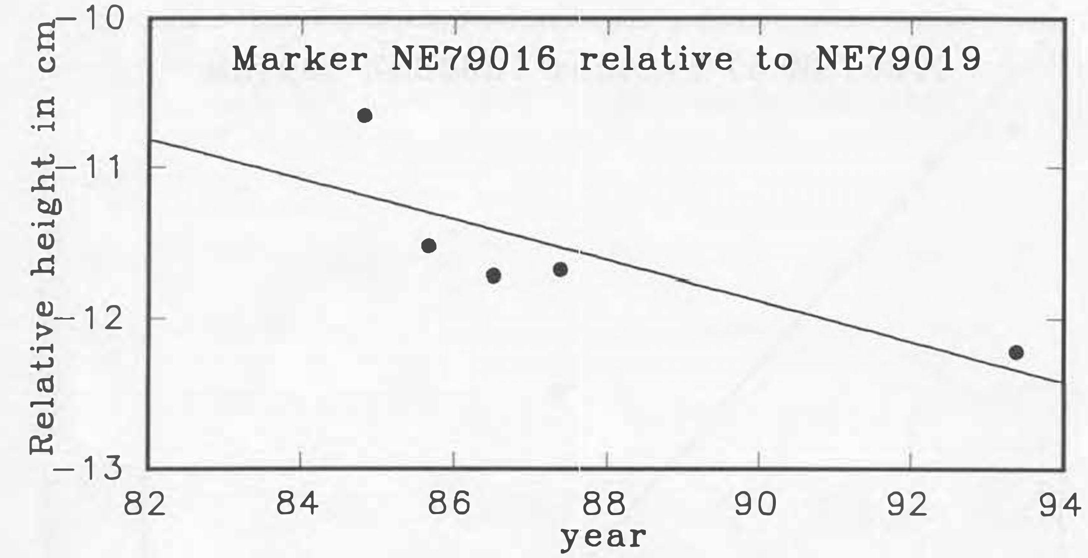

Fig. 6. Height of marker NE79016 relative to NE79019 according to measurements 1984-1993 and corresponding regression line. Marker NE79016 appear to have subsided relative to NE79019 by 0.134 ± 0.038 cm per year. The probability that the subsidence is real exceeds 99%.

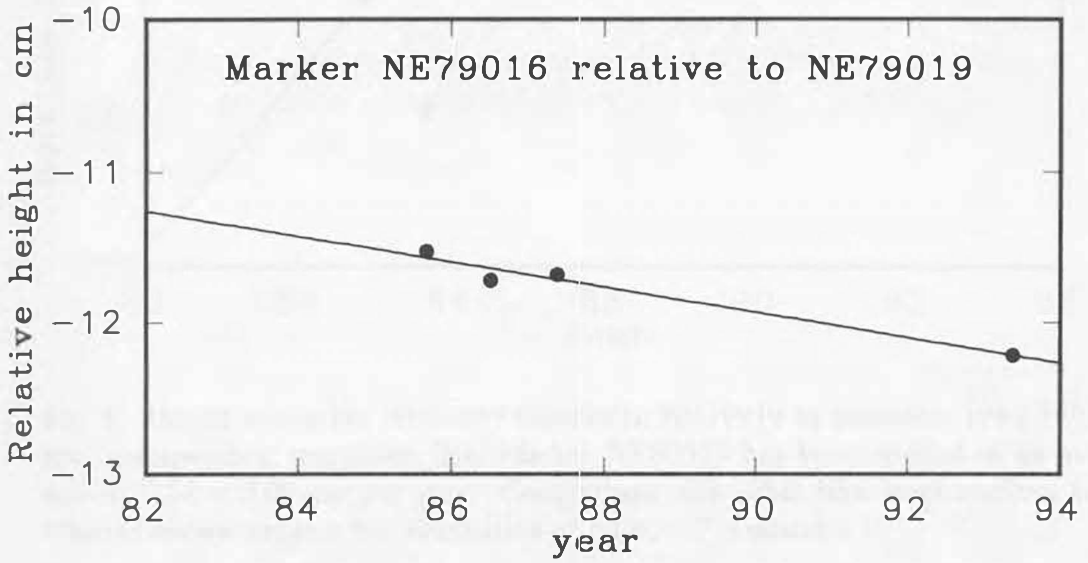

Fig. 7. Relative elevation of bench mark NE79016. Observation of October 1984 is deleted to show how well other observations agree with the regression line which has a slope of -0.084 (± 0.008) cm per year. This may be a better rate of relative subsidence than that of Fig. 6.

