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# Converting NAD83 GPS Heights Into NAVD88 Elevations with LVGEOID, a Hybrid Geoid Height Model for the Long Valley Volcanic Region, California

Scientific Investigations Report 2007–5255

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# Converting NAD83 GPS Heights Into NAVD88 Elevations With LVGEOID, a Hybrid Geoid Height Model for the Long Valley Volcanic Region, California

By Maurizio Battaglia[1], Daniel Dzurisin[2], John Langbein[3], Jerry Svarc[3], and David P. Hill[3]

## Abstract

A GPS survey of leveling benchmarks done in Long Valley Caldera in 1999 showed that the application of the National Geodetic Survey (NGS) geoid model GEOID99 to tie GPS heights to historical leveling measurements would significantly underestimate the caldera ground deformation (known from other geodetic measurements). The NGS geoid model was able to correctly reproduce the shape of the deformation, but required a local adjustment to give a realistic estimate of the magnitude of the uplift. In summer 2006, the U.S. Geological Survey conducted a new leveling survey along two major routes crossing the Long Valley region from north to south (Hwy 395) and from east to west (Hwy 203 – Benton Crossing). At the same time, 25 leveling bench marks were occupied with dual frequency GPS receivers to provide a measurement of the ellipsoid heights. Using the heights from these two surveys, we were able to compute a precise geoid height model (LVGEOID) for the Long Valley volcanic region. Our results show that although the LVGEOID and the latest NGS GEOID03 model practically coincide in areas outside the caldera, there is a difference of up to 0.2 m between the two models within the caldera. Accounting for this difference is critical when using the geoid height model to estimate the ground deformation due to magmatic or tectonic activity in the caldera.

## Introduction

The Global Positioning System (GPS) is commonly referred to as a three-dimensional positioning system, but heights obtained from GPS are typically expressed as elevations above an ellipsoidal model of the Earth, and not the Earth's actual surface. As a result, GPS ellipsoidal heights are not directly comparable with heights above mean sea level, known as orthometric heights, determined by leveling surveys. The conversion from ellipsoid to orthometric heights requires a geoid height model that relates the local ellipsoid to the local geoid, where the geoid is the "equipotential surface" which would coincide exactly with the mean ocean surface (sea level) of the Earth. The difference between these two surfaces can be as large as 100 m in areas with strong topographic or subsurface density gradients.

A GPS survey of leveling benchmarks done in Long Valley in 1999 showed that straightforward application of the National Geodetic Survey (NGS) hybrid geoid model GEOID99 to tie GPS heights to historical leveling measurements significantly underestimated the caldera ground deformation as measured with other geodetic techniques (see Battaglia and others, 2003, for full discussion). The NGS geoid model was able to correctly reproduce the shape of the deformation, but needed a local adjustment to give a realistic estimate of the magnitude of the uplift.

In December 2003, the NGS released the new GEOID03 geoid height model (*http://www.ngs.noaa.gov/GEOID*). The GEOID03 model was developed in the same manner as GEOID99 using an underlying gravimetric geoid, USGG2003, and updated GPS ellipsoidal heights on leveled Bench Marks (GPSBMs). The conversion surface for GEOID03 was developed from 14,185 GPSBMs at a 5 arc-minute grid interval, which provided a substantial increase in the spatial coverage over GEOID99 and reduced errors due to interpolation. The fit to these same points afterwards using the derived GEOID03 model was within 0.0048 m ($2\sigma$) which is comprised of both correlated (attributable to GEOID03) and uncorrelated (GPS observation error) signals (Roman and others, 2004).

In summer 2006, the USGS conducted a new leveling survey along two major routes crossing the Long Valley region from north to south (HWY 395) and from east to west (HWY 203 – Benton Crossing). At the same time, 25 leveling bench marks were occupied with dual frequency GPS receivers to provide a measurement of the ellipsoid heights (fig. 1*A*). Using the heights from these two surveys we were able to (1)

[1]University of Rome "La Sapiensa", Rome, Italy.

[2]U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, WA.

[3]U.S. Geological Survey, Menlo Park, CA.

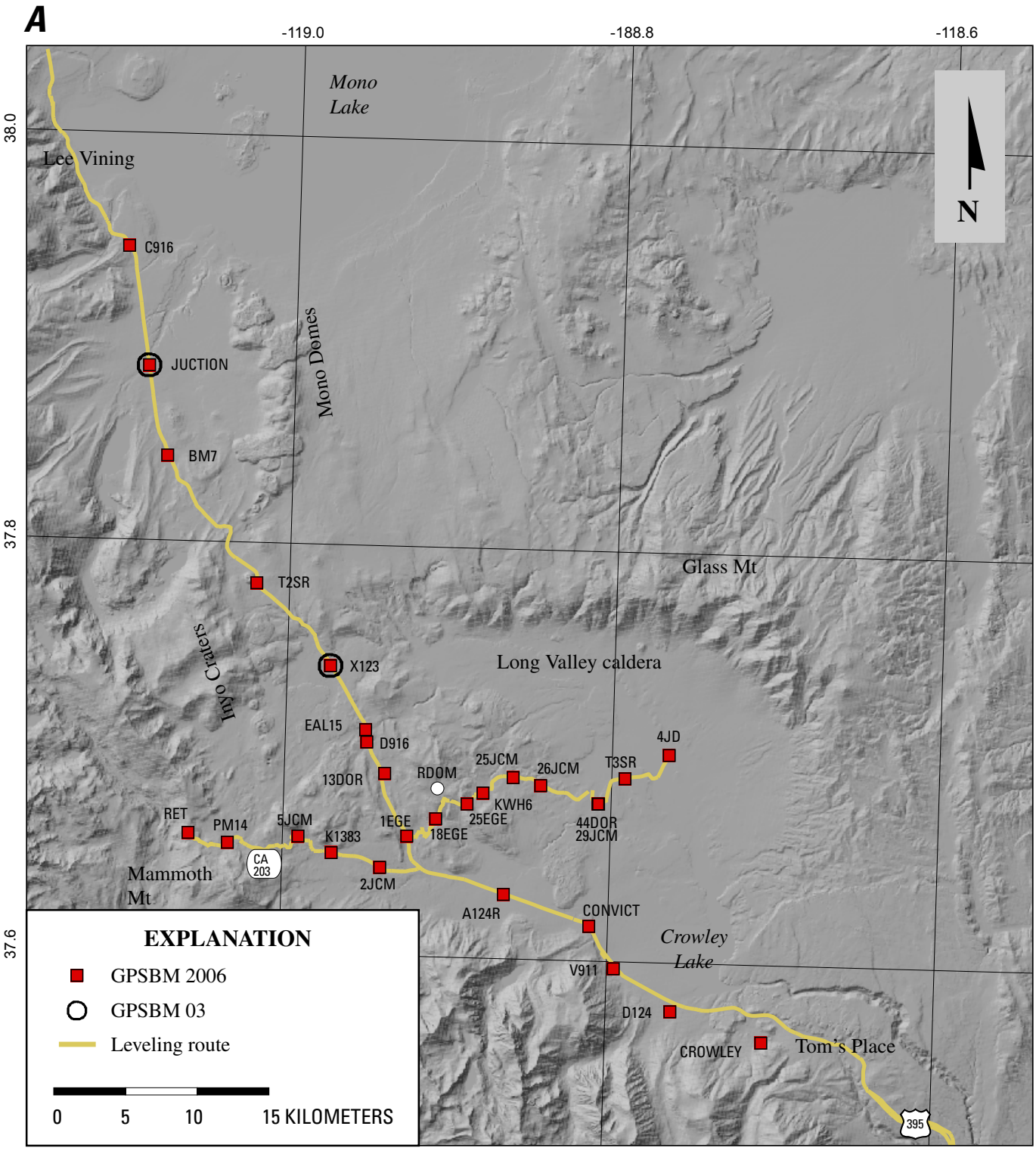


**Figure 1.** (*A*) Map of Long Valley volcanic region with GPS on leveled Bench Mark (GPSBM) sites and leveling routes. The GPSBM 03 label identifies the sites belonging to the NGS GEOID03 data base, whereas GPSBM 2006 the sites occupied by the U.S. Geological Survey in July 2006; (*B*) Map of Long Valley leveling routes and benchmarks.

