Bull Volcanol (1999) 61 : 83–91

ORIGINAL PAPER

D. Dzurisin

Results of repeated leveling surveys at Newberry Volcano, Oregon, and near Lassen Peak Volcano, California

Received: 10 September 1998 / Accepted: 4 December 1998

Abstract Personnel from the U.S. Geological Survey's Cascades Volcano Observatory conducted first-order, class-II leveling surveys near Lassen Peak, California, in 1991 and at Newberry Volcano, Oregon, in 1985, 1986, and 1994. Near Lassen Peak no significant vertical displacements had occurred along either of two traverses, 33 and 44 km long, since second-order surveys in 1932 and 1934. At Newberry, however, the 1994 survey suggests that the volcano's summit area had risen as much as 97 ± 22 mm with respect to a third-order survey in 1931. The 1931 and 1994 surveys measured a 37-km-long, east–west traverse across the entire volcano. The 1985 and 1986 surveys, on the other hand, measured only a 9-km-long traverse across the summit caldera with only one benchmark in common with the 1931 survey. Comparison of the 1985, 1986, and 1994 surveys revealed no significant differential displacements inside the caldera. A possible mechanism for uplift during 1931–1994 is injection of approximately 0.06 km^3 of magma at a depth of approximately 10 km beneath the volcano's summit. The average magma supply rate of approximately 1×10^{-3} km^3/year would be generally consistent with the volcano's growth rate averaged over its 600,000-year history (0.7–1.7 $\times 10^{-3}$ km^3/year).

Key words Newberry volcano · Lassen Peak volcano · Leveling · Volcano geodesy · Crustal uplift

Introduction

Vertical displacements near volcanoes, faults, fluid-withdrawal zones, or other areas of interest can be measured by repeating leveling surveys that were commonly conducted in past decades to establish elevations along roadways or railways. This approach has been used to measure uplift at the Yellowstone caldera in Wyoming between 1923 and 1975–1977 (72.6 cm or 1.4 ± 0.1 cm/year; Pelton and Smith 1982), uplift at the Long Valley caldera in California between 1975 and 1980 (25 cm; Savage and Clark 1982), and subsidence at Medicine Lake Volcano in California between 1954 and 1989 (38.9 ± 4.3 cm or 1.1 ± 0.1 cm/year; Dzurisin et al. 1991). This paper summarizes results of repeated leveling surveys near Lassen Peak in northern California and at Newberry Volcano in central Oregon, two active volcanoes in the Cascade Range with their most recent eruptions in 1914–1917 and approximately 1,300 years ago, respectively.

The leveling surveys

Near Lassen Peak, the National Geodetic Survey (NGS, formerly U.S. Coast and Geodetic Survey, USC&GS) conducted second-order leveling surveys between Mineral and Chester (44 km) in 1932 and between Viola and Old Station (33 km) in 1934 (Fig. 1). In 1991 a team from the U.S. Geological Survey's Cascades Volcano Observatory (USGS/CVO) repeated those surveys to first-order, class-II standards. The traverses were not connected in 1991, because most of the intervening benchmarks had been destroyed. New benchmarks were established approximately 1 km apart as a baseline for future surveys (Yamashita and Iwatsubo 1992).

A third-order leveling traverse across the broad shield of Newberry Volcano (37 km) was first measured by USGS levelman G.A. Fischer in July to August 1931 (Fig. 2). The traverse began 6.2 miles (9.9 km) north of La Pine, Oregon, at the junction of The Dalles-California Highway and the road eastward to Paulina Lake. Fischer started his traverse at a USGS second-order line measured by L.F. Biggs in 1908 with the intention

Editorial responsibility: D. A. Swanson

Daniel Dzurisin
David A. Johnston Cascades Volcano Observatory, U.S. Geological Survey, 5400 MacArthur Blvd., Vancouver, Washington 98661, USA
e-mail: dzurisin@usgs.gov

