DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Deformation of Long Valley Caldera, Eastern California, 1983-1984

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Open-File Report
85-41

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ABSTRACT

Continued deformation of the Long Valley caldera from the summer of 1983 to the summer of 1984 is indicated by resurveys of leveling and trilateration networks. The trilateration surveys can be explained by continued inflation (0.022 km^3) of a spherical magma chamber located 10 km beneath the resurgent dome plus continued right-lateral slip on the uppermost 2 km of the 1983 rupture surface in the south moat of the caldera. The leveling data suggest a minor upwarping over the resurgent dome but are dominated by a regional tilt (0.9 μrad down to the southeast) over 60 km. Although the leveling data satisfy the usual routine tests for absence of systematic error (e.g., no correlation with topography, satisfactory loop closures, satisfactory agreement between the cumulative sums of backward and forward runs), we are unconvinced that the regional tilt is real. Unusual difficulty in obtaining satisfactory section closures in the double-run sections of the leveling is the primary basis for our skepticism.

INTRODUCTION

The U.S. Geological Survey has been monitoring deformation in and around Long Valley caldera (Figure 1) since the sequence of moderate earthquakes (four shocks of magnitude 6 or larger; epicenters shown in Figure 1) near Mammoth Lakes, California, in May 1980. Resurveys of leveling and trilateration networks following those earthquakes suggested that the principal deformation was not so much related to the earthquakes as to reinflation of a magma chamber beneath the resurgent dome within the caldera [Savage and Clark, 1982; Denlinger and Riley, 1984; Rundle and Whitcomb, 1984; Savage and Lisowski, 1984]. Additional resurveys in 1983 indicated that the resurgent dome had continued to rise and right-lateral shear had occurred across a rupture surface in the south moat of the caldera defined by the hypocenters of the January, 1983, earthquake swarm [Rundle and Whitcomb, 1984; Savage and Cockerham, 1984].

This paper is concerned with the deformation measured by leveling and trilateration in the interval August 1983 to August 1984. The trilateration measurements seem to suggest further inflation of a magma chamber beneath the resurgent dome plus shallow right-lateral slip on the 1983 rupture surface in the south moat of the caldera, the same type of deformation that occurred in 1982-1983. The 1983-1984 elevation changes were not at all what was expected. Those changes indicate a regional tilt of 0.9 μrad down to the southeast with only a modest upwarp over the resurgent dome. It is possible that the apparent regional tilt is merely a manifestation of some unidentified systematic error in leveling, but the usual tests for reliability in leveling (e.g., absence of correlation of elevation changes with topography, satisfactory loop closures, reasonable accumulation of the discrepancy between backward and forward runs where double-run) would suggest that the 1984 leveling surveys were valid.

VERTICAL DEFORMATION

To monitor the vertical deformation occurring in the vicinity of Long Valley caldera, the U.S. Geological Survey has releveled in 1982, 1983, and

1984 a 155-km-long network of lines covering the area. About half of this network had been surveyed in 1975 prior to any appreciable deformation around the caldera. Deformation inferred from the earlier leveling surveys (1905, 1914, 1932, 1957, 1975, 1980, 1982, and 1983) has been described by Castle et al. [1984]. Here we are concerned only with the interval summer 1983 to summer 1984.

Line 1 (Figure 1), extending along Highway 395 between Toms Place and Lee Vining, has furnished the principal data that documents the development of the Long Valley uplift. The elevation changes along that line determined from the difference between the 1983 and 1984 surveys are shown in Figure 2. We have arbitrarily assumed that the bench mark (F124) closest to Toms Place remained invariant in elevation in that period. To obtain the absolute elevation-change profile, the actual change in elevation at bench mark F124 would have to be added to all points on the elevation change profile (i.e., the profile should be displaced vertically by the amount of the uplift at F124). Except for the 6-km-long section closest to Toms Place, the elevation-change profile is remarkably linear with a uniform increase of about 0.9 mm/km over 60 km. The elevation-change profile does not correlate well with the topographic profile (bottom curve in Figure 2), nor does it show much similarity to the 1982-1983 elevation-change profile (dashed line in Figure 2).

The 1984 survey of Line 1 was double-run with the forward run (Toms Place to Lee Vining) completed in June and the backward run (Lee Vining to Toms Place) completed in early August. The line was divided into 49 individual sections each of length between 1 and 2 km. First-order leveling procedures require that the net elevation difference over the section as determined by the forward run does not differ from the elevation difference determined in the backward run by more than the rejection limit $\alpha K^{1/2}$ where $\alpha = 4\ \mathrm{mm/km}^{1/2}$ and K is the section length [Federal Geodetic Control Committee, 1974, p. 9]. If this criterion is not met, the section must be rerun until a satisfactory agreement is obtained. Ordinarily about 1 section in 20 will fail to close satisfactorily. In the 1984 leveling of Line 1, 19 of the 49 sections had to be rerun and a few of those 19 sections had to be rerun twice. Thus, there is a clear indication of some problem in the leveling procedures. Two likely sources of error are the use of turning pins (rather than turning plates) in the volcanic ash that lies along much of the route and leveling too close to the highway where the passage of large trucks at high speed may disturb the leveling setup. Because the likely sources of error are not dependent upon the direction in which the line is run, double-running should compensate for such errors. A common check upon the reliability of double-run leveling is to examine the cumulative sum of the elevation differences determined from backward and forward runs (B+F) of the individual sections. This sum is equivalent to the closure error that would have been obtained if the forward and backward runs were considered as forming a single-run closed loop. The cumulative B+F sum for the 1984 leveling from Toms Place to Lee Vining is shown as a dash-dot line in Figure 2. The cumulative B+F sum at Lee Vining is only 15 mm, well within the 40 mm limit allowed for a 65-km line for first-order, class II levels [Federal Geodetic Control Committee, 1974, p. 9]. The slope of the B+F curve indicates the quality of the section closures, with steep sections of the curve indicating poor closures. Marginal closures were encountered near Casa Diablo Hot Springs (Figure 2). The cumulative B+F sum attains its extreme value (-25 mm) just north of Casa Diablo Hot Springs.

Even that extreme value is within the limit (29 mm at 33.5 km) imposed by first-order specifications.

The elevation difference between bench mark F124 near Toms Place and bench mark U123 near Lee Vining as determined in 1932, 1957, 1975, 1982, 1983, and 1984 is shown in Figure 3. Four of the six surveys indicate an elevation difference of about 68.125 m whereas the 1982 survey indicates a somewhat greater elevation difference and the 1984 survey a smaller elevation difference. As explained by Castle et al. [1984], and discussed in detail later, the 1982 elevation difference is very likely contaminated by a systematic error (magnetic deflection of the level compensator), and therefore the 1982 deviation is not regarded as significant. This leaves only the 1984 leveling result to contradict the presumed stability of Toms Place with respect to Lee Vining in the 52-year interval 1932-1984. Thus, there are grounds to suspect some systematic error in the 1984 leveling. However, the 1984 leveling appears to meet the usual tests for reliability (e.g., consistency between backward and forward runs over the entire 65 km route, acceptable loop closures which will be discussed later, absence of correlation between elevation change and topography). Moreover, three different instruments (all Zeiss Ni-1 levels retrofitted with new nonmagnetic compensators in 1982) were employed in the 1984 survey, making it unlikely that any individual instrument itself is at fault. Finally, the 1983 levels, which yielded geophysically plausible results, were run by the same levelman using the same instruments.

Other lines leveled in the 1984 survey are shown in Figure 4. These lines branch off from Line 1 within the caldera and provide control from which the caldera uplift pattern can be better defined. Elevation change profiles for the principal lines in this network are shown in Figures 5, 6, 7, and 8. In each case the observed elevation change profiles are referred to a presumed zero uplift at Toms Place through elevation changes carried along Line 1 to the point where the particular profile branches off. Also shown in those figures as dashed lines are the 1982-1983 elevation changes. The elevation-change profiles do not correlate with topography for any of the lines.

The leveling network (Figure 4) includes three independent loops (labeled A, B, and C in the figure), each of which provides a test of leveling accuracy through loop closures. In this paper we are concerned with the uplift measured between two surveys. Consequently, we will be primarily concerned with the closure in uplift between two surveys rather than closure in elevation for a single survey. The uplift closures for the three loops, as well as for the large loop A+B+C which encloses them, are shown in Table 1 for each of three epochs, 1982-1983, 1983-1984, and 1982-1984. The maximum allowed closures for each of the loops in epochs which include the 1984 survey are shown in the table. (The maximum allowed closures for the 1982-1983 epoch would be somewhat larger as both the 1982 and 1983 surveys were run to second-order standards whereas the 1984 survey employed first-order procedures.) The maximum allowed closure is calculated from $(\alpha_1^2 K_1 + \alpha_2^2 K_2 + \alpha_3^2 K_3)^{1/2}$ where K_1, K_2, and K_3 are the distances surveyed using first-order class II, first-order class III, and second-order class II procedures and α_1, α_2, and α_3 are 4, 5, and 8 mm/km$^{1/2}$, respectively [Federal Geodetic Control Committee, 1974; Whalen and Balazs, 1977]. All of the 1982 and 1983 surveys were run using second-order, class II procedures. The 1984 surveys along Highway 395 were first-order, class II levels and the other 1984 surveys were first-order, class III levels. As an example, consider loop B for the 1983-1984 epoch. In 1984 the 4.5 km along Highway 395 was run according to first-order class II procedures and the remainder was run using first-order class III procedures. All 23.6 km of the loop was surveyed using second-order class II procedures in 1983. The maximum allowed closure is then $(16 \cdot 4.5 + 25 \cdot 19.1 + 64 \cdot 23.6)^{1/2} = 45.4$ mm. All closures in Table 1 are well within the maximum allowable limits.

Routine least-squares adjustment procedures can be used to distribute the loop misclosures along the surveying routes. The procedure involves determining the 1983-1984 elevation changes at the four junction points (bench marks 3EGE, 13DOR, 17JCM and 29JCM; see Figure 4) most consistent with the leveling along the three loops A, B, and C. The elevation changes at these junction points are referred to the assumed zero elevation change at Toms Place by holding the elevation change at 8DOR as determined in Figure 2 (i.e., by unadjusted leveling along Highway 395 from Toms Place to bench mark 8DOR). The observed elevation changes are then adjusted to fit the elevation changes determined at the junction points by distributing the differences linearly along the segment between junction points. The adjusted elevation change profiles are shown between 8DOR and 13DOR via 13EGE in Figure 2, between 3EGE and 29JCM in Figure 5, between 8DOR and 13DOR via 29JCM in Figure 6, and between 13DOR and 17JCM via Line 5 in Figure 7. In general, the adjusted elevation change profiles are reasonably consistent with the observed profiles shown in those figures.

A contour map of the 1983-1984 elevation changes in the Long Valley caldera (Figure 9) has been constructed from the leveling data. The elevation changes are referred to an assumed zero change at Toms Place, and adjusted elevation changes have been used where available to draw the elevation-change contours. The maximum uplifts occur within a small closure near the center of the caldera and along Highway 395 in the northwest corner of the caldera. Notice that the northernmost 20 km of Line 1 is not included in Figure 9.