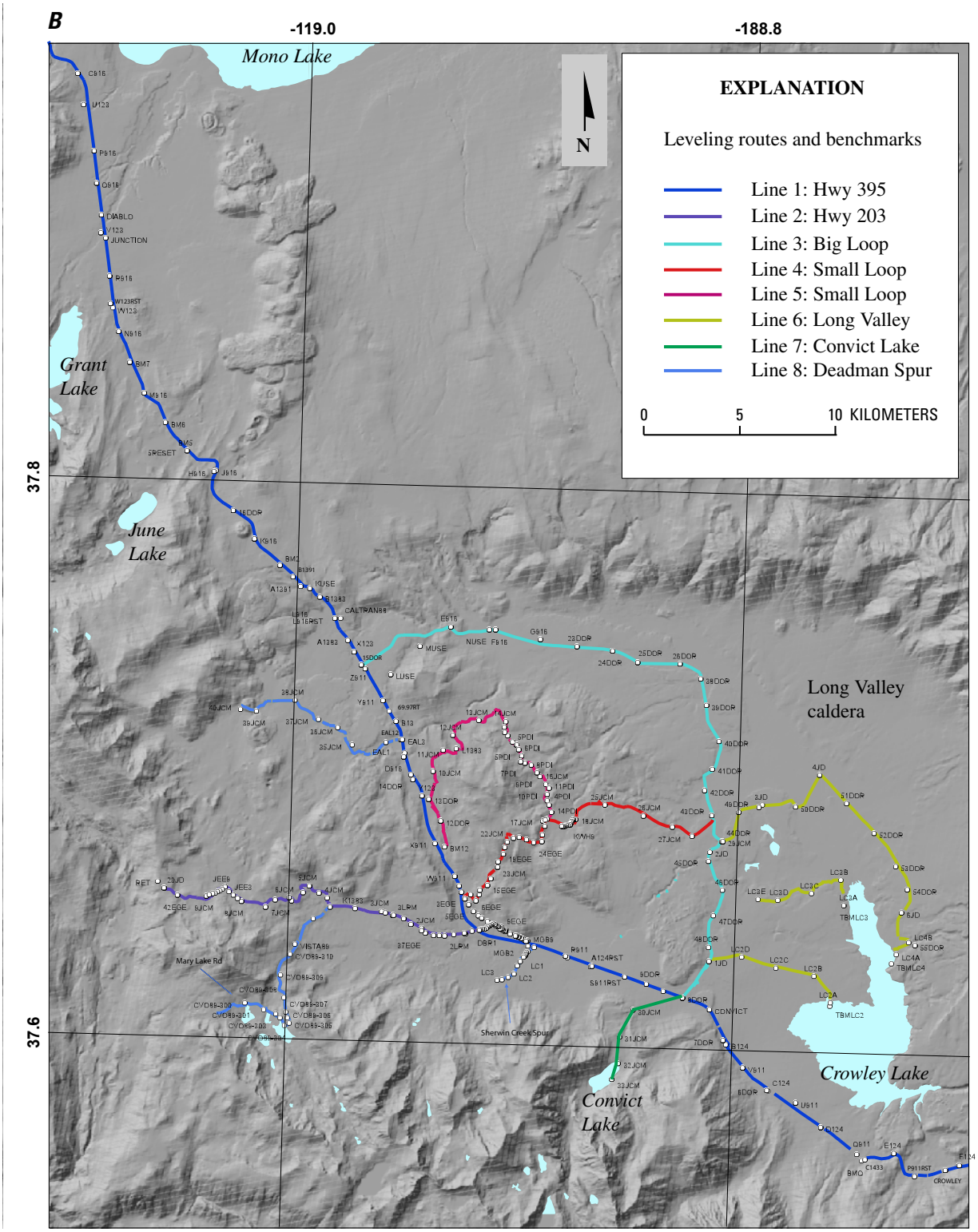


**Figure 1.** (*A*) Map of Long Valley volcanic region with GPS on leveled Bench Mark (GPSBM) sites and leveling routes. The GPSBM 03 label identifies the sites belonging to the NGS GEOID03 data base, whereas GPSBM 2006 the sites occupied by the U.S. Geological Survey in July 2006; (*B*) Map of Long Valley leveling routes and benchmarks—Continued.

assess the accuracy of GEOID03 in the region, (2) improve the estimate of the local adjustment to the geoid height model, and (3) compute a precise geoid height model (LVGEOID) for the Long Valley volcanic region.

Our results show that while LVGEOID and GEOID03 closely coincide in areas outside the caldera, the two models differ by as much as 0.2 m within the caldera. Accounting for this difference is critical when using a geoid height model to estimate ground deformation due to magmatic and tectonic unrest within the caldera.

## Comparing GPS and Leveling

Before vertical GPS measurements can be compared with leveled heights to obtain vertical displacements, the heights must be transformed into the same reference frame (fig. 2). The reference surface for leveling is the geoid, an equipotential surface closely identified with mean sea level (Rapp, 1980). To obtain a homogeneous set of elevations from different leveling surveys, raw leveling heights must be referenced to a common vertical datum. The present vertical datum for the United States is the North American Vertical Datum of 1988 (NAVD88). NAVD88 elevations are expressed by Helmert orthometric heights, which can be computed using the Helmert orthometric reduction (Zilkoski and others, 1992). GPS solutions, however, produce a set of XYZ coordinates that are referenced to the center of an ellipsoid that approximates the Earth's surface. To obtain heights from GPS solutions, the XYZ coordinates must be transformed into geodetic latitude, longitude, and ellipsoidal heights. This transformation is usually performed using the World Geodetic System WGS84 ellipsoid model (Snay and Soler, 2000). In the conterminous United States, horizontal coordinates in WGS84 are practically identical to those of the present North American horizontal Datum of 1983 (NAD83); the two systems agree at the 0.1 mm level (Langley, 1992). Geoid and ellipsoid surfaces, however, do not coincide. The vertical distance between the ellipsoid and the geoid is called the geoid height or the ellipsoid-geoid separation, N. An elevation measured with respect to the geoid (for example, by leveling) is called an orthometric height, and an elevation determined with respect to the reference ellipsoid (for example, by GPS) is called an ellipsoidal height. The value of N ranges from -100 m in Sri Lanka to +70 m in the Marianas Trench. GPS heights can be transformed into the same reference frame as leveled heights by using an appropriate geoid height model (Smith and Milbert, 1999). Geoid height models developed by the National Geodetic Survey enable one to directly convert between NAD83 GPS heights and NAVD88 leveling heights within the United States (*http://www.ngs.noaa.gov/GEOID/*).