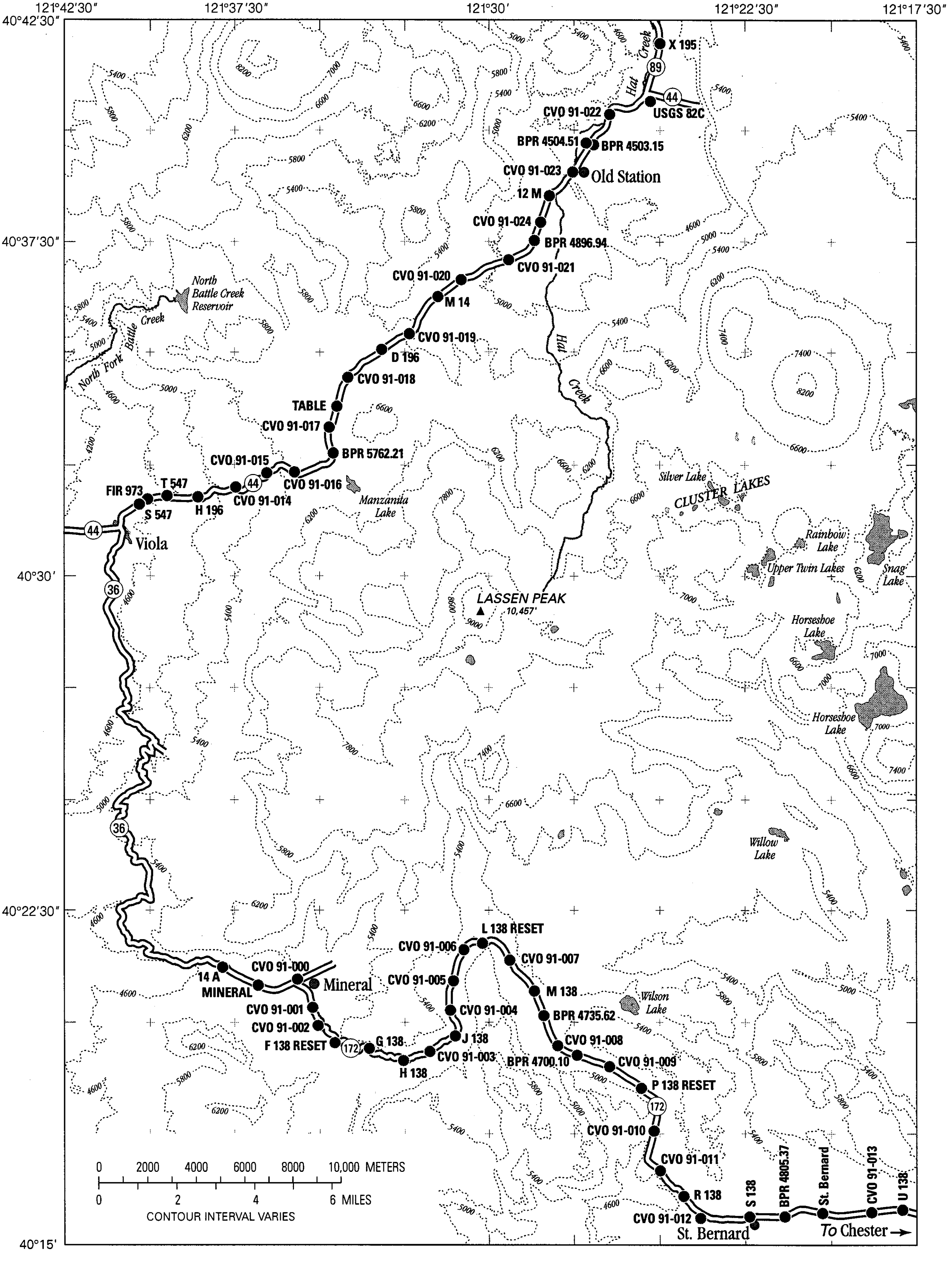
121°42'30"
121°37'30"
121°30'
121°22'30"
121°17'30"
40°42'30"
40°37'30"
40°30'
40°22'30"
40°15'
X 195
89
44
USGS 82C
Hat Creek
CVO 91-022
BPR 4504.51
BPR 4503.15
CVO 91-023
Old Station
12 M
CVO 91-024
BPR 4896.94
CVO 91-021
CVO 91-020
M 14
CVO 91-019
D 196
CVO 91-018
TABLE
CVO 91-017
BPR 5762.21
CVO 91-015
CVO 91-016
T 547
FIR 973
S 547
H 196
CVO 91-014
Viola
36
North Battle Creek Reservoir
North Fork Battle Creek
Manzanita Lake
LASSEN PEAK
10,457'
Silver Lake
CLUSTER LAKES
Rainbow Lake
Upper Twin Lakes
Snag Lake
Horseshoe Lake
Horseshoe Lake
Willow Lake
Wilson Lake
L 138 RESET
CVO 91-006
CVO 91-007
CVO 91-005
M 138
CVO 91-004
BPR 4735.62
14 A
CVO 91-000
MINERAL
Mineral
CVO 91-001
CVO 91-002
J 138
CVO 91-008
F 138 RESET
172
G 138
H 138
CVO 91-003
BPR 4700.10
CVO 91-009
P 138 RESET
CVO 91-010
CVO 91-011
R 138
CVO 91-012
S 138
BPR 4805.37
St. Bernard
CVO 91-013
U 138
St. Bernard
To Chester
0 2000 4000 6000 8000 10,000 METERS
0 2 4 6 MILES
CONTOUR INTERVAL VARIES

Fig. 1 Leveling traverses near Lassen Peak, California. The traverse between Mineral and Chester is 44 km long and was measured in 1932 and 1991. The traverse between Viola and Old Station is 33 km long and was measured in 1934 and 1991 (see Fig. 3). Contours in feet (1 foot = 0.348 meters)

of leveling eastward over Newberry Volcano to China Hat, a distance of 28.5 miles (45.9 km). His plan conformed to standards of the day for third-order surveys: "The grade of work classed as third order should not be extended more than 30 miles from work of higher accuracy" (Birdseye 1928, p 130). Near China Hat, Fischer tied to a third-order line measured in 1929 by Sutherland of the Oregon Geographic Board. The closure between Biggs' traverse near La Pine and Sutherland's traverse near China Hat exceeded the allowable limit of $0.05\cdot\sqrt{L}$ ft, where L is the length of circuit in miles. Following guidelines set forth by Birdseye (1928), Fischer continued his traverse northward from China Hat approximately 13 miles (20.9 km) to Evans Well, where he tied to a USC&GS first-order line. Closure between La Pine and Evans Well was 0.208 ft (6.3 cm), within the allowable limit of 0.323 ft (9.8 cm) over a distance of 41.7 miles (67.1 km). Fischer ended his traverse and distributed the closure error linearly with distance between La Pine and Evans Well. Data used here include this correction plus others described by Birdseye (1928).