HORIZONTAL DEFORMATION

In addition to the leveling measurements in and around Long Valley, extensive trilateration networks have been surveyed frequently to determine the horizontal deformation [Savage and Cockerham, 1984; Savage and Lisowski, 1984]. The basic network presently monitored was established in 1982 and augmented in 1983. Deformation of that network in the 1982-1983 interval was described by Savage and Cockerham [1984, Figure 6]. Deformation of the augmented network for the 1983-1984 interval is shown in Figure 10 and the changes in individual line lengths are given in Table 2. Because trilateration surveys measure only distances within the network without any tie to an external coordinate system, the displacement solution is arbitrary to the extent that any rigid-body motion (translation or rotation) of the network as a whole can be added. This ambiguity has been removed in the solution of Figure 10 by requiring that the sum of the squares of the displacements at four stations (Bald, Crowley, Glass, and Mammoth) distributed roughly symmetrically about the caldera be a minimum, a constraint suggested by the expectation that the displacement pattern will be directed radially outward from the caldera. The resulting displacements are generally directed radially outward from a point within the caldera, and the magnitude of the displacements tend to decrease with distance from the caldera. The displacements at stations Convict and Casa deviate somewhat from this pattern. This deviation is readily explained as a consequence of continued, shallow, right-lateral slip on the 1983 rupture surface (see Figure 10 for location), which is only a few kilometers from those stations. Slip on that rupture surface explained similar displacements at those stations in the 1982-1983 interval [Savage and Cockerham, 1984]. Otherwise, the displacement pattern is fairly well explained by the expansion of a spherical magma chamber located beneath the southern part of the resurgent dome.

A specific source model that provides a reasonable fit to the observed line length changes (Table 2) consists of a 0.022 km^3 symmetric expansion of a spherical source located 10 km beneath a point 3 km north of station Casa plus about 50 mm of right-lateral slip in the depth interval 0 to 2 km on the 1983 rupture surface (see Figure 10 for the location of the rupture surface). The residual line-length changes (O-C) that remain after the length changes predicted by this model are subtracted from the observed length changes are shown in the last column of Table 2. Only two lines (Convict-Glass and Lookout-Val) have O-C values that exceed two standard errors, and both of those lines involve a station that is within a few kilometers of the 1983 rupture surface. Those two observations could be fit at the expense of introducing a more complex model of slip on the rupture surface. Thus, we feel that the simple model of magma-chamber inflation and slip on the 1983 rupture surface provides a good explanation of the horizontal deformation.

Figures 11, 12, and 13 show how the distances between the trilateration stations shown in Figure 10 have changed with time. Only those distances are shown that have been observed three or more times. As can be seen in these figures the 1983-1984 changes are generally comparable to the changes that occurred in the preceding epochs although there is some suggestion that the rate may be slowing down (see particularly the lines terminating at Laurel in Figures 11, 12, and 13).

The rather anomalous length measurement of Casa-Convict (Figure 12) in 1982 merits some comment. Such an aberrant measurement should be regarded with some suspicion. However, this measurement made in July, 1982, was followed in January, 1983, by an intense earthquake swarm on a fault (1983 rupture surface in Figure 10) just 3 km from station Casa. The subsequent measurement of the line (January 10, 1983) followed the earthquake swarm. Thus, the abrupt 1982-1983 line length change in the line Casa-Convict is presumably related to the earthquake swarm. Savage and Cockerham [1984] have shown that the observed line length change is consistent with other changes observed at the same time.

DISCUSSION

Our principal concern in interpreting the 1983-1984 deformation data is the reliability of the measured elevation changes. The fact that so much difficulty was encountered closing double-run sections along Highway 395 (19 out of 49 sections had to be rerun) causes one to question the validity of the 1984 leveling. On the other hand, where tests of the accuracy of the leveling were available (loop closures, accumulated B+F), the 1984 leveling seems quite acceptable. Moreover, the absence of any obvious correlation of elevation change and topography seems to exclude the systematic errors (unequal refraction and rod error) which have been of greatest concern. Bias due to rod settlement has been practically eliminated by double-running along Highway 395 and running in opposite directions on alternate days elsewhere. Finally, the levels used have all been retrofitted to eliminate the magnetic bias known to occur in the earlier Ni-1 levels. Thus, we are unable to identify any obvious source of systematic error.

The argument that the observed vertical deformation is real turns on the fact that there is no demonstrable systematic error in the leveling. Similar leveling in 1975, 1980, 1982, and 1983 demonstrated geophysically reasonable deformation. In fact, the same instrument man and instruments (level and rods) were used in the 1983 survey as in the 1984 survey. The major differences between the 1983 and 1984 surveys were that the procedures were somewhat more rigorous in 1984 and turning pins rather than turning plates were used in 1984.

Certainly one of the more surprising results in the leveling data is the apparent uplift of Lee Vining with respect to Toms Place in 1983-1984 (Figures 2 and 3). It might appear that there is some evidence for similar uplift in the 1982-1983 elevation-change profile (Figure 2). However, the 1982-1983 elevation-change profile is thought to be contaminated by a systematic error caused by a magnetic deflection of the compensator in the Zeiss Ni-1 level used in 1982. Laboratory testing of various Ni-1 levels [Whalen, 1984] suggests that at the magnetic latitude of Long Valley a correction of about 1.85 ± 0.32 mm (mean value for the eight instruments tested with standard error for an individual instrument) for each kilometer farther magnetic north should be added to the measured elevations. The section of Highway 395 from Toms Place to Casa Diablo Hot Springs (Figure 1) is directed N63°W. Magnetic north in Long Valley is about N17°E. Thus, this section of the line makes an angle of 80° with magnetic north, and the accumulated magnetic correction amounts to only about 8.0 ± 1.4 mm. However, north of Casa Diablo Hot Springs Highway 395 runs N29°W, 46° counterclockwise from magnetic north. The correction along this azimuth should accumulate linearly at the rate of about 1.25 ± 0.23 mm/km. The cumulative correction at Lee Vining (8.0 mm for Toms Place to Casa Diablo Hot Springs and 54 mm for the remainder) is about 62 ± 11 mm. This correction should be subtracted from the 1982-1983 elevation differences shown in Figure 2 and the 1982 elevation difference Toms Place less Lee Vining shown in Figure 3. In both cases the change restores the presumed stability of Lee Vining with respect to Toms Place. The correction to the 1982-1983 elevation-change profile is shown graphically in Figure 14. There we have neglected the minor correction between Toms Place and Casa Diablo Hot Springs and assumed that the apparent elevation change at Lee Vining is accounted for by the magnetic error accumulated linearly between Casa Diablo Hot Springs and Lee Vining. The required magnetic correction is then about 1.65 mm per kilometer in the direction of magnetic north, a value reasonably consistent with the mean value 1.85 mm/km for Ni-1 levels found by Whalen [1984]. The corrected elevation-change profile is also more consistent with magma injection into a chamber beneath the resurgent dome (i.e., deformation confined to the vicinity of the caldera). We conclude that the apparent uplift near Lee Vining in the 1982-1983 elevation-change profile is probably an artifact of magnetic error in the 1982 leveling and does not provide a precedent for the apparent uplift of Lee Vining in 1983-1984.

The uniform tilt between Toms Place and Lee Vining that apparently developed in the 1983-1984 interval (Figure 2) is not without precedent, however. Castle et al. [1984] reported a similar tilt, though much larger and in the opposite direction, developed along the same route in the interval 1914-1932. Although the quality of the data available in 1914 (third-order survey using wooden, not invar, rods) is less than we would have wished, sufficient checks upon the data were available (including an earlier 1905 survey) to impart confidence that the data are adequate to define a tilt of so large a magnitude (10 μrad).

CONCLUSION

Our general conclusion is that we mistrust the 1984 leveling although we do not understand what is wrong with it. In contrast, the trilateration data seems to be reliable and appears to define a reasonable model of deformation (injection of 0.022 km^3 of magma into a spherical magma chamber at a depth of 10 km beneath a point 3 km north of trilateration station Casa plus 50 mm of right-lateral slip on the uppermost 2 km of the 1983 rupture surface). We have calculated the uplift distribution expected from that simple model and in Figure 15 show the difference between the observed 1983-1984 elevation change and the change calculated from this model. (In forming this difference the calculated uplift at Toms Place was subtracted from all calculated elevation changes to conform to the same arbitrary constraint imposed upon the observed elevation changes, namely, no elevation change at Toms Place.) To the extent that the model represents the real source of deformation in 1983-1984, the plot in Figure 15 represents the leveling error in the 1983-1984 surveys. The 1983-1984 residuals in Figure 15 are relatively flat in the region southeast of the 30 mm contour. This suggests that locally (i.e., within the caldera) the leveling data is roughly consistent with the source model that explains the horizontal deformation. This local agreement could have been emphasized had we chosen to require the correspondence between observed and calculated uplifts to occur at Mammoth Lakes rather than at Toms Place. That choice would require that 20 mm be subtracted from all O-C values. The zero O-C contour would then run through Mammoth Lakes and a minor depression would occur over the resurgent dome. Except in the northwestern corner, the O-C values within the caldera would all be reduced to reasonable values. Thus, the observed elevation changes within the caldera offer some support for further upwarp of the resurgent dome, although the amplitude of the uplift seems to be somewhat less than required by the source model suggested by the horizontal surveys.

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FIGURE CAPTIONS

Figure 1. Major geologic features and primary level route (line 1) along Highway 395 between Toms Place and Lee Vining. Caldera and resurgent dome boundaries modified from Bailey et al. [1976].

Figure 2. Terrain and height changes (Δh) along Highway 395 between Toms Place and Lee Vining. The elevation change at bench mark F124 near Toms Place has arbitrarily been taken as zero. The 1982-1983 observed elevation changes are shown by the dashed line and the 1983-1984 observed elevation changes by a line connecting open circles. The 1983-1984 adjusted elevation changes between bench marks 8DOR and 13DOR are shown by the continuous line. The dash-dot line represents the cumulative sum of the backward (toward Toms Place) and forward (toward Lee Vining) runs in the double-run survey. The distance scale on the abscissa corresponds to the distances marked along Highway 395 in Figure 1.

Figure 3. The elevation difference Toms Place less Lee Vining as measured in each of six surveys along Highway 395. The error bars represent an estimate of the random error (one standard deviation on either side of the plotted point).

Figure 4. Leveling lines (designated by numbers 2, 3, 4, 5, 6, 7, and 9) within the caldera. The three independent closed leveling loops are indicated by designations A, B, and C. The dotted line outlines the caldera boundary and the dashed line outlines the resurgent dome. The light lines trending north to north-northwest represent the principal faults [Bailey et al., 1976].

Figure 5. Terrain and height changes (Δh) along a west-to-east route (lines 2, 4, and 6; see Figure 4) across the caldera. The dashed line shows the 1982-1983 observed elevation changes and the line connecting open circles shows the 1983-1984 observed elevation changes. The continuous line shows the 1983-1984 adjusted elevation changes between bench marks 3EGE and 29JCM.

Figure 6. Terrain and height changes (Δh) along Line 3 (see Figure 4 for location). The dashed line shows the 1982-1983 observed elevation changes and the line connecting the open circles shows the 1983-1984 observed changes; the 1983-1984 adjusted elevation changes are shown by the continuous line.

Figure 7. Terrain and height changes (Δh) along Line 5 (see Figure 4 for location). The dashed line shows the 1982-1983 observed elevation changes, the line connecting open circles shows the 1983-1984 observed elevation changes, and the continuous line shows the 1983-1984 observed elevation changes.

Figure 8. Terrain and height changes (Δh) along two short spurs (Lines 7 and 9) south of Highway 395 (see Figure 4 for locations). The dashed lines show the 1982-1983 observed elevation changes and the lines connecting open circles show the 1983-1984 observed elevation changes.

Figure 9. A contour map of the 1983-1984 adjusted elevation changes in the caldera. The elevation change at Toms Place has arbitrarily been set to zero. The elevation changes in millimeters are shown at the bench mark locations in the map.

Figure 10. 1983-1984 horizontal displacements measured in and around the Long Valley caldera (dotted oval) as determined by precise trilateration. The heavy bar near station Casa locates the 1983 rupture surface.

