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MEASUREMENT OF GROUND DEFORMATION IN ASKJA 1966 to 1989

by

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Abstract

Measurements of ground deformation in Askja over a period of 23 years, 1966-1989, have convincingly demonstrated that the volcano is continously deforming at a relatively high rate. The rate of deformation of a profile of precision leveling in northeastern Askja has exceeded 10 ppm per year at all times during this 23 year period.

The results of repeated levelings in northeastern Askja and of lake level observations in southeastern Askja have been interpreted as alternating inflations and deflations centered in central Askja, some distance (1 to 2 km) to the north of the northwest corner of lake Öskjuvatn. Two inflation periods and three deflation periods have been identified, with deflations dominating. These observations are not in good agreement with a point source of deformation. If a point source is assumed to be responsible for a significant portion of the observed deformation, then its depth is very uncertain, but a shallow depth, much less than 4 km, is suggested.

Repeated distance measurements in 1982-1986 are in fair agreement with a continous deflation, centered in central Askja, as levelings indicated for that period.

Tilt observations in southwestern Askja in 1988-1989 do not agree with a point source of deflation in central Askja, and a seismic survey conducted in 1989 indicates a center of activity below the east flank of the volcano.

The previous model of a center of deformation in central Askja is thus not in agreement with some of the latest observations, but a substitute model has not been developed. The available data, although rather extensive, appear not to suffice for the construction of a reliable model which agrees with all the existing data.

It is clear that a model which explains all observed ground deformation in Askja must be complicated. Such a model can be constructed only after more information has been obtained. Deformation measurements need to be collected from various parts of the Askja volcano, where no such measurements have been made as yet.

Introduction.

The present report is intended to present all observational data of the ground deformation measurements made by the author in Askja, as of 1989. The initial observations were made in the summer of 1966, less than five years after the last volcanic eruption of Askja, in October to December, 1961.

During 1966 - 1972, while the author was employed at the University of Tulsa, Oklahoma, observational effort was on the vertical component of deformation only. The observational data obtained during this early period consisted of precision leveling data on a 1700 meter profile of precision leveling in the lava of 1961, and lake level observations on lake Öskjuvatn.

The ground deformation measurements in Askja were discontinued after the summer of 1972, and resumed in 1982, when the auther was employed at the Nordic Volcanological Institute, Reykjavik, Iceland. Since 1982, the effort has been on the horizontal component of deformation in addition to the vertical component. The scope of the observations has been expanded by adding to the precision profile, installing bench marks for repeated distance measurements with a 'geodimeter', and constructing optical leveling tilt stations. Less effort has been on the lake level observations, than earlier, partly because elevated lake level has made these observations more difficult and time consuming than before.

The 1966 to 1972 observations were supported by grants from the National Science Foundation, Washington D.C., but the 1982 to 1989 observations were funded by the Nordic Volcanological Institute.

The ground deformation observations in Askja have from the beginning demonstrated that large scale deformation is continously occurring. The pattern of this deformation is somewhat confusing, and the limited scope of observation in 1966 - 1972 did not allow any convincing model to be constructed. The expanded observations after 1982 resulted in the construction of a model of alternating inflations and deflations, centered in the central region of the Askja caldera (Tryggvason 1989). This model implies that great volumes of magma are moving around below Askja, sometimes entering a shallow magma chamber, sometimes leaving this chamber. This large scale movement of magma occurrs without eruptions or noteable changes on the surface.

The leveling profile

The Askja profile of precision leveling lies on the 1961 lava with the bench marks cemented directly on the surface of the lava (Figs 1 and 2). All bench marks appear stable relative to the solid lava into which they are cemented.

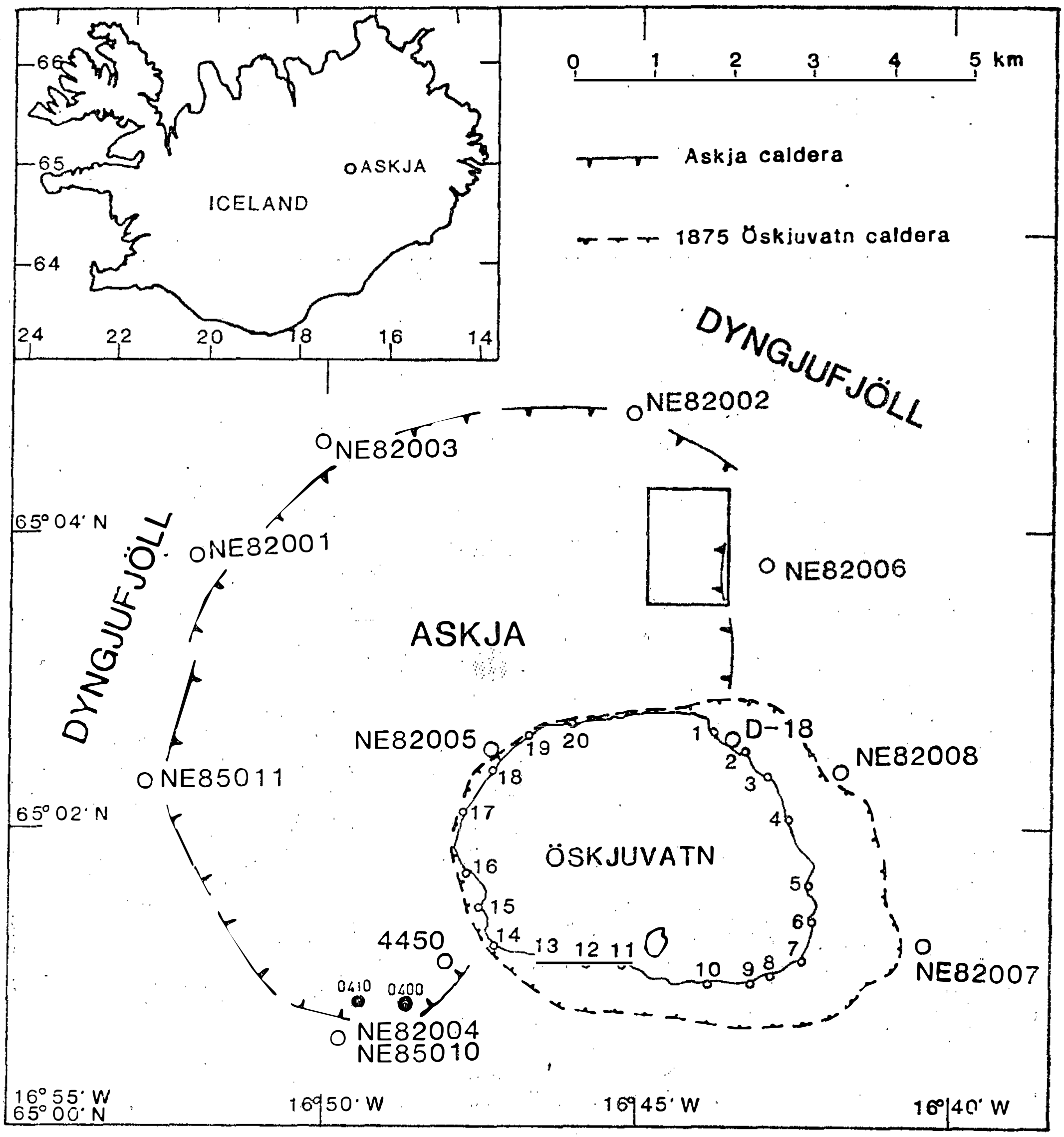

Fig. 1. Sketch map of the volcano Askja, showing lake Öskjuvatn, and the two recent calderas, the principal Askja caldera, and the Öskjuvatn caldera of 1875. Shown are also bench marks for lake level observations (small circles), distance measurements (large circles), and the optical leveling tilt stations (large dots). Shaded circular area indicates the most probable location of point source of deformation according to earlier estimates (Tryggvason, 1989), and a rectangle outlines the area covered by figs 6, 7, 9, 10, 11, and 13 through 19.

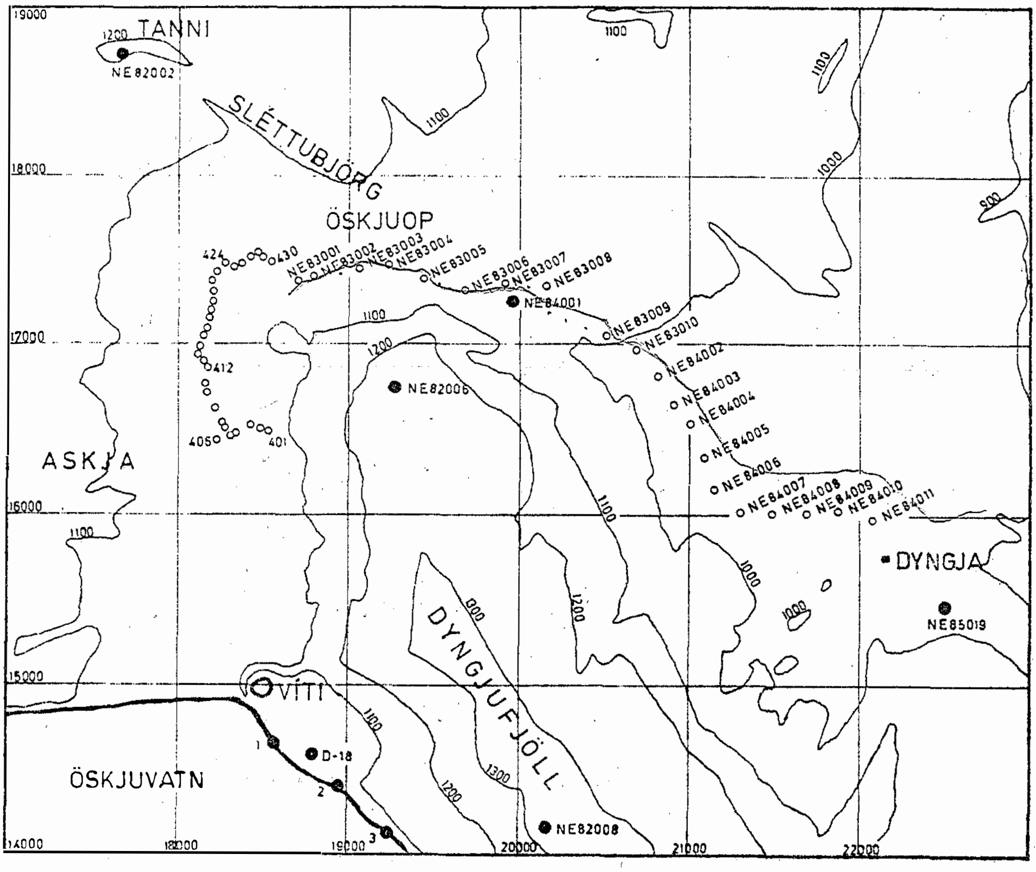

Fig. 2. Map of the profile of precision leveling in northeastern Askja and Öskjuop. Additional bench marks of 1987 have not been mapped. The two bench marks NE84001 and NE85019 are not in the leveling profile, but they were installed for mapping purpose.

The bench marks of the part of the profile which was constructed in 1966 and 1968, consist of cast brass nails with precisely machined convex surface. The stem was placed in a 7 cm deep, 16 mm diameter hole drilled in the lava and cemented with a mixture of portland cement and sand.

The bench marks of the part of the profiles, which was constructed in 1983 and later, consist of machined brass rod, 12 mm in diameter. The top has the shape of half-sphere and stands about 15 mm above the surface of the lava. These benchmarks are cemented into 7-10 cm deep, 12 mm diameter holes with a special plastic cement which is intended for fastening metal in concrete.

The part of the profile (401 to 412) which was constructed in 1966 was intended for use of temporary (portable) markers, with a few marker spacing without temporary markers and a few spacing where one temporary marker was needed during the precision leveling. Five permanent markers were added in this part of the profile in 1987 and 1989, whereafter the measuring rod is always placed on permanent bench marks. The permanent bench marks of 1987 and 1989 were placed between the 1966 permanent markers 403 and 404, 405 and 406, 408 and 409, 409 and 410 and 411 and 412. They bear no identification mark but are in tables named 403a, 405a, 408a, 409a, and 411a.

The part of the profile constructed in 1968 (413 through 430) consists of bench marks spaced approximately 50 m apart in such manner, that no temporary marker is needed, and the measuring rods are always placed on permanent marker during leveling.

TABLE 1

Coordinates of bench marks in the Askja profile of precision leveling, according to measurements made in August 1986. Coordinates are from maps in scale 1:50000 published in 1949 by U. S. Army Map Service. Elevation of the bench marks is based on angle observation, and is not in exact agreement with the leveling results.

stn	east m	north m	elev m
401	18529.51	16468.86	1089.38
402	18484.22	16502.75	1089.54
403	18424.87	16511.05	1090.58
404	18339.74	16467.74	1090.55
405	18306.48	16454.08	1090.43
406	18225.09	16428.23	1090.40
407	18274.79	16503.30	1090.25
408	18256.96	16536.38	1091.68
409	18212.89	16619.56	1090.91
410	18174.03	16711.66	1090.46
411	18155.55	16761.84	1090.35
412	18177.00	16859.77	1091.75
413	18145.23	16898.68	1091.68
414	18110.60	16935.93	1090.86
415	18122.18	16983.39	1090.97
416	18149.53	17043.74	1091.24
417	18170.96	17096.28	1091.86
418	18181.77	17153.79	1090.76
419	18189.34	17200.42	1089.90
420	18207.47	17255.23	1088.78
421	18205.49	17310.11	1088.09
422	18198.60	17374.79	1086.82
423	18225.78	17425.98	1085.31
424	18276.10	17463.06	1085.05
425	18324.10	17449.56	1084.16
426	18371.35	17477.06	1082.05
427	18414.22	17509.63	1079.96
428	18464.08	17535.19	1079.44
429	18497.64	17504.97	1079.25
430	18545.81	17480.37	1077.66
83001	18708.50	17378.36	1078.35
83002	18795.18	17400.40	1075.38
83003	19065.81	17442.86	1066.74
83004	19240.16	17469.80	1064.32
83005	19439.00	17384.93	1061.54
83006	19674.01	17321.82	1042.62
83007	19917.62	17366.92	1032.24
83008	20158.62	17341.98	1020.25
83009	20517.52	17053.45	999.72
83010	20694.99	16973.62	993.87

TABLE 1 (continued)

84001*	19960.00	17250.00	1081.41
84002	20810.99	16817.53	987.50
84003	20911.32	16648.07	983.55
84004	21006.29	16534.10	977.54
84005	21097.82	16338.44	971.55
84006	21153.07	16148.71	968.78
84007	21301.91	16017.24	965.44
84008	21493.76	16015.91	960.68
84009	21689.76	16009.34	958.38
84010	21880.37	16021.05	952.65
84011	22080.84	15970.40	945.19
85019*	22506.88	15658.76	983.40
DYNGJA	22157.70	15751.64	938.29

* Reference stations where geodimeter was placed during mapping of the leveling profile.

The extension of the leveling profile of 1983 and 1984 was intended for use of temporary marker. This was partly required by the terrain with extended patches of AA-lava where no solid basement was easily found. Partly was this a time and material saving practice. A 200 m spacing was intended but shorter and longer spacing were tolerated. In 1987, several additional permanent markers were placed in the longest gaps between 1983 markers. No addition was made to the 1984 section of the profile.

The number of permanent bench marks in the Askja profile of precision leveling is by 1989 as follows

12	bench marks of 1966
18	bench marks of 1968
10	bench marks of 1983
10	bench marks of 1984
8	bench marks of 1987 within 1983 section
3	bench marks of 1987 within 1966 section
2	bench marks of 1989 within 1966 section
63	total number of bench marks.

Field methods of leveling

More or less conventional leveling practice has been applied in Askja. The same Kern invar leveling rods have been used during all levelings. These are 3 m rods with 5 mm scale units. The optical level used in 1966-1972 was Wild N3 with plane plate micrometer, while in 1983 to 1989 a Wild NA2 level was used. The N3 level is considered slightly more accurate than the NA2 level, but slower, due to the continuous manual manipulation.

The practice of backward-forward-forward-backward sequence is generally used and the profile has been leveled in both directions by taking care that rods are interchanged. Originally three complete measurements were made at each location during each coverage of the profile This procedure was modified in 1985 by making use of the 1/2 centimeter marks in the rods. The the reading sequence is:

1. backwards whole cm lower scale
2. backwards half cm lower scale
3. forwards whole cm lower scale
4. forwards half cm lower scale
5. forwards whole cm higher scale
6. forwards half cm higher scale
7. backwards whole cm higher scale
8. backwards half cm higher scale

This sequence is equivalent to two measurements of the older practice and gives 4 independent values of the elevation difference of the two bench marks. If the difference between highest and lowest of these 4 values exceeds or equals 0.2 mm, then another sequence is taken. Otherwise, the next interval is measured.

This leveling practice is found to furnish a rather precise leveling result, corresponding to a standard error of about 0.05 mm on each bench mark interval.

Environmental conditions as bright sunshine on the black lava, strong wind or snow cover, have limited the accuracy of the result on occasions, or prevented remeasurements where intended. Therefore, some measurements are less reliable or less precise than others, and a significant leveling error is indicated in the levelings of 1987, on a section of the profile where double coverage was made impossible by meteorological factors. this error was detected in 1988 when excellent measurements were obtained, and it was found that the 1987 error was confined to a segment between 2 bench marks only. Otherwise the 1987 leveling appears good although a double coverage was not made.

Otherwise, accidental gross errors are not present in the leveling data, although accidental errors amounting to less than 0.2 mm may pass undetected.

Presenting the leveling results

The leveling profile of 1966 and 1968 was leveled once each year 1966 through 1972. During this period of several cold summers, unusually heavy snow was present in the mountains. The part of the leveling profile which lay closest to the mountain slope on the east side of the Askja depression (BM 401, 402 and 403) was not snow free during the time of levelings of 1967, 1968, 1970, 1972, and also in 1983, when one, two, or, three bench marks could not be reached. Otherwise, the whole leveling profile was leveled.

The lowest numbered bench mark which was free of snow during all levelings was BM 404. This bench mark is arbitrarily chosen as reference for vertical displacements. This does not implicate that BM 404 is not moving but no bench mark can be expected to be more stable than another. Therefore a floating reference is accepted.