A USGS/CVO team established a 9-km-long, first-order leveling traverse across the summit caldera of Newberry Volcano in 1985 and measured it again in 1986 (Yamashita and Doukas 1987). The caldera traverse includes only one benchmark recovered from the 1931 survey, so the 1985 and 1986 measurements cannot be compared with the 1931 measurements to determine vertical displacements. In 1994 a USGS/CVO team repeated the larger survey from near Highway 97 eastward across the summit caldera to near China Hat. The 1994 survey conformed to first-order, class-II standards (Yamashita et al. 1995).

Procedures and accuracy

Standards and accuracy for leveling surveys, including changes through time as equipment and procedures improved, were discussed by Vanicek et al. (1980) and by the Federal Geodetic Control Committee (1984). The standard deviation of an elevation difference between benchmarks measured by a leveling survey is given by

$$\sigma(h)=\frac{\beta}{\sqrt{j}}\cdot\sqrt{L}$$

where β is a constant factor for each order, class, and vintage of survey, $j=1$ for single-run surveys or $j=2$ for double-run surveys, and L is the distance in kilometers along the leveling route from a reference benchmark to the benchmark in question. For surveys that are double-run, β can be calculated from observed misclosures. For single-run surveys, Vanicek et al. (1980) assigned a value of β for each order, class, and vintage of survey based on the experience of NGS and USGS.

The standard deviation of a height change measured by comparison of two leveling surveys is given by

$$\sigma(\delta h)=\sqrt{\frac{\beta_1^2}{j_1}+\frac{\beta_2^2}{j_2}}\cdot\sqrt{L}$$

These statistics describe only random errors that remain after appropriate corrections have been made and do not account for uncorrected systematic errors. Both error types can be minimized by proper field procedures. Values of β (from Vanicek et al. 1980), $\sigma(h)$, and $\sigma(\delta h)$ for the surveys discussed here are given in Tables 1 and 2.

Lassen results

At Lassen the 1932 and 1991 surveys between Mineral and Chester and the 1934 and 1991 surveys between Viola and Old Station reveal no changes larger than the

Table 1 Characteristics of leveling surveys

Year	Order, class	Location	Length (km)	β^a (mm/km$^{1/2}$)	$\sigma(h)$ (mm)
Lassen					
1932	Second order, class II	Mineral–Chester	44.1	3.0	$3.0\cdot L^{1/2}$
1934	Second order, class II	Viola–Old Station	33.4	3.0	$3.0\cdot L^{1/2}$
1991	First order, class II	Mineral–Chester	44.1	0.7	$0.7\cdot L^{1/2}$
		Viola–Old Station	33.4	0.7	$0.7\cdot L^{1/2}$
Newberry					
1931	Third order	Hwy 97–China Hat	37.5	6.0	$6.0\cdot L^{1/2}$
1985	First order, class II	Summit caldera	9.3	0.7	$0.7\cdot L^{1/2}$
1986	First order, class II	Summit caldera	9.3	0.7	$0.7\cdot L^{1/2}$
1994	First order, class II	Hwy 97–China Hat	37.5	0.7	$0.7\cdot L^{1/2}$