Figure 11. Length L (less a constant nominal length L_o) as a function of time for trilateration lines out of stations Bald (left column) and Banner (right column). The vertical bar indicates the time of occurrence of the May, 1980, Mammoth Lakes earthquakes.

Figure 12. Length L (less a constant nominal length L_o) as a function of time for trilateration lines out of stations Casa (left column) and Convict (right column). The vertical bar indicates the time of occurrence of the May, 1980, Mammoth Lakes earthquakes.

Figure 13. Length (less a constant nominal length L_o) as a function of time for trilateration lines out of stations Glass (left column) and Laurel and Mono (right column). The vertical bar indicates the time of occurrence of the May, 1980, Mammoth Lakes earthquakes.

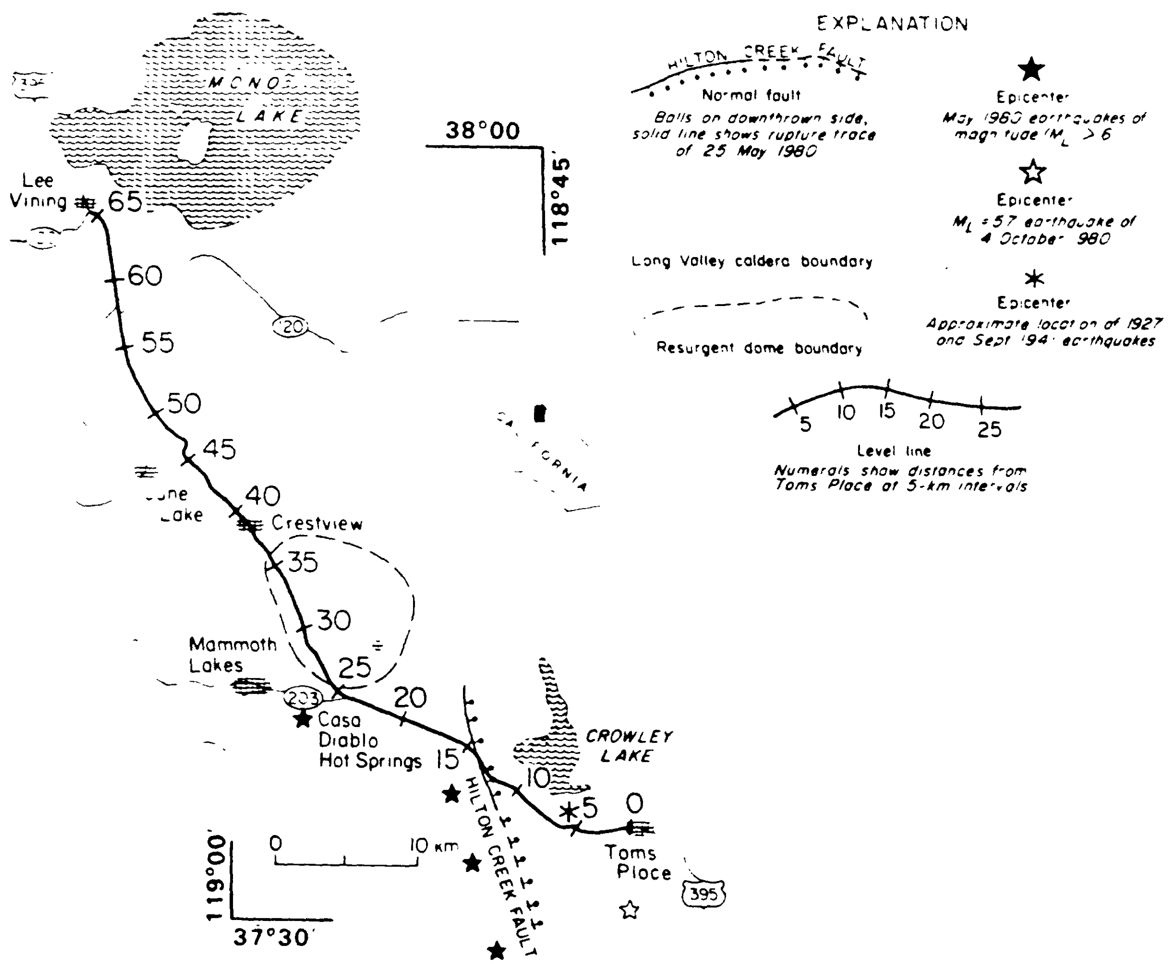
Figure 14. Correction of observed 1982-1983 elevation-change profile (short dashes) along Line 1 (Highway 395) for the magnetic deflection of the compensator. The postulated magnetic correction is shown by the sloping straight line (long dashes), and the corrected elevation-change profile is shown by the continuous line.

Figure 15. The residual elevation change (Observed less :Fedbpdeinx< corrected for uplift predicted for 0.022 km^3 of expansion of a spherical magma chamber at a depth of 10 km beneath the resurgent dome plus 50 mm right slip on the shallowest 2 km of the 1983 rupture surface. If the model of deformation were correct, the contours would represent leveling error.

Table 1. Uplift closures for the 1983-1982, 1984-1983, and 1984-1982 differences for each of the three loops in the leveling network.

Loop	Length	Max. Allowed Closure*	Closure (mm)		
	km	mm	83-82	84-83	84-82
A	46.5	64.3	5.0	17.6	22.6
B	23.6	45.4	12.7	-19.0	- 6.3
C	33.5	53.8	5.8	-20.6	-14.8
A + B + C	49.1	65.1	23.5	-21.9	1.6

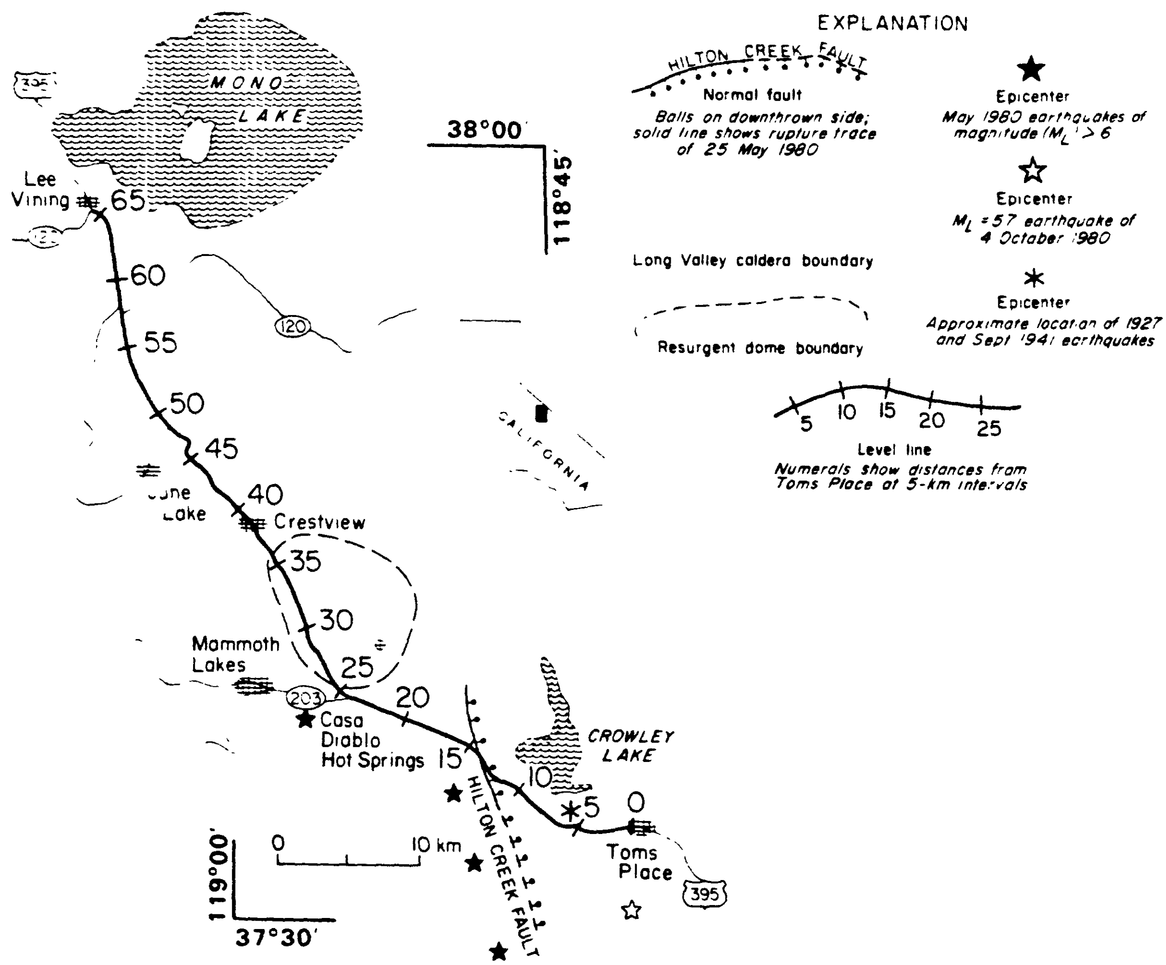
* Max. Allowed Closure in mm = $(16\ K_1 + 25\ K_2 + 64\ K_3)^{1/2}$ where K_1, K_2, and K_3 are the distances run (in km) using first-order class II, first-order class III, and second-order class II procedures.

