DEPARTMENT OF THE INTERIOR

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Preliminary Results of Precise Leveling and Trilateration Surveys in Yellowstone National Park, Wyoming, 1985

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This report is preliminary and has not been reviewed for conformity with U. S. Geological Survey editorial standards. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

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FOREWARD

This report describes preliminary results of precise leveling and trilateration surveys in Yellowstone National Park in September 1985. A companion report (Dzurisin and Yamashita, 1986) describes initial surveys in October 1983 and September 1984. Each report has its own figures and tables; the report by Dzurisin and Yamashita (1986) also contains an appendix with descriptions of 50 benchmarks measured during the leveling surveys.

Table of Contents

List of Tables

List of Illustrations

ABSTRACT

Precise level and trilateration surveys in the eastern part of Yellowstone caldera detected no significant crustal deformation from September 1984 to September 1985. Earlier level surveys had shown that the caldera floor rose by 16-23 mm/yr during 1923-1976, 1976-1983, and 1983-1984. It thus appears that historical uplift at Yellowstone has been relatively steady over time scales of decades, but episodic over time scales of years.

INTRODUCTION

Purpose and Scope

This informal report was prepared to make available to interested parties the results of USGS leveling and trilateration surveys in Yellowstone National Park in September 1985. It also includes a short description of fluvial features in Pelican Valley that might record post-glacial deformation in the eastern part of the caldera. Data reported here are preliminary and subject to revision; final results will be published in the formal literature.

Background

This work is part of a project on Physical Processes in Large Silicic Magma Systems funded by the USGS Volcanic Hazards Reduction Program. The project's goal is to better understand physical processes that contribute to unrest at silicic calderas, as a basis for better assessments of volcanic hazards. "Unrest" includes seismicity, ground deformation, hydrothermal activity, and other processes that commonly occur in magmatic systems beneath young calderas. Many such "restless" calderas are probably capable of future eruptions. Our approach is to measure contemporary ground deformation using precise geodesy, and to determine past deformation using surveys and appropriate dating techniques.

Earlier Work

Our work at Yellowstone began in October 1983 with a first order level survey along the paved road from Indian Pond to Trout Creek. The line was remeasured and extended from Lake Butte to Canyon Junction in September 1984, when a precise trilateration network was added in the northeast part of the caldera (Figures 1 and 2). In September 1985, the level line and trilateration network were resurveyed, and a reconnaissance study of Pelican Valley was conducted. Preliminary results of the 1983 and 1984 level surveys were described by Dzurisin and Yamashita (1986) in a companion report.

Schedule and Participants

As in the past, we began our work this year immediately after Labor Day (September 2, 1985) to avoid the peak tourist season. On September 4, Willie Kinoshita began preparations for the trilateration survey; Dzurisin, Ken Yamashita, Roger Denlinger, and Ron Hanatani began leveling from Lake Butte to Canyon Junction. The level survey was completed on September 13, after poor weather on September 10, 12, and 13 forced postponement of the trilateration survey. Yamashita, Denlinger, and Hanatani left Yellowstone on September 14; they were replaced by Dan Johnson, Karl Gross, and Chuck Stiffler. Fieldwork in Pelican Valley began on September 16; the trilateration survey was completed in marginal weather on September 24, 26, and 27. Gross and Stiffler left Yellowstone on September 28; Dzurisin and Johnson completed the Pelican Valley fieldwork on September 29, and left Yellowstone on September 30.

LEVELING RESULTS

Benchmarks

A complete set of benchmark descriptions for the 1923-1984 level surveys between Lake Butte and Canyon Junction was provided by Dzurisin and Yamashita (1986). In 1984, 3 marks suspected of being unstable (26 MDC, A11 1923, and CVO 84-12) were replaced by nippled marks specifically designed for precise leveling; in 1985, 11 more standard marks were replaced with nippled marks. The abandoned marks and their 1984-1985 replacements are listed in Table 1. About 6 more replacements are planned for 1986. The Lake Butte to Canyon Junction level line is about 43 road kilometers long (33 linear kilometers), with an average benchmark spacing of about 1 km.

Procedures

National Geodetic Survey procedures for first class, second order leveling were followed during the 1983-1985 surveys, with minor exceptions. Briefly, elevation differences between benchmarks were measured using a Wild N-3 spirit level and Wild GPLE-3 Invar 3 m level rods. The N-3 uses a manual spirit level and therefore is not subject to magnetic errors associated with some automatic levels. To increase precision, the maximum acceptable difference between left and right rod readings was reduced to 0.010 cm, without significantly increasing the time required for the survey. The level rods were calibrated annually at the National Bureau of Standards to an accuracy of (0.000015 + 0.000005h) meters, where h is the distance from the bottom of the rod to the graduation of interest. P-K surveying nails driven flush with the pavement were used as recoverable turning points. Temperatures 0.5 m and 2.5 m above the ground surface were recorded to an accuracy of 0.1 degree Celsius. Adjacent benchmarks were double-run the first time they were measured, and single run in opposing directions thereafter to randomize the effect of pin settling. Data were recorded in the field using a Hewlett-Packard 41C calculator. Results reported here include rod scale, rod temperature, and refraction corrections; they do not include astronomic or orthometric corrections, which are negligible in this case. Refraction corrections were based on the model of Kukkamaki (1939), adopted in 1980 by NGS (Balazs and Young, 1982, p. 6).

Standard Errors

The International Geodetic Association resolved in 1948 that standard errors in high precision level surveys should be less than 3 mm x $d^{1/2}$, where d is the distance in km from the start of the survey. The standard error between surveys should be less than 3 mm x $(2d)^{1/2}$ (Bomford, 1980, p. 219). Using improved instruments and rigorous field procedures, these limits can now be reduced under optimum conditions to about 1 mm x $d^{1/2}$ for single surveys, and 1 mm x $(2d)^{1/2}$ between surveys. At Canyon Junction (11 MDC 1976), this corresponds to a standard error of about 6 mm for a single survey and 9 mm between surveys (relative to 36 MDC 1976 near Lake Butte). Near the center of uplift, the calculated errors are about 4 mm and 6 mm. These appear to be realistic estimates for the 1983-1985 surveys, based on observed closures and reproducibility at 11 MDC 1976 between 1984 and 1985.

1923-1984 Results

Precise level surveys in 1923 and 1975-1977 revealed a broad pattern of uplift centered in Yellowstone caldera, along an axis connecting the Mallard Lake and Sour Creek resurgent domes (Pelton and Smith, 1979, 1982). The maximum uplift measured was 726 mm at benchmark B11 1923 near LeHardy Rapids on the Yellowstone River (Figure 3). Thus, the maximum average uplift rate during 1923-1976 was 14 mm/yr (the Lake Butte-Canyon Junction line was measured in 1976 during the 1975-1977 survey).

Our level survey from Indian Pond to Trout Creek in October 1983 detected 78 mm of additional uplift at benchmark DA 3 1934 near LeHardy Rapids, relative to benchmark 32 MDC 1976 at Indian Pond (Figure 4). This result was confirmed by the more complete 1984 survey, which showed that DA 3 1934 had beed uplifted since 1976 by 179 mm relative to 36 MDC 1976 (Figure 5), at an average rate of 22 mm/yr. The shape of the 1976-1983 uplift profile between Indian Pond and Trout Creek is similar to the 1976-1984 profile in that area, so the 1976-1983 result at DA 3 1932 (78 mm relative to 32 MDC 32 MDC) can be extrapolated to an assumed stable base outside the caldera (162 mm relative to 36 MDC), using the 1976-1984 profile as a guide. This yields an average uplift rate at DA 3 1932 during 1976-1983 of 23 mm/yr, about 70% greater than during 1923-1976. The maximum inferred uplift during 1983-1984 is 23 mm at F11 A (Figure 6), suggesting that the uplift rate was essentially constant from 1976 to 1984. Slight differences between the above results and those reported by Dzurisin and Yamashita (1986) are caused by different extrapolations of the 1983 results.

There are at least 3 viable explanations for the apparent rate increase during 1976-1984: 1) uplift may have accelerated since 1976; 2) uplift may have started sometime after the first level survey in 1923; or 3) uplift may be episodic over short time scales. More on this later.

1985 Results

Benchmark elevations in September 1984 and September 1985, and elevation changes during that interval, are listed in Table 2 and plotted versus road distance in Figure 7. There were no changes larger than expected error during September 1984 - September 1985. The largest positive change along the line (+7.6 mm) occcurred at CVO 84-16 at Mary Bay. The largest negative change (-5.9 mm) occurred at CVO 84-6 in Hayden Valley. The net change at DA 3 1934 near the former center of uplift was 0.0 mm; the net change from 36 MDC 1976 at Lake Butte to 11 MDC 1976 at Canyon Junction was +3.2 mm. In short, the entire line was stable within our detection limit.