[a] From Vanicek et al. 1980

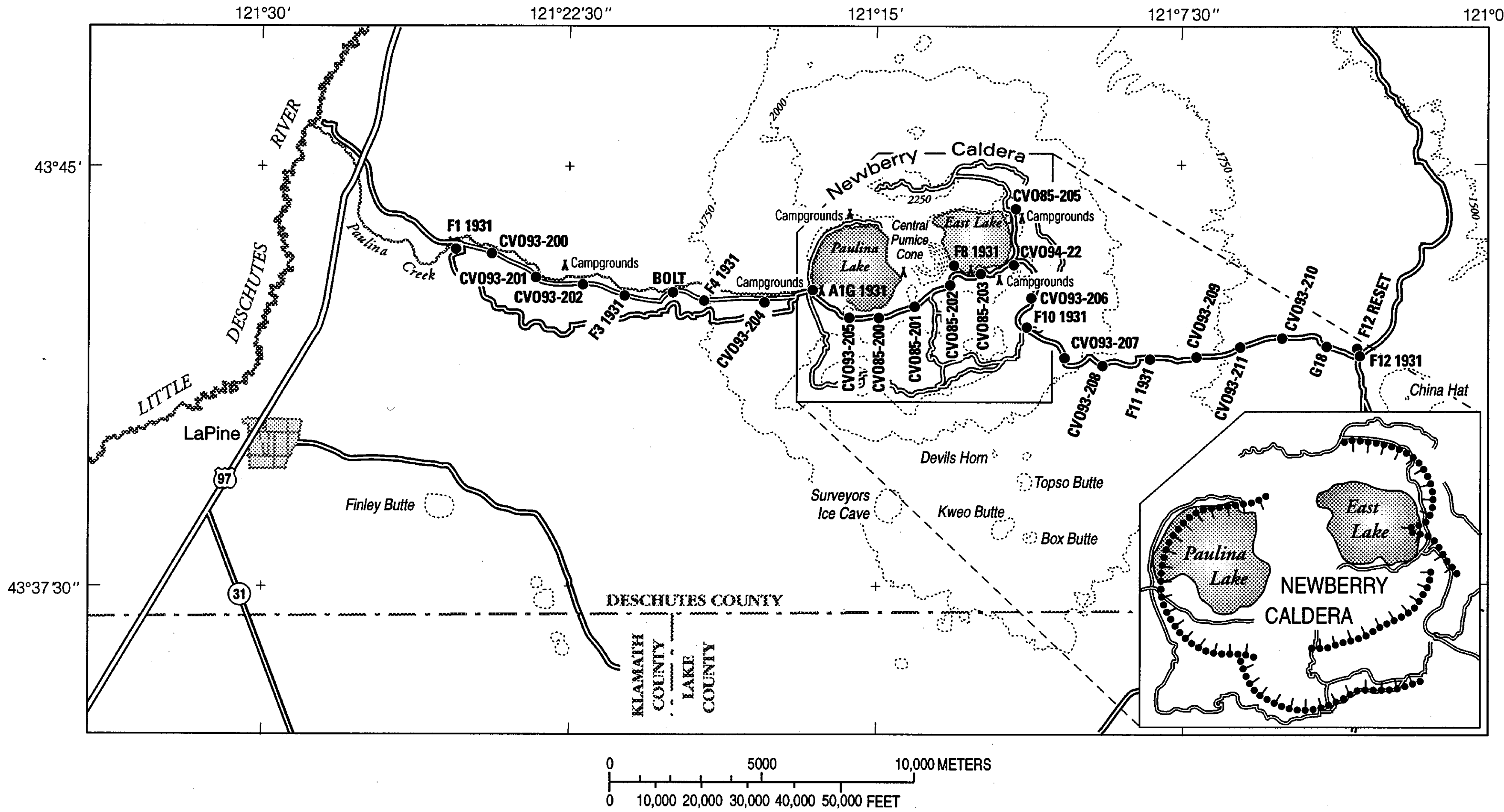

Fig. 2 Leveling traverse across Newberry Volcano, from near Highway 97 north of La Pine, Oregon, eastward to near China Hat (37 km, benchmarks F1 1931–F12 RESET), measured in 1931 and 1994. The 1931 survey continued northward approximately 13 miles (20.9 km) from China Hat to Evans Well (not shown). A 9-km-long portion of the traverse across the summit caldera was measured in 1985, 1986, and 1994 (see Fig. 4). Approximate caldera outline in *inset* is from MacLeod et al. (1995). Contours in feet

Table 2 Uncertainty in height change, $\sigma(\delta h)$

Survey interval	Location	$\sigma(\delta h)$
Lassen		
1932–1991	Mineral–Chester	$3.1 \cdot L^{1/2}$
1934–1991	Viola–Old Station	$3.1 \cdot L^{1/2}$
Newberry		
1931–1985	Summit caldera	$6.1 \cdot L^{1/2}$
1931–1994	Hwy 97–China Hat	$6.1 \cdot L^{1/2}$
1985–1986	Summit caldera	$1.0 \cdot L^{1/2}$
1985–1994	Summit caldera	$1.0 \cdot L^{1/2}$
1986–1994	Summit caldera	$1.0 \cdot L^{1/2}$

uncertainty in the measurements (Fig. 3). Benchmarks 14 A near Mineral and H196 near Viola were held fixed for this analysis. Elevation changes are less than $\sigma(\delta h)$ for 8 of 13 benchmarks and less than $2\sigma(\delta h)$ for 12 of 13, consistent with the expected statistical variation in the measurements if no real changes occurred. Apparently, the area was stable from 1932 to 1991.

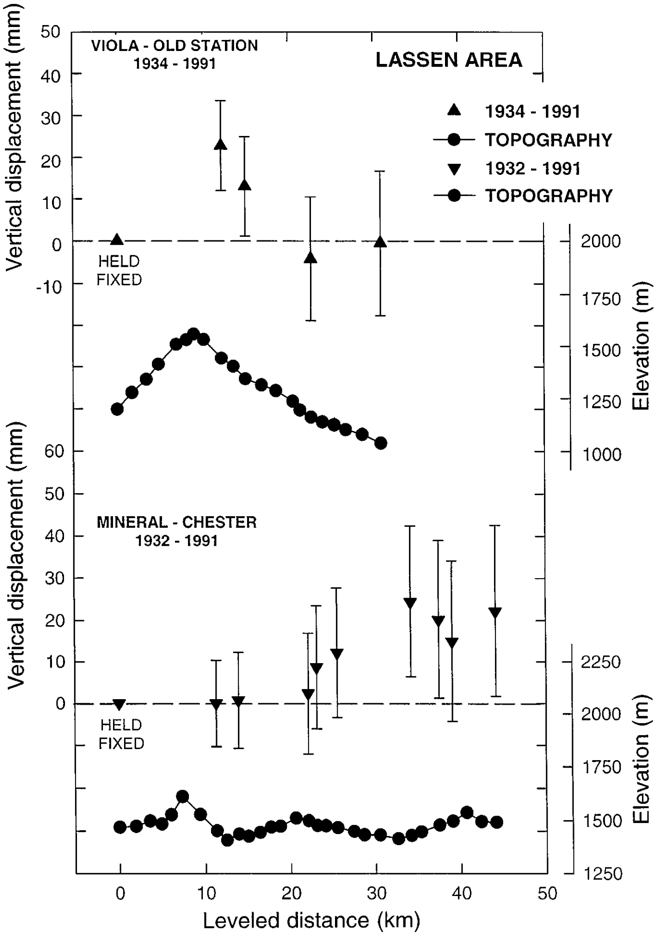

Fig. 3 Vertical displacements and topography between Viola and Old Station and between Mineral and Chester for the periods 1934–1991 and 1932–1991, respectively. Benchmarks H196 near Viola and 14 A near Mineral were held fixed. *Error bars* represent one standard deviation from expected random leveling error