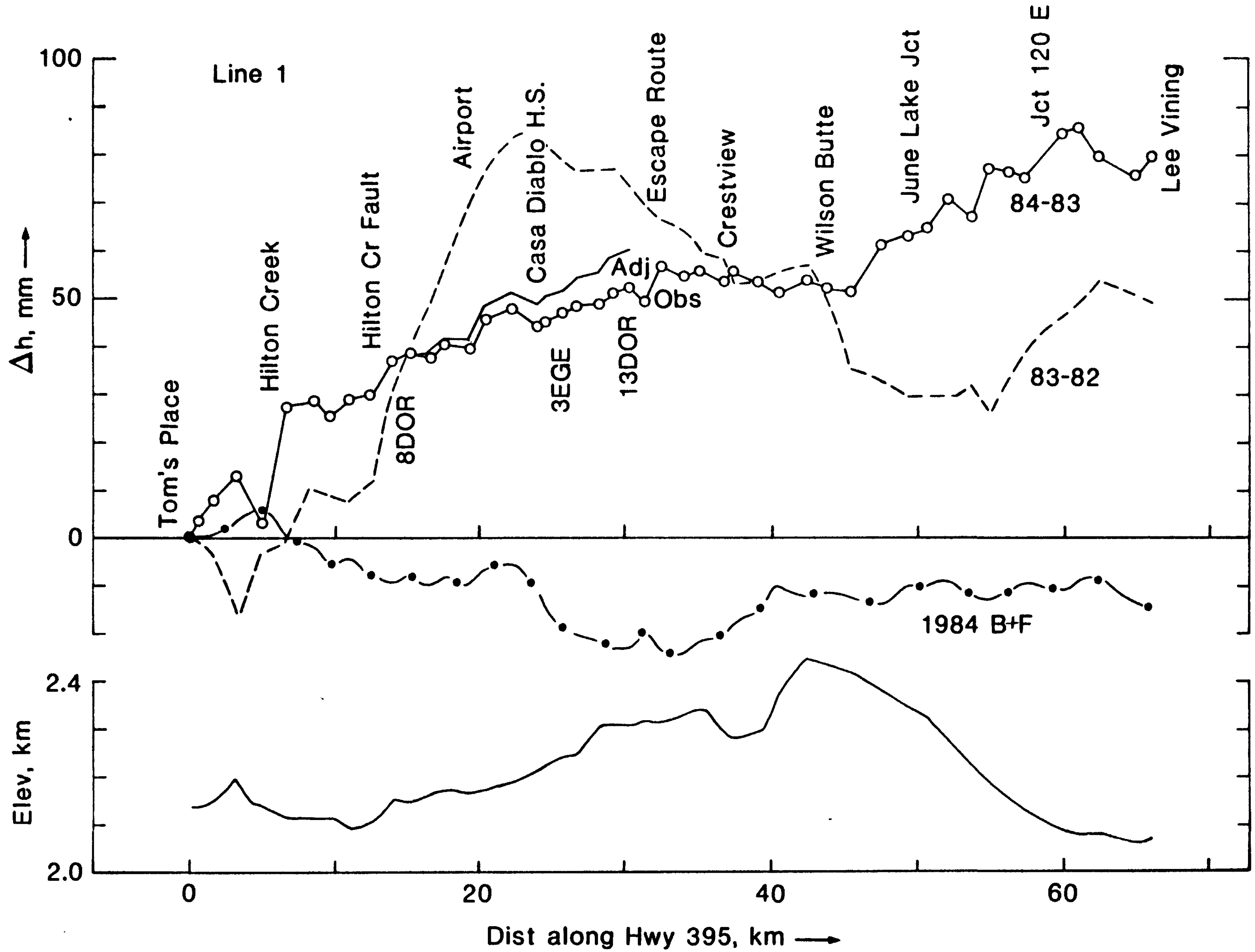


EXPLANATION
HILTON CREEK FAULT
Normal fault
Balls on downthrown side, solid line shows rupture trace of 25 May 1980
Long Valley caldera boundary
Resurgent dome boundary
Level line
Numerals show distances from Toms Place at 5-km intervals
MONO LAKE
38°00
118°45
Lee Vining
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Crestview
Mammoth Lakes
203
20
395
Casa Diablo Hot Springs
CROWLEY LAKE
HILTON CREEK FAULT
Toms Place
0
10 km
119°00
37°30

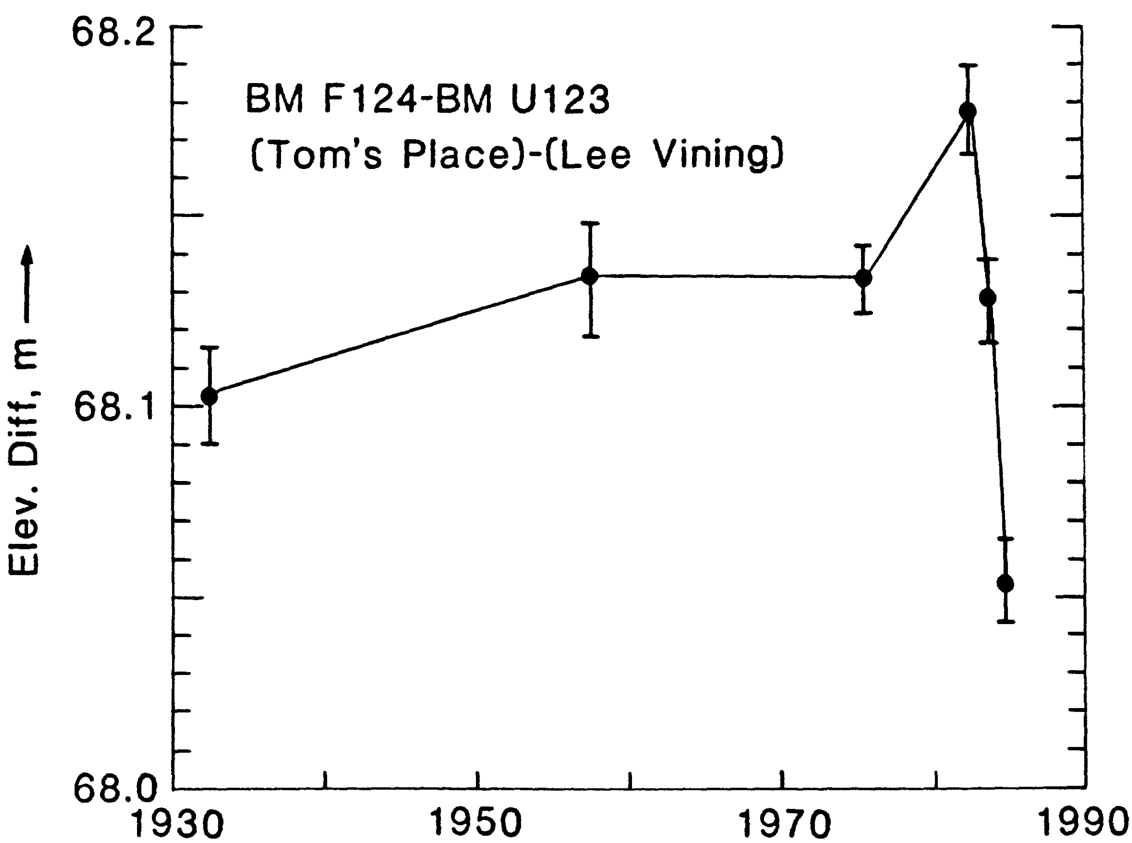
Table 2. Line length change (ΔL) with standard deviation (σ) for each of the 40 lines observed in the trilateration network (Figure 10) in 1983-1984. Also shown is the difference (O-C) between the observed length change and that predicted by the simple model described in the text.

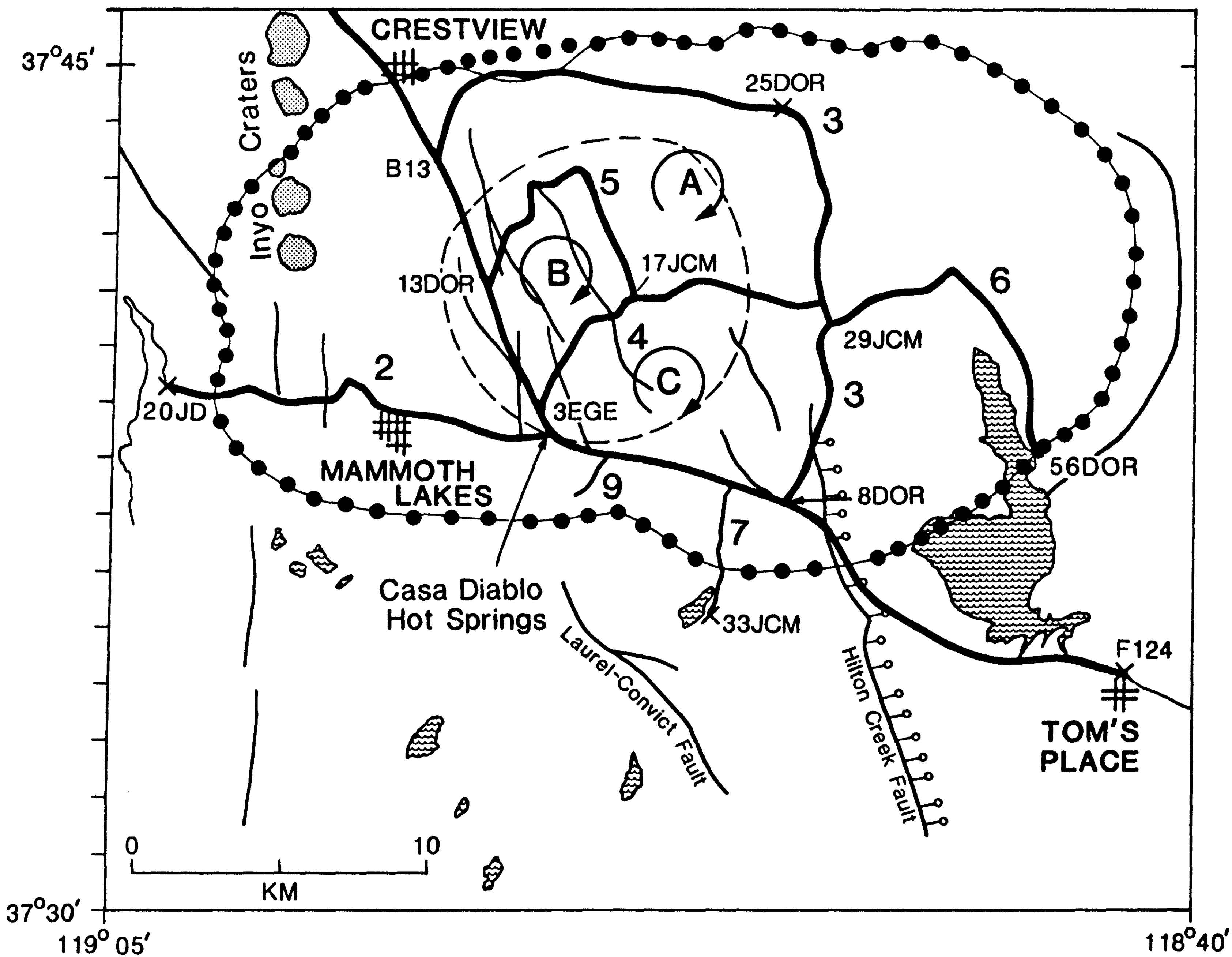
From	To	L km	ΔL mm	σ mm	O-C mm
Bald	Casa	15.5	28.4	6.1	- 5.4
	Crooked	8.4	3.6	4.9	7.1
	Crowley	28.8	26.7	9.2	3.1
	Glass	17.0	10.2	6.4	0.3
	Laurel	22.6	31.0	7.7	0.1
	Lookout	7.4	4.0	4.7	- 3.0
	Mammoth	20.6	27.4	7.2	2.0
	Mono	14.0	1.8	5.8	8.1
	Val	20.0	34.1	7.1	1.9
Banner	Casa	28.6	2.5	9.1	- 1.6
	Crowley	19.7	2.9	7.0	- 1.1
	Glass	14.0	0.6	5.8	- 0.6
	Laurel	30.6	13.4	9.6	- 0.8
	Sherwin	23.8	7.1	8.0	1.7
Casa	Convict	8.2	0.7	4.8	- 6.5
	Glass	22.0	10.0	7.5	- 7.2
	Laurel	7.1	- 2.3	4.7	0.9
	Lookout	10.4	33.8	5.2	- 3.3
	Mammoth	12.1	29.6	5.5	9.9
	Val	4.6	9.5	4.4	7.1
Convict	Crowley	9.4	- 4.9	5.0	5.2
	Glass	19.9	- 4.5	7.0	-17.1
	Laurel	8.0	26.0	4.8	8.5
Crooked	Glass	14.6	7.6	5.9	0.4
	Horse	15.1	2.3	6.0	8.0
	Mono	14.4	5.0	5.9	1.5
Crowley	Glass	23.3	13.4	7.8	1.2
Glass	Horse	24.3	7.1	8.1	6.4
	Laurel	27.0	14.7	8.7	- 8.3
	Lookout	21.7	14.3	7.5	- 3.4
	Mammoth	32.8	32.0	10.2	6.0
	Mono	28.7	20.0	9.2	10.1
	Sherwin	30.3	9.3	9.6	- 0.6
	Val	26.0	14.7	8.5	-14.4
Horse	Mono	20.7	15.9	7.2	14.1
Laurel	Mammoth	13.7	14.5	5.7	- 1.8
	Sherwin	20.2	7.3	7.1	6.1
Lookout	Val	14.3	52.4	5.9	22.3
Mammoth	Mono	27.6	15.6	8.9	3.3
	Val	11.3	11.0	5.3	3.8