Benchmark elevations from each survey since 1923 are listed in Table 3; elevation changes between surveys are listed in Table 4. The maximum uplift measured between Lake Butte and Canyon Junction during 1923-1985 was 889 mm at B11 1932 relative to 36 MDC 1976. Since 1976, uplift has been centered about 2 km north of B11 1932, between Mud Volcano and LeHardy Rapids. We therefore estimate the true maximum uplift during 1923-1985 as 970 mm, at an average rate of 16 mm/yr. Average uplift rates for each of the surveyed intervals since 1923 are listed in Table 5.

TRILATERATION RESULTS

The Network

A precise trilateration network of 9 lines was established in September 1984 to complement the first order level monitor. The trilateration lines are 11.3 km to 34.7 km long; together they span the northeast part of Yellowstone caldera (Figure 2), including a low velocity zone that Smith and Braile (1982) attribute to the presence of shallow partial melt above the Yellowstone hot spot. A larger network spanning the entire caldera would have been preferable, but lines-of sight are obscured by dense forest in most of the central and western caldera.

1984-1985 Results

The trilateration network was measured in September 1984 and September 1985 to a precision of a few parts in 10^7 using a Geodolite, a precise electro-optical distance meter. Atmospheric refractivity corrections were based on measurements from an aircraft flown along the line of sight during ranging. The longest line, Washburn - Chittenden, was not measured in 1984 owing to high winds; all 9 lines were measured in 1985.

Results of the 1984 and 1985 trilateration surveys are listed in Table 6. No significant changes occurred in the network during that interval. Five of 8 lines changed by less than 1 standard deviation, 7 of 8 by less than 2 standard deviations, and the eighth line (Washburn-Amethyst) changed by less than 3 standard deviations: the expected error distribution for a stable network. Together, the level and trilateration results show conclusively that no detectable crustal deformation occurred in the eastern part of Yellowstone caldera from September 1984 to September 1985.

PELICAN VALLEY RECONNASSAINCE

Work by Meyer and Locke (1985) and by Hamilton and Vincent (written communication, 1985) has demonstrated the utility of surveying lake and stream terraces at Yellowstone to detect prehistoric deformation. Combined with radiocarbon and hydration rind dating, this technique might eventually provide a reasonably complete record of Holocene deformation at Yellowstone. With this in mind, Dzurisin and Johnson spent several days in Pelican Valley this year looking for fluvial features that might record paleo-deformation in the eastern caldera. Two promising areas were identified for further study.

From its headwaters along the eastern margin of the Sour Creek resurgent dome to its mouth near the outlet of Yellowstone Lake, Pelican Creek is well situated to record post-glacial deformation in the eastern part of Yellowstone caldera (Figure 8). The stream's southerly upper reach occupies a narrow saddle between the eastern margin of the resurgent dome and the eastern wall of the caldera. The central reach meanders westward through a broad flat valley cut into Pinedale lake and kame deposits, before the stream turns southward again below a bedrock narrows to enter Yellowstone Lake. The historic deformation pattern defined by Pelton and Smith (1979, 1982) would cause eastward or southeastward, cross-valley tilting in Pelican Valley's upper and lower reaches, and upstream longitudinal tilt of the stream's middle reach. Such tilting would increase the gradient of the upper reach slightly, and decrease the gradient of the central reach. If uplift were instead centered at the Sour Creek dome, the upper and central regions would experience cross-valley tilting, and the lower reach would be steepened.

We were first intrigued by the sharp southward bend that Pelican Creek makes to reach Yellowstone Lake, rather than continuing westward to the Yellowstone River. We therefore looked for evidence that the stream had once continued westward to the river, before being diverted to its present course by differential uplift of the central caldera floor. We found no such evidence, and concluded that Pelican Creek has probably occupied its present valley at least since late Pinedale time.

Our next goal was to identify terraces or strand lines of Pinedale lakes in Pelican Valley, to asses the feasibility of surveying them for evidence of post-glacial deformation. Richmond (1976, 1977) discussed a series of such lakes, but he mapped no terraces or strand lines associated with them in Pelican Valley. We walked both banks of the valley from Yellowstone Lake to Raven Creek, and inspected the upper valley by helicopter during the trilateration survey, but found no shoreline features suitable for such a study.

On the other hand, we did find numerous stream terraces in the lower reach of Pelican Valley that could be surveyed to assess post-glacial deformation there. Richmond (1977) mapped several stream terrace scarps on the south bank of the valley just below its bedrock narrows; we found more examples on both banks throughout the narrows. Farther downstream, in the southerly lower reach, there is a clear distinction between the number of terraces preserved on opposite banks. Along the eastern bank between the narrows and the lake, we found only 2 terrace scarps at a single location. Along the corresponding western bank, we found more than 20 terrace scarps, from less than 1 m to more than 10 m above the current flood plain. Presumably, the eastern terraces have been erased by preferential erosion of the eastern bank.

Another promising topic is the response of Pelican Creek itself to long term tilting of Pelican Valley. Ouchi (1985) recently described the response of meandering and braided streams to tectonic tilting, and his results are applicable to Pelican Valley. Briefly, a meandering stream subject to an increasing gradient will respond with increasing sinuosity, bank erosion, and point-bar growth. The same stream subject to a decreasing gradient will flood its point bars and deposit fines in response to a reduced flow velocity. As a first attempt to identify such responses at Pelican Creek, we compared 1954 and 1984 aerial photographs of the area, available at the National Park Service photo library in Mammoth. Our casual examination of the photos revealed surprisingly little change during the past 30 years: the current sinuous channel has been modified only slightly during that interval. However, there is independent evidence that Pelican Creek has responded in other ways to historic deformation.

Work in progress by W. L. Hamilton (written communication, 1985) shows that the level of Yellowstone Lake has risen perceptibly in response to differential uplift of its outlet since the turn of the century. As a result, the base level of Pelican Creek has risen, and the stream has flooded point bars in its lower reach. The stream there has become increasingly sluggish, forcing the movement of a fish trap and then reducing the efficiency of the new installation (J. Varley, oral communication, 1985). Oxbow lakes are much more numerous along the stream's lower reach than elsewhere, suggesting differential sinuosity changes that might reflect differential tilting or base level changes in different reaches of the stream.

DISCUSSION

Is Yellowstone's Uplift Steady or Episodic?

Until recently, available evidence suggested that uplift at Yellowstone has been relatively steady for at least the past few decades, and possibly for many centuries. Level surveys in 1923, 1976, and 1984 suggested that the uplift rate varied by less than 50% on those time scales, and the incomplete 1983 survey suggested that the annual rate during 1983-1984 was comparable to the average rate during 1976-1983 (Table 5). Surveying of deformed shoreline terraces at Yellowstone Lake showed that uplift has occurred there at 60-65% of the 1976-1984 rate for at least the past few thousand years (Meyer and Locke, 1985). The average 1923-1985 uplift rate (16 mm/yr) is 70% of the 1976-1984 rate (22 mm/yr), so the average rate for the past few thousand years (terraces) is essentially the same as the average rate for the past 62 years (leveling). The implication in 1984 was that uplift is a relatively steady, long term process.

This view must now be modified to accommodate two new pieces of evidence. First, Hamilton (written communication, 1985) used gaging records from Yellowstone Lake and the upper Yellowstone River to determine the annual uplift history there since 1923. He showed that uplift has been relatively steady, with several notable exceptions. Uplift at about 5 times the average rate occurred during 1940-1943 and 1952-1956. At other times, uplift was too slow to be detected for several years. Short periods of unusually rapid deformation may have accompanied the magnitude 7 Hebgen Lake earthquake in 1959 and the magnitude 6 Yellowstone Park earthquake in 1975.

The 1923-1985 level surveys reinforce the view that uplift has been steady over time scales of decades, but episodic over time scales of years. A separate result from the terrace study by Meyer and Locke (1985) is that uplift during the past few millennia has occurred at about the same rate as during the past few decades. Finally, Hamilton (1985) has argued that higher terraces on the southeast shore of Yellowstone Lake are best explained by a model including substantial intracaldera subsidence starting in the early Holocene, followed by uplift from the late Holocene to the present.

Thus, it appears that the uplift rate has changed significantly on time scales of years (1984-1985 leveling) and millennia (high terraces), but that it has been relatively constant on time scales of decades (1923-1984 leveling and lake gaging) and centuries (lower terraces). Not surprisingly, our picture of Yellowstone's post-glacial deformation history is becoming increasingly complex; much work remains to be done before its implications for volcanic hazards can be properly assessed.

Is Yellowstone Cooling Down or Heating Up?

Fournier and Pitt (1985) concluded that Yellowstone's magmatic system is probably cooling down, because the heat input they infer from the observed uplift is not enough to balance the heat output they calculate from hydrothermal measurements. They recognized that the true heat input at depth may exceed their estimate based on uplift at the surface, and qualified their conclusion accordingly. This issue has clear implicatons for future volcanic hazards at Yellowstone, and it therefore deserves careful consideration. The following comments summarize current knowledge and explore two alternate approaches to this important question.