Newberry Results, 1931–1994

At Newberry Volcano, comparison of the 1931 and 1994 surveys reveals changes that exceed $\sigma(\delta h)$ everywhere except at the end of the traverse (Fig. 4). In fact, the changes exceed $2\sigma(\delta h)$ along more than half of the traverse, including the upper flanks and summit area. Benchmark F1 at the west end of the traverse near Highway 97 was held fixed. The computed vertical displacements are essentially the same if F12 at the east end of the traverse is held fixed, because the relative change between the two marks is only 16 ± 37 mm. The largest change, 97 ± 22 mm with respect to F1, occurs at A1G near the west rim of the summit caldera, at the bridge over Paulina Creek. The pattern of changes mimics the topography in a general way, raising the possibility of systematic error in one or both of the surveys.

Potential sources of systematic error

The most common types of systematic leveling error are rod scale error and refraction error. Rod scale error occurs because the graduations on leveling rods cannot be perfectly scribed: There is always a discrepancy be-

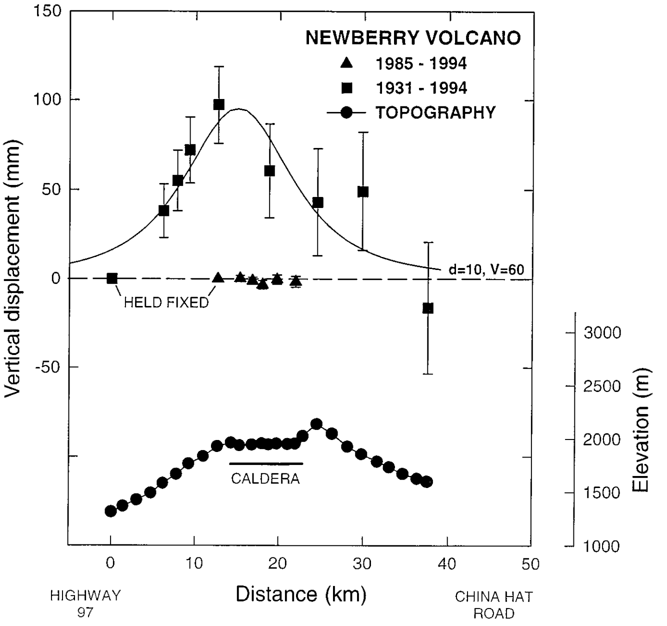

Fig. 4 Vertical displacements and topography at Newberry Volcano from leveling surveys in 1931, 1985 (caldera only), and 1994. Benchmark F1 near Highway 97 was held fixed for the 1931–1994 comparison, and benchmark A1G near the west rim of the summit caldera was held fixed for the 1985–1994 comparison. Not shown is a comparison of surveys across the caldera in 1985 and 1986, which revealed no differences larger than 1.9 ± 1.6 mm. *Error bars* represent one standard deviation from expected random error. *Smooth curve* is the vertical displacement profile predicted by an elastic model (Mogi 1958) in which a volume $V = 0.06$ km^3 of magma is injected at a depth $d = 10$ km beneath A1G

tween the intended location of a graduation and its true distance from the base of the rod. The effects of scribing error can be partly removed by calibrating rods and using the results to correct readings made in the field. This introduces a second, generally much smaller source of error called calibration error. A helpful discussion and analysis of scribing and calibration errors are in Strange (1980a).

Scale differences between rods can give rise to systematic error that accumulates with elevation. For example, imagine using one perfect rod and one flawed rod to measure a traverse across a mountain. The graduations on the flawed rod are too far apart by an amount that increases linearly with distance from the bottom of the rod (as if the rod were stretched after scribing). On the uphill part of the traverse, the effect of the flawed rod would be to overestimate by a small amount the true elevation difference between rods whenever the flawed rod is used at the foresight, and to underestimate by a larger amount the elevation difference whenever the flawed rod is used at the backsight. The net effect would be to underestimate the height of the summit. On the downhill part of the traverse, the elevation difference between rods would be overestimated by a small amount whenever the flawed rod was used at the backsight and underestimated by a larger amount whenever the flawed rod was used at the foresight. The net effect is the same: The true height of the mountain would be underestimated. This error could not be detected by double running the traverse with the same rods, because the effect is repeatable. If results of the flawed survey were compared with those from a subsequent perfect survey, the mountain would appear to have grown in stature even in the absence of any real movement.

The effect of rod scale error can be mostly eliminated from modern surveys by using rods that have been accurately calibrated. Calibration establishes the actual distance from the base of the rod to each graduation as a basis for applying corrections to height differences measured in the field. For older surveys conducted with uncalibrated rods, a simple test can be used to estimate the likelihood that rod scale error is present. The test is not definitive, because the possibility of a real link between deformation and topography cannot be discounted.

If one or both leveling surveys being compared are contaminated with rod scale error, measured elevation changes between adjacent benchmarks (tilts) will correlate with elevation differences between the benchmarks (slope). The present author explored this possibility for the Newberry surveys using a linear regression technique described by Stein (1981). Regression coefficients m, Y intercepts b, and correlation coefficients r for the equation $\tau = m\theta + b$, where τ and θ represent tilt and slope, respectively, were calculated for each section along the traverse. Two weighting functions were used: (a) equal weight for all data points ("nonweighted"); and (b) $1/\sigma(\delta h)^2$. The second approach takes account of the fact that tilt is better determined for long sections than for short sections. Results are given in Table 3. For comparison, see a similar analysis for Medicine Lake Volcano by Dzurisin et al. (1991).