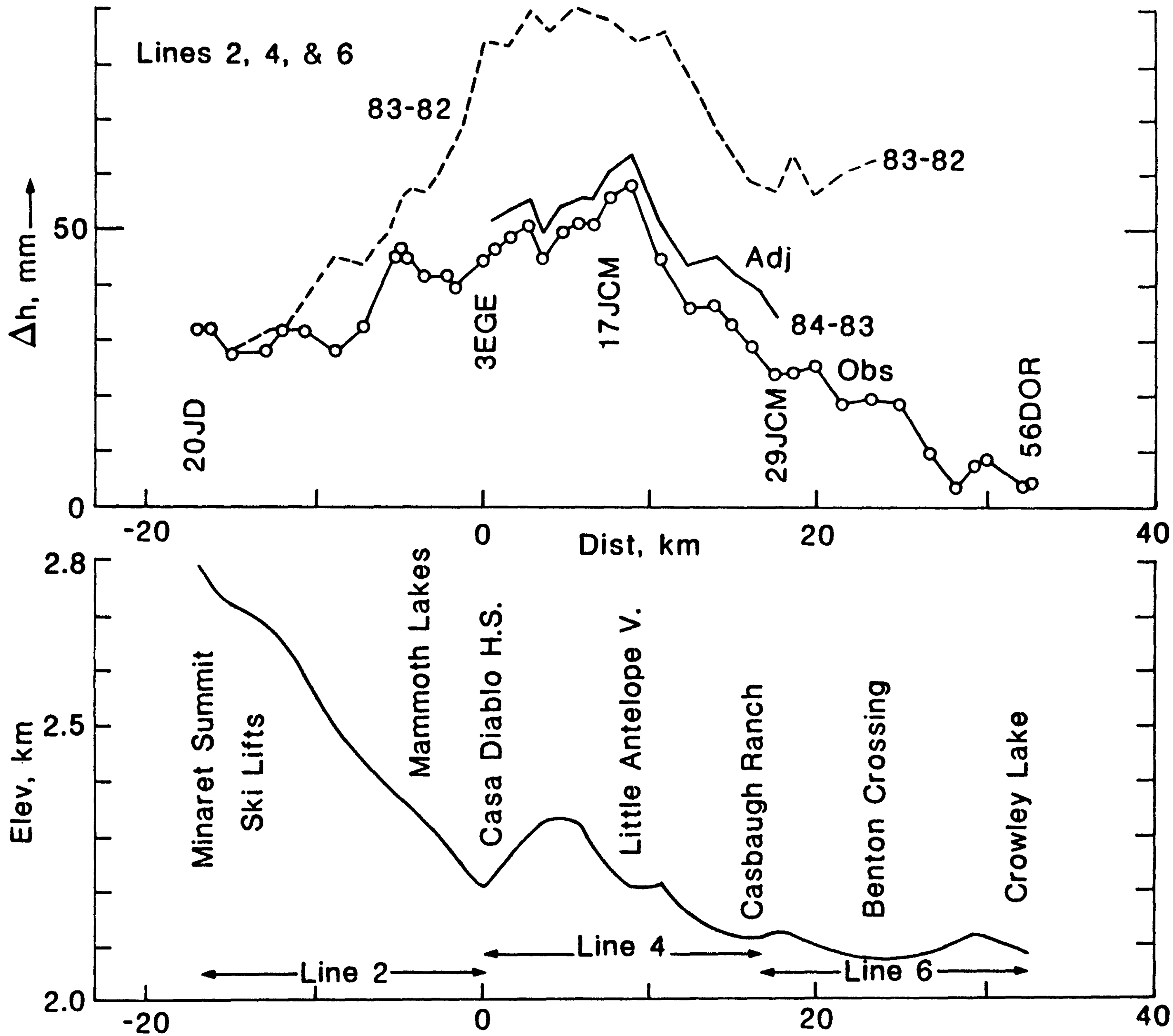

EXPLANATION
HILTON CREEK FAULT
Normal fault
Balls on downthrown side; solid line shows rupture trace of 25 May 1980
Epicenter
May 1980 earthquakes of magnitude (M_L) > 6
Epicenter
M_L = 5.7 earthquake of 4 October 1980
Epicenter
Approximate location of 1927 and Sept 1941 earthquakes
Long Valley caldera boundary
Resurgent dome boundary
5
10
15
20
25
Level line
Numerals show distances from Toms Place at 5-km intervals
MONO LAKE
38°00′
118°45′
Lee Vining
65
60
55
50
45
40
35
30
25
20
15
10
5
0
120
Crestview
Mammoth Lakes
203
Casa Diablo Hot Springs
CROWLEY LAKE
HILTON CREEK FAULT
Toms Place
395
0
10 km
119°00′
37°30′

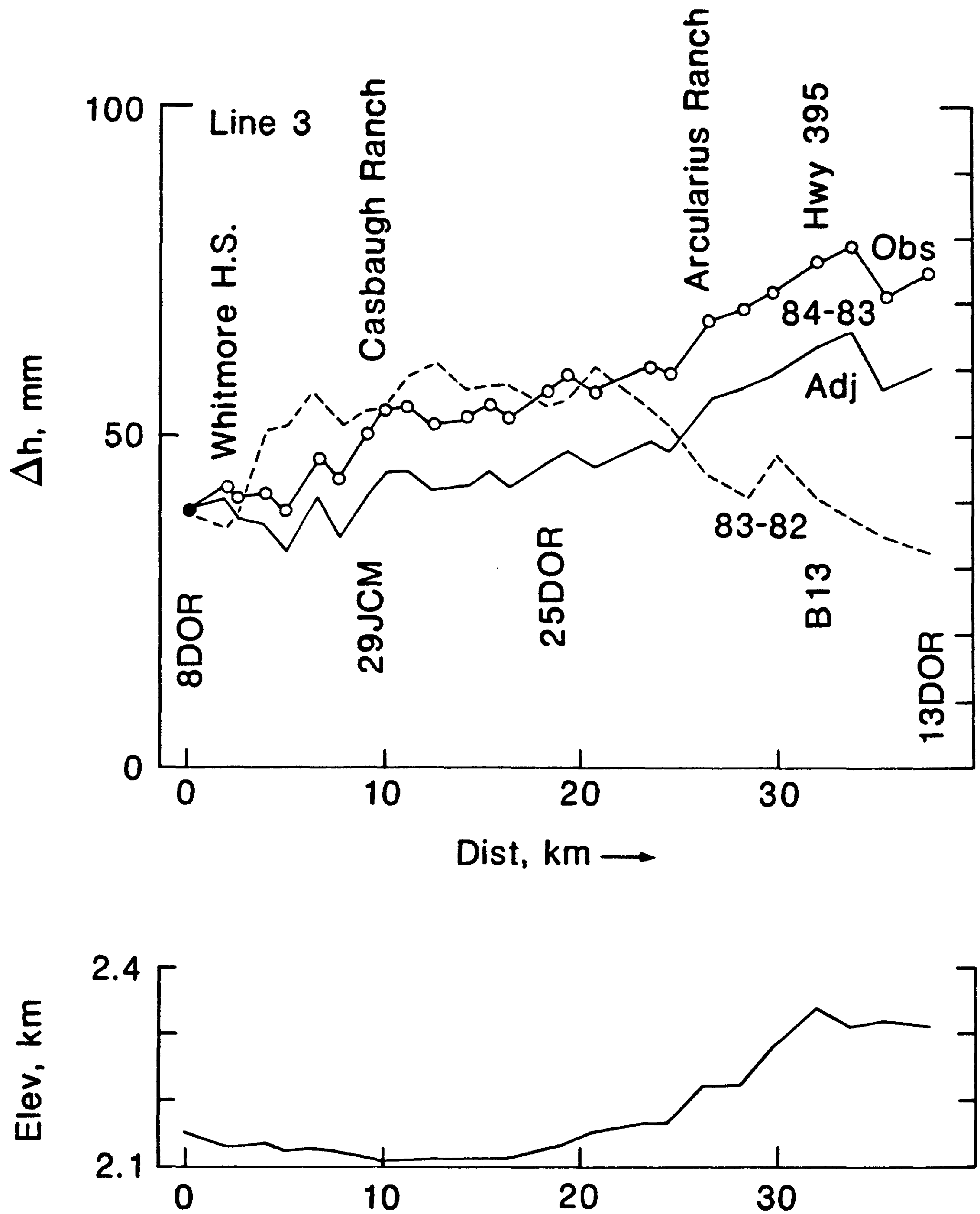


Line 1
Tom's Place
Hilton Creek
Hilton Cr Fault
8DOR
Airport
Casa Diablo H.S.
3EGE
13DOR
Adj
Obs
Escape Route
Crestview
Wilson Butte
June Lake Jct
Jct 120 E
Lee Vining
84-83
83-82
1984 B+F
Δh, mm
100
50
0
Elev, km
2.4
2.0
0
20
40
60
Dist along Hwy 395, km

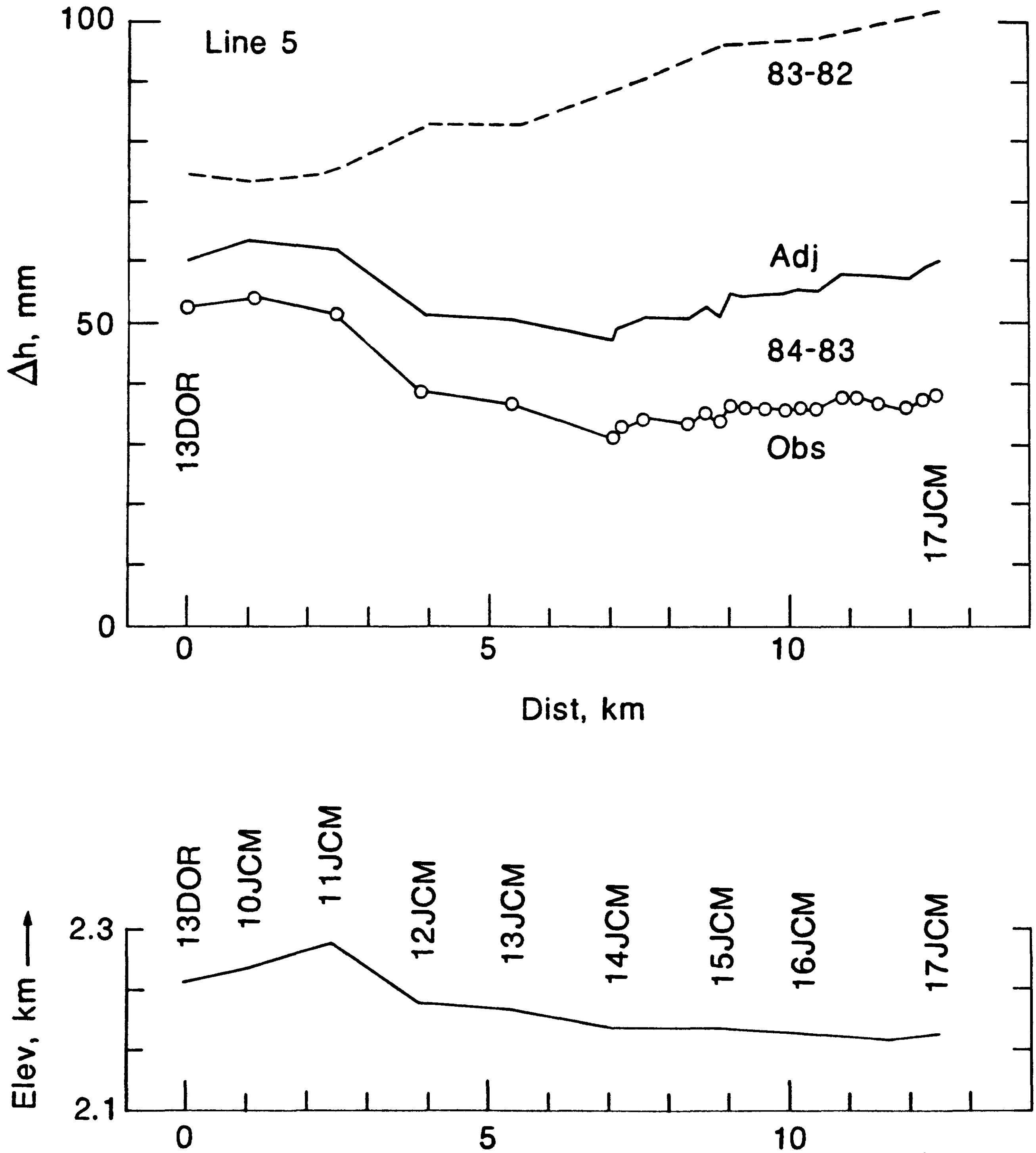

BM F124-BM U123
(Tom's Place)-(Lee Vining)
Elev. Diff, m
68.2
68.1
68.0
1930
1950
1970
1990