The most likely cause of uplift at Yellowstone is the influx of basaltic magma near the base of a large silicic magma reservoir (Pelton and Smith, 1982). Basaltic intrusions beneath silicic calderas cause uplift for at least two reasons: 1) they increase the volume of magma in the reservoir, and 2) they add heat to the silicic magma, causing it to expand. Under some conditions, basaltic intrusions may also cause uplift by triggering vesiculation. This process of basaltic underplating is a primary source of heat for silicic reservoirs in the upper crust. If the heat input from basaltic intrusions does not balance the heat loss from thermal conduction and hydrothermal convection, a silicic reservoir cools and eventually solidifies. At least 0.01 km^3/yr of basaltic underplating is required to maintain a large silicic magma reservoir in the upper crust (Smith, 1979; Smith and Shaw, 1975, 1979; Shaw, 1984).

The volume of uplift within Yellowstone caldera during 1923-1985, calculated from Pelton and Smith's (1982) map scaled to include the 1976-1985 leveling results, is about 0.75 km^3. The average rate of volume increase is thus about 0.012 km^3/yr. The minimum average thermal flux from Yellowstone's hydrothermal system is 1800 mW/m^2 throughout 2,500 km^2. This corresponds to the amount of heat released by crystallization and partial cooling of about 0.085 km^3/yr of basalt (Fournier and Pitt, 1985). If we assume that the surface uplift rate equals the basaltic influx rate, the hydrothermal output is about 7 times the magmatic input, and the Yellowstone system is cooling down.

An alternate approach is to assume that Yellowstone's magmatic and hydrothermal systems operate at or near steady state thermal equilibrium, which requires a hidden heat source to account for the high contemporary heat flux. One possibility is that the current hydrothermal output reflects a significantly higher magmatic heat input sometime in the recent geologic past. As noted above, uplift at Yellowstone has been episodic over both short and long time scales. Hamilton's (1985) model suggests that the current uplift rate is the highest since the early Holocene, but available evidence does not preclude earlier periods of rapid uplift. Is it possible that today's hydrothermal system's reflect's magmatic conditions more than 10,000 years ago? This question might be resolved by estimating the probable lag between a heat pulse at the base of the reservoir and its thermal manifestation at the surface.

A second possibility is that the volume of basalt contributing heat to the base of the silicic reservoir is significantly greater than the volume of surface uplift. Fournier and Pitt (1985) recognized this possibility when they wrote: "Unless additional thermal energy is being derived from basaltic magma that intrudes the crust, cools slightly (melting silicic material), and then convects back down to the mantle, the Yellowstone magmatic-hydrothermal system as a whole is cooling down rather than heating up." The existence of a "thermal conveyor belt" in the upper mantle is entirely speculative, but it deserves additional consideration. The fundamental issue is the relationship between hydrothermal heat flux, magmatic cooling in the shallow crust, and magmatic heating near the base of the crust. If hydrothermal systems have their roots in the shallow crust, they are trademarks of dying silicic systems. But if some are more deeply rooted (i. e., if they reflect deep magmatic heat input), they may provide important information about magmatic processes that have no other surface manifestation.

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TABLE 1
ABANDONED BENCHAMRKS AND THEIR 1984-1985 REPLACEMENTS[1]

NEW MARK	REPLACES
CVO 84-22	26 MDC 1976
CVO 84-23	A11 1923
CVO 84-27	CVO 84-12
CVO 85-220	CVO 84-11
CVO 85-221	CVO 84-10
CVO 85-222	CVO 84-9
CVO 85-223	CVO 84-8
CVO 85-224	CVO 84-7
CVO 85-225	CVO 84-5
CVO 85-226	CVO 84-4
CVO 85-227	CVO 84-6
CVO 85-228	CVO 84-3
CVO 85-229	CVO 84-2
CVO 85-230	CVO 84-1
	J11 1923[2]
	B11 1932[2]
	CVO 84-13[2]
	CVO 84-14[2]
	CVO 84-15[2]
	CVO 84-16[2]

[1]All new marks on culverts except CVO 85-230, on large boulder. All new marks within 1 m of old marks, except CVO 84-27, on nearest culvert.

[2]To be replaced in 1986.

TABLE 2
YELLOWSTONE LEVEL CHANGES
1984-1985

BENCHMARK	1984 ELEV (M)	1985 ELEV (M)	CHANGE (MM)	DISTANCE (KM)
36MDC	2545.6183	2545.6183	0.0	0.0
CVO84-21	2547.1431	2547.1418	-1.3	0.7
CVO84-20	2465.6213	2465.6226	1.3	2.3
CVO84-26	2437.8181	2437.8198	1.7	3.3
CVO84-25	2379.1235	2379.1269	3.4	4.7
CVO84-24	2360.5466	2360.5491	2.5	5.3
CVO84-19	2360.5254	2360.5298	4.4	6.2
CVO84-18	2376.9187	2376.9221	3.4	7.4
CVO84-14	2366.0044	2366.0081	3.7	8.2
CVO84-13	2358.8972	2358.9045	7.3	9.4
CVO84-17	2358.3665	2358.3740	7.5	10.6
CVO84-16	2359.2473	2359.2549	7.6	11.6
CVO84-12	2371.9861	2371.9927	6.6	12.9
32MDC	2366.0959	2366.1018	5.9	14.0
CVO84-15	2362.2903	2362.2969	6.6	14.5
USBPR7743	2360.5535	2360.5571	3.6	15.7
31MDC	2363.9453	2363.9468	1.5	17.0
CVO84-23	2374.4888	2374.4900	1.2	18.2
A11 1923	2375.4822	2375.4814	-0.8	18.2
L19NPS	2395.1367	2395.1374	0.7	19.1
30MDC	2390.3977	2390.3970	-0.7	19.6
CVO84-11	2380.6475	2380.6462	-1.3	20.3
B11 1923	2365.9248	2365.9233	-1.5	21.2
CVO84-10	2362.8496	2362.8486	-1.0	22.1
29MDC	2368.7695	2368.7703	0.8	22.9
DA3	2353.3108	2353.3108	0.0	23.4
28MDC	2359.2585	2359.2573	-1.2	24.3
CVO84-9	2350.7136	2350.7126	-1.0	25.1
27MDC	2351.2476	2351.2461	-1.5	26.4
CVO84-8	2354.3914	2354.3896	-1.8	27.3
CVO84-22	2363.6130	2363.6094	-3.6	28.6
26MDC	2364.3606	2364.3657	5.1	28.6
CVO84-7	2369.5935	2369.5947	1.2	29.5
E11 A2	2344.9790	2344.9770	-2.0	30.3
F11 A	2343.6973	2343.6939	-3.4	31.1
CVO84-5	2343.2456	2343.2458	0.2	32.1
CVO84-4	2345.1052	2345.1035	-1.7	33.2
CVO84-6	2369.8560	2369.8501	-5.9	34.0
CVO84-3	2341.2048	2341.1992	-5.6	34.9
25MDC	2340.8975	2340.8923	-5.2	35.5
CVO84-2	2342.0845	2342.0803	-4.2	36.7
24MDC	2344.9592	2344.9560	-3.2	37.4
23MDC	2340.4609	2340.4595	-1.4	38.8
22MDC	2346.2927	2346.2927	0.0	39.5
LC58	2366.0410	2366.0395	-1.5	40.6
J11 1923	2377.5525	2377.5527	0.2	41.5
CVO84-1	2413.1499	2413.1464	-3.5	42.2
11MDC	2413.0373	2413.0405	3.2	43.3