A practical and conventional method to present data on the vertical component of ground deformation is to draw on a map lines of equal displacements. Absolute displacements are generally not known, and certainly not in the Askja region. In case of irregularly shaped leveling profile, as the one in Askja, the location and approximate direction of each equi-displacement line can be determined along the path of the leveling profile. Extrapolation of these lines of equal vertical displacements outside the profile of leveling is generally uncertain and will be influenced by the individual who makes the extrapolation, whether this is done by some visual estimate or by sophisticated computer operation.

Another way to present the result is to plot the vertical displacement against distance along the leveling profile or against bench mark numbers. This method of presentation is best fitted on near linear leveling profiles but less well suited on irregularly shaped profiles. A variant of this method is to project each bench mark on a straight line and plot displacement against distance along each line of projection. This variant works well if the projection line is approximately perpendicular to mapped lines of equal displacements. It is also practical to compare results with theoretical models, especially single point source model.

Still another method of presenting data on vertical component of ground deformation is to compute tilt vectors and place these on a map of the surveyed area. This method is especially practical if there are several lines of precision leveling not connected. It can also be applied on a single line of precision leveling if the shape of the line is sufficiently irregular. The tilt can be computed from relative vertical displacement of three or more bench marks. If the number of bench marks applied exceeds 3, then a measure of precision of the tilt is obtained. This precision depends on size and shape of the array of bench marks used in the calculation, and it is azimuth dependent with minimum error along the long axis of the bench mark array.

The final method to present result of repeated leveling for deformation study, to be described here, is tabulation of the data. This method is practical for those who will do some study on the data, especially if computers are applied, but generally not practical for visual conception of the result. The tabulation need to include coordinates of bench marks and one or more of the following tables:

1. Table of relative elevation of bench marks at all times of leveling.
2. Table of relative vertical displacements of the bench marks between times of levelings.
3. Tables of various derived data, as tilt, estimated absolute displacements, distances from estimated point source etc.
4. Various tables of deviation from models.

TABLE 2

Elevation of bench marks of the Askja profile of precision leveling, relative to bench mark 404. All levelings were performed in late July or August, except the 1989 leveling which was done in early September.

stn	1966	1967	1968	1969	1970
401	-129.0497			-129.5748	
402	-105.9777		-106.7759	-106.2566	
403	-9.5783		-9.4774	-9.1264	-8.9311
404	0.0000	0.0000	0.0000	0.0000	0.0000
405	-15.3732	-15.4596	-15.4030	-15.4948	-15.5392
406	-29.5099	-29.8454	-29.6341	-29.9230	-30.1057
407	-34.5419	-34.8615	-34.7854	-35.0333	-35.1718
408	110.3659	109.9639	110.0615	109.7450	109.5509
409	33.8360	33.2561	33.4140	32.9601	32.6531
410	-8.2091	-8.9358	-8.7792	-9.3170	-9.6847
411	-16.1619	-16.9669	-16.8273	-17.4382	-17.8197
412	116.9544	116.0752	115.9383	115.3213	114.9817
413			105.6613	104.9494	104.5626
414			28.7496	27.9938	27.5708
415			38.8247	39.0397	38.6437
416			60.2128	59.5053	59.1479
417			127.1362	126.3927	126.0509
418			11.4414	10.7756	10.4870
419			-72.4402	-72.9826	-73.2083
420			-187.1158	-187.5932	-187.7786
421			-249.8513	-250.3135	-250.4819
422			-372.9256	-373.6662	-373.9339
423			-493.1276	-493.5216	-493.5953
424			-556.3277	-556.6796	-556.7511
425			-637.2467	-637.5549	-637.5850
426			-853.6989	-853.9357	-853.9173
427			-1055.2935	-1055.3930	-1055.2674
428			-1112.2793	-1112.2974	-1112.1076
429			-1127.4639	-1127.4553	-1127.2323
430			-1282.1150	-1282.0813	-1281.9362

TABLE 2 (continued)

stn	1971	1972	xxxx	1983	1984
401					-126.6299
402					-103.4957
403	-9.0850				-7.4981
404	0.0000	0.0000		0.0000	0.0000
405	-15.4570	-15.2744		-15.7975	-15.8716
406	-29.7767	-29.2615		-30.9474	-31.2025
407	-35.1354	-34.9164		-36.3181	-36.4577
408	109.5662	109.8029		108.0359	107.8496
409	32.6487	32.9566		30.3241	30.0837
410	-9.7171	-9.3001		-12.2881	-12.5214
411	-17.8213	-17.4037		-20.2329	-20.4376
412	114.7811	115.0517		113.4547	113.3836
413	104.4122	104.7942		103.3380	103.3074
414	27.5436	28.0973		26.8338	26.8511
415	38.4914	38.9200		38.1992	38.2963
416	58.8552	59.0258		58.9029	59.0763
417	125.5782	125.5682		125.9970	126.2338
418	9.9291	9.7586		10.7988	11.1270
419	-73.8729	-74.1502		-72.5383	-72.1592
420	-188.5383	-189.0639		-186.7689	-186.3234
421	-251.3439	-252.0126		-249.2265	-248.6902
422	-375.0687	-375.8362		-374.6705	-374.0532
423	-494.7347	-495.7361		-491.5942	-490.8964
424	-558.1224	-559.5005		-554.7195	-553.9152
425	-639.0902	-640.6627		-635.7433	-634.9084
426	-855.5736	-857.3880		-851.8474	-850.9675
427	-1057.0459	-1059.0982		-1052.8019	-1051.8671
428	-1114.0153	-1116.3468		-1109.6639	-1108.6547
429	-1129.1476	-1131.5145		-1124.7659	-1123.7612
430	-1284.0065	-1286.4855		-1281.0663	-1280.0431
83001				-1213.9838	
83002				-1512.2921	
83003				-2385.9114	

TABLE 2 (continued)

stn	1985	1986	1987	1988	1989
401	-126.2921	-125.9187	-125.6917	-125.3353	-124.9876
402	-103.2557	-102.9659	-102.7705	-102.5238	-102.2360
403	-7.3634	-7.2023	-7.0960	-6.9602	-6.7845
403A					104.5467
404	0.0000	0.0000	0.0000	0.0000	0.0000
405	-15.9375	-15.9944	-16.0469	-16.0996	-16.1712
405A					-7.6885
406	-31.4260	-31.5946	-31.7830	-31.9361	-32.1385
407	-36.5936	-36.6869	-36.8230	-36.9162	-37.0860
408	107.7031	107.5839	107.4211	107.3019	107.1275
408A				-52.5189	-52.7648
409	29.8670	29.6859	29.5070	29.3348	29.0786
409A				-90.0732	-90.3457
410	-12.7329	-12.9171	-13.0941	-13.2688	-13.5103
411	-20.6124	-20.7637	-20.9208	-21.0738	-21.2805
411A				-69.6255	-69.7591
412	113.3725	113.3605	113.3550	113.3233	113.2669
413	103.2954	103.3119	103.3225	103.3125	103.2774
414	26.8261	26.8494	26.8861	26.8671	26.8612
415	38.3587	38.4611	38.5624	38.6358	38.6512
416	59.2076	59.4042	59.5830	59.7576	59.8537
417	126.4439	126.7083	126.9429	127.1831	127.3407
418	11.4070	11.7238	12.0180	12.3355	12.5087
419	-71.8211	-71.4488	-71.0883	-70.7273	-70.4985
420	-185.8987	-185.4676	-185.0252	-184.6144	-184.3075
421	-248.1881	-247.7013	-247.2085	-246.7383	-246.3570
422	-373.4370	-372.9341	-372.3690	-371.8333	-371.4080
423	-490.1876	-489.5913	-488.9520	-488.3330	-487.8234
424	-553.1450	-552.4798	-551.7689	-551.0762	-550.5424
425	-634.1144	-633.4178	-632.7018	-631.9852	-631.4159
426	-850.1121	-849.3727	-848.5982	-847.8106	-847.2287
427	-1050.9082	-1050.1118	-1049.2614	-1048.4152	-1047.7402
428	-1107.6599	-1106.8252	-1105.9201	-1105.0384	-1104.3151
429	-1122.7689	-1121.9166	-1121.0332	-1120.1550	-1119.4402
430	-1279.0574	-1278.1808	-1277.2805	-1276.4362	-1275.7353
83001		-1210.8660	-1209.9086	-1208.9459	-1208.1697
83002		-1508.9832	-1507.9737	-1506.9571	-1506.1238
87009			-1993.4594	-1992.3571	-1991.4619
83003		-2382.0620	-2380.8831	-2379.7128	-2378.7186
83004		-2616.7826	-2615.5731	-2614.4118	-2613.4226
83005		-2893.3462	-2892.0844	-2890.8009	
87008			-3610.9954	-3610.2917	
87007			-4368.1955	-4367.5252	
83006		-4785.0302	-4783.2168	-4782.4184	
87006			-5362.0278	-5361.1369	
83007		-5821.2664	-5819.2512	-5818.2643	
87005			-6255.3508	-6254.3348	
83008		-7002.8085	-7000.8086	-6999.8117	
87004			-7467.1029	-7466.0470	
87003			-7808.2319	-7807.1480	
87002			-8597.1210	-8595.9884	

TABLE 2 (continued)

stn	1985	1986	1987	1988	1989
83009		-9073.5945	-9071.3773	-9070.2453	
83010		-9664.7555	-9662.6627	-9661.7295	
84002		-10290.2591	-10287.9686	-10286.8047	
84003		-10700.5812	-10698.2960	-10697.2157	
84004		-11295.6114	-11293.1757	-11291.9157	
84005		-11893.9553	-11891.5575	-11890.4385	
84006		-12172.9405	-12170.4969	-12169.2268	
84007		-12506.0158	-12503.4504	-15202.1787	
84008		-12945.3108	-12942.7195	-12941.3810	
84009		-13209.8556	-13207.2668	-13205.8957	
84010		-13782.7362	-13780.1155	-13778.6679	
84011		-14528.8471	-14526.1736	-14524.6584	

TABLE 3

Elevation of several bench marks at the east end of the Askja profile of precision leveling, relative to the bench mark NE84011 (see Fig. 2).

stn	1985	1986	1987	1988	1989
84011	0.0000	0.0000	0.0000	0.0000	0.0000
84010	746.1665	746.1109	746.0581	745.9905	745.9708
84009	1319.1260	1318.8806	1318.9068	1318.7627	1318.6672
84008	1583.7501	1583.5364	1583.4541	1583.2774	1583.1127
84007	2023.1152	2022.8314	2022.7232	2022.4797	2022.2470
84006	2356.2122	2355.9067	2355.6767	2355.4316	
84005	2635.2682	2634.8909	2634.6161	2634.2199	
84004	3233.5714	3233.2358	3232.9979	3232.7427	
84003	3828.7679	3828.2660	3827.8776	3827.4427	
84002	4239.0066	4238.5881	4238.2050	4237.8537	
83010	4864.7309	4864.0917	4863.5109	4862.9289	
83009	5455.6741	5455.2527	5454.7963	5454.4131	

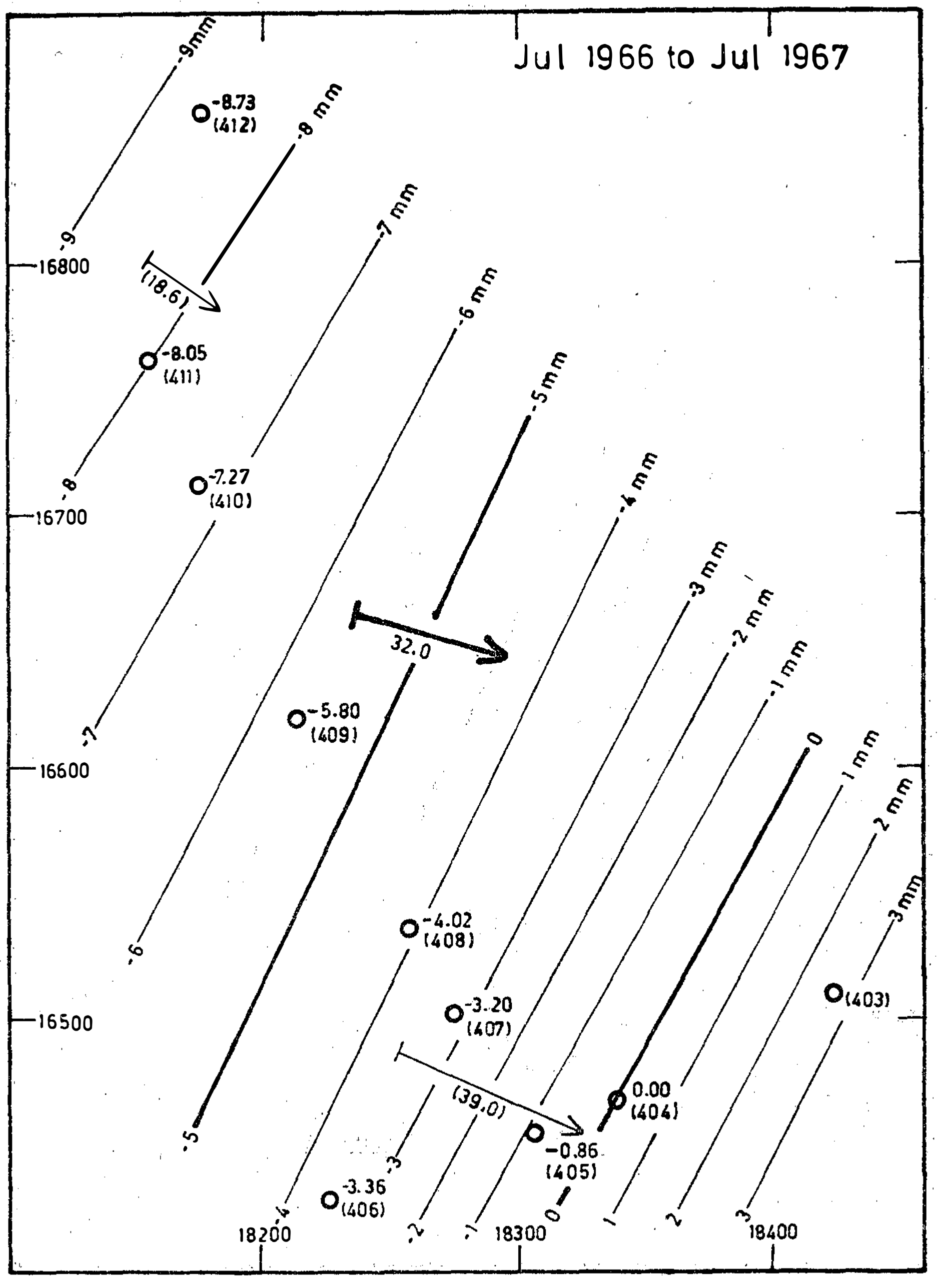

Fig. 3. The Askja profile of precision leveling as of 1966 and observed vertical displacement of each observed bench mark between levelings of late July 1966 and late July 1967 (upper number) relative to the bench mark 404. Identification numbers of the bench marks are given in parentheses. Tilt vectors are shown for the least squares solution of all points (thick arrow) and for selected triangles in northern and southern parts of the profile (thin arrows) Numbers by the arrows indicate magnitude of tilt in microradians. Lines of equal vertical displacements are drawn as estimated by the author. Coordinates in meter at the left and bottom edge of the figure are north and east coordinates of the U. S. Army Map Service maps of Iceland in scale 1:50000 published in 1949.

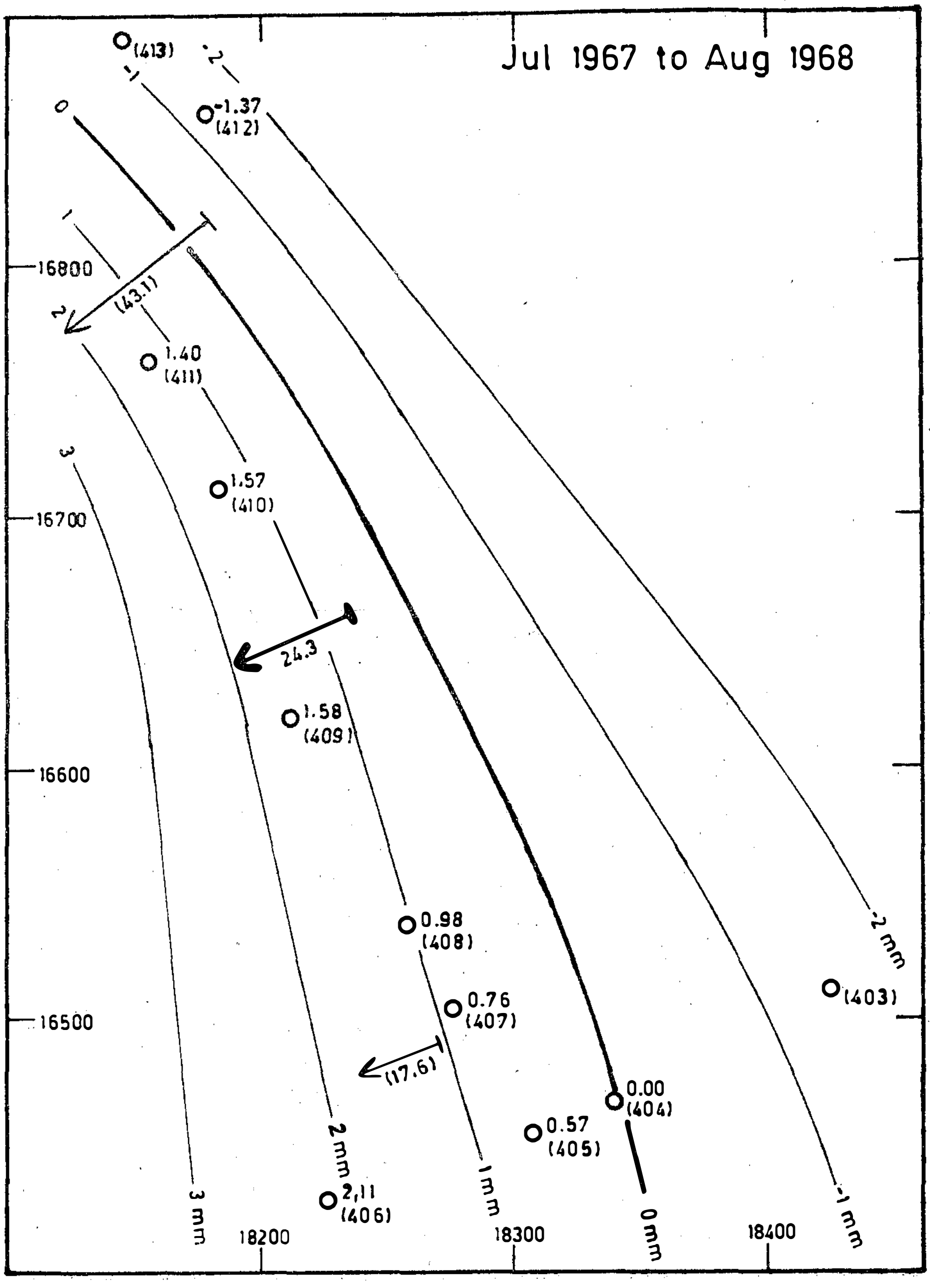

Fig. 4. Observed vertical displacements between levelings of late July 1967 and mid August 1968. See Fig. 3 for explanations.