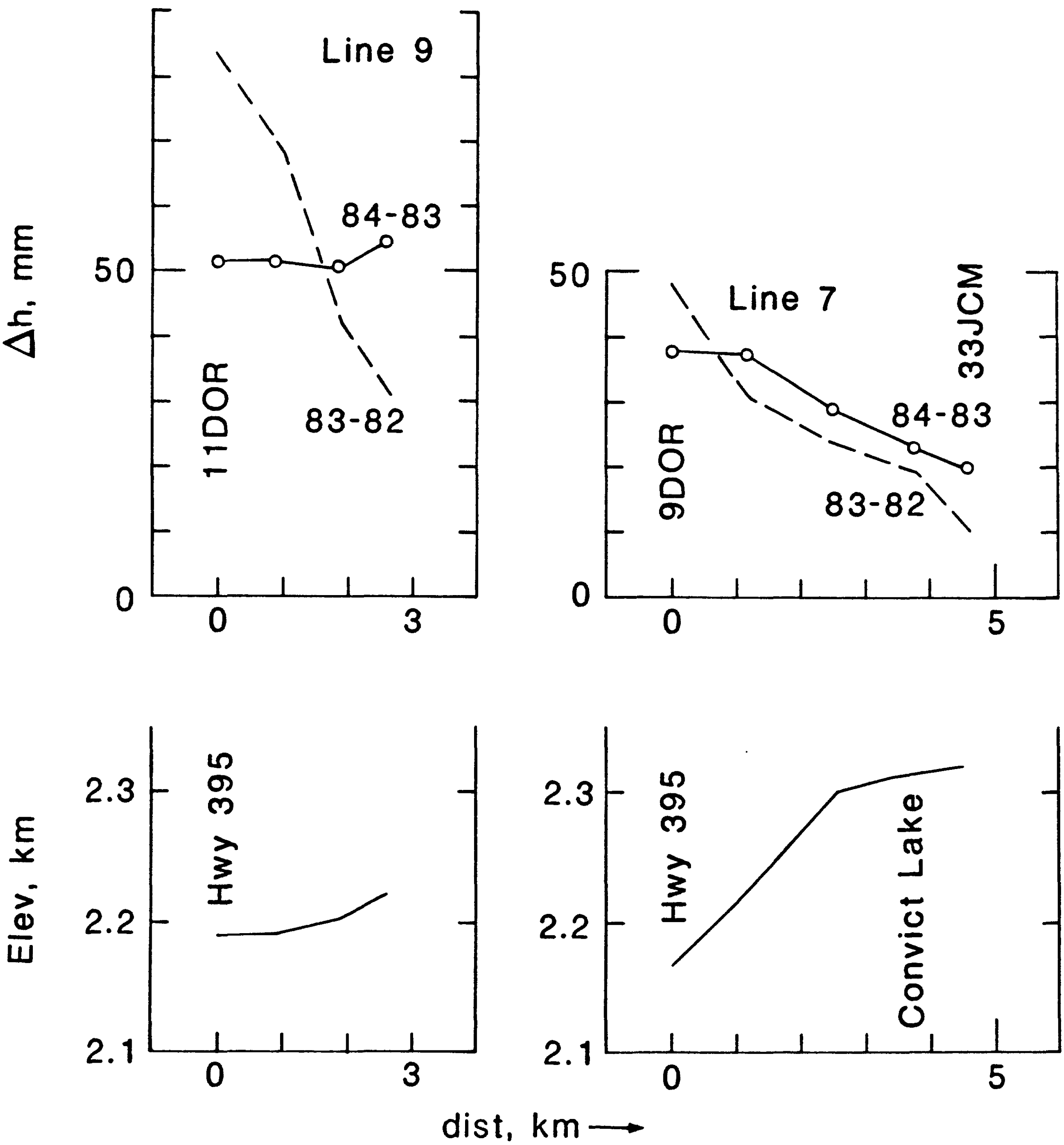

CRESTVIEW
Inyo
Craters
25DOR
3
B13
5
A
13DOR
B
17JCM
6
4
29JCM
2
C
3
20JD
3EGE
MAMMOTH
LAKES
56DOR
9
8DOR
7
Casa Diablo
Hot Springs
33JCM
Laurel-Convict Fault
Hilton Creek Fault
F124
TOM'S
PLACE
0
10
KM
37°45′
37°30′
119° 05′
118°40′


Lines 2, 4, & 6
83-82
83-82
Δh, mm
50
0
20JD
3EGE
17JCM
Adj
84-83
Obs
29JCM
56DOR
-20
0
20
40
Dist, km
2.8
2.5
2.0
Elev, km
Minaret Summit
Ski Lifts
Mammoth Lakes
Casa Diablo H.S.
Little Antelope V.
Casbaugh Ranch
Benton Crossing
Crowley Lake
Line 2
Line 4
Line 6
-20
0
20
40

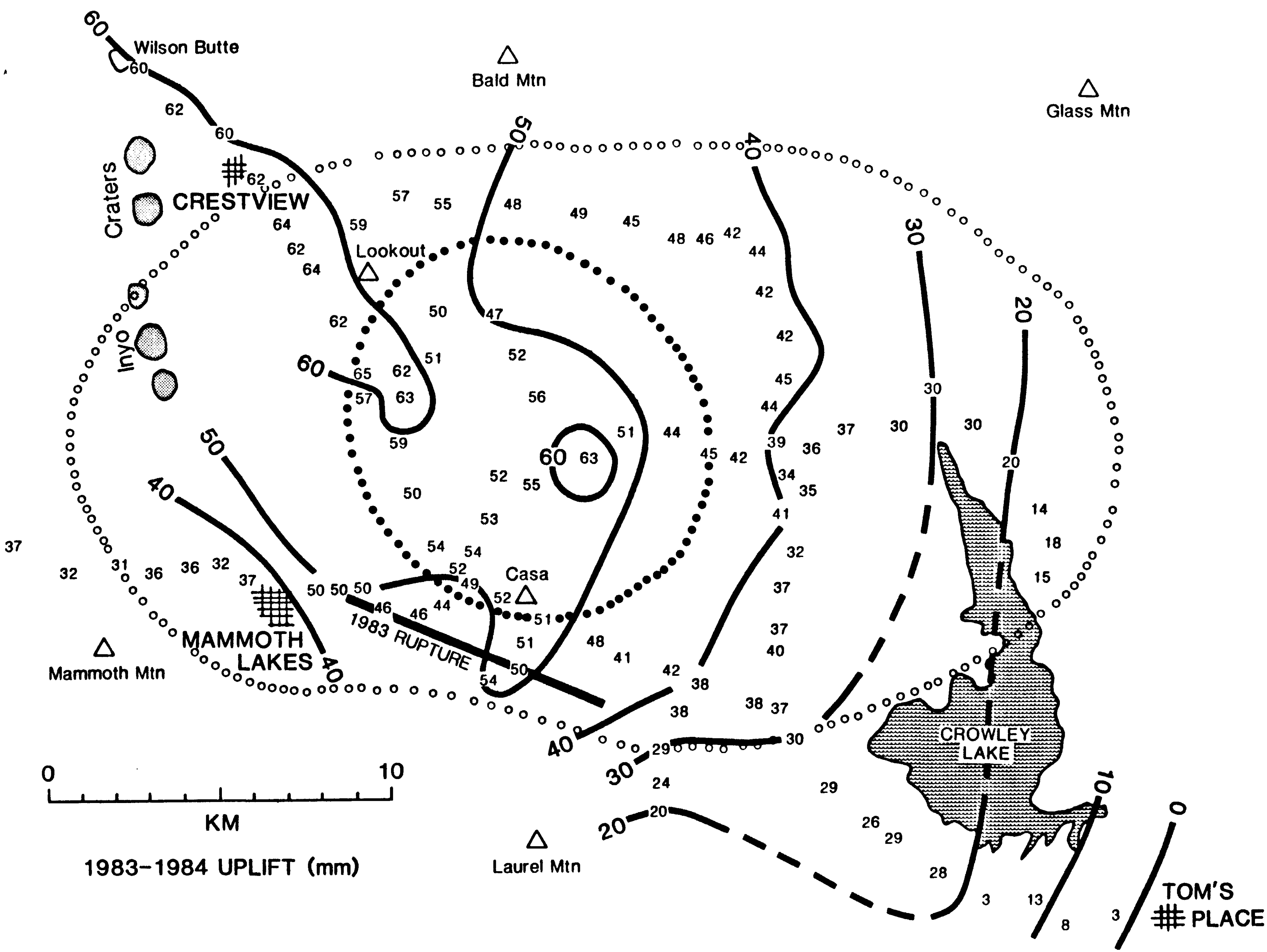

Line 3
Whitmore H.S.
Casbaugh Ranch
Arcularius Ranch
Hwy 395
Obs
84-83
Adj
83-82
8DOR
29JCM
25DOR
B13
13DOR
Δh, mm
100
50
0
0
10
20
30
Dist, km
Elev, km
2.4
2.1
0
10
20
30