The results for Newberry Volcano permit the interpretation that most or all of the changes measured by the 1931 and 1994 surveys are a result of slope-dependent error. However, this interpretation implies an unusually large relative rod scale error (160 ppm; see below). Tilt-slope correlation coefficients are 0.716 (nonweighted) and 0.637 (weighted), corresponding to less than 5% likelihood that tilt and slope are uncorrelated. Of course, correlation does not necessarily imply cause; real uplift and subsidence profiles at volcanoes commonly correlate with topography. If the 1931–1994 elevation changes are "corrected" using the regression coefficients in Table 3 (i.e., the correlated portion of the signal is removed), the remaining changes are within measurement uncertainty. This means that the changes could be due entirely to slope-dependent error, presumably relative scale error between the rods used for the 1931 and 1994 surveys.

Strange (1980a) analyzed data from 64 leveling surveys over 17 profiles (i.e., 47 repeat surveys) in southern California for evidence of relative rod scale error. In general, scale errors were less than 30 parts per million (ppm). In 44 of the 47 cases analyzed, scale errors were less than 80 ppm; only 3 cases had scale errors of 140–160 ppm. If the 1931–1994 changes at Newberry Volcano were entirely a result of relative rod scale error, the error would be 97 mm over 615 m of elevation difference, or 160 ppm. The rods used for the 1994 survey were calibrated several times, and the resulting scale corrections were less than 30 ppm. Therefore, if differences between the 1931 and 1994 surveys are entirely caused by relative rod scale error, the rods used for the 1931 survey were unusually poor in this respect.

In an attempt to assess this possibility, this author obtained a copy of the original field notes for the 1931 survey from the USGS archive in Denver, Colorado (D.P. Benson, pers. commun.). Levelman G.A. Fisher noted that level Y 167 and New York rod 543 were used for the survey. New York rods are 6.5 ft (198 cm) long and extendible to twice that length. Following

Table 3 Linear Regression Statistics, 1931 and 1994 leveling surveys, Newberry Volcano

	Nonweighted	Weighted
Regression coefficient	$1.260 \pm 0.434 \times 10^{-4}$	$1.066 \pm 0.456 \times 10^{-4}$
Correlation coefficient	0.716	0.637
Y intercept	$-1.225 \pm 19.689 \times 10^{-4}$	$-1.243 \pm 1.829 \times 10^{-4}$

guidelines set forth by Birdseye (1928, p 129), Fischer noted that rod 543 was tested, presumably by the Bureau of Standards, on 29 January 1926. The rod was short 0.001 in. at 11 ft, which corresponds to approximately 7 ppm. This is remarkably good, even by modern standards, especially when compared with the results of Strange (1980a) described previously. Thus, it seems unlikely that relative rod scale error is a dominant cause of the differences measured by the 1931 and 1994 surveys.

Another potential source of systematic error is refraction error. This arises when air in the first few meters above the ground is poorly mixed and therefore temperature stratified. The resulting change in the index of refraction with height causes the line-of-sight from the level instrument to the rod to be bent in a systematic way. The effect is greatest in steep terrain, where a typical setup involves the lower part of one rod and the upper part of the other. Refraction error cannot be removed by double-running, because atmospheric conditions change between runnings and temperature stratification is repeatable in a general way (i.e., the ground is usually colder than the air immediately above it in the morning, and warmer in the afternoon).

A correction for refraction error can be made if the difference in air temperature at two heights near the ground is measured either during a survey or estimated from regional and seasonal climate information. Strange (1980a) showed that good results are obtained from a simple formulation by Kukkamaki (1938):

$$R=-4\times10^{-9}\cdot\gamma L^{2}\Delta h\Delta t$$

where R is the refraction correction, γ is a function of certain physical constants of air and the value of the constant c in the equation below, L is the distance from the level instrument to the rod at a setup with the instrument midway between the two rods, Δh is the height difference measured at the setup, and Δt is the difference in temperature between two points 0.5 and 2.5 m above the ground.

This formulation is based on the assumption that the temperature variation near the ground has the form:

$$t=a+bZ^{c},$$

where t is the temperature, Z is the height above the ground, and a, b, and c are constants to be derived from measurements.

Strange (1980b) gave justifications for using as an approximation for Δt in California values that are twice those found by Best (1935) in England. This corresponds to $\Delta t=0.5$–$1.5\,°\mathrm{C}$. Under this assumption, and by assigning a value of 70 to γ (based on the results of Kukkamaki 1939), Strange (1980a) estimated the magnitude of R for a range of conditions (Table 4). His results emphasize that sight length, L, is the dominant factor affecting R (a consequence of the L^2 dependence). For example, if 20-m sight lengths were used along a traverse with 1 km of relief and the average value of Δt changed by 1.0 °C between two levelings, the refraction correction R would be 2.2 cm. Using 100-m sight lengths instead increases R to 56 cm.