measurement. If this observation is excluded (Fig. 7), the remaining four observations agree very well with uniform subsidence of 0.084 (± 0.008) cm per year relative to NE79019. This rate is considered more reliable than the subsidence rate of 0.134 ± 0.038 cm per year calculated from all 5 observations. The very close linearity of the four observations of Fig. 7 suggest good stability of NE79016.

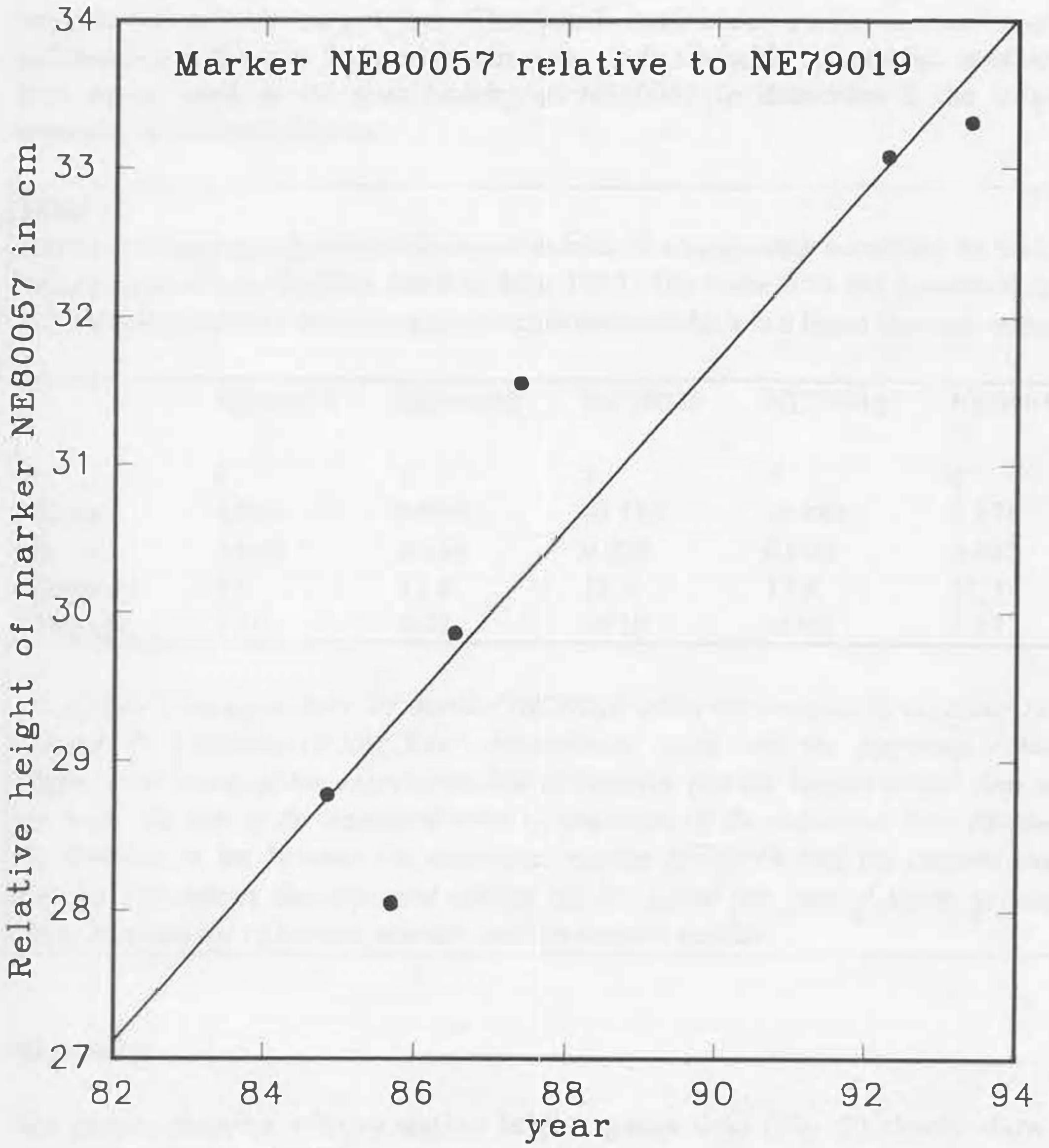

Fig. 8. Height of marker NE80057 relative to NE79019 as measures 1984-1993 and the corresponding regression line. Marker NE80057 has been uplifted at an average rate of 0.58 ± 0.09 cm per year. Comparison with other lake level markers at lake Skorradalsvatn suggest that foundation of NE80057 is unstable.

Bench mark NE80057 at the east end of lake Skorradalsvatn was placed into a very large boulder which may not be attached to or laying on solid bedrock. This place was judged to be stable at the time it was selected for lake level bench mark, but later observations indicate some instability (Fig. 8). The observations show that this marker has been uplifted at an average rate of almost 0.6 cm per year relative to NE79019, and the standard error of the slope of the regression line is 0.092 cm per year, very much greater error than that observed at the other lake level stations. The observed relative uplift of NE80057 does not agree with the gentle relative displacement of other bench marks on lake Skorradalsvatn shore. It is presently assumed that the big boulder where bench mark NE80057 is placed has been uplifted from 1984 to 1993 relative to the bedrock, probably because of freezing and thawing of the surroundings. This uplift is not far from being a linear function of time although its rate varies between 0.2 and 1.7 cm per year. This bench mark is not usable to observe ground deformation in the lake Skorradalsvatn area. It is advisable to establish another lake level bench mark in the near vicinity of NE80057 to determine it the suspected instability of NE80057 is real.

Table 13