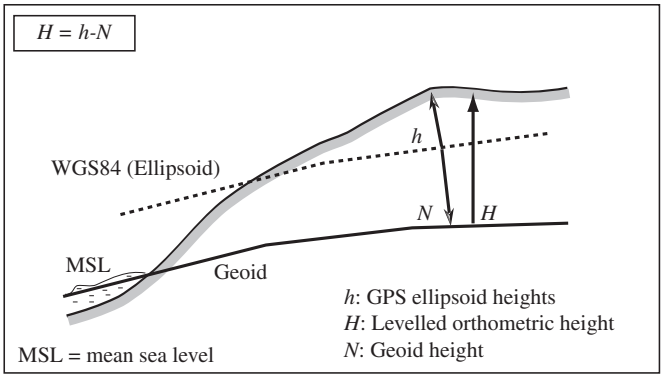


**Figure 2.** Relationship between the ellipsoid height *h*, orthometric height *H*, and geoid height *N*.

## Leveling

Beginning in 1975, a series of repeated leveling surveys, in which orthometric height differences between stations are measured with a precise optical level, have been used to measure vertical deformation along the 65-km-long line along Hwy 365 from Tom's Place to Lee Vining and along several other routes within Long Valley caldera (fig. 1*B*; tables 1–5 are at the back of this report). Bench mark C916 (fig. 1) is the elevation datum for all the leveling surveys. In other words, the height of C916 is assumed to be fixed. This assumption introduces a small bias in heights determined by any given survey, but it does not affect the shape of the vertical displacement field computed by differencing two surveys. The magnitude of the bias is unknown, but the flat shape of vertical displacement profiles along Hwy 395 in the vicinity of C916 suggests that any real motion there is small (that is, no more than a few millimeters).

The Highway 395 route was surveyed in 1932, 1957, 1975, 1980, each summer from 1982 to 1988, 1992, 1995, 1997 and 2006. Complete leveling of the caldera occurred each summer from 1982 to 1986, and in 1988 and 1992 (Langbein and others, 1995). The leveling surveys were run to standards equal to those required for first-order, class II surveys, as established by the National Geodetic Survey (Federal Geodetic Control Committee, 1984). The standard error for height differences between marks determined by a single survey can be taken to be 0.7 mm·km1/2/L1/2, where L is the cumulative distance between bench marks in km (*http://www.ngs.noaa.gov/heightmod/Leveling/requirements.html*). The standard (white noise) error for height changes computed by differencing results of two surveys is 1.0 mm·km1/2/L1/2. Leveling observations were corrected for rod scale and temperature, level collimation, and for astronomic, refraction and magnetic effects (Balazs and Young, 1982). In general, leveling surveys are not referenced to the NAVD88 datum because the U.S. Geological Survey (USGS) is mainly interested in monitoring relative elevation changes within the caldera, rather than determining absolute elevations.

## Helmert Orthometric Heights

The first stage in the computation of a geoid height model within Long Valley Caldera requires the 2006 leveling survey to be referenced to the NAVD88 vertical datum by transforming the raw leveling heights into Helmert orthometric heights (Milbert and Smith, 1996). The NAVD 88 datum is expressed in Helmert orthometric heights, and was computed in 1991. The NAVD 88 datum was realized by a single datum point, Father Point/Rimouski, in Quebec, Canada. The strategy and the value of the constraint were based on a number of factors. But, the foremost requirement was to minimize recompilation of national mapping products.

The transformation is a two-step process – (1) the geopotential number associated with a leveling bench mark is computed, and (2), the Helmert height using the orthometric reduction formula (Heiskanen and Moritz, 1967, p. 167) is calculated.

The geopotential number $C_B$ represents the difference between the potential at the geoid and the potential at the observation point *B* on the Earth's surface (Heiskanen and Moritz, 1967, p. 162)

$$C_B = W_0 - W_B = \int_0^{h_B} g\,dh, \qquad (1)$$

where 0 is a point at mean sea level (on the geoid), $h_B$ is the raw leveling height at point *B* relative to 0, *g* is the external gravity (a function of the elevation *h*), and *W* is the gravitational potential. If *A* is the leveling survey datum (or primary base station) and *B* a second point on the leveling route, we have

$$C_B = W_0 - W_B = (W_0 - W_A) + (W_A - W_B) = C_A + \int_{h_A}^{h_B} g\,dh, \qquad (2)$$

For normal orthometric heights, $C_A$ is given by (Heiskanen and Moritz, 1967, p. 162)

$$C_A = \gamma_0 H^{dyn}, \qquad (3)$$

where $H^{dyn}$ is a local dynamic height expressed in the NAVD88 vertical datum and $\gamma_0$ is, by convention, the normal gravity value computed on the Geodetic Reference System ellipsoid of 1980 (GRS80) at 45° degrees latitude. Dynamic heights scale the geopotential number by a global constant $\gamma_0$ = 980.6199 gal, converting the geopotential number into a length. The dynamic height for the bench mark C916 (the elevation datum for the Long Valley Caldera leveling network) is $H^{dyn}$ = 2071.409 m (see the data sheet for C916, PID = HR0097, available from the NGS server at *http://www.ngs.noaa.gov/cgi-bin/datasheet.prl*). To solve the integral in equation , values of the surface gravity g at every leveling bench mark between *A* and are necessary. These values may be computed using the NAVD 88 Modeled Gravity software, available from the NGS server at *http://www.ngs.noaa.gov/TOOLS*. Geopotential numbers are measured in g.p.u. (geopotential units), where 1 g.p.u. = 1 kgal m = 10 ms-2 m.

To compute the orthometric height at *B*, $C_B$ is substituted into the Helmert's height reduction formula (Heiskanen and Moritz, 1967, p. 167)

$$H_B = \frac{C_B}{\overline{g}} = \frac{C_B}{g + 0.0424 H_B}, \qquad (4)$$

where HB is the orthometric height expressed in $10^3$ m and $\overline{g}$ is the mean value of the gravity along the plumb line between the geoid and the surface. Using the simplified Prey reduction formula for the gravity, then $\overline{g} = g + 0.0424 H_B$ (Heiskanen and Moritz, 1967, p. 167), where g is the gravitational acceleration at *B* expressed in gal (1 gal = 0.01 m/s$^2$). The approximated formula (4) is often sufficient for standard topography. Solving the algebraic equation yields the value for the orthometric height at the leveling bench mark *B*

$$H_B = \frac{-g + \sqrt{g^2 + 4 \times 0.0424\, C_B}}{2 \times 0.0424}, \qquad (5)$$

Orthometric heights for the 2006 leveling survey are shown in table 1. The difference between the lowest (U123) and the highest (RET) leveled elevations is about 750 m. The standard errors for orthometric heights, taken to be the same as those of the leveled elevations (Zilkoski and others, 1992), range from 1 mm (station U123) to 6 mm (station F124) and average 5 mm within the caldera.

## GPS Ellipsoidal Heights

During the GPS survey in 2006, phase and pseudorange data were recorded on Ashtech Z-12 and Z-Xtreme receivers using Dorne-Margolin choke-ring antennas. Data were recorded for sessions that lasted at least 6 hours at every sites. GPS survey sites were chosen based on their relatively uniform spacing along the leveling lines and good sky view (to maximize the data quality). At some locations, 5JCM and 18EG in particular, the sky view was not completely clear but was better than other nearby leveling sites.