TABLE 3
BENCHMARK ELEVATIONS

BENCHMARK NAME	ROAD DISTANCE (KM)	ELEVATION 1923 (M)	ELEVATION 1976 (M)	ELEVATION 1983 (M)	ELEVATION 1984 (M)	ELEVATION 1985 (M)
11 MDC 1976	43.3	-	2413.0200	-	2413.0373	2413.0405
CVO 84-1	42.2	-	-	-	2413.1499	2413.1464
CVO 85-230	42.2	-	-	-	-	2413.2910
J11 1923	41.5	2377.3269	2377.5324	-	2377.5525	2377.5527
LC 58 1977	40.6	-	-	-	2366.0410	2366.0395
22 MDC 1976	39.5	-	2346.2685	-	2346.2927	2346.2927
23 MDC 1976	38.8	-	2340.4325	-	2340.4609	2340.4595
24 MDC 1976	37.4	-	2344.9191	-	2344.9592	2344.9560
CVO 84-2	36.7	-	-	-	2342.0845	2342.0803
CVO 85-229	36.7		-	-	-	2342.0759
25 MDC 1976	35.5	-	2340.8244	-	2340.8975	2340.8923
CVO 85-228	34.9	-	-	-	-	2341.2146
CVO 84-3	34.9	-	-	-	2341.2048	2341.1992
CVO 84-6	34.0	-	-	-	2369.8560	2369.8501
CVO 85-227	34.0	-	-	-	-	2369.9104
G11 1923	33.5	2358.2080	2358.6691	-	-	-
CVO 84-4	33.2	-	-	-	2345.1052	2345.1035
CVO 85-226	33.2	-	-	-	-	2345.0749
CVO 84-5	32.1	-	-	-	2343.2456	2343.2458
CVO 85-225	32.1	-	-	-	-	2343.2891
F11 A	31.1	-	2343.5588	2343.6743	2343.6973	2343.6939
E11 A2	30.3	-	2344.8323	2344.9568	2344.9790	2344.9770
CVO 84-7	29.5	-	-	-	2369.5935	2369.5947
CVO 85-224	29.5	-	-	-	-	2369.6235
26 MDC 1976	28.6	-	2364.1762	2364.3401	2364.3606	2364.3657
CVO 84-22	28.6	-	-	-	2363.6130	2363.6094
CVO 84-8	27.3	-	-	-	2354.3914	2354.3896
CV0 85-223	27.3	-	-	-	-	2354.4307
27 MDC 1976	26.4	-	2351.0709	2351.2251	2351.2476	2351.2461
CVO 84-9	25.1	-	-	-	2350.7136	2350.7126
CVO 85-222	25.1	-	-	-	-	2350.5684
28 MDC 1976	24.3	-	2359.0792	2359.2385	2359.2585	2359.2573
DA 3 1934	23.4	-	2353.1317	2353.2937	2353.3108	2353.3108
29 MDC 1976	22.9	-	2368.5925	2368.7529	2368.7695	2368.7703
CVO 84-10	22.1	-	-	-	2362.8496	2362.8486
CV0 85-221	22.1	-	-	-	-	2362.9141
B11 1923	21.2	2365.0341	2365.7604	2365.9075	2365.9248	2365.9233
CVO 84-11	20.3	-	-	-	2380.6475	2380.6462
CV0 85-220	20.3	-	-	-	-	2380.6714
30 MDC 1976	19.6	-	2390.2493	2390.3848	2390.3977	2390.3970
L19 1977	19.1	-	-	-	2395.1367	2395.1374
A11 1923	18.2	2374.7207	2375.3398	2375.4705	2375.4822	2375.4814
CVO 84-23	18.2	-	-	-	2374.4888	2374.4900
31 MDC 1976	17.0	-	2363.8227	2363.9341	2363.9453	2363.9468
USBPR7743	15.7	-	2360.4440	2360.5420	2360.5535	2360.5571
CVO 84-15	14.5	-	-	-	2362.2903	2362.2969
32 MDC 1976	14.0	-	2366.0016	2366.0853	2366.0959	2366.1018

TABLE 3
BENCHMARK ELEVATIONS
(CONT)

BENCHMARK NAME	ROAD DISTANCE (KM)	ELEVATION 1923 (M)	ELEVATION 1976 (M)	ELEVATION 1983 (M)	ELEVATION 1984 (M)	ELEVATION 1985 (M)
CVO 84-12	12.9	-	-	-	2371.9861	2371.9927
CVO 84-27	12.9	-	-	-	-	2376.1045
33 MDC 1976	11.9	-	2381.6153	-	-	-
CVO 84-16	11.6	-	-	-	2359.2473	2359.2549
CVO 84-17	10.6	-	-	-	2358.3665	2358.3740
D12 1923	9.9	2436.8932	2437.1036	-	-	-
CVO 84-13	9.4	-	-	-	2358.8972	2358.9045
34 MDC 1976	8.7	-	2411.7201	-	-	-
CVO 84-14	8.2	-	-	-	2366.0044	2366.0081
CVO 84-18	7.4	-	-	-	2376.9187	2376.9221
E12 1923	6.9	2425.0619	2425.1851	-	-	-
CVO 84-19	6.2	-	-	-	2360.5254	2360.5298
CVO 84-24	5.3	-	-	-	2360.5466	2360.5491
CVO 84-25	4.7	-	-	-	2379.1235	2379.1269
F12 1923	3.5	2475.9387	2475.9292	-	-	-
CVO 84-26	3.3	-	-	-	2437.8181	2437.8198
CVO 84-20	2.3	-	-	-	2465.6213	2465.6226
35 MDC 1976	1.6	-	2492.5972	-	-	-
CVO 84-28	1.5	-	-	-	-	-
CVO 84-21	0.7	-	-	-	2547.1431	2547.1418
36 MDC 1976	0.0	-	2545.6183	2545.6183	2545.6183	2545.6183

TABLE 4

ELEVATION CHANGES

BENCHMARK NAME	ROAD DISTANCE (KM)	CHANGE 1923-1976 (MM)	CHANGE 1923-1983 (MM)	CHANGE 1923-1984 (MM)	CHANGE 1923-1985 (MM)	CHANGE 1976-1983 (MM)	CHANGE 1976-1984 (MM)	CHANGE 1976-1985 (MM)	CHANGE 1983-1984 (MM)	CHANGE 1983-1985 (MM)	CHANGE 1984-1985 (MM)
11 MDC 19	43.3	-	-	-	-	-	17.3	20.5	-	-	3.2
CVO 84-1	42.2	-	-	-	-	-	-	-	-	-	-3.5
CVO 85-23	42.2	-	-	-	-	-	-	-	-	-	-
J11 1923	41.5	205.5	-	225.6	225.8	-	20.1	20.3	-	-	0.2
LC 58 197	40.6	-	-	-	-	-	-	-	-	-	-1.5
22 MDC 19	39.5	-	-	-	-	-	24.2	24.2	-	-	0.0
23 MDC 19	38.8	-	-	-	-	-	28.4	27.0	-	-	-1.4
24 MDC 19	37.4	-	-	-	-	-	40.1	36.9	-	-	-3.2
CVO 84-2	36.7	-	-	-	-	-	-	-	-	-	-4.2
CVO 85-22	36.7	-	-	-	-	-	-	-	-	-	-
25 MDC 19	35.5	-	-	-	-	-	73.1	67.9	-	-	-5.2
CVO 85-22	34.9	-	-	-	-	-	-	-	-	-	-
CVO 84-3	34.9	-	-	-	-	-	-	-	-	-	-5.6
CVO 84-6	34.0	-	-	-	-	-	-	-	-	-	-5.9
CVO 85-22	34.0	-	-	-	-	-	-	-	-	-	-
G11 1923	33.5	461.1	-	-	-	-	-	-	-	-	-
CVO 84-4	33.2	-	-	-	-	-	-	-	-	-	-1.7
CVO 85-22	33.2	-	-	-	-	-	-	-	-	-	-
CVO 84-5	32.1	-	-	-	-	-	-	-	-	-	0.2
CVO 85-22	32.1	-	-	-	-	-	-	-	-	-	-
F11 A	31.1	-	-	-	-	115.5	138.5	135.1	23.0	19.6	-3.4
E11 A2	30.3	-	-	-	-	124.5	146.7	144.7	22.2	20.2	-2.0
CVO 84-7	29.5	-	-	-	-	-	-	-	-	-	1.2
CVO 85-22	29.5	-	-	-	-	-	-	-	-	-	-
26 MDC 19	28.6	-	-	-	-	163.9	184.4	189.5	20.5	25.6	5.1
CVO 84-22	28.6	-	-	-	-	-	-	-	-	-	-3.6
CVO 84-8	27.3	-	-	-	-	-	-	-	-	-	-1.8
CV0 85-22	27.3	-	-	-	-	-	-	-	-	-	-
27 MDC 19	26.4	-	-	-	-	154.2	176.7	175.2	22.5	21.0	-1.5
CVO 84-9	25.1	-	-	-	-	-	-	-	-	-	-1.0
CVO 85-22	25.1	-	-	-	-	-	-	-	-	-	-
28 MDC 19	24.3	-	-	-	-	159.3	179.3	178.1	20.0	18.8	-1.2
DA 3 1934	23.4	-	-	-	-	162.0	179.1	179.1	17.1	17.1	0.0
29 MDC 19	22.9	-	-	-	-	160.4	177.0	177.8	16.6	17.4	0.8
CVO 84-10	22.1	-	-	-	-	-	-	-	-	-	-1.0
CV0 85-22	22.1	-	-	-	-	-	-	-	-	-	-
B11 1923	21.2	726.3	873.4	890.7	889.2	147.1	164.4	162.9	17.3	15.8	-1.5
CVO 84-11	20.3	-	-	-	-	-	-	-	-	-	-1.3
CV0 85-22	20.3	-	-	-	-	-	-	-	-	-	-
30 MDC 19	19.6	-	-	-	-	135.5	148.4	147.7	12.9	12.2	-0.7
L19 1977	19.1	-	-	-	-	-	-	-	-	-	0.7
A11 1923	18.2	619.1	749.8	761.5	760.7	130.7	142.4	141.6	11.7	10.9	-0.8
CVO 84-23	18.2	-	-	-	-	-	-	-	-	-	1.2
31 MDC 19	17.0	-	-	-	-	111.4	122.6	124.1	11.2	12.7	1.5
USBPR7743	15.7	-	-	-	-	98.0	109.5	113.1	11.5	15.1	3.6
CVO 84-15	14.5	-	-	-	-	-	-	-	-	-	6.6
32 MDC 19	14.0	-	-	-	-	83.7	94.3	100.2	10.6	16.5	5.9

TABLE 4

ELEVATION CHANGES (CONT)