Table 4 Approximate value of refraction correction (cm/100 m) for differing sight lengths (L) and temperature differences (Δt). (From Strange 1980a)

Temperature difference (Δt)	Sight length (m)				
	20	25	50	60	100
0.5	0.11	0.17	0.7	1.0	2.8
1.0	0.22	0.35	1.4	2.0	5.6
1.5	0.33	0.52	2.1	3.0	8.4

The present author found no information about sight lengths for the 1931 survey at Newberry, but they were undoubtedly limited by relatively steep topography along the traverse. Standards for third-order surveys of the day allowed for sight lengths up to 300 ft (Birdseye, p 132). However, our experience during the 1994 survey was that the terrain restricted most sight lengths to less than 30 m, typically approximately 20 m. Therefore, even though much longer sight lengths would have been tolerated for the earlier, third-order survey, the terrain serves to limit any difference in the average value of L. This assumes that backsight and foresight lengths were balanced for the 1931 survey, as called for in the standards for third-order surveys (Birdseye 1928, pp 132–133). Lacking more specific information, the present author assumed that L_{ave} was 20 m for both surveys and Δt between the surveys was 1.0 °C. From Table 4 the cumulative refraction correction between the low and high points on the Newberry traverse ($\Delta h=820$ m) is $R=1.8$ cm. If $L_{\mathrm{ave}}=25$ m, $R=2.9$ cm. If $L_{\mathrm{ave}}=25$ m and $\Delta t=1.5\,°\mathrm{C}$ (worst case?), $R=4.2$ cm. Given the steepness of the terrain, any larger value of L_{ave} is implausible. Thus, it seems unlikely that uncorrected refraction error accounts for a large portion of the difference between the 1931 and 1994 surveys.

In summary, neither rod scale error nor refraction error can easily account for all of the difference between the 1931 and 1994 surveys. Both types of error presumably exist in the 1931 survey and, to a lesser degree, in the 1994 survey, but they are unlikely to account for more than half of the maximum displacement measured along the traverse (97 ± 22 mm near Paulina Lake).

Newberry Results, 1985–1994

Results from the 1985, 1986, and 1994 leveling surveys across the summit caldera at Newberry Volcano are identical within measurement uncertainty (Fig. 4). The largest vertical displacements anywhere along the traverse with respect to benchmark A1G near the west caldera rim are 1.9 ± 1.6 mm (1985–1986) and

–3.3 ± 2.3 mm (1985–1994). Therefore, any differential movement that might have occurred inside the caldera during 1931–1994 had stopped by 1985. This result is ambiguous, however, because the 1931–1994 uplift profile spans the entire volcano and differential displacements inside the caldera are relatively small (Fig. 4). Another leveling survey of the entire Newberry traverse (or measurements using another geodetic technique such as GPS) is needed to determine if the summit area is actually rising.

The Newberry leveling results are also equivocal with respect to geologic evidence for ground deformation during the past few millennia. Jensen and Chitwood (1996) reported differential uplift of terraces at Paulina Lake, which occupies the western part of Newberry caldera, by 4–6 m since a large flood lowered lake level approximately 2,000 years ago. They speculated that several intracaldera eruptions during Holocene time were accompanied by episodes of uplift, subsidence, and tilting of the caldera floor and recommended that results of repeated leveling surveys be examined for any evidence of historical ground deformation.

If the deformation rate were constant, which seems unlikely, the terrace information would imply an average differential uplift rate inside the caldera of 2–3 mm/year. A rate that high would have been detected by the 1985 and 1994 leveling surveys; thus, either the uplift stopped before 1985 or the uplift rate varies with time. The suggestion by Jensen and Chitwood (1996) that most of the deformation inside the caldera is associated with eruptive or intrusive events, and therefore deformation rates during quiescent periods are likely to be low, is both plausible and consistent with the available data.

The meaning of the 1931–1994 leveling results is unclear. Firstly, the possibility of systematic error in the 1931 survey cannot be dismissed entirely, although it is unlikely to be a dominant factor. Secondly, the terrace information pertains only to deformation inside the caldera, and no other geologic information is available to evaluate the possibility of volcano-wide deformation. Finally, there are few mechanisms to account for broad uplift of the entire volcano.

Discussion

Newberry Volcano is located in a zone of crustal extension adjacent to the Basin and Range tectonic province. Crustal thinning as a result of extension would facilitate subsidence, not uplift. Loading of the crust beneath the volcano, which is likely to be hot and weak as a result of repeated magmatic intrusions and fracturing, might also cause subsidence. Dzurisin et al. (1991) attributed edifice-wide subsidence at Medicine Lake Volcano, which is geologically similar to Newberry Volcano, to a combination of these two processes. MacLeod et al. (1995) showed broad downwarping of subvolcanic rocks in their interpretive cross sections of Newberry Volcano, based on geologic mapping and drill hole results. Historical uplift at Newberry runs counter to this long-term trend.

The only reasonable explanation for edifice-wide uplift at Newberry, other than uncorrected leveling error, is pressurization of a source volume beneath the volcano. To cause surface uplift, the pressurization rate must be high enough to overcome the effects of crustal thinning and loading. A simple elastic model (Mogi 1958) that fits the general form of the leveling results includes a volume increase of 0.06 km^3 at a depth of 10 km (Fig. 4). Moving the inflation source to 5 or 15 km depth produces a fit to the data that is obviously worse. More detailed modeling is probably not justified by the limited amount and quality of leveling data available. If uplift was caused by inflation of a magma body at 10 km depth, the average magma supply rate during 1931–1994 was approximately 1×10^{-3} km^3/year.