GPS data were processed with the Gipsy/Oasis II software (Lichten and Border, 1987), using a bias-fixed, fiducial-free, precise point positioning strategy (Zumberge and others, 1997). We did not solve for the satellite orbits or clock errors, using instead solutions for these parameters provided by the Jet Propulsion Laboratory (JPL). Further precision was obtained by regional filtering, which removes most of com-

mon-mode signals (Wdowinski and others, 1997). An elevation mask of 15 degrees was used during data processing.

We included a globally distributed subset of IGS stations, typically 25 to 30 stations, in our solutions. Using the ITRF00 positions of these stations, a Helmert transformation was done to transform each daily solution into the ITRF00 reference frame. The ITRF00 XYZ solutions were transformed into geodetic latitude, longitude, and ellipsoidal heights using the NAD83 ellipsoidal model for the conterminous United States and the Horizontal Time Dependent Positioning (HTDP) software, available from the NGS server at *http://www.ngs.noaa.gov/TOOLS*. GPS ellipsoid heights and their uncertainties for the 2006 survey are reported in table 2. The formal errors obtained in the GIPSY solutions have been scaled by a factor of two to produce a scaled formal error level that approximates the observed RMS about the linear fit to the time series. The errors also include both white noise and random walk components (Prescott and others, 2001). Uncertainties in the GPS ellipsoidal heights range from 12 mm (station D124) to 42 mm (station 5JCM), averaging 19 mm.

# The Geoid Height Model

Equation (6) gives the general relationship between ellipsoid heights (heights between the external surface and the ellipsoid), $h$, orthometric heights (heights between the external surface and the geoid), $H$, and geoid height (distance between the ellipsoid and the geoid), $N$ (see fig. 2)

$$h = H + N, \tag{6}$$

In the conterminous United States, the geoid surface is beneath the ellipsoid; thus, geoid heights $N$ are negative, and the ellipsoidal height $h$ is smaller in magnitude than the orthometric height $H$ at a given point. By subtracting the orthometric heights $H$ from the ellipsoid heights $h$, we obtain the geoid heights $N$ (Milbert and Smith, 1996).

Gravity points, digital elevations, and altimetrically derived gravity anomalies can be processed to compute a geocentric gravimetric geoid height model (Smith, 1998; Roman and others, 2004). We cannot, however, transform directly between NAD83 GPS ellipsoid heights and NAVD88 orthometric heights using a gravimetric geoid. There is a systematic offset between the NAVD 88 reference level and the current best estimate of global mean sea level, and a transcontinental tilt is introduced by the non-geocentricity of the NAD83 ellipsoid (Smith and Milbert, 1999), which prevents the conversion. To complete the transformation between GPS ellipsoid heights and orthometric heights, the gravimetric geoid height $N$, the ellipsoidal heights $h$ and the orthometric heights $H$ must be related through an empirical conversion surface $s$ (Milbert, 1995; Kotsakis and Sideris, 1999). If subscripts are used to denote the height reference systems, then we can rewrite as

$$H_{88} = h_{83} - (N+s), \tag{7}$$

where H88 indicates the GPS-based orthometric heights relative to NAVD88 and $h_{83}$ the GPS ellipsoid heights relative to NAD83. The new geoid model $N+s$ is called a hybrid geoid (Smith and Milbert, 1999). The most recent gravimetric geoid model (USGG2003) and hybrid geoid model (GEOID03) for the conterminous United States were released by the National Geodetic Survey in December 2003 (Roman and others, 2004; *http://www.ngs.noaa.gov/GEOID/*). Using these models, the leveled orthometric heights $H_{88}$ (table 1) can be subtracted from the GPS ellipsoid heights $h_{83}$ (table 2) to compute the experimental value of the hybrid geoid model $N+s$ at the 25 colocated leveling and GPS benchmarks in Long Valley Caldera (table 3).

The measured geoid height model can then be compared against the published NGS GEOID03 model (fig. 3). The profiles shown in fig. 3 indicate that the geoid shapes are similar, but the NGS model underestimates the geoid height within the caldera. In particular, the difference reaches a maximum at sites on the caldera's resurgent dome and appears negligible at Lee Vining and Tom's Place, outside the caldera to the north and south, respectively. The GEOID03 model is globally accurate but requires a local adjustment (Smith and Roman, 1999), probably because the NGS used only six GPS/leveling comparisons (BRIDGEPORT, E 818, JUCTION, OASIS, T 1391, X 123) to estimate the conversion surface s in Mono County (*http://www.ngs.noaa.gov/GEOID/GPSonBM03/index.html*), and only two of these sites (JUCTION and X 123) are within the Long Valley volcanic region (fig. 1*A*). It is worth noting that the 4th site along Hwy 395 (T2SR, approximately at km 20) and the 2nd site along Hwy 203 (PM14, approximately at km 5) show a suspiciously large difference between the geoids and can probably be considered as outliers. These outliers may reflect local anomalies in the gravity field.

# The Long Valley Caldera Hybrid Geoid Height Model LVGEOID

## Conversion surface

Following Milbert and Smith (1996), we modeled a "locally adjusted" conversion surface $s$ to improve the hybrid geoid for Long Valley Caldera. As a first step, we computed the conversion surface $s$ at the colocated sites (table 4)

$$s = h_{83} - N_{03} - H_{88}, \tag{8}$$

where $N_{03}$ is the gravimetric geoid USGG2003 height. Then we interpolated the "locally corrected" conversion surface $s$ at sites where we have no direct measurements. Finally, we estimated the interpolation error (see appendix for details). We