BENCHMARK NAME	ROAD DISTANCE (KM)	CHANGE 1923-1976 (MM)	CHANGE 1923-1983 (MM)	CHANGE 1923-1984 (MM)	CHANGE 1923-1985 (MM)	CHANGE 1976-1983 (MM)	CHANGE 1976-1984 (MM)	CHANGE 1976-1985 (MM)	CHANGE 1983-1984 (MM)	CHANGE 1983-1985 (MM)	CHANGE 1984-1985 (MM)
CVO 84-12	12.9	-	-	-	-	-	-	-	-	-	6.6
CVO 84-27	12.9	-	-	-	-	-	-	-	-	-	-
33 MDC 19	11.9	-	-	-	-	-	-	-	-	-	-
CVO 84-16	11.6	-	-	-	-	-	-	-	-	-	7.6
CVO 84-17	10.6	-	-	-	-	-	-	-	-	-	7.5
D12 1923	9.9	210.4	-	-	-	-	-	-	-	-	-
CVO 84-13	9.4	-	-	-	-	-	-	-	-	-	7.3
34 MDC 19	8.7	-	-	-	-	-	-	-	-	-	-
CVO 84-14	8.2	-	-	-	-	-	-	-	-	-	3.7
CVO 84-18	7.4	-	-	-	-	-	-	-	-	-	3.4
E12 1923	6.9	123.2	-	-	-	-	-	-	-	-	-
CVO 84-19	6.2	-	-	-	-	-	-	-	-	-	4.4
CVO 84-24	5.3	-	-	-	-	-	-	-	-	-	2.5
CVO 84-25	4.7	-	-	-	-	-	-	-	-	-	3.4
F12 1923	3.5	-9.5	-	-	-	-	-	-	-	-	-
CVO 84-26	3.3	-	-	-	-	-	-	-	-	-	1.7
CVO 84-20	2.3	-	-	-	-	-	-	-	-	-	1.3
35 MDC 19	1.6	-	-	-	-	-	-	-	-	-	-
CVO 84-28	1.5	-	-	-	-	-	-	-	-	-	-
CVO 84-21	0.7	-	-	-	-	-	-	-	-	-	-1.3
36 MDC 19	0.0	-	-	-	-	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 5
AVERAGE MAXIMUM UPLIFT RATES AT YELLOWSTONE CALDERA[1]

INTERVAL	MAXIMUM UPLIFT[2]	UPLIFT RATE[2]
1923-1976	792 mm	16 mm/yr[2]
1923-1983	952 mm	16 mm/yr
1923-1984	971 mm	16 mm/yr
1923-1985	969 mm	16 mm/yr
1940-1976	792 mm	22 mm/yr[3]
1940-1984	971 mm	22 mm/yr[3]
1976-1983	162 mm	23 mm/yr[4]
1976-1984	179 mm	22 mm/yr
1976-1985	179 mm	20 mm/yr
1983-1984	23 mm	23 mm/yr
1983-1985	21 mm	11 mm/yr
1984-1985	0 mm[5]	0 mm/yr[5]

[1]Maximum measured uplift divided by the number of years between level surveys, unless otherwise noted.

[2]Uplift values and rates for intervals starting in 1923 have been multiplied by 1.09 to account for the fact that the 1923 survey did not include a benchmark at the post-1976 center of uplift.

[3]Assumes 1940 onset.

[4]Post-1976 rates exclude 26 MDC 1976, which is unstable.

[5]Based on change at DA 3 1934 near former center of uplift, assuming small changes elsewhere reflect only measurement uncertainty.

TABLE 6
LINE LENGTH CHANGES
SEPTEMBER 1984 - SEPTEMBER 1985

STATION 1	STATION 2	MARK TO MARK DISTANCE 1984 (M)	MARK TO MARK DISTANCE 1984 (M)	CHANGE (MM)	CHANGE (PPM)
AMETHYST	CONE	20591.8633	20591.8616	-1.7 ±7.2	0.08
AMETHYST	TROUT	30878.4928	30878.4864	-6.4 ±9.5	0.21
AMETHYST	WASHBURN	14615.9699	14615.9850	15.1 ±5.9	1.03
CHITTENDEN	CONE	11309.1762	11309.1705	-5.7 ±5.3	0.50
CHITTENDEN	TROUT	27632.4211	27632.4207	-0.5 ±8.8	0.02
CHITTENDEN	WASHBURN	-	34745.9005	-	-
CONE	TROUT	25025.5312	25025.5300	-1.2 ±8.2	0.05
CONE	WASHBURN	25291.8931	25291.8830	-10.0 ±8.2	0.40
TROUT	WASHBURN	21000.5582	21000.5587	0.5 ±7.3	0.02

YELLOWSTONE LEVEL LINE

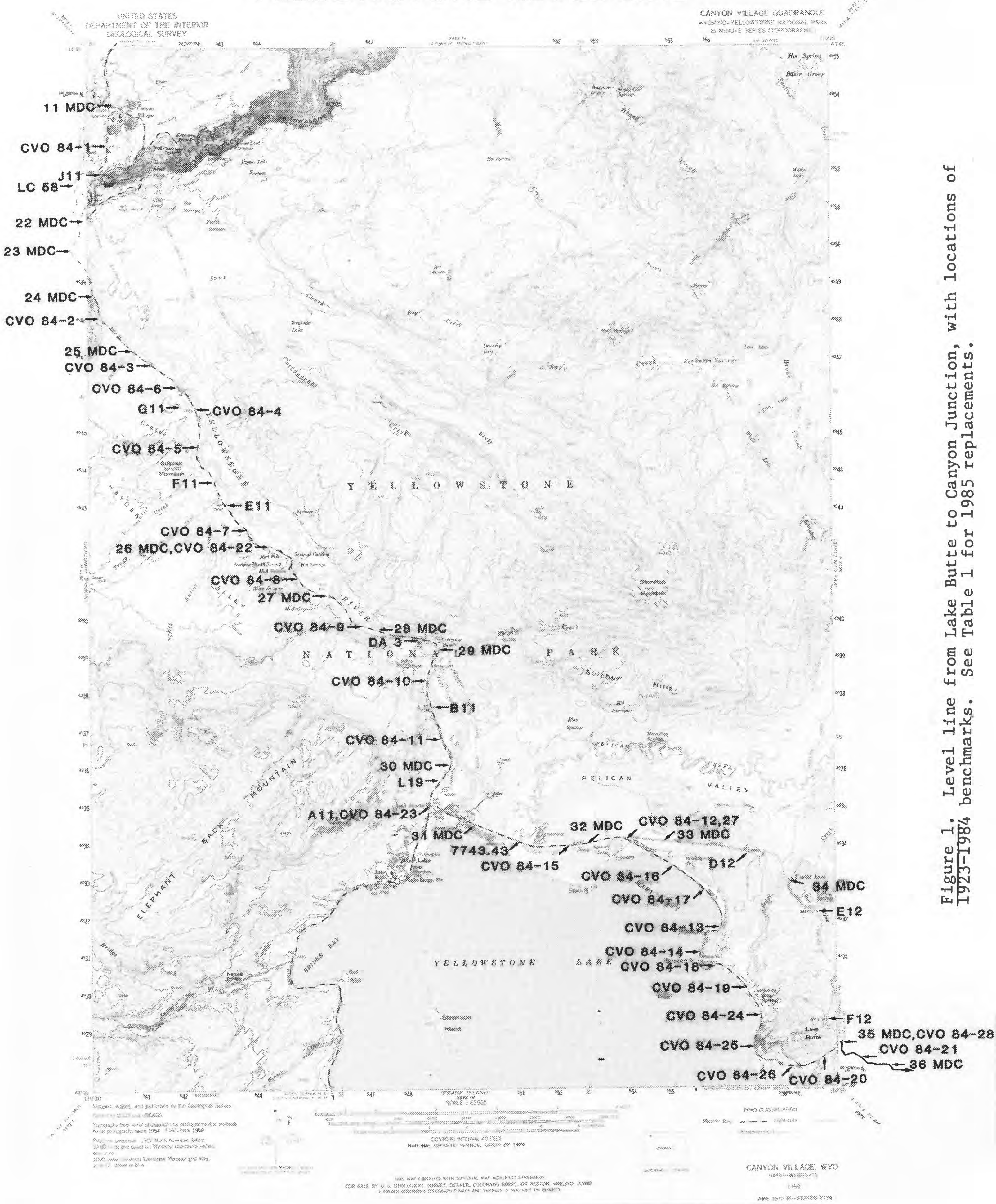

Figure 1. Level line from Lake Butte to Canyon Junction, with locations of 1923-1984 benchmarks. See Table 1 for 1985 replacements.