Principal results

The first releveling in 1967, one year after the first leveling, showed considerable relative vertical displacements of the individual bench marks (Fig. 3). These displacements represented a regular pattern which could be described as a general tilt of the ground, down towards northwest, the tilt amounting to approximately 20 microradians.

The bench marks were placed in a lava which erupted in late 1961, and was thus less than 5 years old in July 1966 when first leveling was made. The lava was still warm in places, although it appeared cold at the location of the short leveling profile. It was expected that some deformation caused by cooling of the lava could be observed, but the regular pattern of deformation showed that the source of deformation was much deeper than within the new lava. The tilt did not point to a source below the 1961 eruption site. Thus, the first reveling of the Askja profile of precision leveling showed significant ground deformation which was apparently unrelated to the cooling of the recent lava and not clearly related to the site of the recent eruption.

A third leveling in 1968 showed again considerable deformation (Fig. 4), but the pattern of deformation was quite different from that observed a year earlier. A general tilt down towards east was observed between levelings of 1967 and 1968, and again, the pattern of deformation precluded a shallow source, within the recent lava.

Levelings of 1969 and 1970 showed again ground tilting down in westerly direction (Figs. 5, 6, and7), similar to the 1966-1967 deformation. The extension of the leveling profile in 1968 provided a mean to estimate the curvature of lines of equal vertical displacement. These lines were clearly concave towards west indicating a westerly source which was deflated between levelings of 1966 and 1967 and also between 1968 and 1970 but inflated between the summer of 1967 and 1968.

Levelings of 1971 and 1972 showed again inflation towards west (Figs. 8, 9, and 10) and the rate of deformation was more rapid than in previous years.

The deformation measurements in Askja were discontinued after the 1972 observation, but at that time two periods of inflation and two periods of deflation had been observed. If the source of deformation was to the west of the leveling profile, as indicated by the shape of the lines of equal vertical displacement, then deflation prevailed between 1966 and 1967 levelings and also from 1968 leveling until 1970 leveling, but inflation prevailed between levelings of 1967 and 1968 and also after the 1970 levelings. The relatively small apparent inflation between August 1970 and August 1971 compared to the large apparent inflation between August 1971 and August 1972 indicate that this period of inflation started several months after the 1970 leveling.

No leveling was perfoemed on the Askja profile of precision leveling in 1973 through 1982 but leveling was resumed in 1983 (Fig. 11) and carried out once each year until 1989. The old leveling profile has been leveled every year and the 1983 and 1984 extensions were leveled throughout its entire length in 1986, 1987 and 1988, and parts of the extension was leveled in 1983, 1985, and 1989. The 1983 to 1989 levelings show continuous deflation centered to the west of the leveling profile (Figs. 12 through 19). The rate of deflation has been rather uniform and the pattern of deformation near identical throughout the 6 year period. This rate of deformation is similar to that observed in 1966 through 1971.

There is apparently a very slight decrease in the rate of deformation from 1983 to 1989, amounting to 4 to 6 per cent per year.

The rate of tilt decreases towards east on the 1983-1984 extension of the leveling profile, strengthening the opinion of a center of deformation located to the west of the profile.

The deformation between the 1972 leveling and the 1983 leveling is significant deflation to the west of the profile, showing that the inflation of 1970 to 1972 ceased at some early time in this 11 year period of no measurements.

It can be assumed that the inflation continued at the 1971-72 rate until deflation commenced, and that the deflation began at a rather high rate and then slowed down by about 5% per year, as is indicated in the 1983 to 1989 observational data, then the deflation probably started in 1974. However, this is quite uncertain. There may have been more periods of deflations and inflations, although this is not likely. Further, the pattern of deflation from August 1973 to August 1983 (Fig. 11) is somewhat different from that observed after 1983 (Fig. 19) and the difference cannot wholly be explained by the difference in the inflation pattern of 1971-1972 and the deflation pattern 1983-1989.

Therefore, the history of ground deformation in Askja in 1972-1983 cannot be resolved with confidence, although it is very probable that the inflation of 1970-1972 continued for at least one year after the 1972 observation, and the deflation of 1983-1989 commenced at least seven years before the observation of 1983.

The computed tilt vectors of sections of the Askja profile of precision leveling, between dates of levelings, are shown on the Figs 3 through 19 (except 5 and 8), and tabulated in Tables 4 and 5. The tilt vectors are positive in up-dip direction.

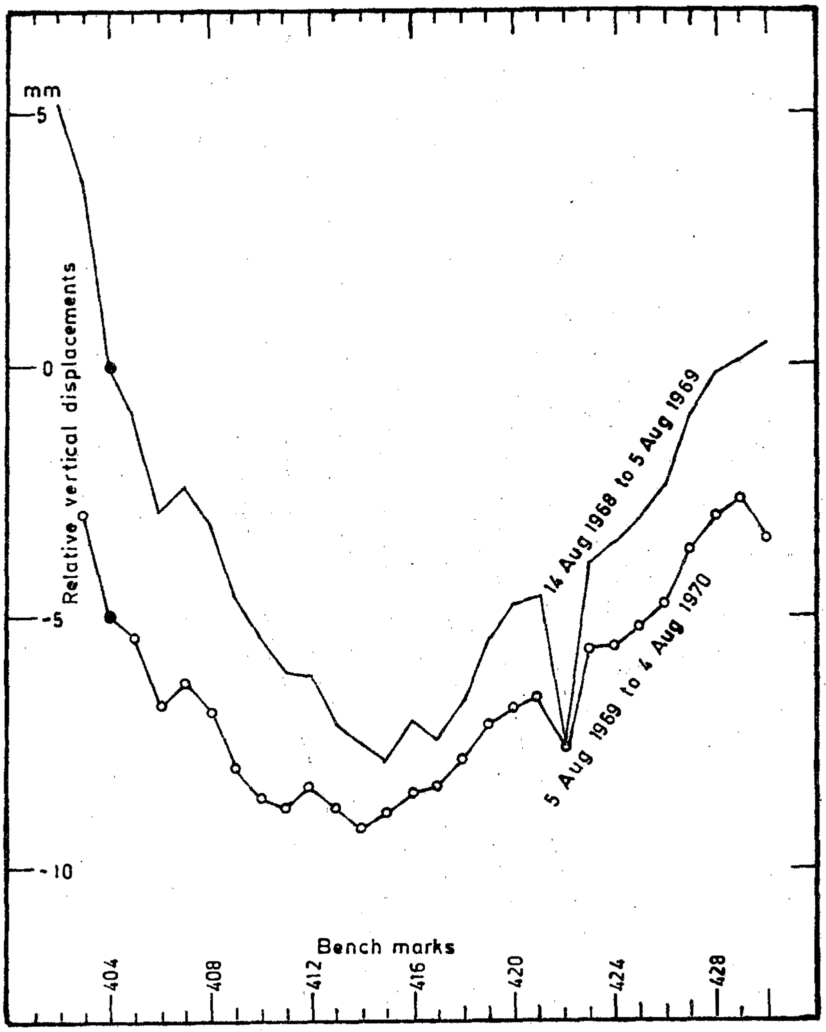

Fig. 5. Relative vertical displacements of bench marks of the Askja profile of precision leveling between levelings of 1968, 1969, and 1970, plotted against the bench mark numbers. Bench mark 404 (filled circle) is used as reference. Data of 1969 to 1970 is displaced 5 mm downwards relative to the data of 1968 to 1969. Irregularities of the curve are partly caused by irregular layout of the profile (e.g. 406 and 412), amd partly by erratic bench mark movements (e.g. 422 and 430).

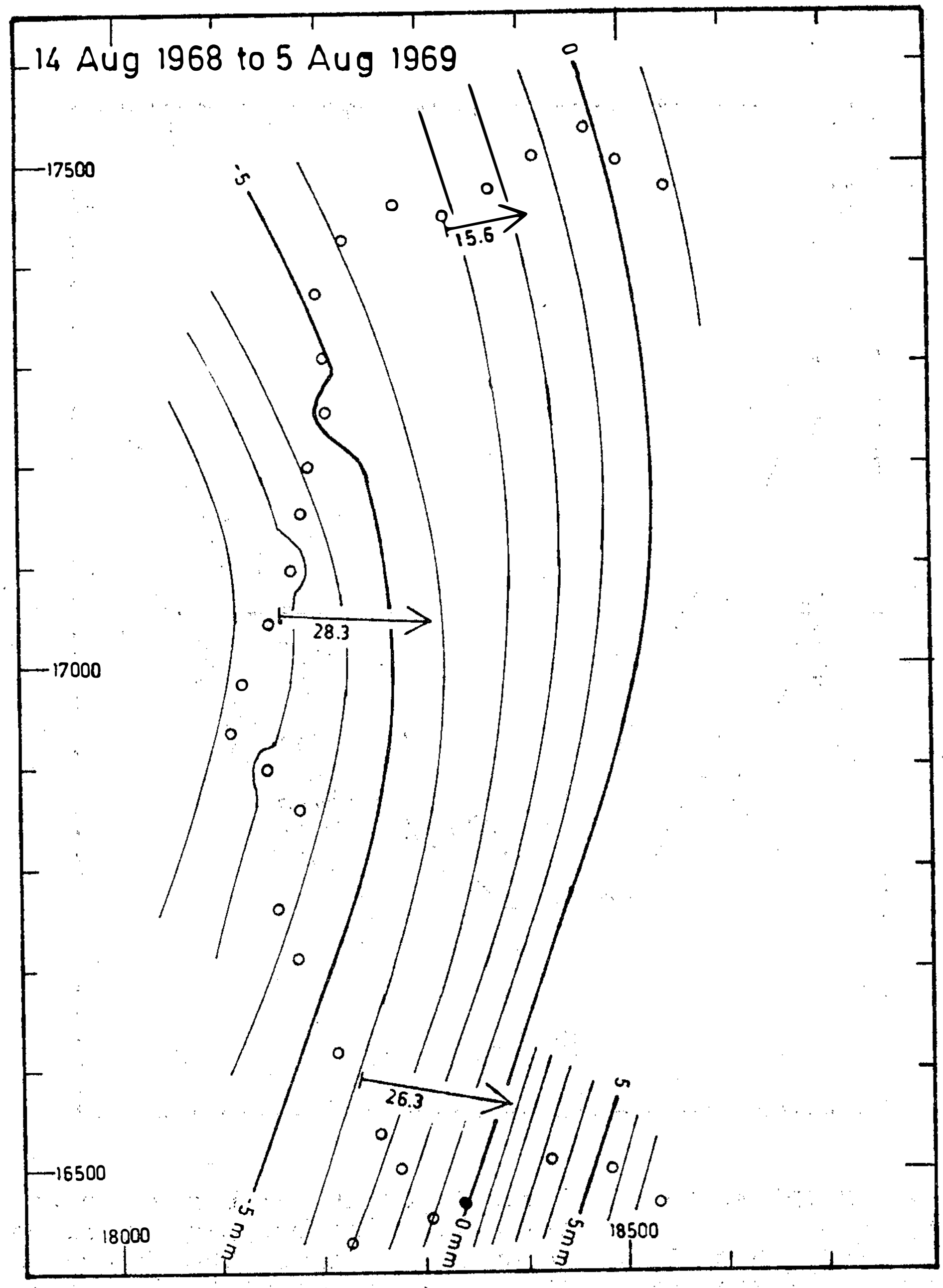

Fig. 6. Vertical displacements of the Askja profile of precision leveling between levelings of mid August 1968 and early August 1969, relative to bench mark 404 (filled circle). Computed ground tilt for three sections of the profile (b.m. 404 through 412, 412 through 420, and 420 through 429 omitting 422, see Fig. 20) is presented by arrows pointing up-dip and magnitude of tilt in microradians. Lines of equal vertical displacements are drawn at one mm intervals and show the authors estimate based on the tilt vectors and numerical data of Table 2.

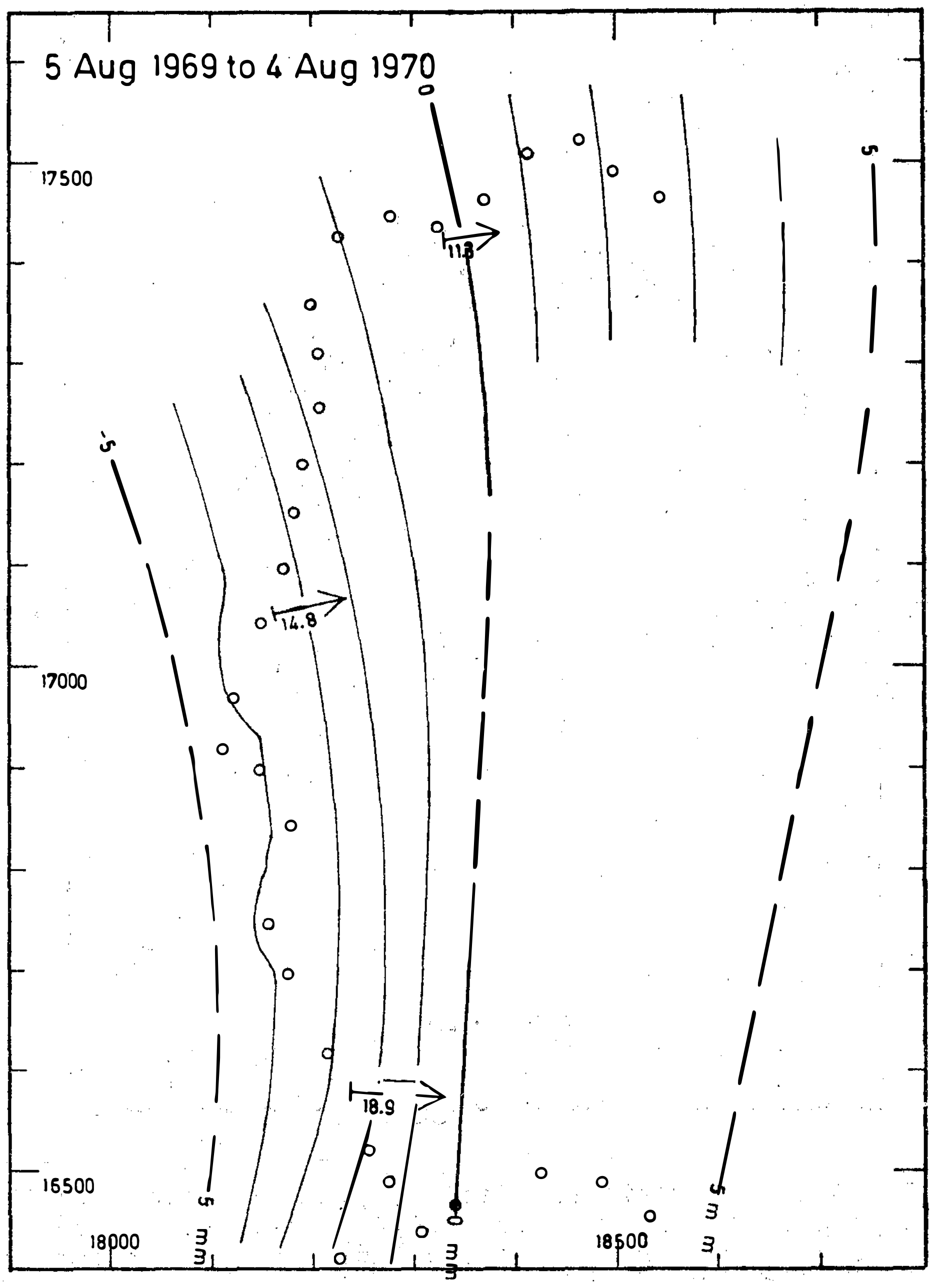

Fig. 7. Vertical displacements of the Askja profile of precision leveling from early August of 1969 to early August 1970, relative to bench mark 404. See Fig. 6 for further explanation.