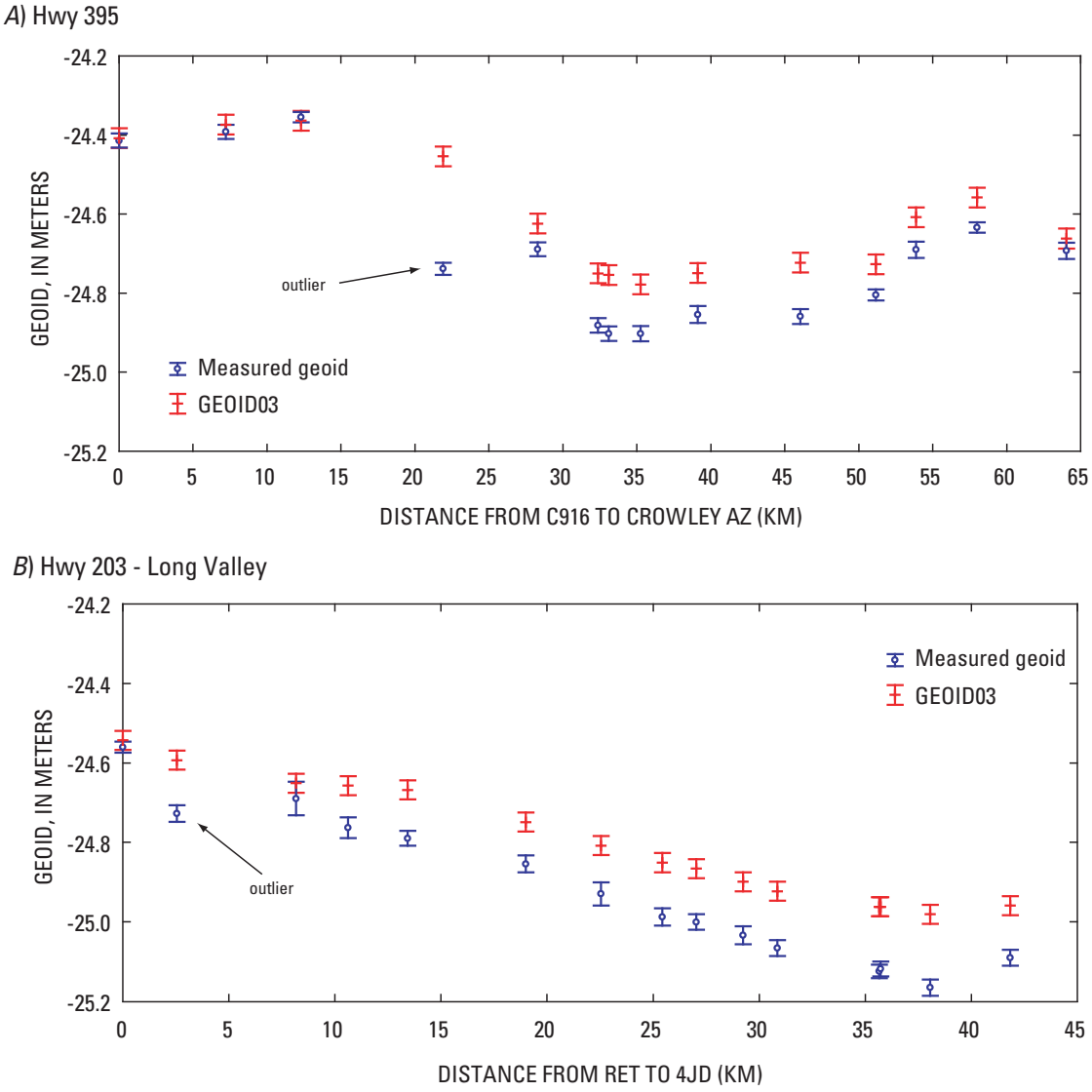


**Figure 3.** Profiles of the measured geoid and GEOID03 along the GPS-on-Bench Mark sites in the Long Valley region. Hwy 395 (*A*) crosses Long Valley caldera from north to south (the caldera extends approximately between the 30 km and 50 km distances along the leveling route), whereas Hwy 203 - Long Valley (*B*) crosses Long Valley caldera from west to east. See fig. 1 for bench mark locations. The 4th site along HWY 395 (T2SR, approximately at km 20) and the 2nd site along Hwy 203 (PM14, approximately at km 5) show a suspiciously large difference between the geoids and can probably be considered as outliers.

calculated the new "locally adjusted" hybrid geoid height at each leveling bench mark (see table 5) by adding *s* to the NGS gravimetric geoid USGG2003 (Smith and Roman, 1999). The stated uncertainties in the "locally corrected" hybrid geoid model are from the propagation of errors from interpolation only, since there is no formal accuracy estimate for the gravimetric geoid (Roman, NGS, written commun.). Geoid uncertainties average 0.022 m with a median value of 0.021 m and a standard deviation of 0.008 m.

A plot of the "locally corrected" geoid LVGEOID against GEOID03 is shown in fig. 4, whereas the spatial distribution of the difference between LVGEOID and GEOID03 is shown in fig. 5.

## Summary and Conclusions

We have tied GPS and leveling to a common reference frame in the Long Valley area so that we can compute the vertical deformation by differencing GPS-based and leveled orthometric heights. To transform directly between GPS ellipsoid heights and orthometric heights, we related the gravimetric geoid height *N*, the ellipsoidal heights *h*, and the orthometric heights *H* through an empirical conversion surface *s*. The new geoid model *N*+*s* is called a hybrid geoid (Smith and Milbert, 1999). In December 2003, the National Geodetic Survey released the latest gravimetric geoid model (USGG2003) and hybrid geoid model (GEOID03) for the conterminous United States.

We compared the NGS GEOID03 model against the experimental values of the geoid height measured at 25 GPSBM sites. These sites were occupied in the summer of 2006 by both GPS and leveling surveys. From the profiles shown in figure 3, we can see that although the geoid shapes are similar, the NGS model underestimates the geoid height within the caldera. The difference reaches a maximum of 18.5 cm close to the caldera's resurgent dome and appears negligible at Lee Vining and Tom's Place, outside the caldera.

We used geostatistics (ordinary kriging and Gaussian simulation) to estimate the new conversion surface *s* in the Long Valley region at any unsampled leveling benchmark from the 25 available data points. We calculated the new "locally adjusted" hybrid geoid height (LVGEOID) at each leveling bench mark (see table 5) by adding *s* to the NGS gravimetric geoid USGG2003 (Smith and Roman, 1999). The average LVGEOID uncertainty of 0.022 m compares well with the published uncertainty for GEOID03 (0.024 m).

A quantitative check can be made by comparing the vertical displacements calculated for the intervals 1985 to 1999 and 1985 to 2006 using the different geoid height models (fig. 6). There are several reasons to choose these intervals – (1) Electronic Distance Measurement (EDM) coverage of the caldera began in 1985; (2) in 1999, Battaglia and others (2003) performed GPS surveys on Bench Marks in the Long Valley volcanic region; (3) the latest leveling survey was in 2006; and (4) continuous GPS results suggest that as little as 4 to 7 mm of net vertical displacement occurred from 1999 to 2006 (fig. 7; *http://quake.wr.usgs.gov/research/deformation/gps/auto/LongValley/rdom/index.html*). Although the 1999-1985 GPS-leveling vertical deformation estimated using LVGEOID compares satisfactorily with the 2006-1985 leveling-leveling uplift, both GEOID03 and GEOID99 underestimate the GPS based orthometric heights for 1999, and thus the vertical deformation between 1999 and 1985. At the resurgent dome (the area with the most pronounced deformation in Long Valley Caldera), the deformation determined used the NGS geoid is underestimated by 0.10 to 0.15 m.

The geodetic data set for the 1999-85 differences (44 height measurements, and 34 EDM baseline length changes) can be inverted to have an estimate of the parameters of the intrusion beneath the resurgent dome. A prolate spheroidal source is used to parameterize the horizontal and vertical deformation. The inversion of the data is performed using a weighted least square algorithm, whereas the penalty function minima are searched by a Nelder-Mead simplex direct search algorithm. A bootstrap algorithm is used to estimate the 95 percent (two standard deviations) bounds on the parameters. Preliminary results (see table 6) point to a deeper, larger source than that previously inferred.

**Table 6.** Ninty-five-percent (two standard deviations) bounds on intrusion source parameters.

| | GEOID99 (after Battaglia and others, 2003) | | LVGEOID | |
|---|---|---|---|---|
| X (UTM) | 332188 | | 332411 | 332831 |
| Y (UTM) | 4172064 | | 4171963 | 4172579 |
| Depth (km) | 4.9 | 7.6 | 7.2 | 8.2 |
| Aspect ratio | 0.25 | 0.65 | 0.52 | 0.64 |
| Volume change ($km^3$) | 0.06 | 0.13 | 0.13 | 0.15 |

[§] Dimensionless pressure: pressure change/shear modulus.