Statistics of change of marker elevation at lake Skorradalsvatn according to lake level measurements from October 1984 to May 1993. The same data are presented in Figs 4-7. Data in this table assumes ground deformation which is a linear function of time.

	NE79017	NE79020	NE79016	NE79016*	NE80057
N	6	6	5	4	6
Slope	0.054	0.019	-0.134	-0.084	0.575
St. err	0.014	0.019	0.038	0.008	0.092
Distance	5.3	11.0	13.4	13.4	15.7
Tilt rate	0.10	0.02	-0.10	-0.06	0.37

) Column 5 presents data for marker NE79016 when observation of October 1984 is deleted. **N is number of lake level observations made with the improved technique. **Slope** is the slope of the regression line of relative marker height versus time in cm per year. **St. err.** is the standard error of the slope of the reference line. **Distance** is the distance in km between the reference marker NE79019 and the current marker, and the **Tilt rate** is the apparent rate of tilt in μ-rad per year if linear ground tilt exists between the reference marker and the current marker.*

Discussion

The graphs showing relative station height against time (Fig. 3) clearly show that observations before 1985 were less precise than later observations. As an example we consider height of NE79017 and NE79020 relative to NE79019. The change in relative height between observations after 1984 are generally less than 0.3 cm, suggesting standard error of relative height not greater than 0.2 cm. Observations before 1985 fluctuate considerably, suggesting standard error of relative height of about one cm. The third observation at NE79017, that of 9 May 1983, gives very low relative height, about 2 cm lower than other observations of 1982-84. Similar anomaly is observed at the station NE79011. This suggests that the observed height of the reference station NE79019 is in error during the 9 May 1983 observations. This observation was made when the lake level was low and tape measurement from the marker down to the lake surface required removal of sand and gravel so water could reach the marker site. This apparently caused error in the observed lake level at NE79019, amounting 2 to 3 cm.