YELLOWSTONE TRILATERATION NETWORK

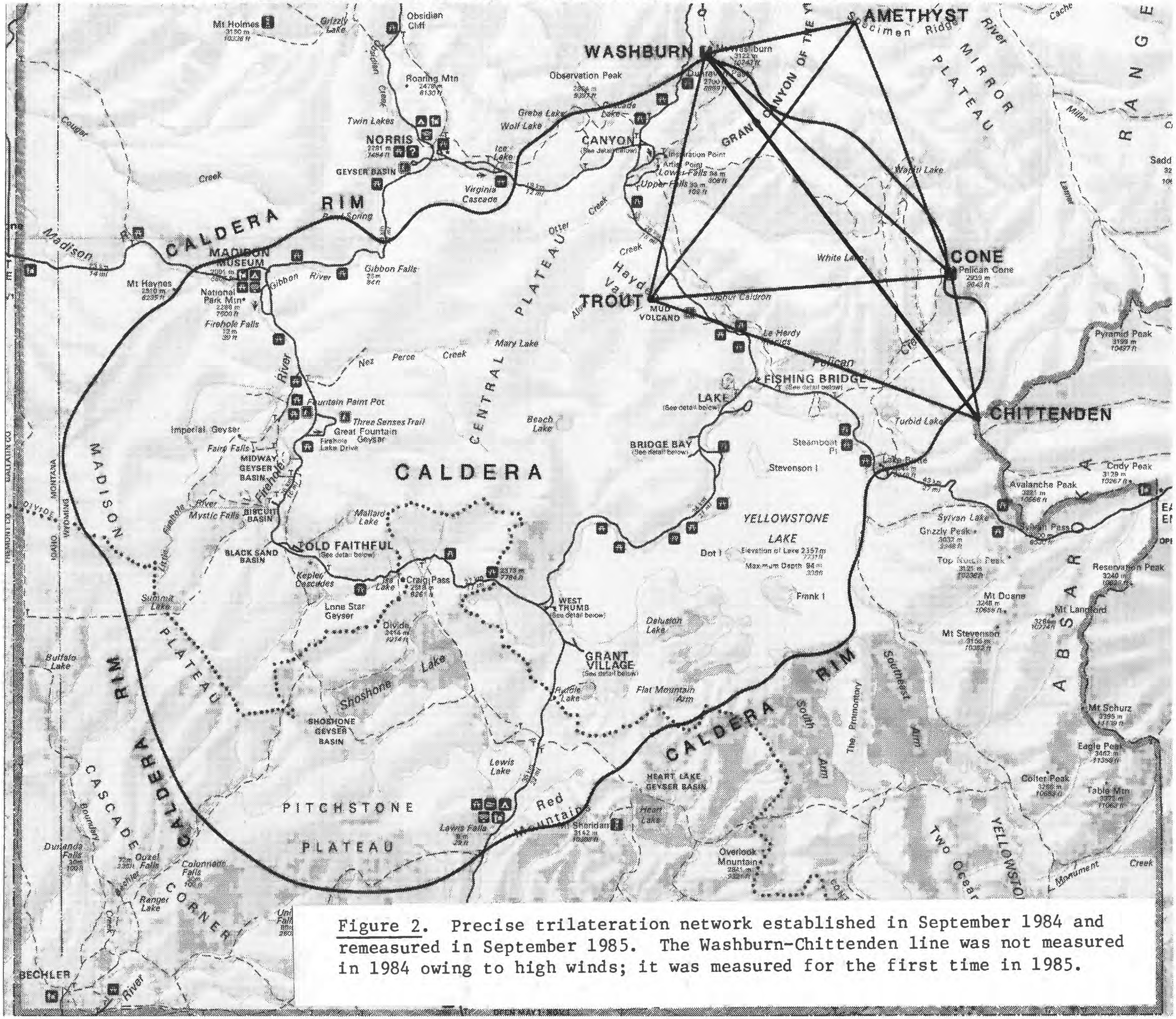

Figure 2. Precise trilateration network established in September 1984 and remeasured in September 1985. The Washburn-Chittenden line was not measured in 1984 owing to high winds; it was measured for the first time in 1985.

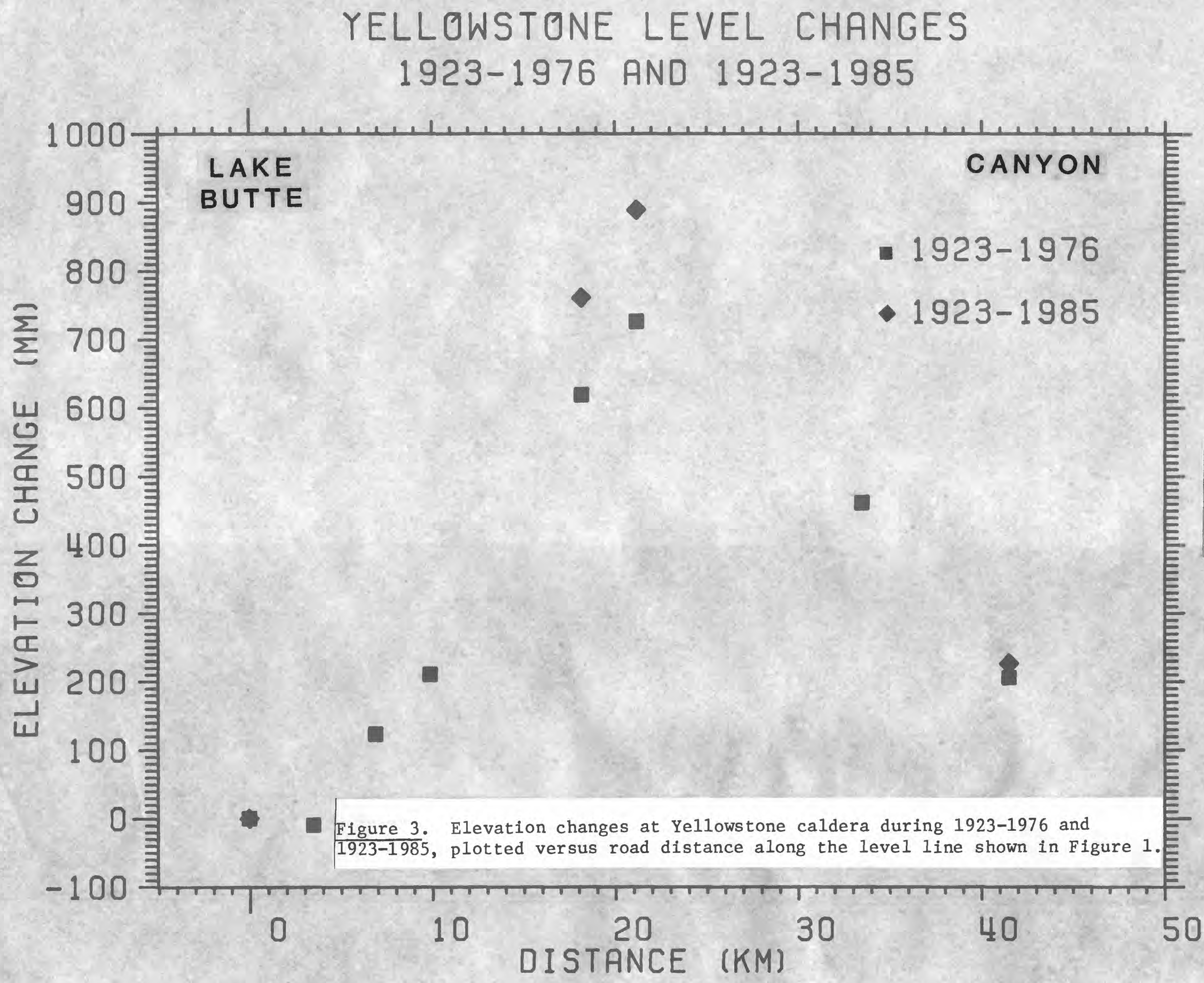

Figure 3. Elevation changes at Yellowstone caldera during 1923-1976 and 1923-1985, plotted versus road distance along the level line shown in Figure 1.