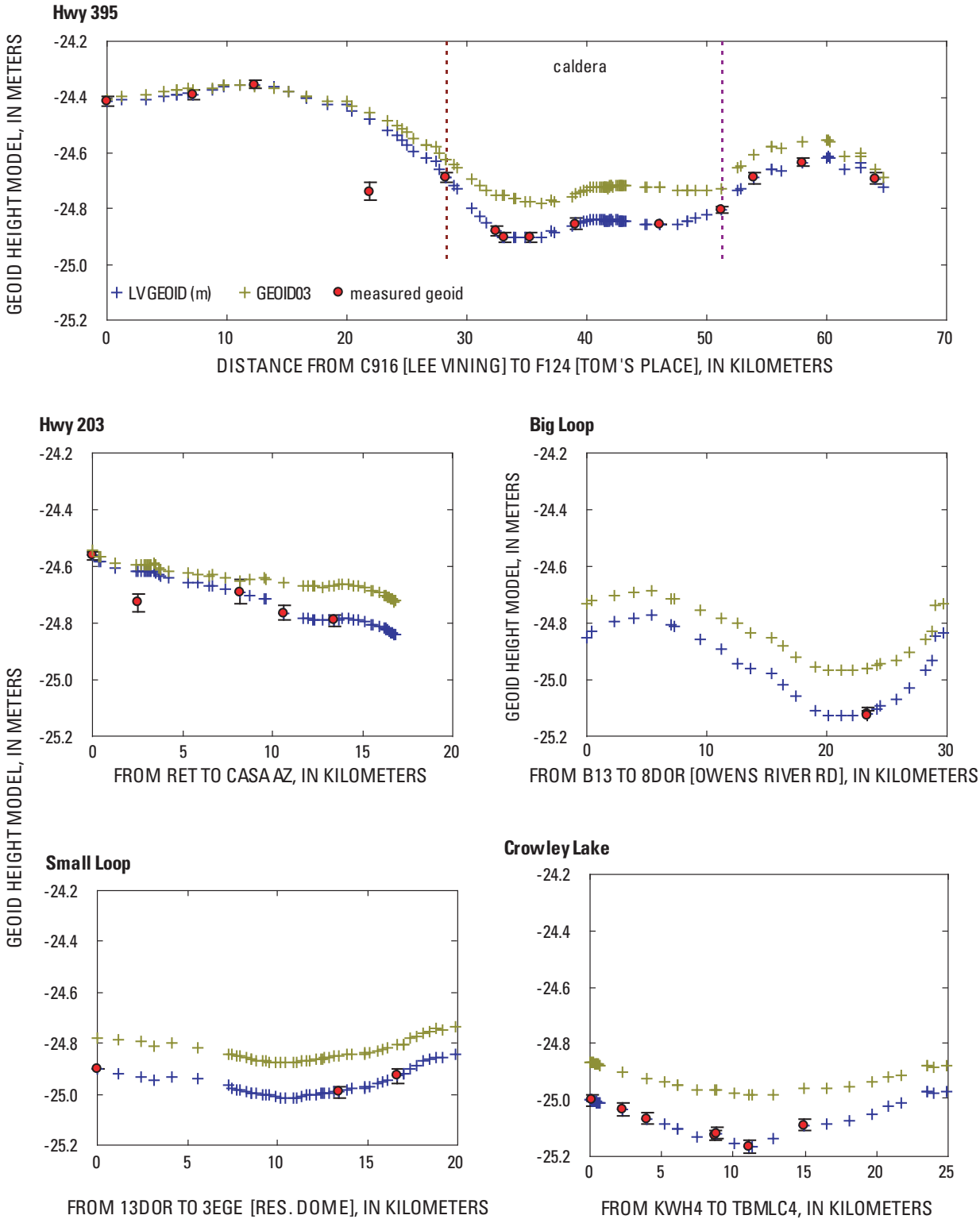


**Figure 4.** Geoid height profiles from leveling surveys in the Long Valley region. The two outliers are benchmarks T2SR (Hwy 395) and PM14 (Hwy 203).