The low precision of lake level measurements before 1985 or rather before new measuring technique was introduced in October 1984, makes the first observations of no or very limited value when ground deformation is considered. Therefore only observations of 31 October 1984 and later are considered in the following discussion (Figs 4-7).

Stations NE79017 and NE79020 appear to have been uplifted relative to NE79019 from October 1984 to May 1993 at a uniform rate of 0.054 and 0.019 cm per year respectively. The standard error of observations correspond to about 0.02 cm per year, suggesting the indicated uplift to be statistically significant station NE79017, but not statistically significant at station NE79020. As the distance from NE79019 to these stations is about 5.3 and 11 km respectively, and the azimuth from 79019 to these stations is 117 and 108 respectively, the component of ground tilt along this azimuth is small, about 0.1 (± 0.03) μ-rad per year between NE79019 and NE79017 and 0.02 (± 0.02) μ-rad per year from NE79019-NE79020.

Station NE79016, about 13.4 km ESE (110) from NE79019, appear to have subsided relative to NE79019 from 1984 to 1993. The relative subsidence rate of the station NE79016 appear to be significant, 0.084 (± 0.008) cm per year.

The station NE80057 at the east end of lake Skorradalsvatn, about 15.7 km ESE (112) from NE79019, appear to have been uplifted 4.54 cm from October 1984 to May 1993. The relative uplift of this station is statistically significant, but comparison with other lake level stations at Skorradalsvatn suggests that this station is not attached to the underlying bedrock, and that the result can not be used to determine ground deformation.

Station NE79011 was not observed on or after October 31 1984 until May 1993. Therefore, no significant information on its vertical movement is available.

The orientation of lake Skorradalsvatn is at near right angle to the orientation of the Þingvellir graben, which lies 25 to 30 km south-east of the east end of the lake. Observations in the Þingvellir graben have shown relative subsidence of its central axis and at the flanks of the graben, tilt rate of about 0.25 μ-rad per year was observed (Tryggvason 1990). The observed ground deformation at lake Skorradalsvatn may be related to processes in the Þingvellir graben. If so, the uplift away from the graben continues for a distance of about 35 km, the distance from the central axis of the graben to lake level marker NE79017, but still farther away from the graben, slight tilt, down away from the graben is suggested. As no observation of the vertical component of deformation have been made at distances between 5 and 25 km from the graben axis, we can only estimate crudely the rate of uplift of the Skorradalsvatn area relative to the axis of the Þingvellir graben. If the average rate of ground tilt, up away from the graben, in the area between the graben and lake Skorradalsvatn, is half that observed in the immediate vicinity of the graben, or 0.125 , then the annual uplift of the lake area relative to the axis of the graben is about 5 mm per year.