6

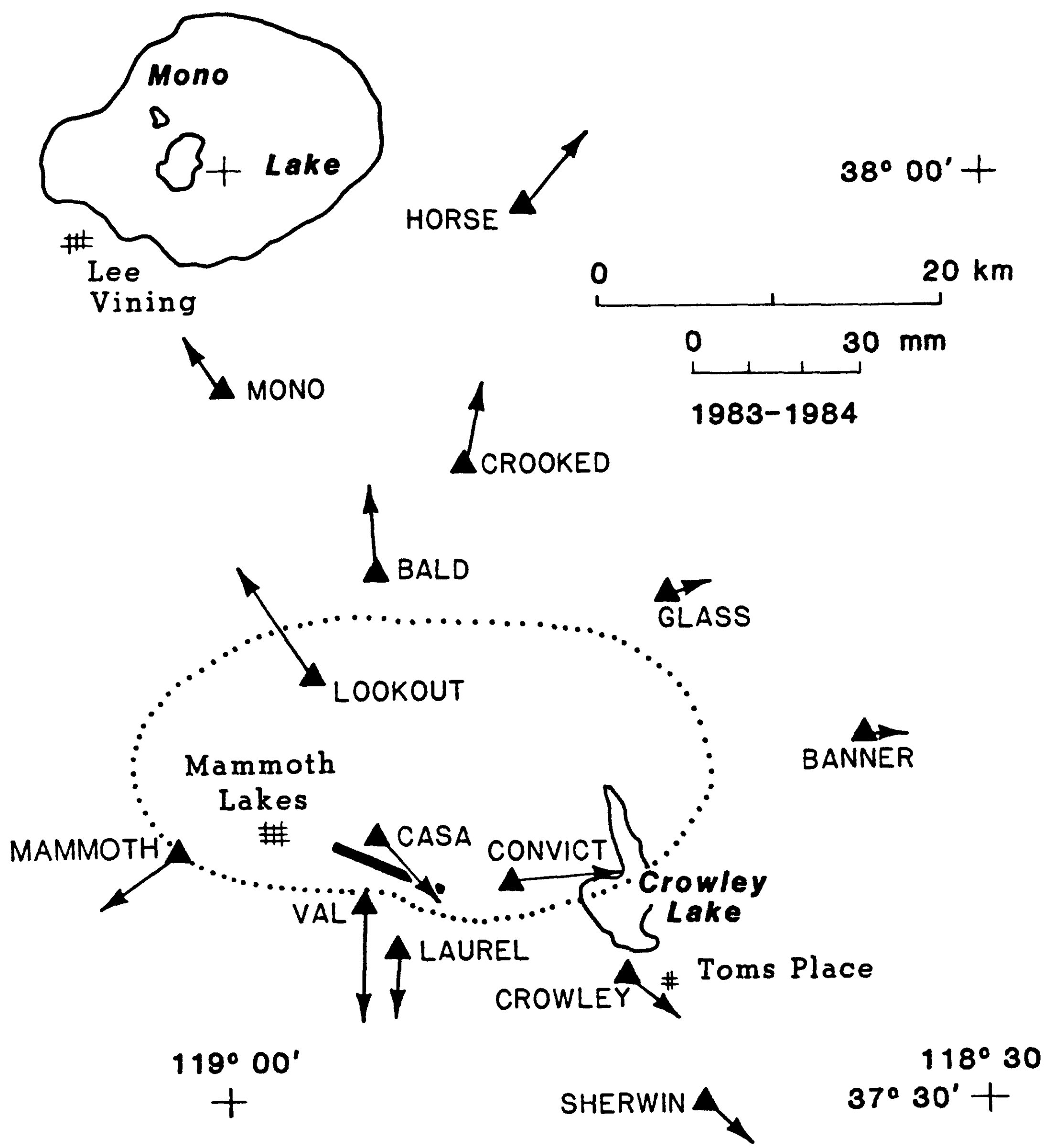

100
Line 5
83-82
Adj
Δh, mm
50
84-83
13DOR
Obs
17JCM
0
0
5
10
Dist, km
13DOR
10JCM
11JCM
12JCM
13JCM
14JCM
15JCM
16JCM
17JCM
2.3
Elev, km
2.1
0
5
10

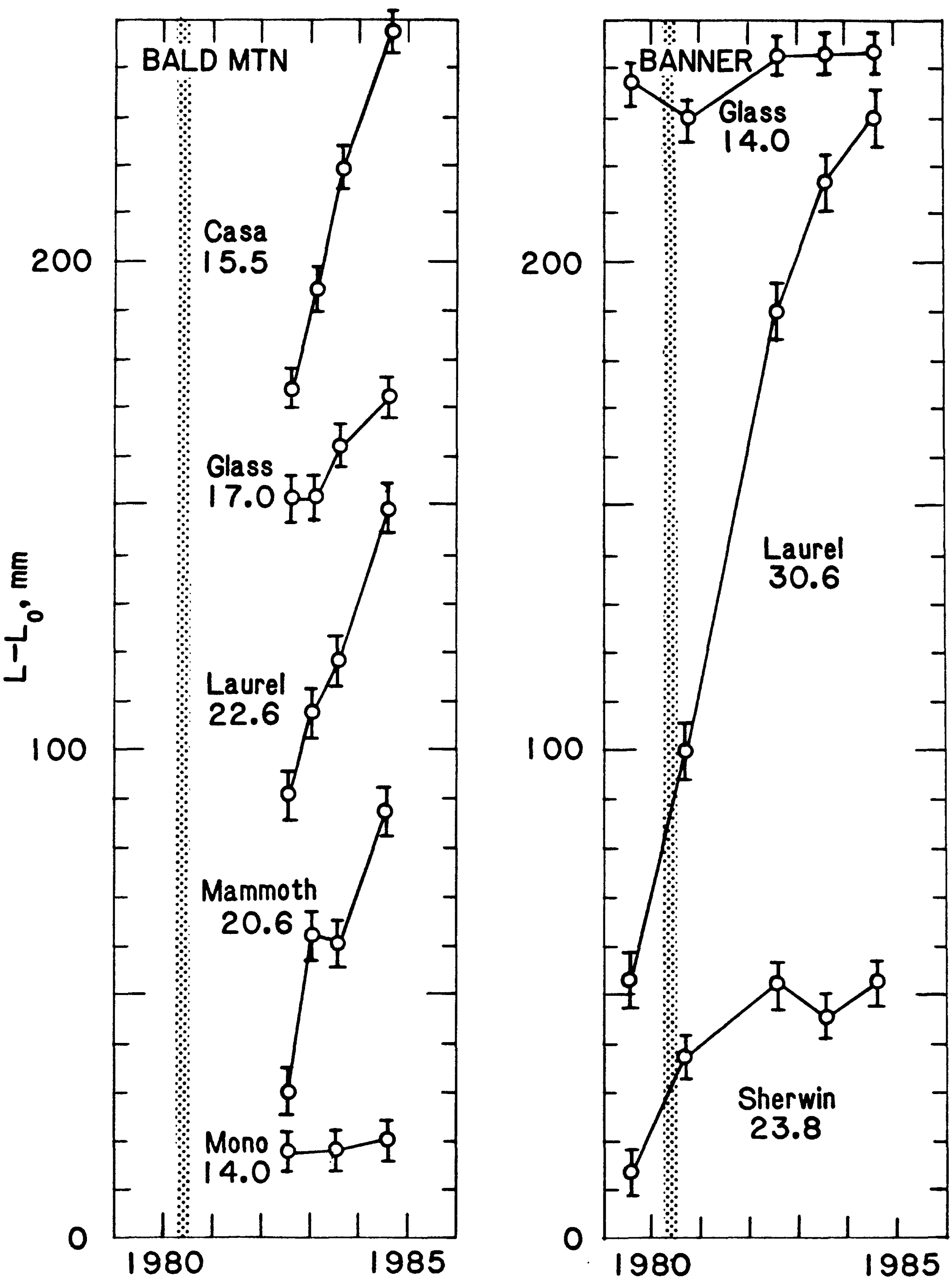


Line 9
84-83
83-82
11DOR
Δh, mm
50
0
0
3
Line 7
33JCM
84-83
83-82
9DOR
50
0
0
5
Elev, km
2.3
2.2
2.1
Hwy 395
0
3
2.3
2.2
2.1
Hwy 395
Convict Lake
0
5
dist, km