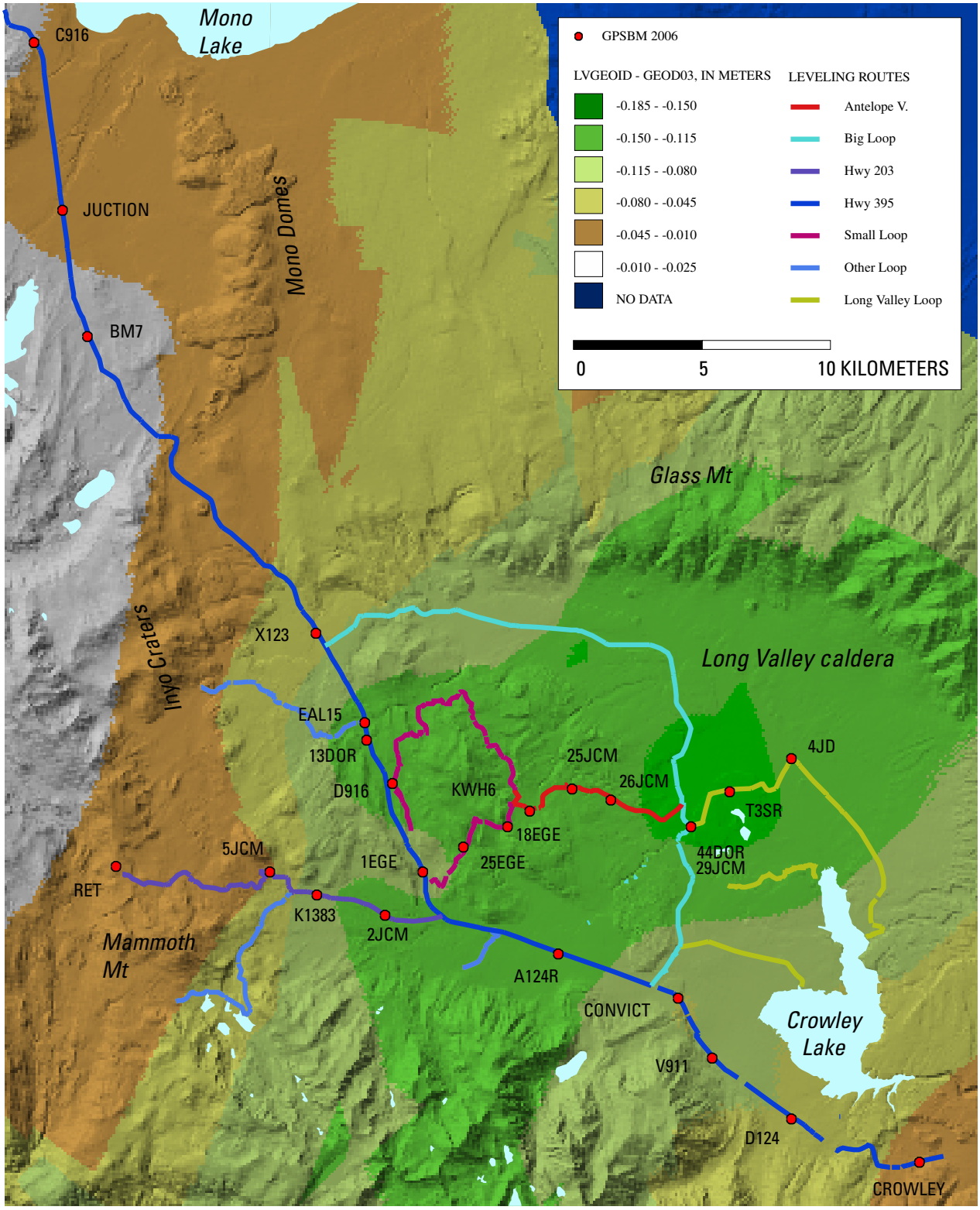


**Figure 5.** Map of the difference between LVGEOID and the GEOID03 NGS geoid height model in the Long Valley region.

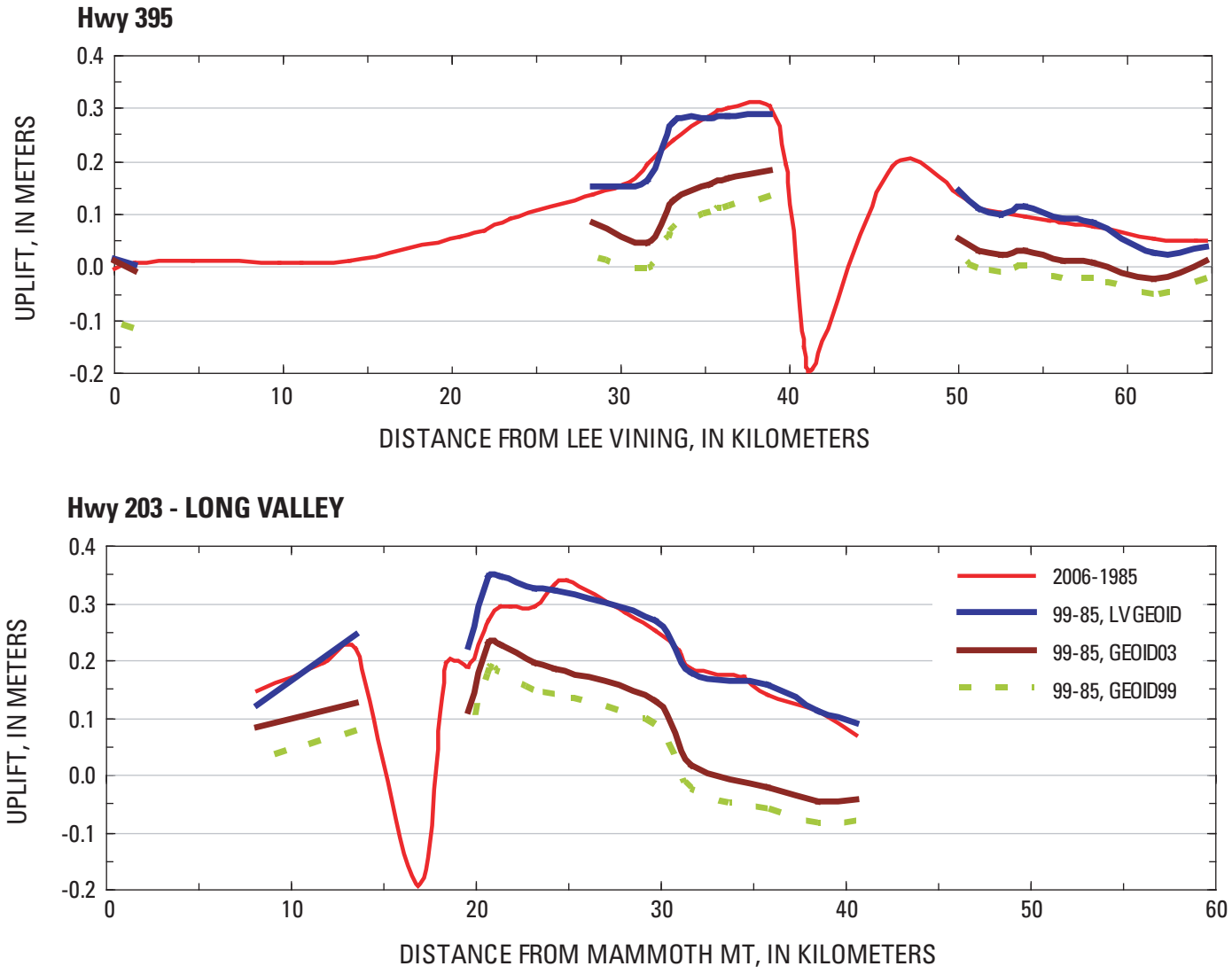


**Figure 6.** Vertical deformation in the Long Valley region measured along the two leveling routes occupied in the summer of 2006. 2006-1985 is the deformation computed by differencing the 2006 and 1985 leveling surveys. The other three lines show the deformation between 1999 and 1985 obtained differencing the 1999 GPS based orthometric heights and the 1985 leveled orthometric heights. LVGEOID, GEOID03, and GEOID99 are the three geoid height models employed to compute the GPS based orthometric heights.

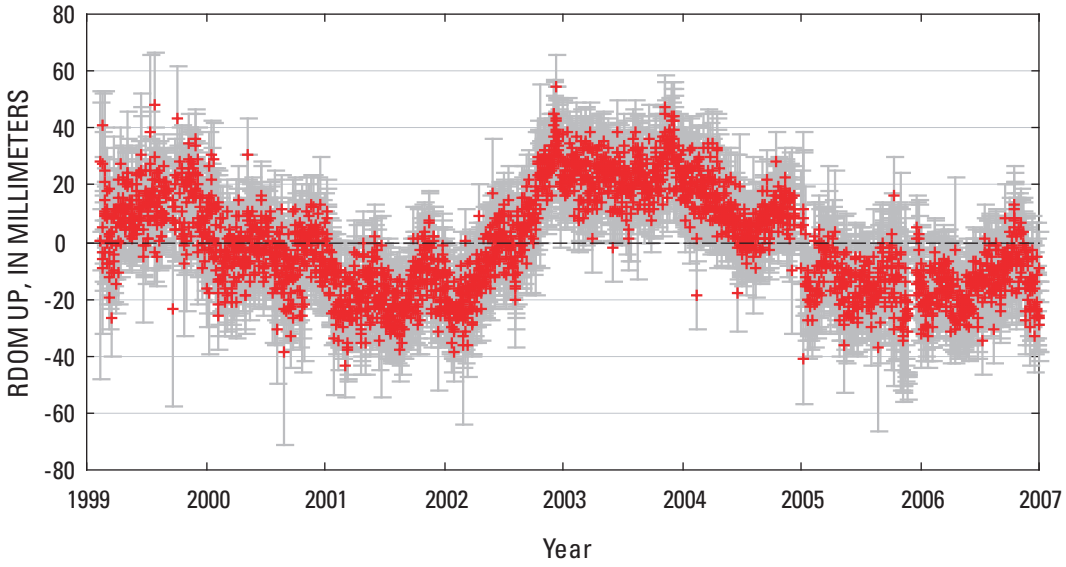


**Figure 7.** Vertical deformation at the permanent GPS site RDOM in Long Valley Caldera. The site is on the caldera resurgent dome (see also fig. 1*A*). Vertical velocity is 0.6 to 1.0 mm/yr. In the 7 years between the 1999 GPS ellipsoid heights on leveled on bench marks (GPS-on-Bench Mark) and the 2006 GPS and leveling surveys, the expected deformation is on the order of 4 to 7 mm (*http://quake.wr.usgs.gov/research/deformation/gps/auto/LongValley/rdom/index.html*).