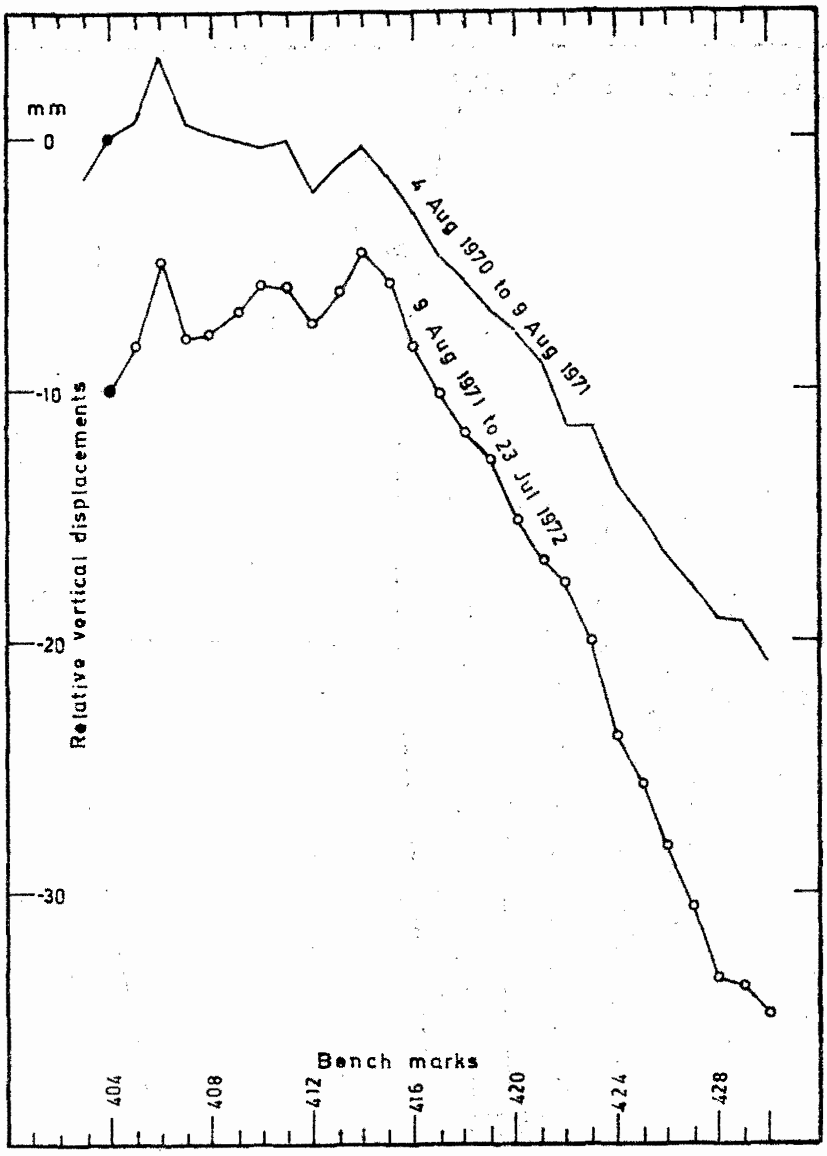

Fig. 8. Relative vertical displacements of bench marks of the Askja profile of precision leveling between levelings of 1970, 1971, and 1972, plotted against the bench mark numbers. The curve of 1971 to 1972 is displaced 10 mm downwards relative to the curve of 1970 to 1971. See Fig. 5 for further explanation.

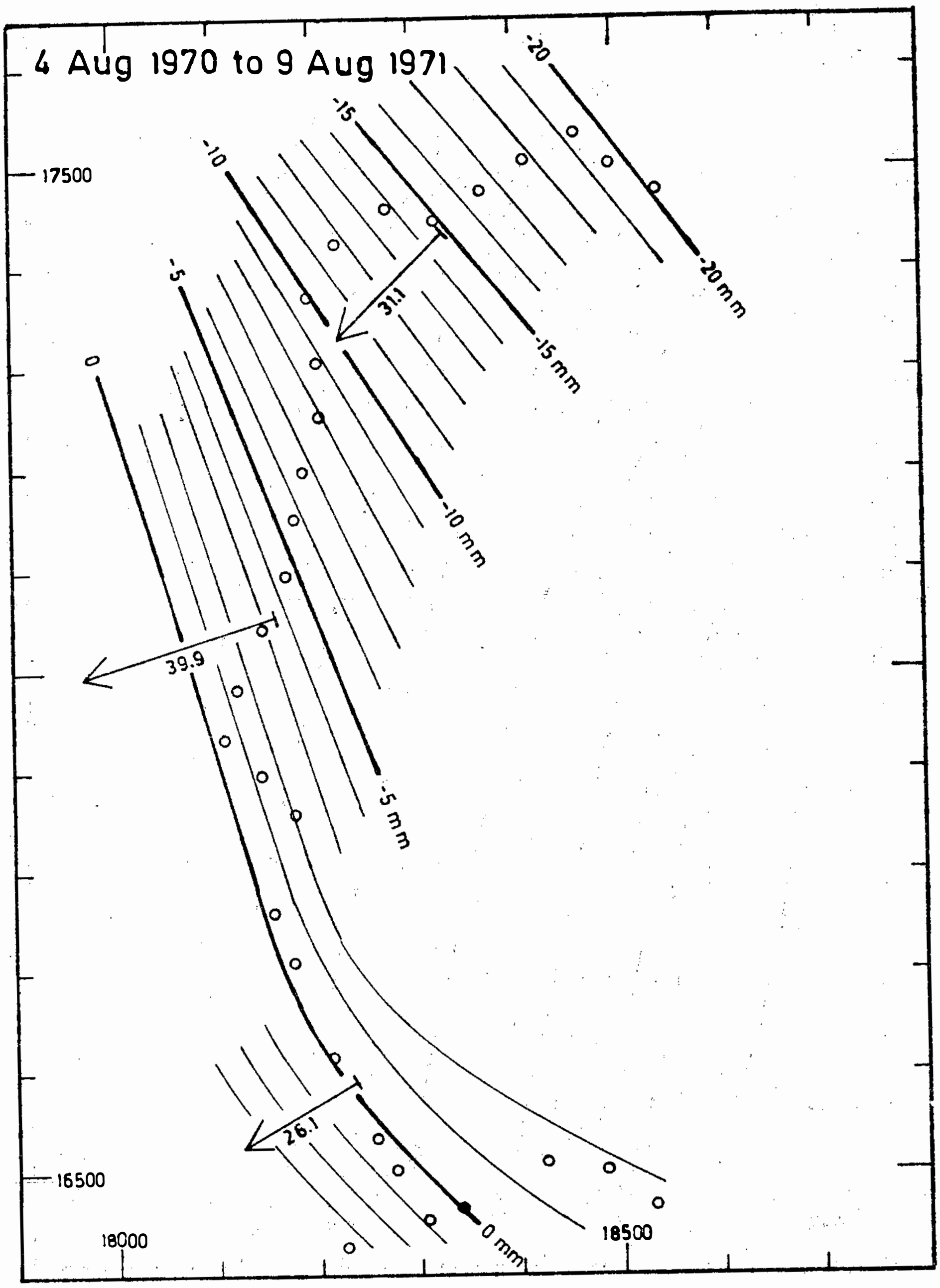

Fig. 9. Vertical displacement of the Askja profile of precision leveling from early August 1970 to early August 1971. See Fig. 6 for further explanation.

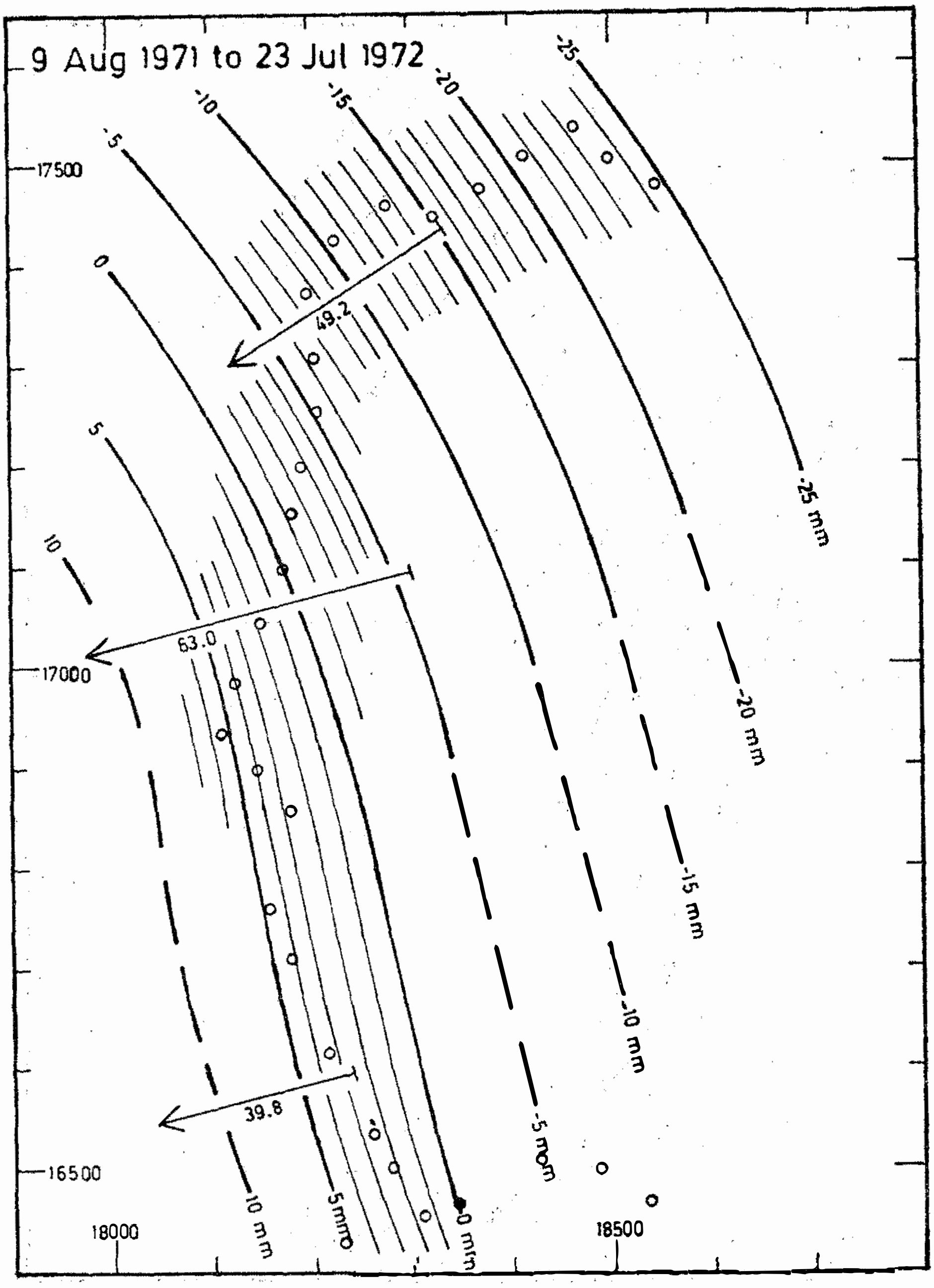

Fig. 10. Vertical displacement of the Askja profile of preciaion leveling from early August 1971 to late July 1972. See Fig. 6 for further explanation.

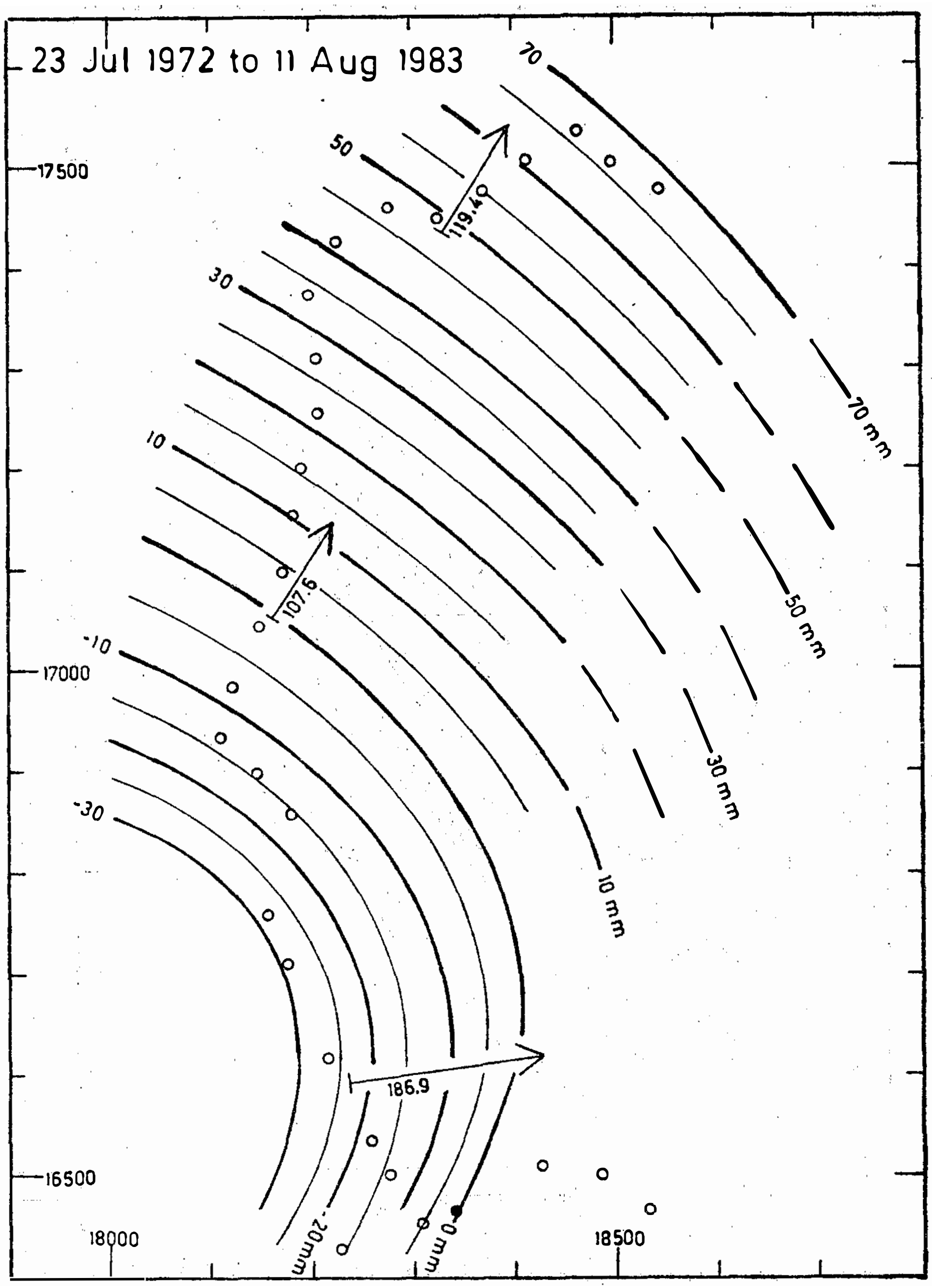

Fig. 11. Vertical displacement of the Askja profile of precision leveling between levelings of late July 1972 and mid August 1983, but no levelings were made in Askja during this period. Lines of equal vertical displacement are drawn at 5 mm intervals. See Fig. 6 for further explanation.

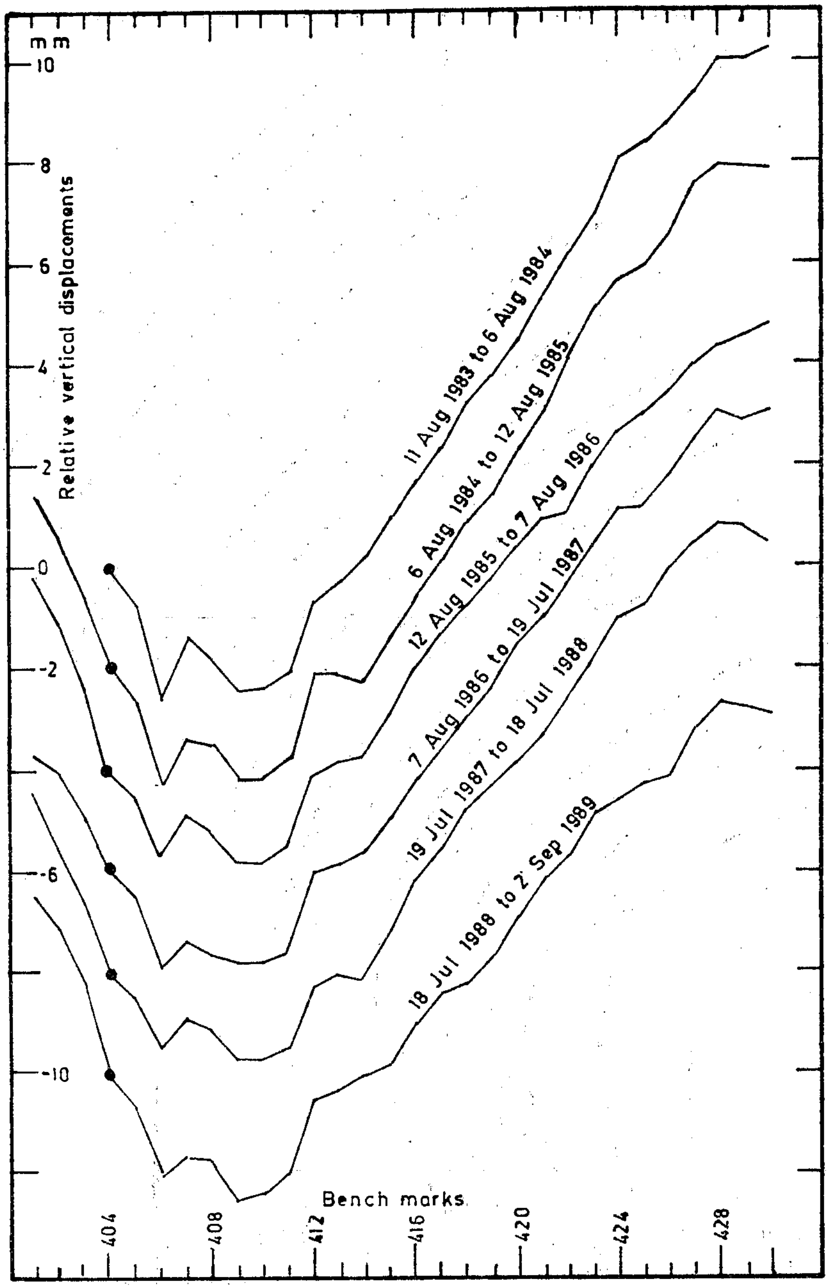

Fig. 12. Relative vertical displacement of the Askja profile of precision leveling between annual levelings of 1983 through 1989 are plotted against bench mark numbers. Each years data is displaced 2 mm downwards relative to previous year's data. Note that bench mark 422 is not anomalous as in 1968 to 1971. See Fig. 5 for further explanation.