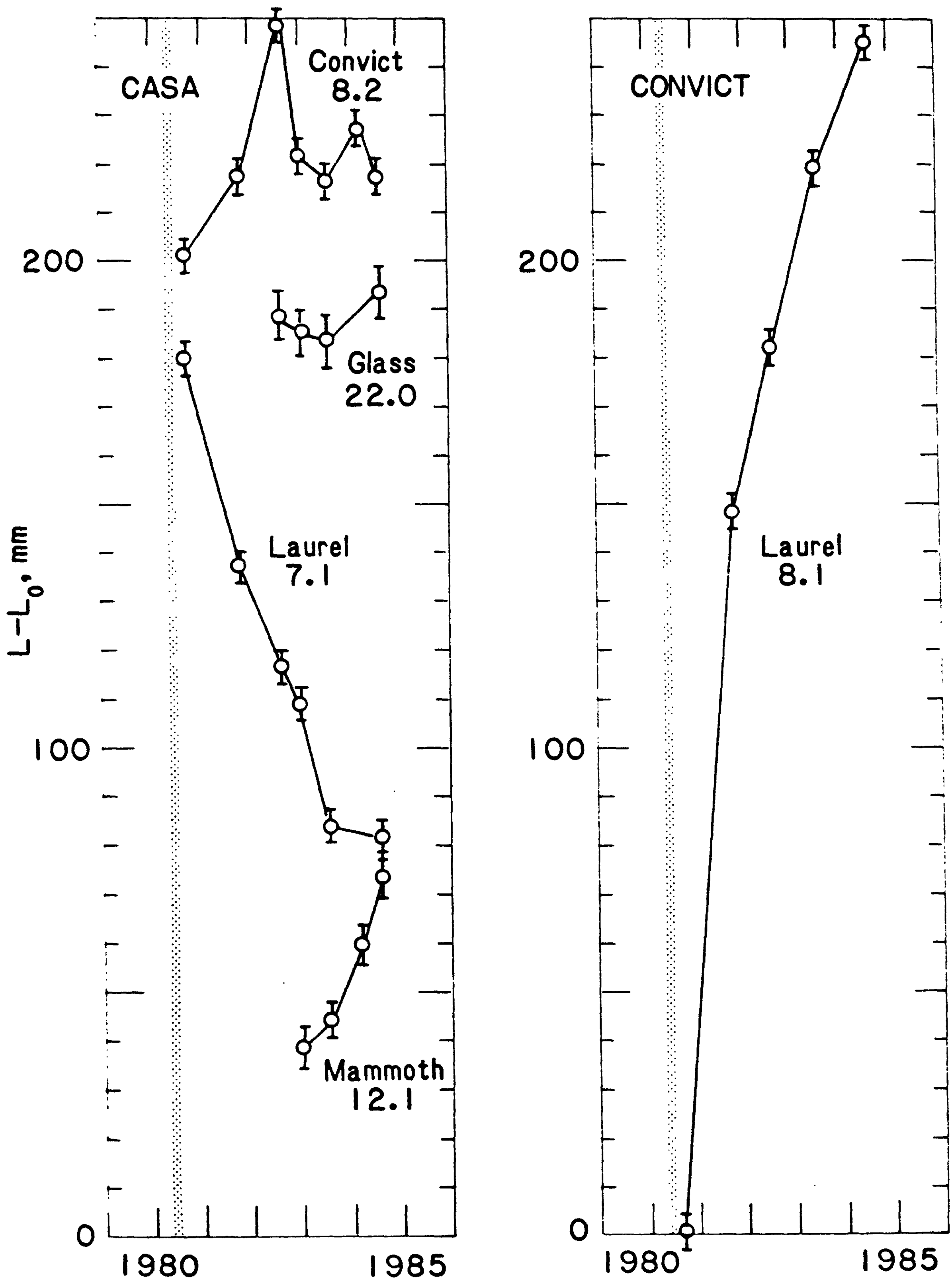


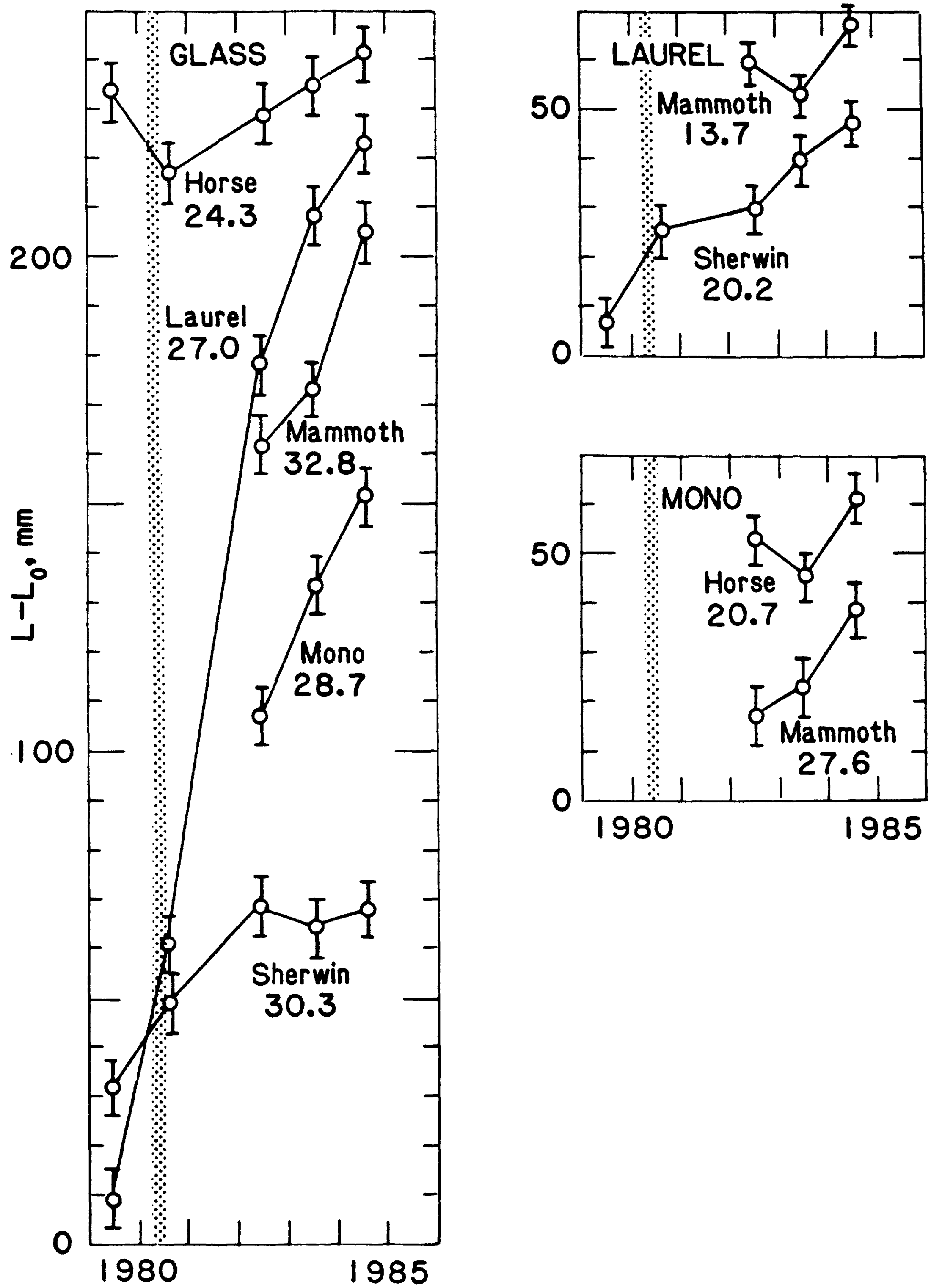
1983-1984 UPLIFT (mm)

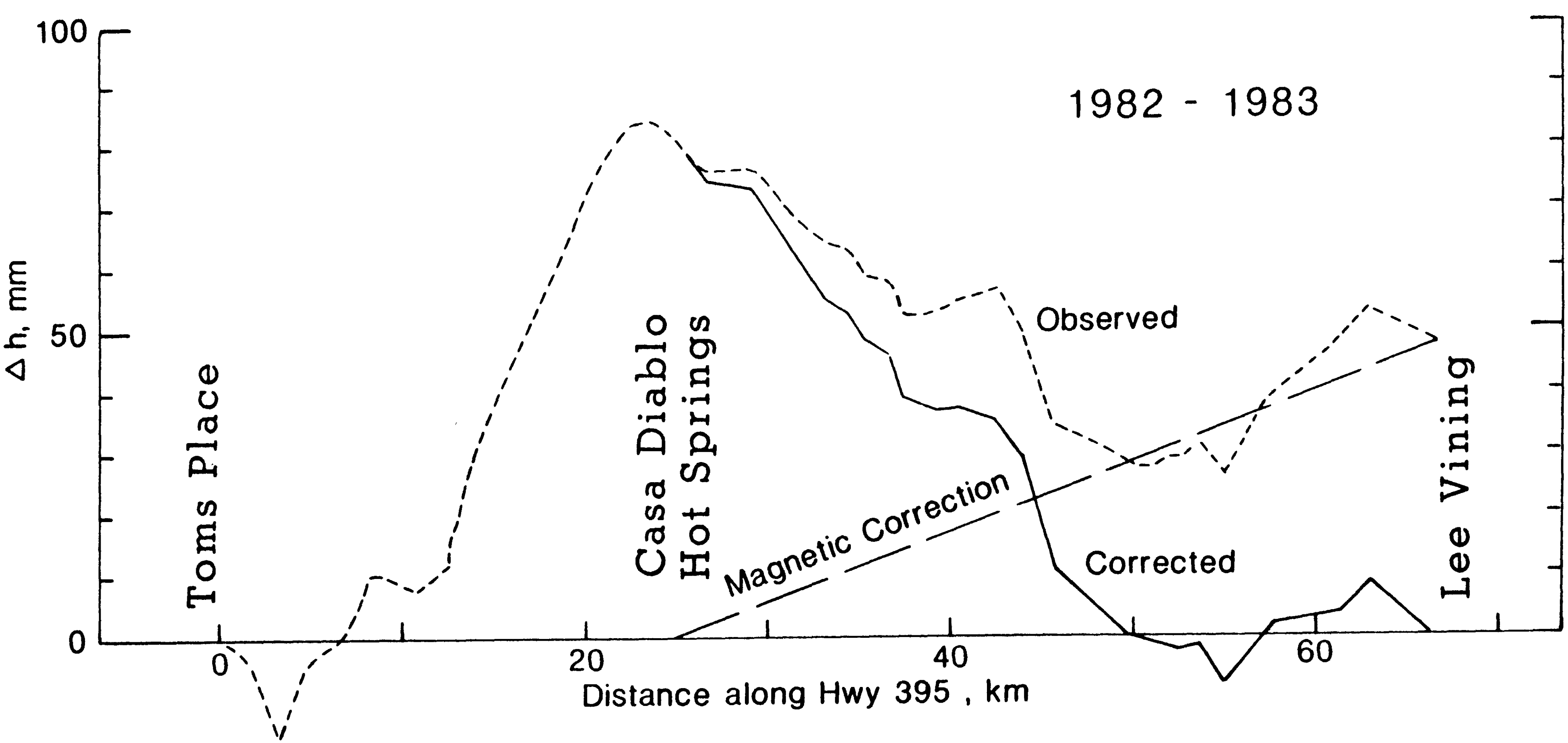

Mono
Lake
Lee
Vining
HORSE
38° 00′
0
20 km
0
30 mm
1983-1984
MONO
CROOKED
BALD
GLASS
LOOKOUT
BANNER
Mammoth
Lakes
CASA
CONVICT
MAMMOTH
Crowley
Lake
VAL
LAUREL
Toms Place
CROWLEY
119° 00′
118° 30′
37° 30′
SHERWIN

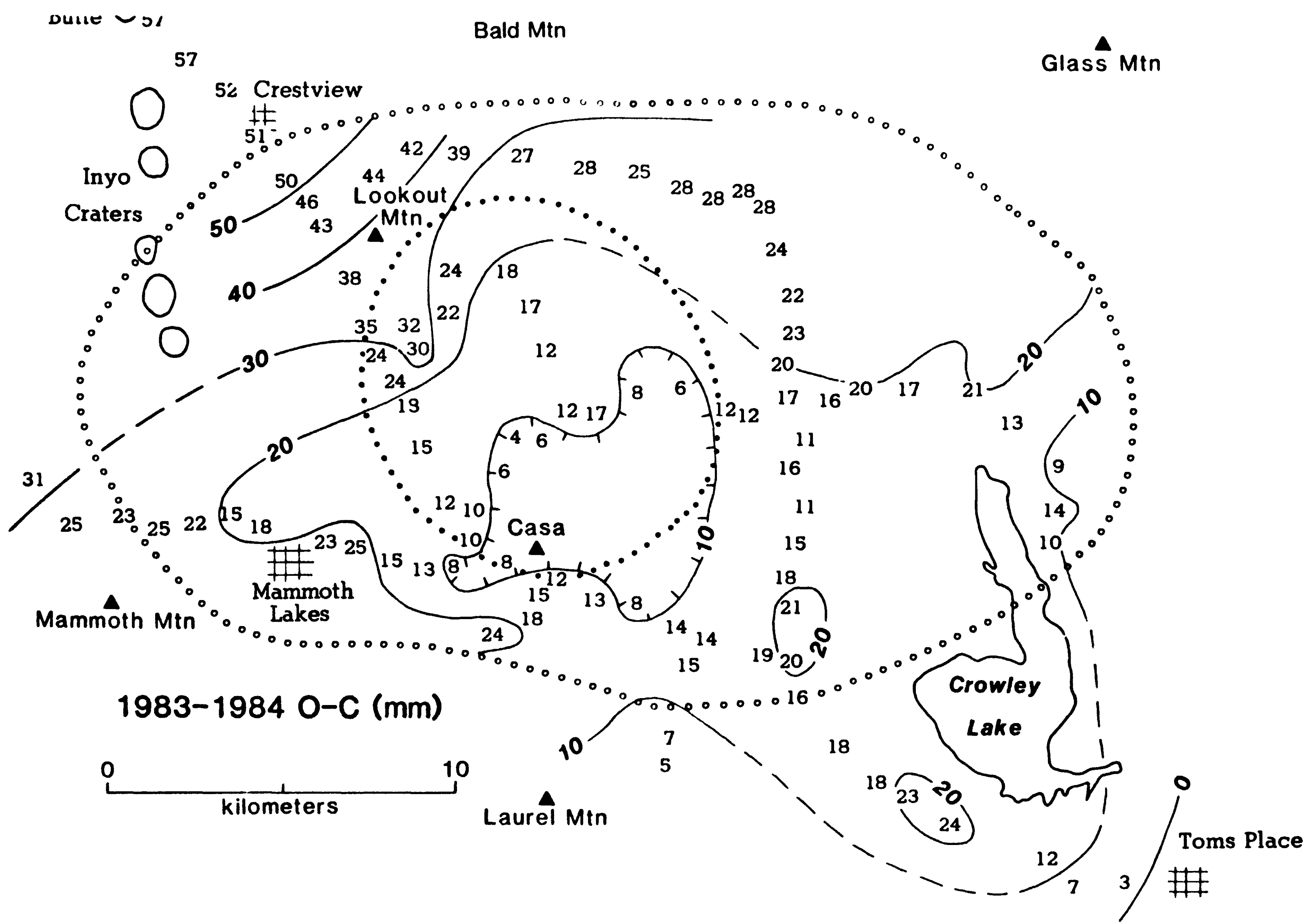

BALD MTN
Casa
15.5
Glass
17.0
Laurel
22.6
Mammoth
20.6
Mono
14.0
BANNER
Glass
14.0
Laurel
30.6
Sherwin
23.8
L−L0, mm
200
100
0
1980
1985

11


CASA
Convict
8.2
Glass
22.0
Laurel
7.1
Mammoth
12.1
CONVICT
Laurel
8.1
L-L0, mm
200
100
0
1980
1985


GLASS
Horse
24.3
Laurel
27.0
Mammoth
32.8
Mono
28.7
Sherwin
30.3
L−L0, mm
200
100
0
1980
1985
LAUREL
Mammoth
13.7
Sherwin
20.2
50
0
MONO
Horse
20.7
Mammoth
27.6
50
0
1980
1985


1982 - 1983
Δ h, mm
100
50
0
Toms Place
Casa Diablo
Hot Springs
Lee Vining
Observed
Corrected
Magnetic Correction
0
20
40
60
Distance along Hwy 395 , km



1983-1984 O-C (mm)