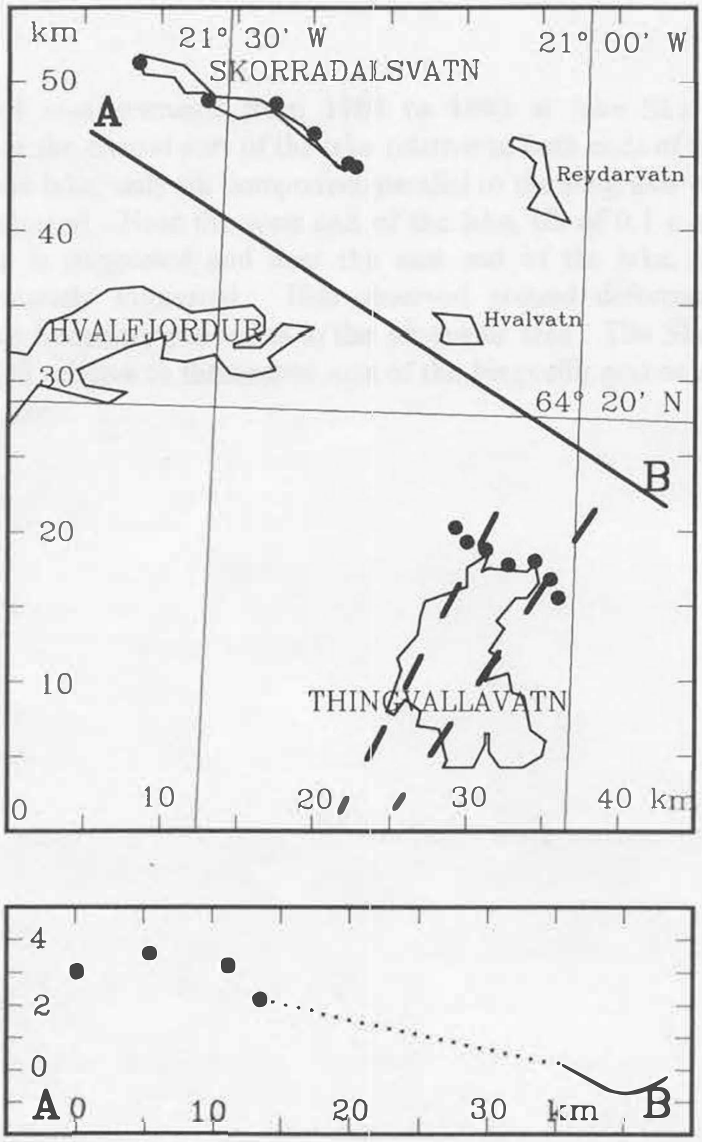

Fig. 9. Sketch map of the Þingvellir-Skorradalsvatn area, south-western Iceland, showing lake level stations at lake Skorradalsvatn and line of repeated precise levelling at Þingvellir (solid circles), and the eastern and western order of the presently active Þingvellir graben (dashed thick lines). At the bottom is shown rate of relative vertical displacements along the line **A-B**. Displacement of the Skorradalsvatn area (left) relative to the Þingvellir area (right) is unknown but dotted line shows the authors estimate.

Conclusion

The lake level measurements from 1984 to 1993 at lake Skorradalsvatn suggest ground uplift at the central part of the lake relative to both ends of the lake. Because of the shape of the lake, only tilt component parallel to the long axis of the lake, E20°S - W20°N, is indicated. Near the west end of the lake, tilt of 0.1 μ-rad per year, up in ESE direction is suggested and near the east end of the lake, tilt in the opposite direction is vaguely suggested. This observed ground deformation is supposedly related to plate boundary processes in the Þingvellir area. The Skorradalsvatn region is being uplifted relative to the central axis of the Þingvellir graben at an estimated rate of 5 mm per year.

References

Brander, JL, Mason, RG and Calvert, RW. 1976. Precise distance measurements in Iceland. Tectonophysics, 31: 193-206.

Czubik, E. 1988. Präzisionshöhenmessungen in Island 1986. Das Markscheidewesen 95, Nr 3: 89-92.

Decker, RW. Einarsson, P. and Plumb, R. 1976. Rifting in Iceland: Measuring horizontal movements. Soc. Scient. Isl. Greinar V: 61-71.

Gerke, K. 1969. Measurement of recent crustal movements in Iceland. In: Boulanger et al.(eds) Recent crustal movements: 237-246. (USSR Acad of Sci).

Gerke, K. 1974. Crustal movement in the Myvatn- and in the Thingvallavatn-area, both horizontal and vertical. In: L. Kristjansson (ed), Geodynamics of Iceland and the North Atlantic area, D. Reidel Publ. Co.: 263-275.

Orkustofnun, Vatnamælingar 1957. Skorradalsvatn mælt af Vatnamælingum með bergmálsmæli í júní 1957. (map), Fnr 3989.

Sundquist U. and Tryggvason, E. 1982. Deformation measurement in the Hengill region. Initial measurements in 1979. Nordic Volcanological Institute 8204: 1-30.

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

Tryggvason, E. 1973. Hve hratt síga Þingvellir? Náttúrufræðingurinn, 43: 175-182.

Tryggvason, E. 1987. Myvatn lake level observations 1984-1986 and ground deformation during a Krafla eruption. J. Volcanol. Geotherm. Res. 31: 131-138.

Tryggvason, E. 1990. Höggun Almannagjár, Mælingar á Þingvöllum 1990. Nordic Volcanological Institute 9001: 1-24.