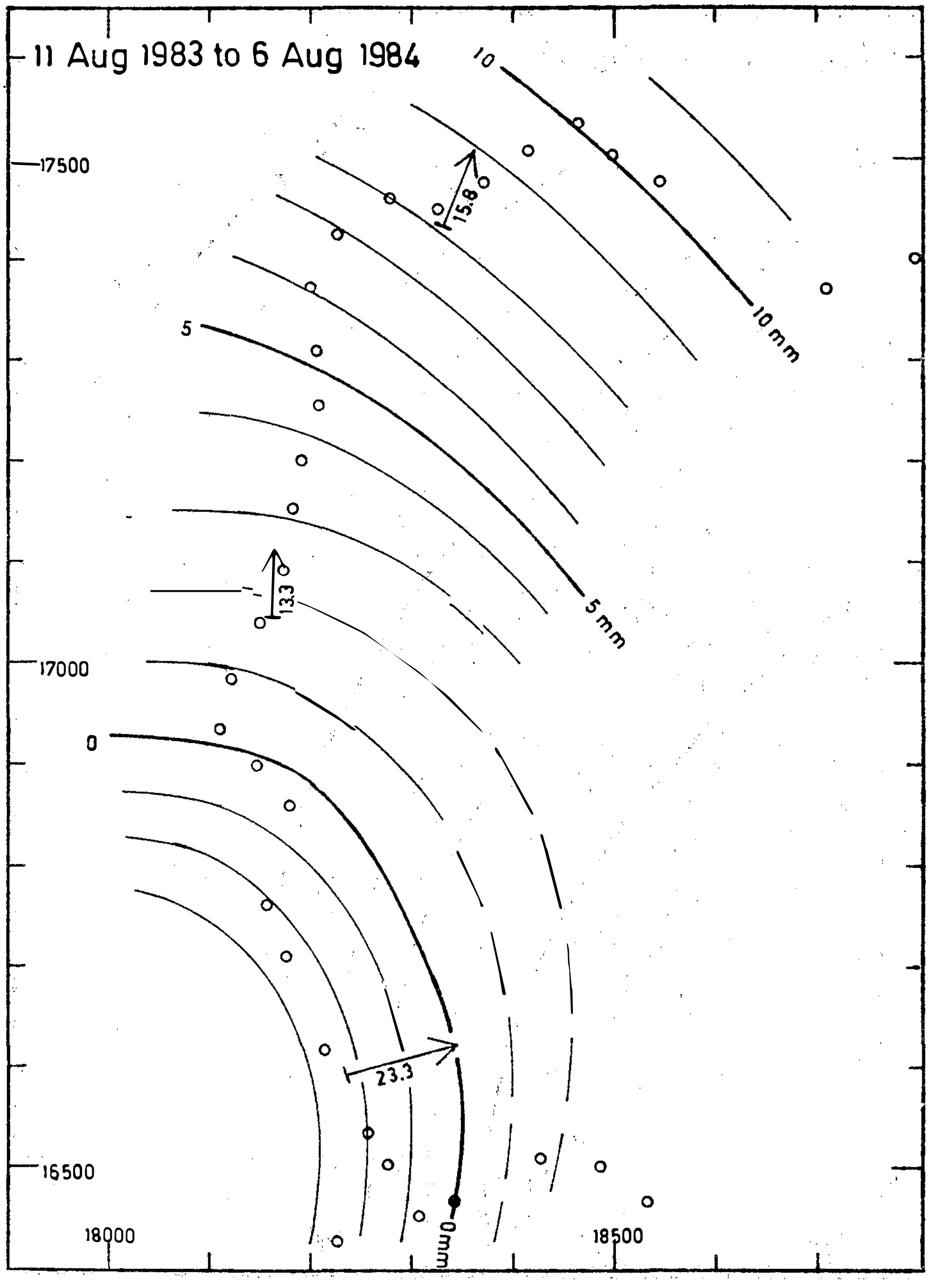

Fig. 13. Vertical displacement of the Askja profile of precision leveling from mid August 1983 to early August 1984. See Fig. 6 for further explanation.

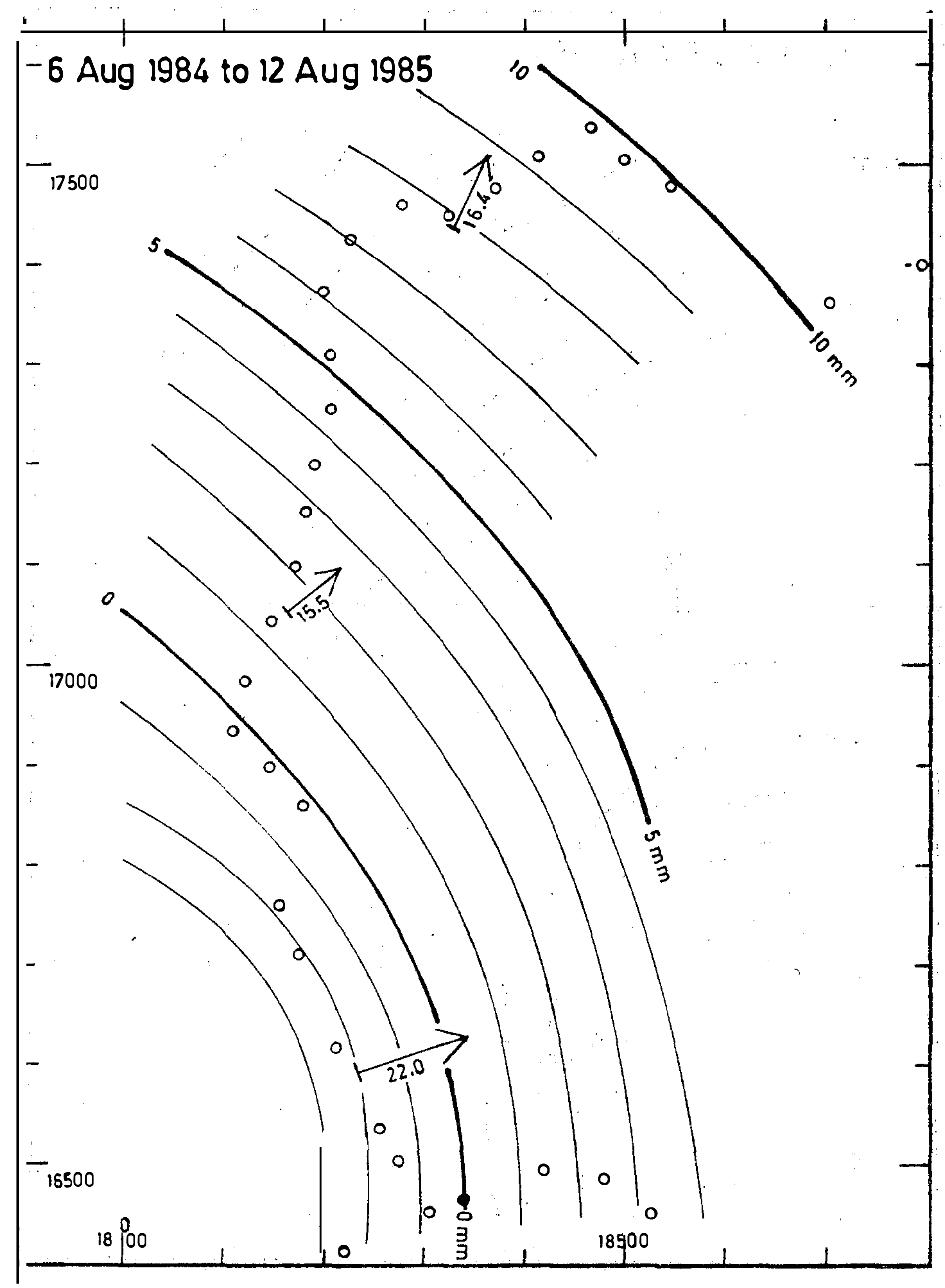

Fig. 14. Vertical displacement of the Askja profile of precision leveling from early August 1984 to mid August 1985. See Fig. 6 for further explanation.

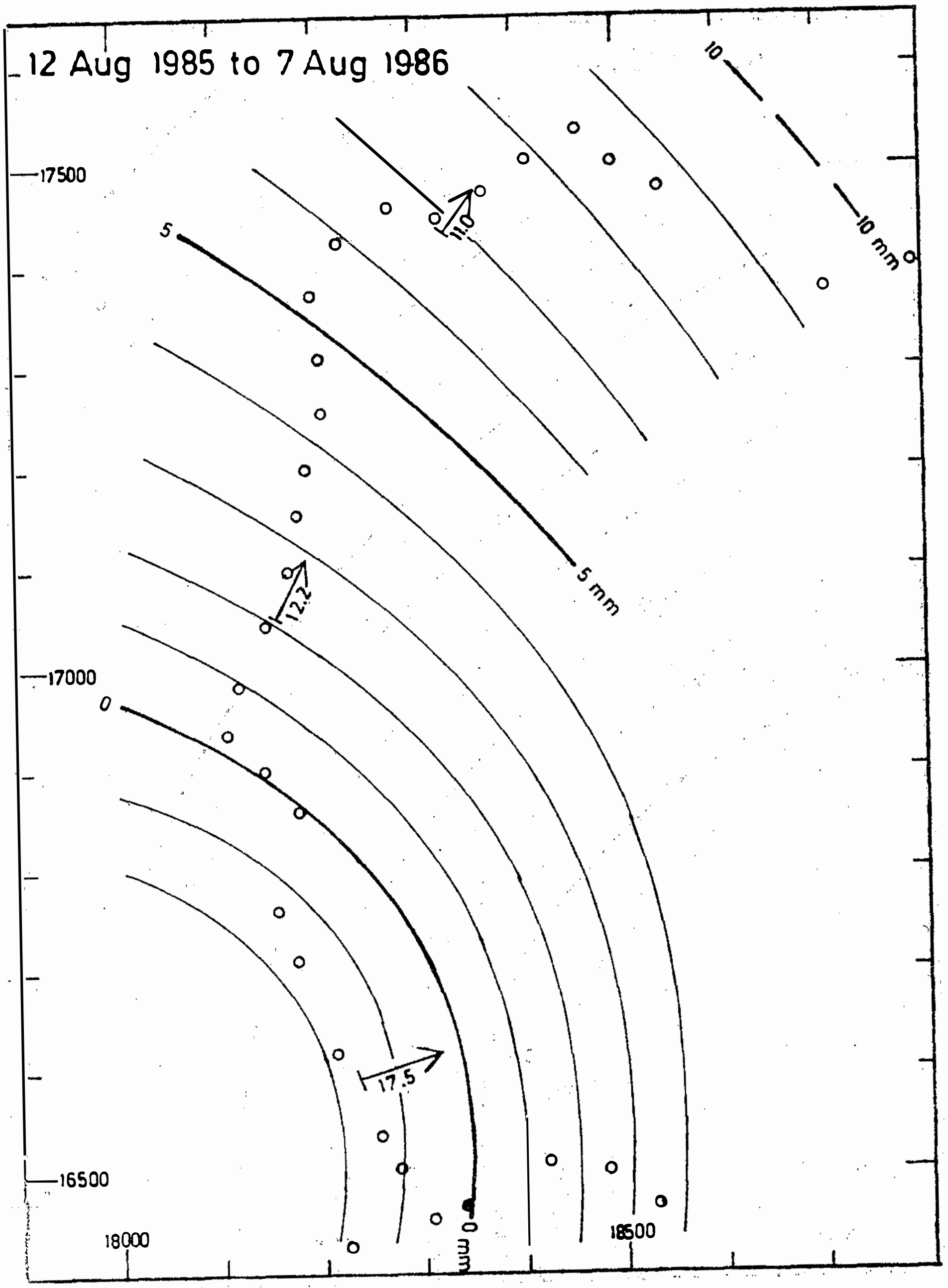

Fig. 15. Vertical displacement of the Askja profile of precision leveling from mid August 1985 to early August 1986. See Fig. 6 for further explanation.

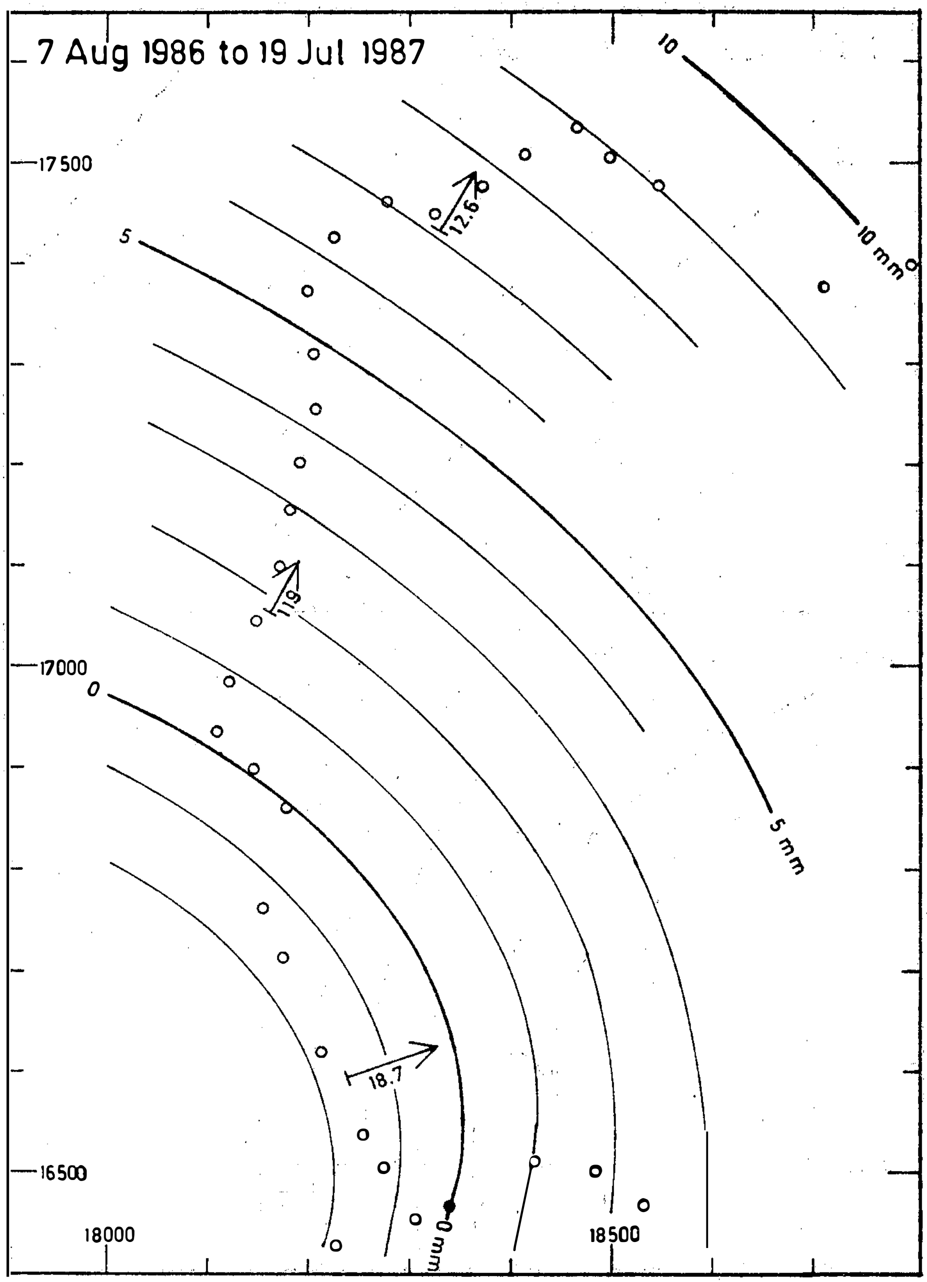

Fig. 16. Vertical displacement of the Askja profile of precision leveling from early August 1986 to mid July 1987. See Fig. 6 for further explanation.

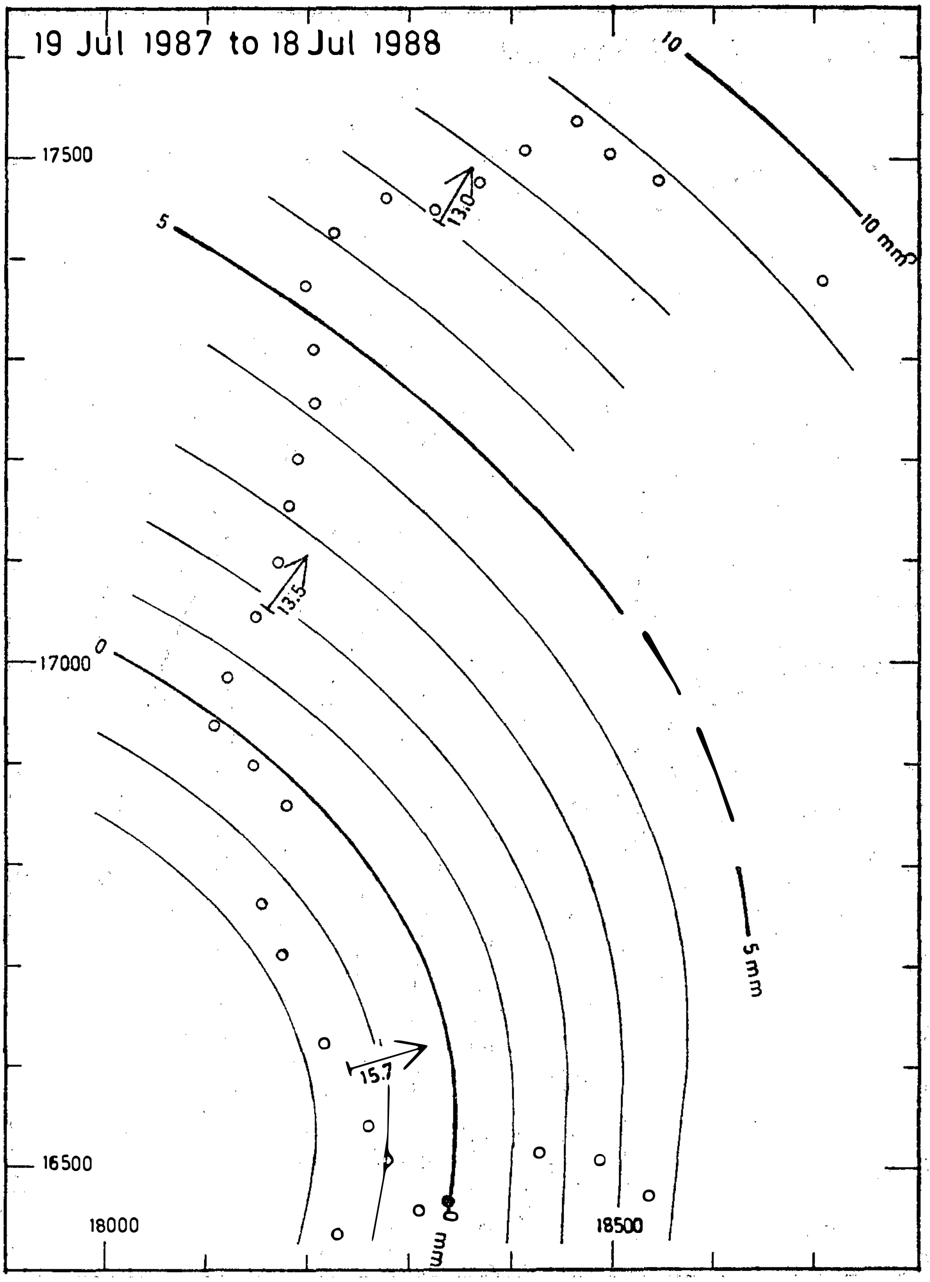

Fig. 17. Vertical displacement of the Askja profile of precision leveling from mid July 1987 to mid July 1988. See Fig. 6 for further explanation.