For comparison, the volume of the Newberry volcanic edifice above the surrounding plain is 400–500 km^3, and the total volume erupted may be twice as great (MacLeod et al. 1995). The volcano began its growth about 600,000 years ago, so the average magma supply rate to the surface has been $0.7\text{–}1.7 \times 10^{-3}$ km^3/yr. The point of this comparison is not to support magmatic inflation as the mechanism for historical uplift, but only to demonstrate that the average supply rate derived from leveling results is reasonable within the context of the volcano's long-term eruptive history.

There is no evidence from very limited seismic coverage in the Newberry area for any historical earthquake swarms that might have marked the occurrence of magmatic intrusions beneath the volcano. Local seismicity has been monitored only since 1987 with a single station on the volcano's east slope (Norris 1991). Another station was operated at Pine Mountain, 25 km northeast of the caldera, from December 1979 through 1981. Owing to apparently low seismicity and sparse, discontinuous station coverage, very few earthquakes have been reliably located in the region. A search of the University of Washington's Pacific Northwest Seismic Network earthquake catalog turned up no earthquakes larger than magnitude 2 in the region bounded by 43.0°-44.5°N and 120.5°-122.0°W, centered on the volcano, for the period 1931 to the present; however, smaller earthquakes could have gone undetected, especially before 1987.

Additional geodetic measurements will be necessary to evaluate the intriguing possibility that Medicine Lake Volcano is subsiding while Newberry Volcano, in a similar tectonic setting, is rising, and to better determine the causes of ground movements at both volcanoes.

Acknowledgements This work was supported by the USGS Volcano Hazards Program. The author is grateful to crew chief K. Yamashita and numerous other USGS staff members and volunteers who conducted the USGS/CVO leveling surveys. D. P. Benson searched the USGS leveling archive for much-needed information about the 1931 survey at Newberry Volcano. C. Tanda Kindly drafted two maps for the manuscript. A. Miklius, D. Swanson, and R. Stein provided thoughtful reviews that were particularly helpful in revising the manuscript.

References

Best AC (1935) Transfer of heat and momentum in the lowest layers of the atmosphere. Geophysical Memoirs, no. 65–8(VII), Air Ministry Meteorological Office, His Majesty's Stationery Office, London

Birdseye CH (1928) Topographic instructions of the United States Geological Survey. US Geol Surv Bull 788

Dzurisin D, Donnelly-Nolan JM, Evans JR, Walter SR (1991) Crustal subsidence, seismicity, and structure near Medicine Lake Volcano, California. J Geophys Res 96:16,319–16,333

Federal Geodetic Control Committee (1984) Standards and specifications for geodetic control networks. Report, National Oceanic and Atmospheric Administration, Rockville, Maryland

Jensen RA, Chitwood LA (1996) Evidence for recent uplift of caldera floor, Newberry Volcano, Oregon. EOS 77:F792

Kukkamaki TJ (1938) Uber die nivellitsche refraktion. Publication of the Finnish Geodetic Institute, no. 27, 18 pp

Kukkamaki TJ (1939) Formeln und tabellen zue berechnung der nivellitischen refraktion. Publication of the Finnish Geodetic Institute, no. 25, 48 pp

MacLeod NS, Sherrod DR, Chitwood LA, Jensen RA (1995) Geologic map of Newberry Volcano, Deschutes, Klamath, and Lake counties, Oregon. US Geol Surv Map I-2455, 1:62,500 and 1:24,000 scales

Mogi K (1958) Relation between the eruptions of various volcanoes and the deformation of the ground surfaces around them. Bull Earthq Res Inst Univ Tokyo 36:99–134

Norris RD (1991) The Cascade volcanoes: monitoring history and current land management. US Geol Surv Open-File Rep 91–31:42–44

Pelton JR, Smith RB (1982) Contemporary vertical surface displacements in Yellowstone National Park. J Geophys Res 87:2745–2761

Savage JC, Clark MM (1982) Magmatic resurgence in Long Valley caldera, California: possible cause of the 1980 Mammoth Lakes earthquakes. Science 217:531–533

Stein RS (1981) Discrimination of tectonic displacement from slope-dependent errors in geodetic leveling from southern California, 1953–1977. In: Simpson DW, Richards PG (eds) Earthquake prediction: an international review. Am Geophys Union, Washington DC, Maurice Ewing Series 4:441–456

Strange WE (1980a) The effect of systematic errors on geodynamic analysis. In: Second International Symposium on Problems Related to the Redefinition of North American Vertical Geodetic Networks, Canadian Institute of Surveying, Surveys and Mapping Branch, Ottawa, pp 704–729

Strange WE (1980b) The impact of refraction corrections on leveling interpretations in California. EOS 61:365

Vanicek P, Castle RO, Balazs EI (1980) Geodetic leveling and its applications. Rev Geophys 18:505–524

Yamashita KM, Doukas MP (1987) Precise level lines at Crater Lake, Newberry Crater, and South Sister, Oregon. US Geol Surv Open-File Rep 87–293:1–31

Yamashita KM, Iwatsubo EY (1992) Descriptions and elevations for leveling bench marks and leveling results along traverses near Old Station and Mineral, California. US Geol Surv Open-File Rep 92–247:1–29

Yamashita KM, Wieprecht DE, Sako MK (1995) Elevations and descriptions for leveling bench marks at Newberry Crater, Oregon. US Geol Surv Open-File Rep 95–99:1–18