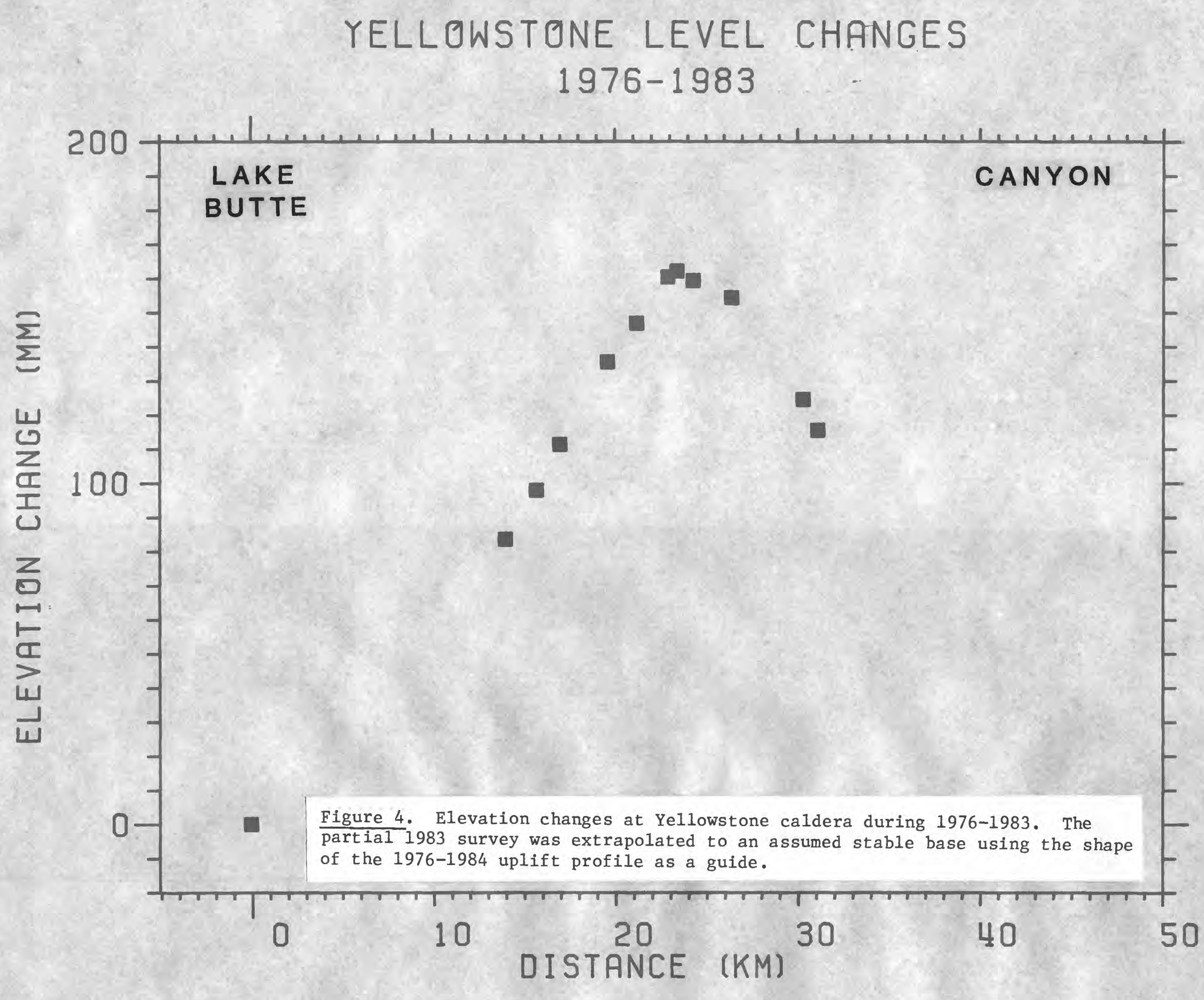

Figure 4. Elevation changes at Yellowstone caldera during 1976-1983. The partial 1983 survey was extrapolated to an assumed stable base using the shape of the 1976-1984 uplift profile as a guide.

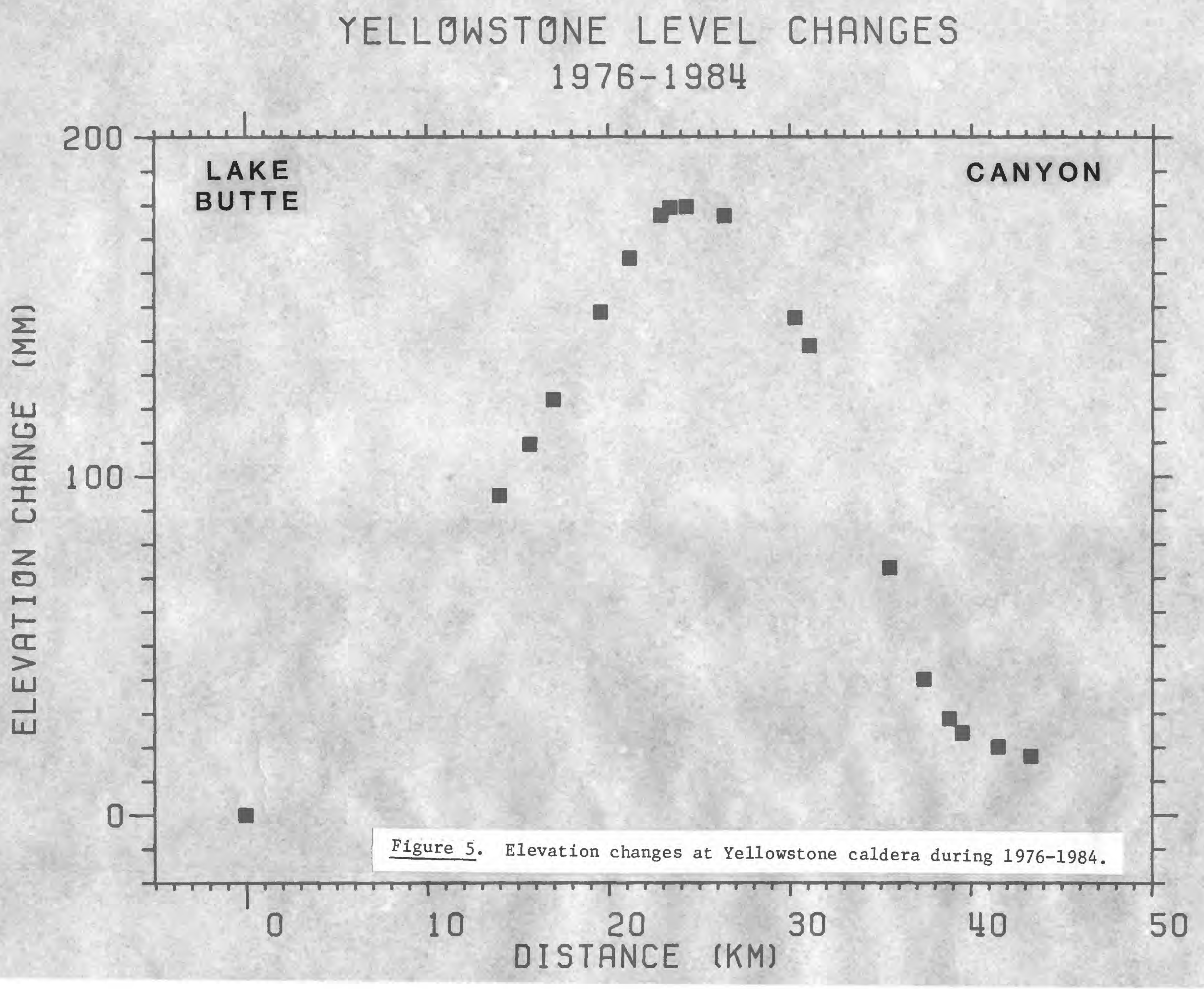

Figure 5. Elevation changes at Yellowstone caldera during 1976-1984.

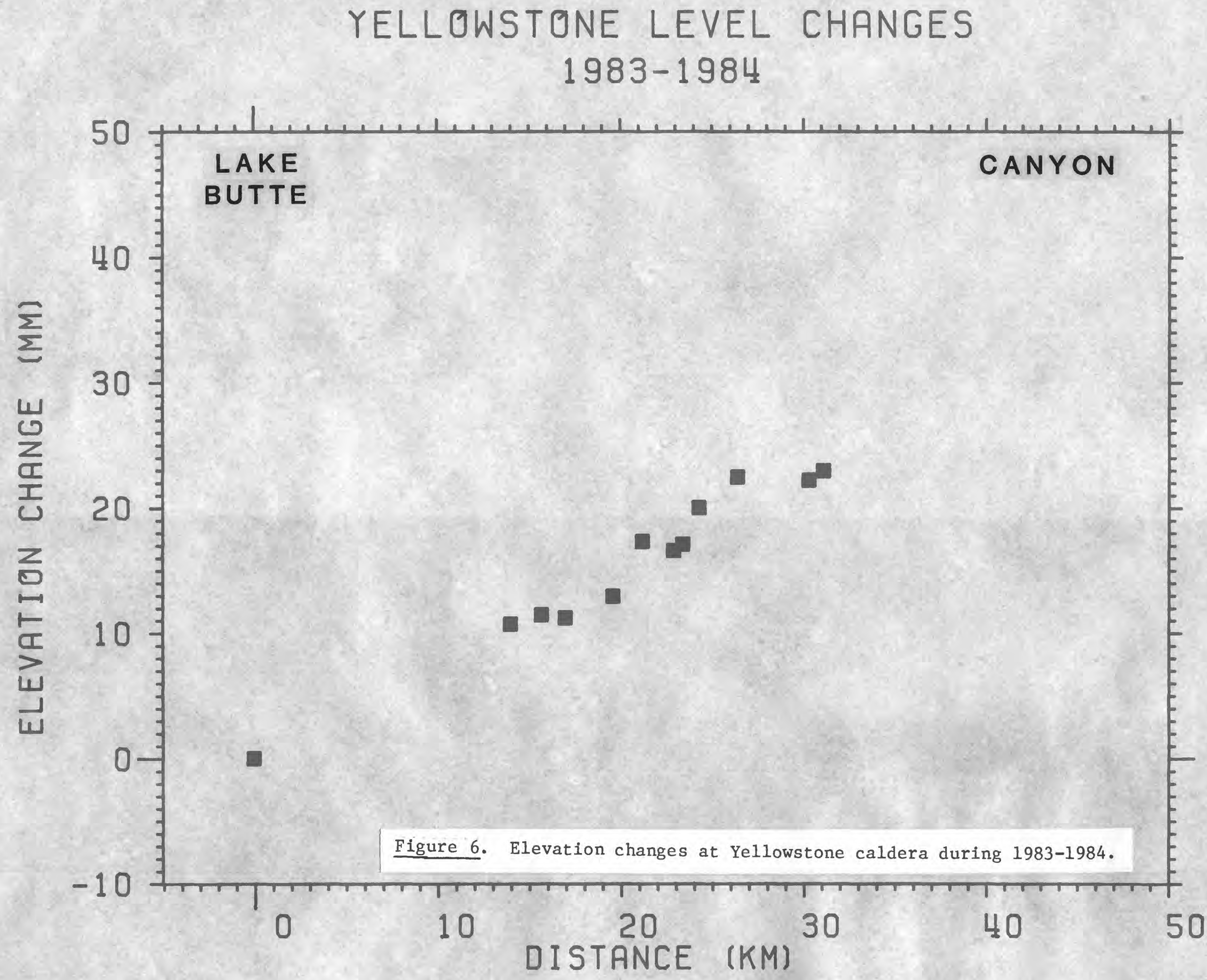

Figure 6. Elevation changes at Yellowstone caldera during 1983-1984.