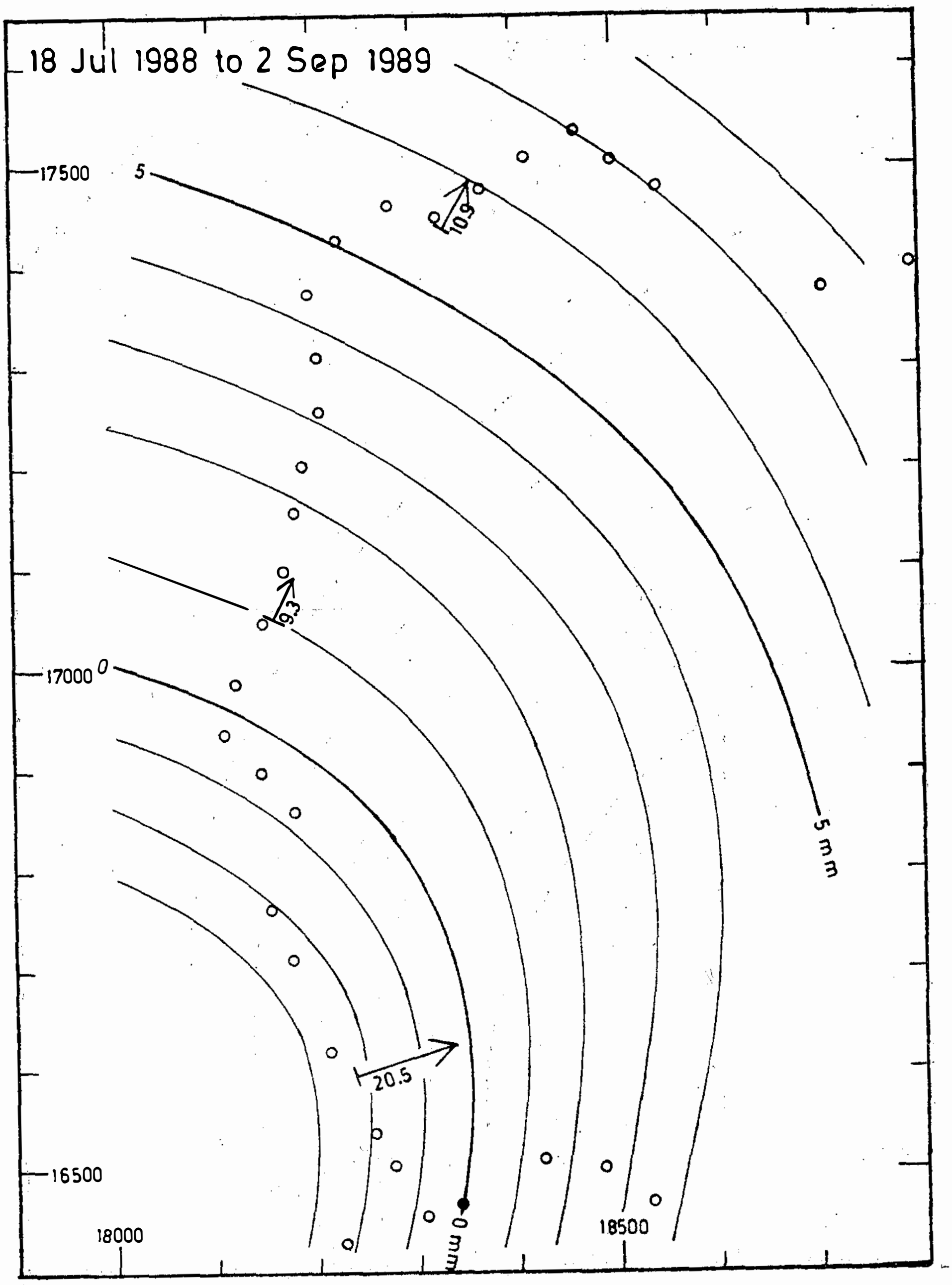

Fig. 18. Vertical displacement of the Askja profile of precision leveling from mid July 1988 to early September 1989. See Fig. 6 for further explanation.

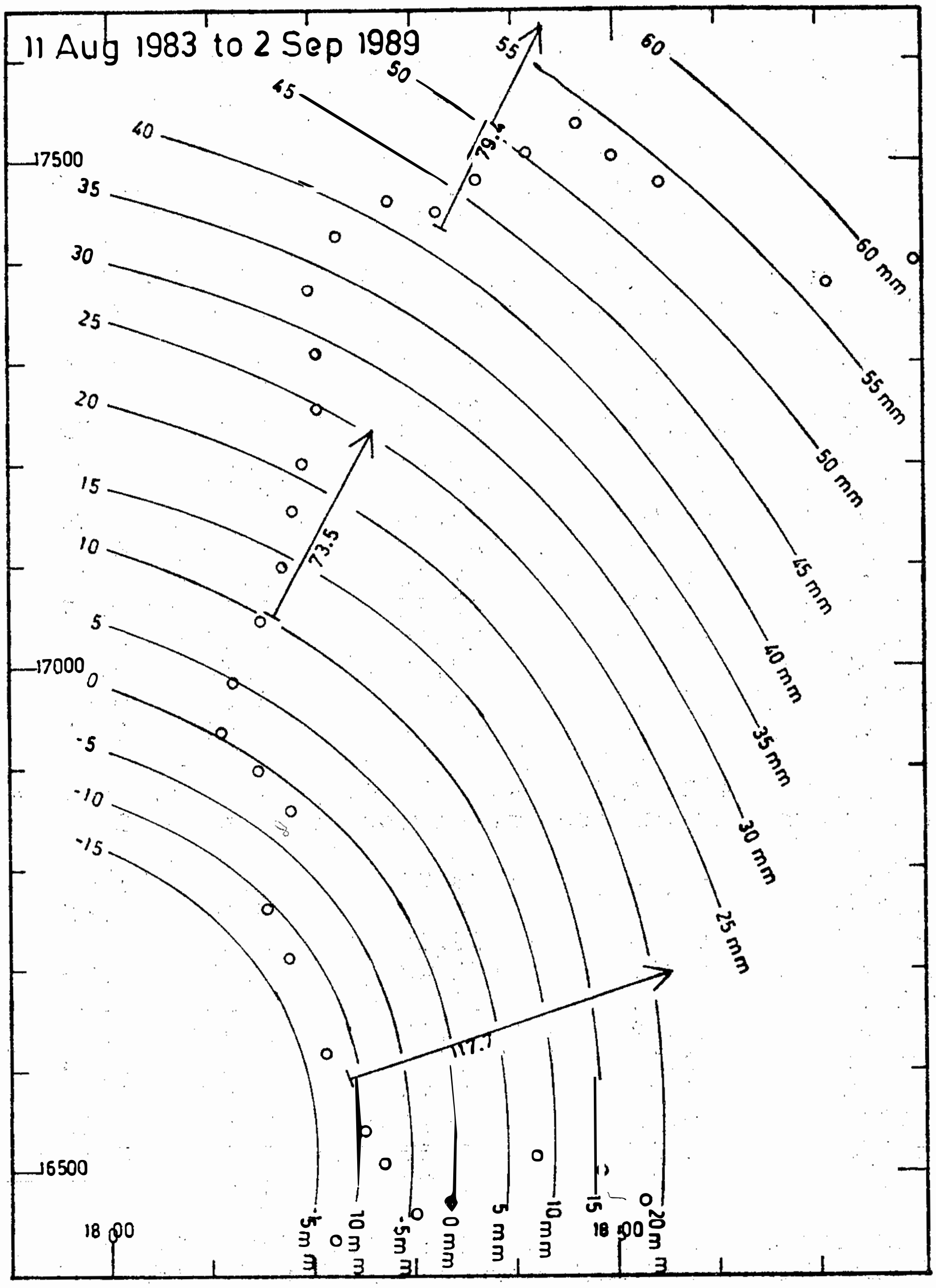

Fig. 19. Vertical displacement of the Askja profile of precision leveling for a 6 year period from mid August 1983 to early September 1989. Lines of equal vertical displacement are drawn at 5 mm intervals. See Fig. 6 for further explanation.

TABLE 4

Computed ground tilt for sections of the Askja profile of precision leveling for periods between levelings

Period	Components of tilt in microradians N-comp	E-comp	standard error in microradians max	min
A: Bench marks 404, 405, 406, 407, 408, 409, 410, 411, 412. Azimuth of maximum standard error of tilt: 70.7°				
1966-1967	-8.20	30.89	3.66	0.80
1967-1968	-9.80	-22.22	4.67	1.02
1968-1969	-4.13	25.94	2.70	0.59
1969-1970	-1.44	18.88	2.33	0.51
1970-1971	-14.10	-22.00	3.22	0.70
1971-1972	-9.90	-38.51	2.18	0.48
1972-1983	22.33	185.54	39.10	8.54
1983-1984	6.80	22.26	3.00	0.66
1984-1985	7.15	20.86	3.51	0.77
1985-1986	5.33	16.68	3.15	0.69
1986-1987	6.21	17.63	3.56	0.78
1987-1988	4.41	15.06	2.81	0.62
1988-1989	5.70	19.74	4.52	0.99
B: Bench marks 412, 413, 414, 415, 416, 417, 418, 419, 420. Azimuth of maximum standard error of tilt: 99.2°				
1968-1969	-0.88	28.27	8.94	1.47
1969.1970	3.57	14.34	5.18	0.85
1970-1971	-11.38	-38.24	2.40	0.39
1971-1972	-14.22	-61.42	2.97	0.49
1972-1983	92.50	54.94	9.36	1.54
1983-1984	13.32	0.29	1.02	0.17
1984-1985	9.95	11.90	1.19	0.20
1985-1986	11.06	5.19	1.61	0.26
1986-1987	10.73	5.22	1.14	0.19
1987-1988	11.14	7.69	2.24	0.37
1988-1989	8.47	3.90	1.88	0.31
C: Bench marks 420, 421, 423, 424, 425, 426, 427, 428, 429. Azimuth of maximum standard error of tilt: 140.6°				
1968-1969	2.08	15.48	2.16	0.64
1969-1970	1.97	11.16	2.31	0.68
1970-1971	-22.74	-21.24	2.77	0.82
1971-1972	-26.39	-41.55	2.28	0.68
1972-1983	98.32	67.72	5.09	1.51
1983-1984	14.45	6.28	1.10	0.33
1984-1985	15.16	6.29	0.94	0.28
1985-1986	8.87	6.43	0.64	0.19
1986-1987	11.11	5.94	0.43	0.13
1987-1988	11.49	6.20	0.75	0.22
1988-1989	9.57	5.18	1.33	0.40

TABLE 4 (continued)

D: Bench marks 428, 430, 83001, 83002, 83003.
Azimuth of maximum standard error of tilt: 8.8°

1983-1986	10.49	18.77	1.60	0.35

E: Bench marks 428, 430, 83001, 83002, 83003, 83004, 83005.
Azimuth of maximum standard error of tilt: 4.3°

1986-1987	3.24	4.36	1.60	0.22
1987-1988	-0.59	4.35	2.51	0.35

F: Bench marks 428, 430, 83001, 83002, 83003, 83004.
Azimuth of maximum standard error of tilt: 3.0°

1988-1989	-0.38	3.95	4.81	0.88

G: Bench marks 83005, 83006, 83007, 83008, 83009, 83010, 84002.
Azimuth of maximum standard error of tilt: 22.2°

1986-1988	2.54	6.76	6.43	1.00

H: Bench marks 83009, 83010, 84002 through 84011.
Azimuth of maximum standard error of tilt: 39.7°

1985-1986	-0.15	3.23	1.50	0.35
1986-1987	-2.78	1.57	1.13	0.26
1987-1988	0.50	3.12	1.04	0.24

I: Bench marks 84007, 84008, 84009, 84010, 84011.
Azimuth of maximum standard error of tilt: 2.6°

1987-1988	-1.82	2.98	3.03	0.15
1988-1989	10.56	3.62	0.69	0.03

Models

The observed vertical component of ground deformation of the precision leveling profile in Askja, points to an alternating swelling and subsidence to the west of the profile. If the maps showing lines of equal displacement or the maps showing tilt vectors (Fig. 20) are studied, it appears that the hypothetical source lies a short distance west of the profile. In 1966 to 1972, the apparent source of subsidence (deflation) appears to lie farther north than the source of inflation. Also the source of deflation in 1966-1970 apparently lies farther north than the source of deflation in 1983-1989.

Thus, there appear not to be a stationary single point source which can explain the observed ground deformation.

A study of the deformation in 1983-1989 shows that tilt vectors of the leveling profile of 1966-1968 point toward a region about 500 m west of the south end of the profile. Lines of equal vertical displacement of the southernmost part of the profile (BMs 401-414) indicate even nearer source. If only the leveling data of the part of the leveling profil that was installed in 1966 and 1968 are studied, and the center of deformation is taken to be where tilt vectors of northern and southern part of the profile intersect each other, then the apparent depth of the source is about 1000 m, and the total vertical displacement in the center of the deflated area is about 4 cm per year.

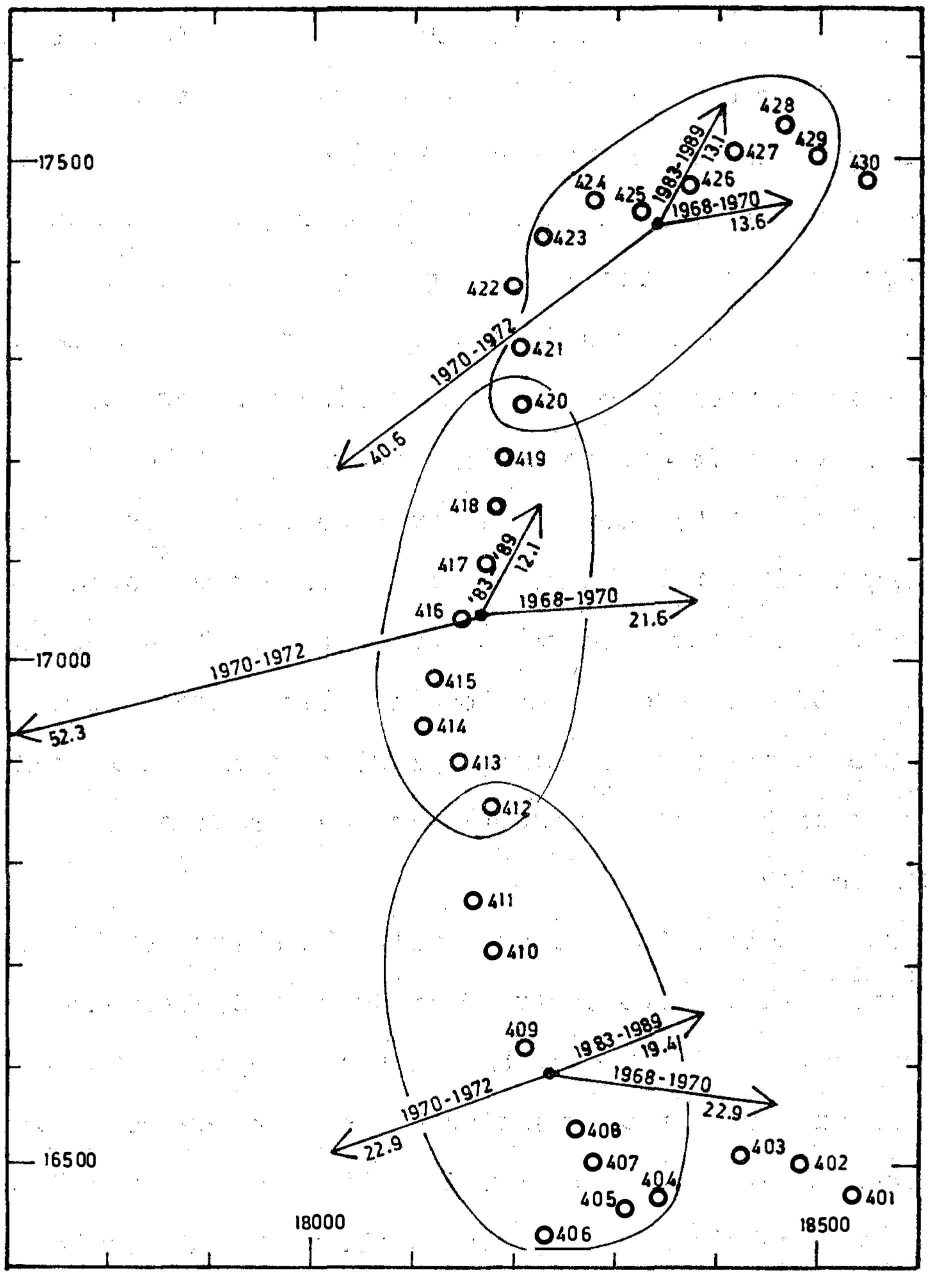

Fig. 20. Map of the Askja profile of preciaion leveling of 1968. Coordinates are from the U. S. Army Map Service maps of Iceland in scale 1:50000 published in 1949. Tilt vectors for three periods are shown for three sectfions of the profile as indicated by the ovals drawn around the bench marks used for each tilt computation. Average annual tilt in microradians is presented at each tilt vector.

This shallow, near source can explain most of the deformation observed within the area of BM 401 through BM 430. Deformation within the area of the 1983-1984 extension of the leveling profile (Figs. 21, 22, 23, and 24) can be in agreement with the same source location, but then the depth of the source must be greater, probably 3 km.

Thus the observed deformation on the whole leveling profile is in poor agreement with a single point source.

Observed deformation on the shore of lake Öskjuvatn (Tryggvason, 1989) correlates very well with the precision leveling result, but the source of deformation appears to lie below the northwestern part of the lake, or to the northwest of the lake. That location lies much farther away from the precision leveling profile than indicated by direction of the tilt vectors in the region of BM 404 through BM 430.

Two circular, 25 m radius tilt leveling stations in southwest Askja were observed in July 1988, September 1988 and September 1989. One of the stations appear to be on poor foundation, and irregular bench mark movement furnish tilt error similar to calculated tilt, so no significant result was obtained. The other station showed significant, but small tilt (7 microradians), down towards east. This result is only marginally significant, and future observations may give different results, but the present result is not in agreement with a point source of subsidence in the central part of the Askja caldera.

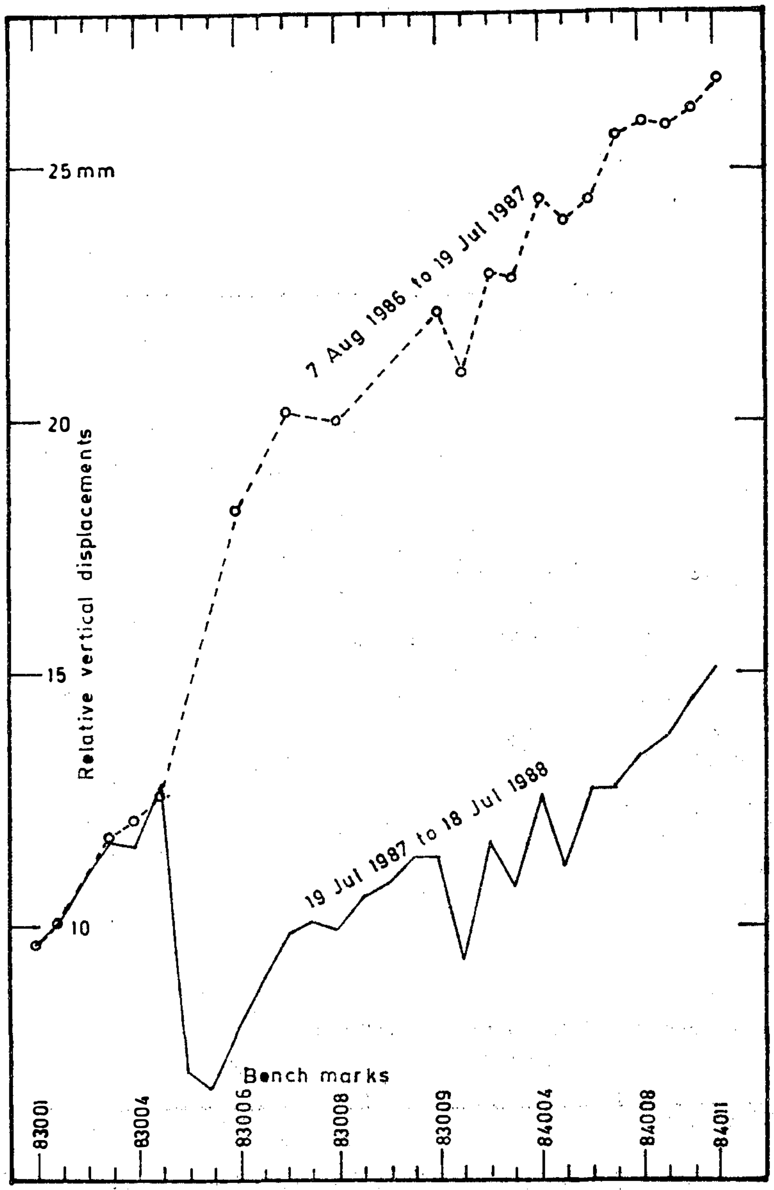

Fig. 21. Observed vertical displacement of the 1983 - 1984 extension of the Askja profile of precision leveling from early August 1986 to mid July 1987 and from mid July 1987 to mid July 1988, plotted against bench mark numbers. The displacement is relative to bench mark 404 of the older part of the leveling profile. Obvious error of about 5 mm occurred between bench marks 83005 and 83006 during the 1987 leveling, but the conventional foreward - backward leveling could not be made in 1987. Otherwise very similar deformation is observed during both years.

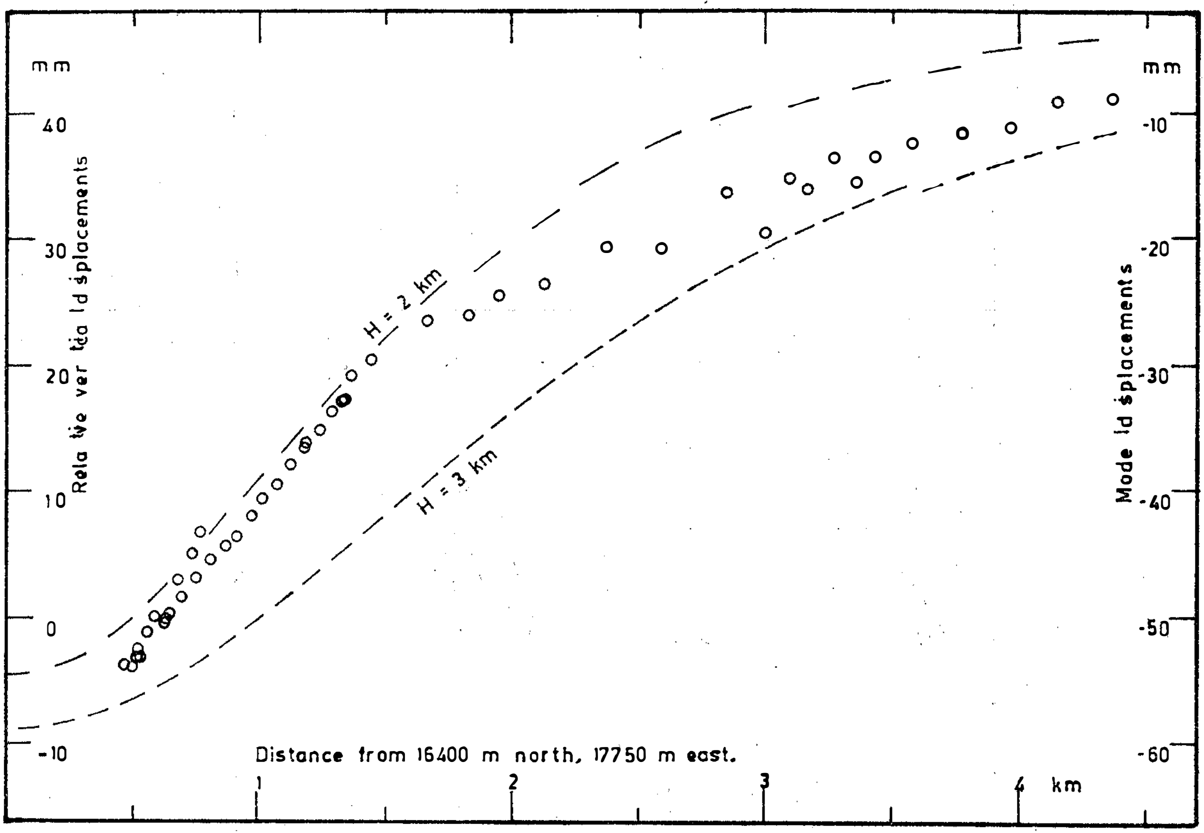

Fig. 22. Observed vertical displacements, relative to bench mark 404, between levelings of early August 1986 and mid July 1988 (open circles), plotted against horizontal distance from a point defined by the tilt vectors computed from the northern and southern part of the leveling profile of 1968 (see Fig. 20). Dashed lines show the predicted vertical displacement if a point source lies 2 or 3 km below the location from which the distance is measured, and relative displacement of nearest and farthest marker of the leveling profile is equal that observed. The fit between observations and model displacements is poor.

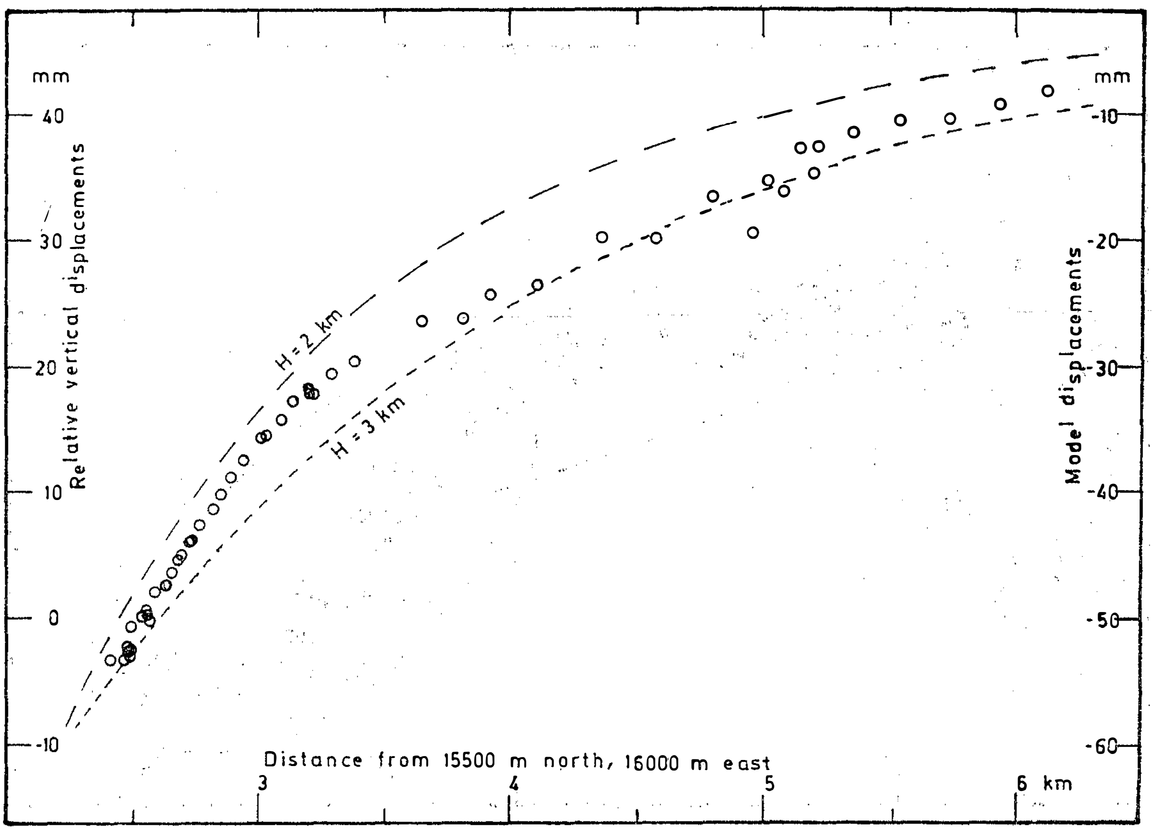

Fig. 23. Observed vertical displacements of each bench mark of the Askja profile of precision leveling, relative to bench mark 404, between levelings of early August 1986 and mid July 1988 (open circles), plotted against distance from a hypothetical point source in central Askja as estimated earlier (Tryggvason, 1989). Dashed lines show the predicted vertical displacement if the source lies at 2 or 3 km depth respectively, and relative displacement between nearest and farthest bench mark is equal that observed. The central subsidence for the models is 195.0 mm if source depth is 2 km and 116.4 mm if source depth is 3 km over a period of 2 years. The observations of the old profile (distance less than 3.2 km) fit well to the 2 km deep source while the remaining observations fit better the 3 km source. Still deeper source may agree better to the most distant part of the leveling profile.

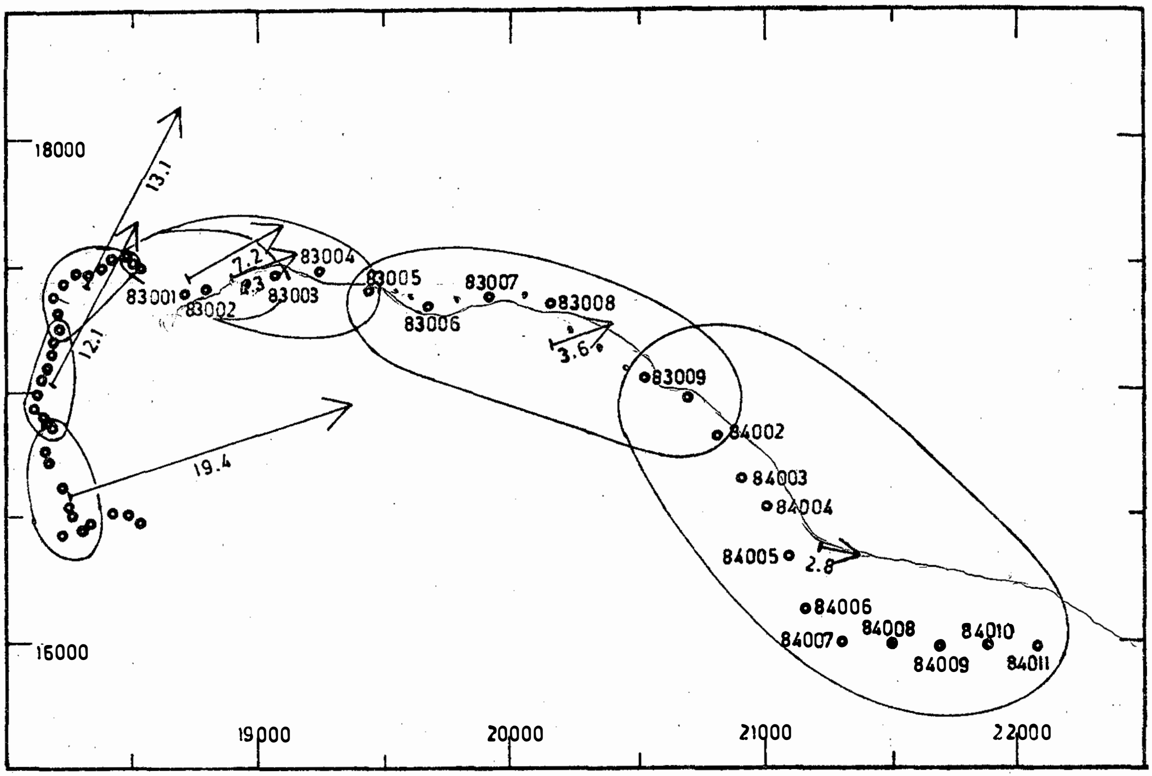

Fig. 24. Tilt vectors for various parts pf the Askja profile of precision leveling for 1983 to 1989 or shorter periods during that time interval. Numbers by the tilt vectors give the average annual tilt in microradians. It is clear that the tilt vectors do not all radiate from a single point, making the point source model inappropriate.

In conclusion, the observed ground deformation in Askja is not in agreement with a single point source. A point source below the central part of Askja can explain a significant part of the observed deformation of both the lake shore and the precision leveling profile, but not the observed tilt at the tilt leveling station in southwest Askja. Several point sources can explain the observed deformation, but the observations are not sufficiently distributed in the Askja caldera to define several sources.

It may be assumed that the deflation of Askja of 1966-1967, 1968-1970 and 1983-1989 is caused by withdrawal of magma from below the Askja caldera. Similarly, the inflation of 1967-1968 and 1970-1972 was supposedly caused by influx of magma into a reservoir below the Askja caldera. The volume or mass of material that has moved into or out of the hypothetical Askja magma reservoir cannot be determined with any reasonable degree of accuracy from the available information. A crude estimate of the volume of the subidence bowl can be made by assuming that a point source at 2.5 km depth is causing the subsidence of 1983-1989. The observations are in fair agreement with 8 cm/year subsidence at the center of the Askja caldera. This is equivalent to a volume of about 3 million cubic meter per year. However, gravity observations inside Askja show decreasing gravity at the time of subsidence (H. Rymer, pers. comm. 1989). This may indicate that the volume of magma, which is drained away from the Askja reservoir, is much greater than the apparent volume of the subsidence bowl.

Accuracy of the Askja precision levelings

Repeated precision leveling, as has been performed in Askja since 1966, has the purpose of detecting and observing deformation of the ground surface. The accuracy of observed ground deformation depends partly on the accuracy of levelings, but also on the stability of the bench marks used and on the configuration of the bench marks.

The accuracy of leveling observations has not been investigated for the work in Askja, similar leveling performed elsewhere in Iceland in 1966 and 1977 was found to have an average probable error of 0.15 L mm, where L is the square root of the length in km of the leveling profile (Tryggvason 1968). The Askja levelings were frequently performed under less than optimum condition with regard to the atmospheric conditions, so it can be expected that the leveling accuracy in Askja was slightly worse than elsewhere in Iceland. We can assume that the standard error of the leveling in Askja is no more than 0.2 L mm, making the standard error of the difference between two levelings 0.3 L mm. As the average distance between bench marks in the Askja leveling profile of 1966-1968 is about 50 m, the standard error of observed elevation difference of two adjacent bench marks can be estimated as about 0.3/(sqrt 20) = 0.07 mm.

The accuracy of obtained ground deformation can be estimated by applying statistical treatment to the observational data. The ground tilt was computed by the least squares method from three groups of 9 bench marks each of the leveling profile of 1966-1968 (Table 4). This tilt determination covered all periods between succeeding levelings. The standard error of tilt was computed for the maximum and minimum axes of the error ellipse. An outstanding feature of the tabulated data (Table 4) is that the tilt error is much greater for the 11 year period between levelings of 1972 and 1983, than for each one-year period. This cannot be because of opservation errors, but must be because of progressing erratic bench mark displacements, or progressing irregular ground deformation.