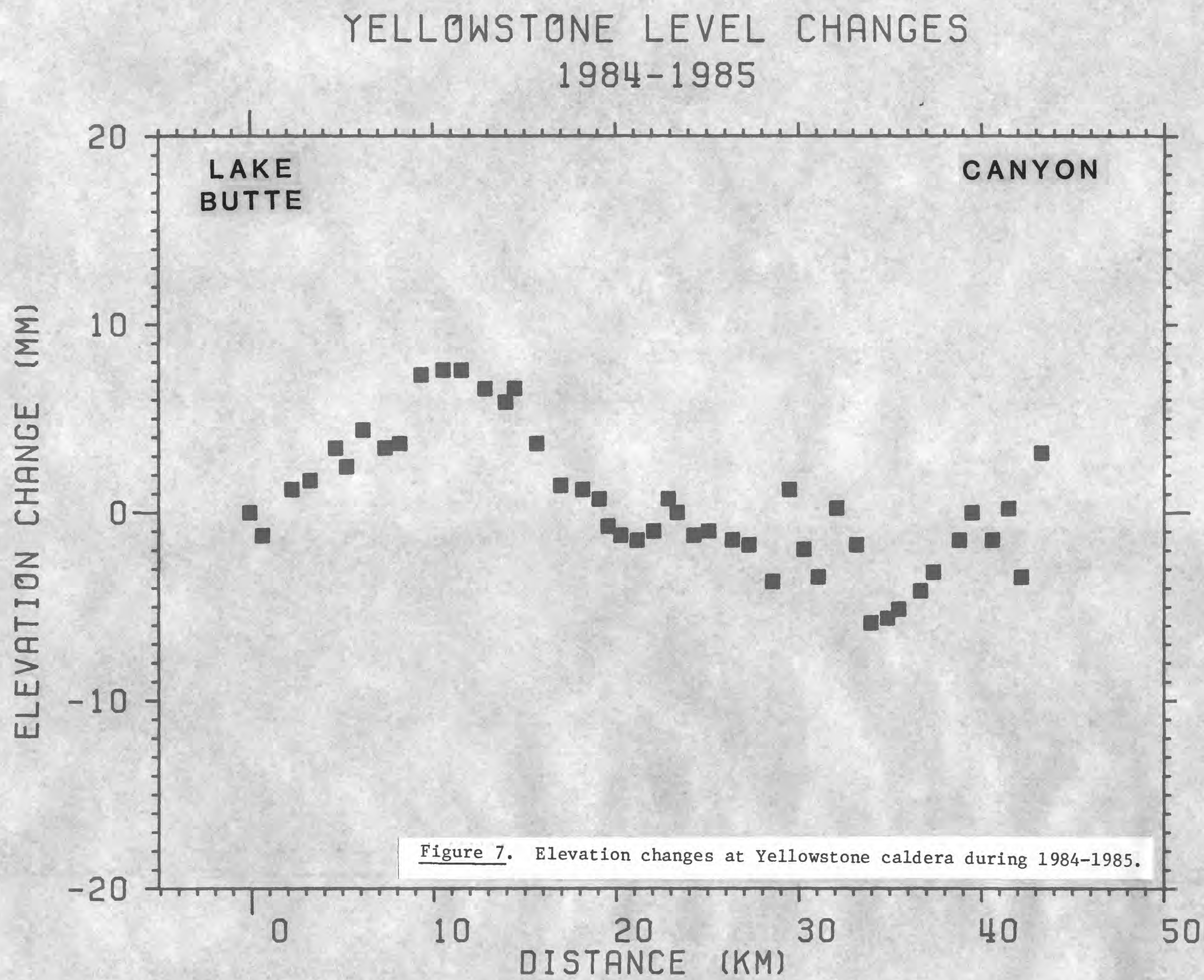

Figure 7. Elevation changes at Yellowstone caldera during 1984-1985.

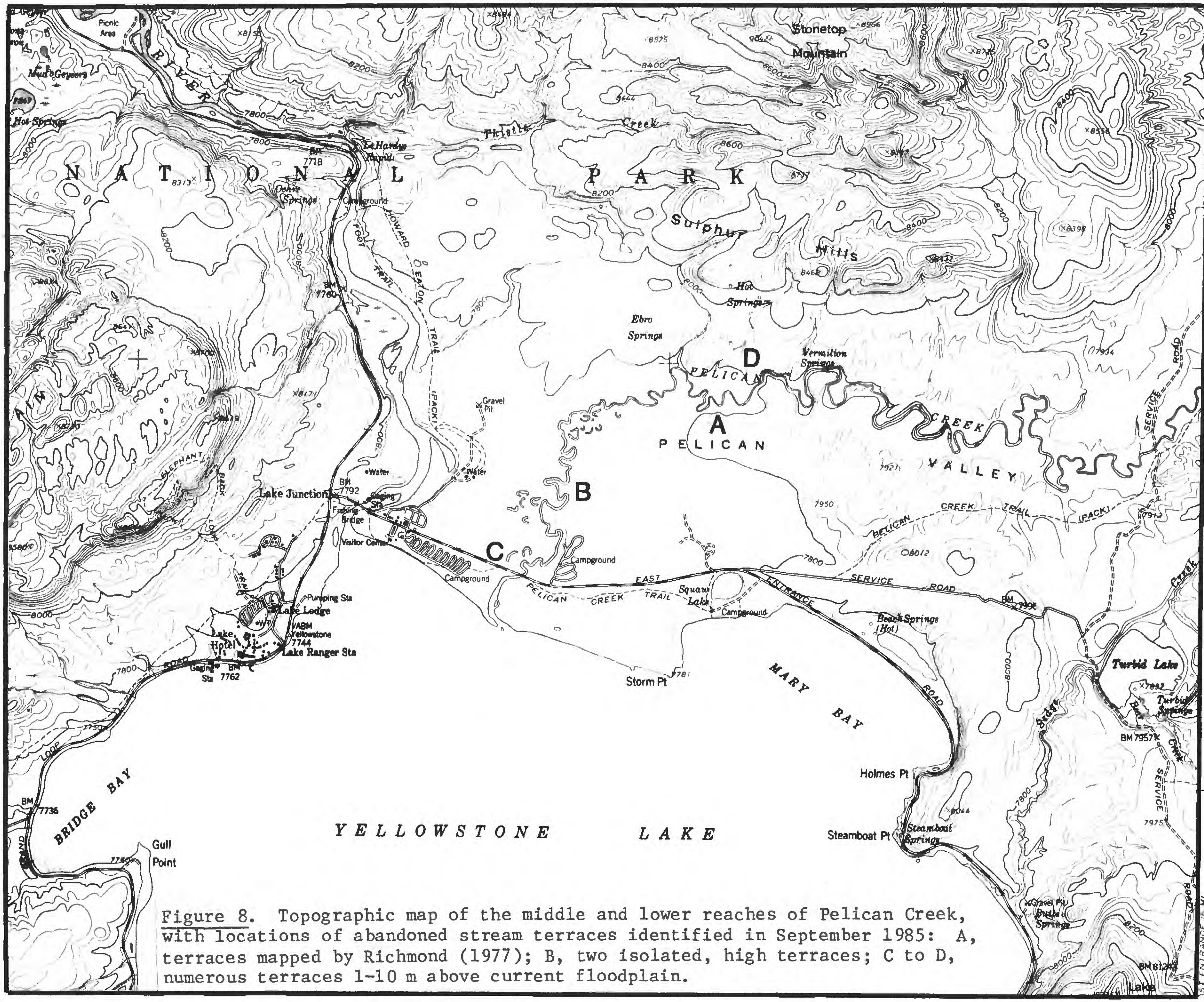

Figure 8. Topographic map of the middle and lower reaches of Pelican Creek, with locations of abandoned stream terraces identified in September 1985: A, terraces mapped by Richmond (1977); B, two isolated, high terraces; C to D, numerous terraces 1-10 m above current floodplain.