Another noteable feature of Table 4 is that computed standard error of tilt is greater for the bench mark group 404-412 (Table 4 A), than for bench mark groups 412-420 and 420-429 (Table 4 B, C) This is caused by systematic deformation within the bench mark group 404-412, clearly visible on Figs 3 and 4 where the tilt vectors for the northern and southern part of this bench mark group are shown. Also, Figs 11 and 13 through 19 show this systematic non-linear component of deformation by the distinct curvature of lines of equal vertical displacements in the region of bench marks 404 to 412.

Still another feature of Table 4 is that the computed standard error of ground tilt is greater for levelings of 1966 to 1972, than for levelings of 1983 to 1989. The reason for this is certainly not because of inferior levelings before 1972, as the same field criteria were applied to determine if the leveling was accepteble. Actual irregular or random ground deformation must have been greater before 1972 than after 1983. The reason for this may be that the lava, on which the leveling profile was constructed, had not settled completely during the earlier series of levelings. This lava was produced in late 1961, and was thus only 5 to 11 years old during these observations, and still warm in the vicinity of the eruptive vent. During the 1983-1989 levelings, the lava was more than 20 years old and no heat was observed, not even in the cinder cones. This indicates that before 1983, the lava had reached equilibrium with regard to internal strain, while it was being influenced by thermal strain during the period 1966 - 1972.

Because of this, only tilt computations from data obtained after 1983 on the two northern sections of the Askja leveling profile of 1966-1968 can be used to estimate the accuracy of leveling for the purpose of ground deformation studies.

The standard deviation of bench marks from the center of gravity of each group of benchmarks, along the axis of minimum tilt error is 132.5 m, and 131.9 m respectively for the bench mark groups 412-420 and 420-429 . The average standard error of annual tilt for the period 1983-1989 along the axis of minimum tilt error, is 0.25 and 0.26 microradians respectively. This corresponds to a standard deviation of each bench mark displacement from the corresponding regression line of 0.10 mm on the average (0.1325 * 0.25 * (sqrt 9)). This can be regarded as the average standard error of leveling differences per bench mark interval, but this error includes observational error of two levelings in addition to erratic displacements of the bench marks over a period of one year, between levelings.

It was previously estimated that the standard error of the difference of elevation of adjacent bench marks, is about 0.07 mm because of observational errors alone. This indicates that the erratic irregular displacements of the bench marks over a period of one year is also about 0.07 mm on the average, as the accumulated error is equal the square root of the sum of each error squared.

The conclusion of this discussion is that the Askja levelings are of similar excellent quality as the most precise optical levelings elsewhere in Iceland. Furthermore, that the 1961 Askja lava had reached thermal equilibrium with its environment by 1983, and that all the bench marks are very stable.

Other deformation measureements in Askja

A: Optical leveling tilt observations.

Two optical leveling tilt stations were constructed in the southernmost part of Askja in September, 1988. These stations consist of 6 permanent bench marks each, five markers in a circle of 25 m radius, and the sixth marker in the center if the circle. One of the stations, identified as 0400, lies on the Mývetningahraun lava, immediately below the steep marginal slope of the Askja caldera, below the pass Suðurskarð. The other station, identified as 0410, lies on a flat lava, immediately south of the Mývetningahraun lava, about one kilometer to the west from station 0400, and some one hundred meter from the north slope of the peak Vatnsfell (see Fig. 1 for location).

Measurements were made at these stations on 22 July and 13 September, 1988, and on 1 September, 1989 (Tables 5 and 6). These measurements indicate slight uplift towards west, but the result is barely significant, and therefore, not convincing.

TABLE 5

Optical leveling tilt atation 0400, Suðurskarð, approximate coordinates 11430 m north, 14660 m east.

B.M.	Relative coordin. north	east	Relative elevation in cm 22/7 88	13/9 88	1/9 89
0401	24.98	0.91	9.6529	9.6476	9.6337
0402	14.36	-20.46	28.3223	28.3151	28.3207
0403	-10.99	-22.45	-25.3865	-25.3849	-25.3825
0404	-20.32	14.57	-23.5590	-23.5557	-23.5580
0405	10.58	22.65	10.9703	10.9777	10.9859

Computed tilt in microradians

period	N-comp	E-comp	Standard err.
22/7/88-13/9/88	-1.631	1.896	0.790
13/9/88-1/9/89	-1.145	-0.220	1.940
22/7/88-1/9/89	-2.776	1.677	2.500

TABLE 6

Optical leveling tilt station 0410, Vatnsfell, approximate coordinates 11950 m north, 14080 m east.

B.M.	Relative coordin. north	east	Relative elevation in cm 22/7 88	13/9 88	1/9 89
0411	23.74	-7.84	-0.4148	-0.4139	-0.4072
0412	-1.31	-24.97	13.0875	13.0913	13.1081
0413	-24.73	3.68	-1.5756	-1.5806	-1.5829
0414	-0.95	24.98	-2.4172	-2.4167	-2.4269
0415	20.14	14.81	-8.6800	-8.6803	-8.6913

Computed tilt in microradians

period	N-comp	E-comp	Standard err.
22/7/88-13/9/88	0.874	-0.734	0.520
13/9/88-1/9/89	-0.140	-5.913	0.585
22/7/88-1/9/89	0.734	-6.648	1.006

B: Öskjuvatn lake level measurements.

Twenty permanent bench marks were installed near the shores all around lake Öskjuvatn in August 1968, for the purpose of using the lake level to study the ground deformation. The height of these markers above the surface of the lake has been measured 8 times (Table 7), and significant ground deformation has been observed (Tryggvason, 1989).

The lake level has been rising gradually since 1968, inundating several bench marks. Other bench marks have been destroyed by rock falling from the steep mountains.

The gradual rise of the lake level in 1968 to 1986 is apparently caused by processes associated with the 1961 eruption. This process is indicated in a high shoreline around lake Öskjuvatn, which was clearly visible at numerous locations in August, 1968, when the elevation of this shoreline was measured at numerous locations (Table 8). This high shoreline is made of pumice that has been floating on the lake, and it probably marks the highest lake level since the formation of the Öskjuvatn caldera in 1875. This shoreline existed before the 1961 Askja eruption, as evidenced by the significant subsidence of the lake level during and/or soon after the eruption (Fig. 25). It was formed after the Bátshraun and Mývetningahraun lavas were erupted in 1921 and 1922 as the shoreline is seen in these lavas.

TABLE 7

Lake level measurements at lake Öskjuvatn

Marker	Marker height above lake level in cm							
	1968 14 Aug	1969 5 Jun	1969 5 Aug	1970 5 Aug	1971 10 Aug	1972 25 Jul	1985 6 Aug	1986 14 Aug
1	358.0	446.0	335.0	326.5	274.8	262.8	181.08	150.60
2	458.5		436.0	430.5	374.0	363.5	284.57	254.56
3	451.5	547.0	433.0	425.0	369.0	354.8	283.17	253.64
4	181.2	272.0	162.0	(141.5)				
5	305.8	398.0	289.0	277.0	221.0			
6	227.0		207.0	199.0	142.0		54.78	29.09
7	324.2		300.0	290.0	235.0	234.0		
8	106.2	195.0	86.2	76.0	25.0			
9	189.5	280.0	168.5	160.0	92.0	77.0		
10	160.0	250.0	139.0	130.0	74.5	65.0		
11	356.5	443.5	335.0	323.5	272.2	263.5	183.11	
12	277.8	366.0	256.5	248.5	193.0	184.0		
13	239.5	326.0	217.5	208.8				
14	228.5		211.0	198.5	142.5	131.0		22.32
15	184.8		164.0	151.8	99.0		-	-25.68
16	321.2		299.0	286.0	236.5	232.4		
17	298.2		274.5	262.0	217.5	220.5	112.29	79.88
18	462.8		439.0	425.0	382.5	385.0	270.60	237.60
19	431.2		407.0	398.0	352.5	357.2		
20	519.5		502.0	489.5	449.0			
10A							31.03	1.85
NE85018								73.74

Notes:

Marker 10A is a temporary marker that will not be occupied in the future, it lies near the site of marker 10, and was in 1986 replaced by a permanent marker NE85018. Two markers, 4 and 13, were destroyed by rock fall before August, 1971, and marker 4 had apparently been displaced slightly before August 1970.

TABLE 8

Measured high shorelines around lake Öskjuvatn on August 14, 1968.

Location and description.	m above lake
In Bátshraun, 300 m east of 1*), highest shore	8.45
650 m east of 4, highest visible shore	3.47
15 m south of 6, highest visible shore	3.47
250 m south of 6, highest shore	3.91
Same location, second highest shore	3.51
200 m south of 6, highest shore	4.03
30 m south of 7, highest shore	4.62
20 m south of 7, shore, not highest	3.39
100 m west of 8, only visible shore	1.78
Same location, possible shore	2.56
70 m west of 9, highest shore	3.33
40 m west of 12, shore	3.24
South margin of Mývetningahraun, 15 m north of 15, highest shore	4.82
150 m north of 15, highest shore	5.19
Same location, old shore in lava	4.45
300 m north of 15 in Mývetningahraun, very clear highest shore	4.97
Same location, old shore	4.43
180 m north of 18, (highest) shore	6.26
Near 19, shore	5.49
Same location, highest shore	7.50
Near 20, very dubious shore	8.82
Same location, clear shore	7.80

*) Numbers relate to the bench marks for lake level measurements, installed in 1968. See Fig. 1 for location.

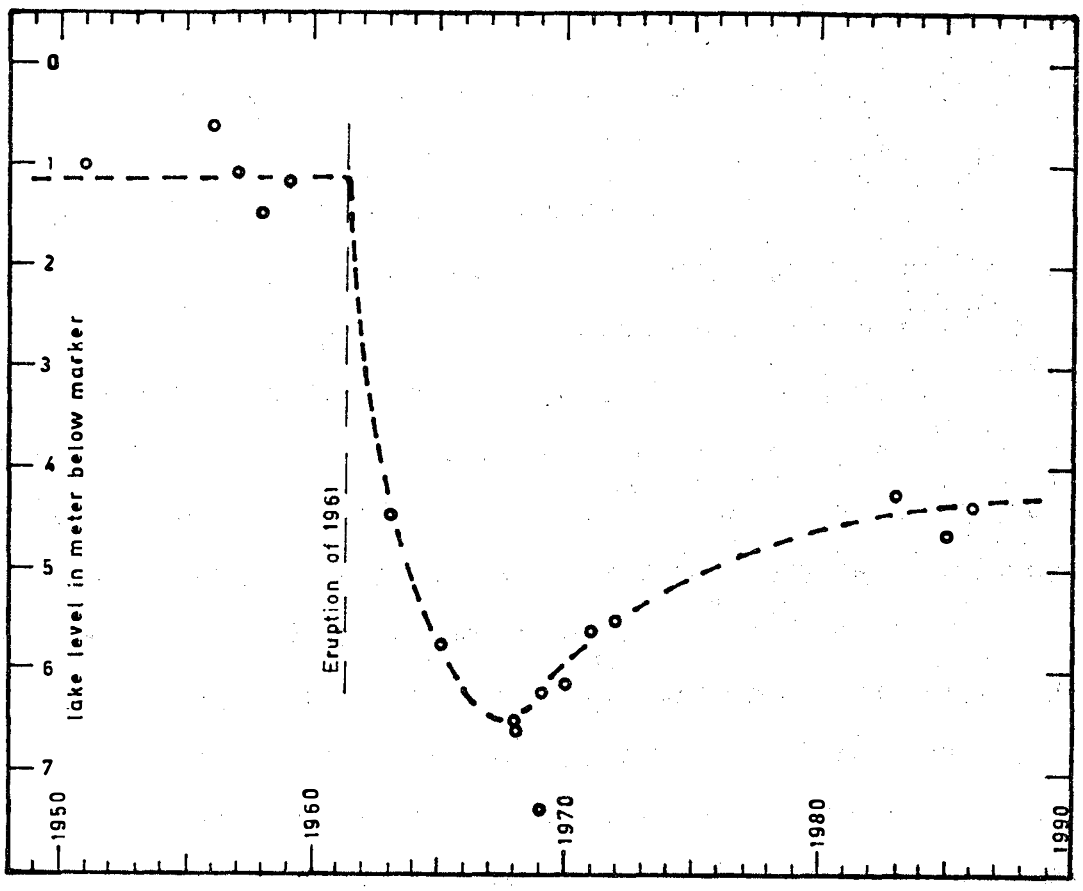

Fig. 25. Observed level of lake Öskjuvatn relative to a marker in the Bátshraun lava at the northeast corner of the lake, near the lake level bench mark 1. Observation of the lake level have been made by visitors to Askja, and more observations may exist, than those indicated. Observations before 1968 are partly from the "gestabók" of "Knebelsvarða", and partly from Sigurjón Rist, personal communication. Measurements of 1968 and later are made by Eysteinn Tryggvason. The low value of 1969 was observed in early June while higher value was observed in early August 1969, showing 111 cm increase in the lake level in about 60 days. Dashed line shows the authors interpretation of the variation of lake level with time, assuming that observations are made in late summer at relatively high water stage.

A few measurements of the level of lake Öskjuvatn in the Bátshraun lava do exist. A marker, consisting of an iron nail, was installed in a vertical face of the lava in 1951, and measurements were made from the nail, vertically down to the water level. These measurements show a rather steady lake level before the eruption of 1961, but measurements after the eruption show subsidence of the lake level by several meter (Fig. 25).

It is assumed that the deformation of the lake shore, indicated by the shore line measurements of 1968 (Table 8) did occur at the same time as the lowering of the lake level seen in Fig. 25. This would imply that the lake level subsided by different amount at different locations around the lake, or rather, that the lake shore was displaced vertically at the same time as the lake subsided.

The highest shoreline as measured in 1968 was found to be more than 8 meters above the simultaneous lake level at the northeast and northwest shore, while it was only 3 to 4 meter above the lake in the southeast and southwest part of the lake. This indicates an uplift of the north shore of the lake, relative to its south shore, of about 5 meter. If the source of this deformation was to the north of lake Öskjuvatn, as is found for later ground deformation in Askja (Tryggvason, 1989), then a very significant inflation of Askja occurred in relation to the 1961 eruption, contrary to what is normally expected when lava is drained from a magma chamber below a volcano.

It may be speculated that the inflation of Askja, which is indicated by the shore line measurements of 1968, did occur before the 1961 eruption, and that the eruption was triggered by this inflation. That would indicate that the volume of magma which came to the surface as lava during the eruption was only a fraction of the volume of magma which entered the Askja magma chamber before (or during) the eruption.

TABLE 9

Distances between bench marks in the Askja geodimeteer network. Reported are slope distances in meter.

geodim. station	reflect. station	1982 29 Aug	1985 15 Aug	1986 18 Aug
D-19	D-18	3011.749 (-48.70)		
NE82005	D-18	3009.210 (-48.70)	3009.131 (-48.80)	3009.093 (-48.80)
NE82005	NE82001	4404.125 (265.79)	4404.100 (265.78)	4404.102 (265.88)
NE82005	NE82002	4518.577 (112.55)	4518.487 (112.51)	4518.454 (112.16)
NE82005	NE82003	4447.369 (235.62)	4447.342 (235.88)	4447.336 (235.62)
NE82005	NE82004	4099.388 (199.44)	4099.296 (199.48)	
NE82005	NE82006	4130.404 (111.79)	4130.338 (112.01)	4130.315 (112.02)
NE82005	NE82007	5959.676 (279.31)	5959.654 (279.47)	5959.655 (279.55)
NE82005	NE82008	4404.292 (257.87)	4404.246 (258.16)	4404.252 (258.18)
NE82005	NE85010		4099.570 (199.77)	4099.574 (199.65)
NE82005	NE85011		4328.333 (246.70)	4328.351 (246.61)
NE82005	4450		2718.533 (83.66)	2718.510 (83.78)

Notes:
Numbers in parentheses are elevations of the reflector bench marks relative to the geodimeter bench mark in meter, calculated from the vertical angles and average light refraction. Elevation of NE82005 above sea level is taken as 1123.2 m, based on the reported elevation of 4450 equal to 1206.93±0.5 m.

C: Distance measurements.

On August 27 to 30, 1982, eight bench marks were installed in Askja and the surrounding Dyngjufjöll mountains with the intension to measure repeatedly distances for ground deformation study. At the same time, the distances from one marker in central Askja were measured with a 'geodimeter'. Two markers installed by R. W. Decker in July, 1967 were also occupied in 1982.

These distance measurements were repeated on August 15, 1985, and August 18, 1986. Two additional bench marks were installed in 1985, and one stake of other agencies (4450) was also occupied. Most of these bench marks are located on the caldera rim (Fig. 1), with one marker for the 'geodimeter' in the central part of the Askja caldera. The markers installed by Decker in 1967 are located near the Öskjuvatn lake shore, one in Bátshraun, another near bench mark NE82005. The stake marked 4450 lies to the west of the southwest corner of lake Öskjuvatn.

Observed distances are given in Table 9. All the measured distances, with possible exception of NE82005-NE85010 and NE82005-NE85011, have shortened. Distance changes over a period of one year are too small to be observed with confidence. This shortening of the lines from central Askja to the caldera rim is in agreement with the subsidence of central Askja as indicated by precision leveling and lake level observations.

Concluding remarks

Extensive measurements of ground deformation in Askja over a period of 23 years have demonstrated that the volcano Askja has been deforming at a relatively high rate. This deformation cannot be directly related to volcanic activity, as Askja has not erupted since 1961.

The observed deformation has been interpreted as alternating deflations and inflations of the volcano, and that a center of deformation can be defined in central Askja (Tryggvason, 1989).

This interpretation is seriously challanged by the first tilt observations near the south margin of the Askja caldera. Tilt down towards north was expected at these stations, while observations indicate slight tilt down towards east.

Seismic survey of Askja in 1989 showed a concentration of epicenters to the east of Askja, but no microseismic activity was observed near the hypothetical center of deformation in central Askja (Lassen, pers. comm.).

It is clear that the extensive deformation measurements to date in Askja have failed to define a reliable model of the processes which are causing the observed deformation. More observations are needed, and the emphasis should be on widely dispersed observations, within the area of the Askja volcano. Precise tilt observations made once a year at several locations are believed to offer the most information in relation to time and effort spent.

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