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# Appendix. Geostatistical Analysis

## Spatial Interpolation

We used ordinary kriging, a linear least-square regression algorithm, to estimate the experimental conversion surface s at unsampled leveling benchmarks (Goovaerts, 1997, p. 132). The geostatistical analysis and interpolation was carried out using the geostatistical software library GSLIB (Deutsch and Journel, 1998; *http://www.gslib.com/*). Kriging interpolates the value of the continuous attribute s at any unsampled locations u using only the values of s available over our study area, the data $s(\mathbf{u}_\alpha)$ (see 8 and table 4).

The linear estimator is defined as

$$s(\mathbf{u}) - m(\mathbf{u}) = \sum_{\alpha=1}^{n(\mathbf{u})} \lambda_\alpha(\mathbf{u})\left[s(\mathbf{u}_\alpha) - m(\mathbf{u}_\alpha)\right], \quad (9)$$

where $\lambda_\alpha(\mathbf{u})$ is the weight assigned to the datum $s(\mathbf{u}_\alpha)$, and the quantities $m(\mathbf{u})$ and $m(\mathbf{u}_\alpha)$ are the expected values (means) of $s(\mathbf{u})$ and $s(\mathbf{u}_\alpha)$. The number of data involved in the estimation, as well as their weights, may change from one location to another. In practice, only the $n(\mathbf{u})$ data within a

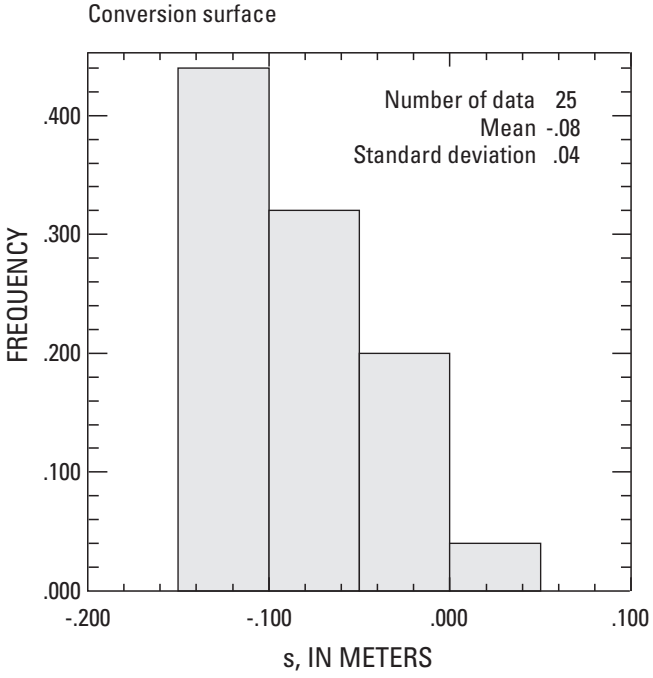


**Figure 8.** Histogram of the conversion surface. Compare this non-Gaussian distribution with the normal distribution in figure 10 obtained through the transformation described in the accompanying text.

given neighborhood $W(\mathbf{u})$, centered on the location $\mathbf{u}$ being estimated, are retained. Ordinary kriging accounts for local fluctuations of the mean assuming that $m(\mathbf{u})$ is constant, but unknown, within $W(\mathbf{u})$ (Goovaerts, 1997, p. 126). It is well known that kriging smoothes the fit of a curve or surface to data and that the histogram of the values estimated by kriging will display more values around the mean but less extreme values than the histogram of the observations (for example, Biau and others, 1999).

The key function in the interpolation is the variogram $\lambda_\alpha(\mathbf{u})$. The variogram describes the spatial dependence of $s$, and is used to calculate the weights $\lambda_\alpha(\mathbf{u})$ and the mean $m(\mathbf{u})$ applied in . Typically, the variogram function is inferred and modeled from the experimental variogram computed from the experimental data (Goovaerts, 1997, p. 82; fig. 9). Variogram models can be divided into two types; those that reach a plateau (called a "sill", and designated as $c$) and those that do not. The distance at which they reach this plateau is called the "range," $a$. The variogram discontinuity at the origin is called the "nugget effect," $n$. More than one theoretical model can fit the experimental variogram (fig. 9).

We choose the best model using cross-validation (Isaaks and Srivastava, 1989, ch. 15). In cross-validation, actual data points are dropped one at a time and re-estimated using the remaining neighboring data. Each datum is replaced in the data set once it has been re-estimated. We accepted the model with the highest correlation between true and estimated values (the power model for the conversion surface, see table 7). Although cross-validation can detect possible problems, it does not ensure that the interpolation will give "realistic" results (Journel, 1989). We report the interpolated values in table 5.

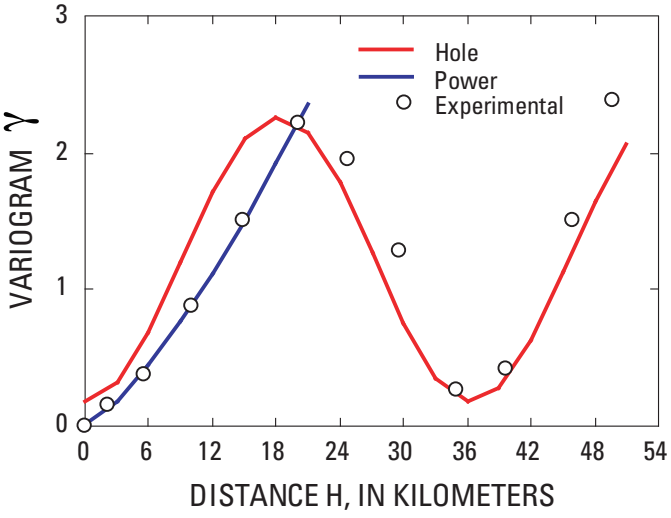


**Figure 9.** The conversion surface variogram inferred from the 25 measured values. Hole effect model defined by a length a to the first peak and positive variance contribution c. Power model defined by a power $0 < \omega < 2$ and positive slope c. n is the nugget effect (Deutsch and Journel, 1998, p. 28).

- Hole (a, c, n: 18.2112 1.0403 0.1794) - $\gamma_H(h) = c \cdot \left[1 - \cos\left(\pi\, h/a\right)\right]$
- Power (ω, c, n: 0.0399 1.3382 0.0122) - $\gamma_P(h) = c \cdot h^{\omega}$

**Table 7.** Cross-validation of the variogram model for the conversion surface.

| | Data | Power model | Hole model |
|---|---|---|---|
| Mean | -0.0845 | -0.0893 | -0.0868 |
| Standard deviation | 0.0449 | 0.0419 | 0.0409 |
| Correlation | | 0.8269 | 0.7221 |

## Assessment of Spatial Uncertainty

A by-product of kriging is the kriging variance, which is dependent on the variogram model and the data configuration, and is independent of the data values. Thus, given a variogram model, two identical data configurations would yield the same kriging variance no matter what the data were. In this sense, the kriging variance is only a ranking index of the data geometry and size (that is, the kriging variance increases when the location $\boldsymbol{u}$ being estimated gets farther away from the data location $\boldsymbol{u}_\alpha$)-not a measure of the local spread of errors (Goovaerts 1997, p. 179).

The smoothing effect of kriging on the interpolation is due to a missing error component. Consider the variable $S(\mathbf{u})$ as the sum of the estimator $s(\mathbf{u})$ and the corresponding error $r(\mathbf{u})$

$$S(\mathbf{u}) = s(\mathbf{u}) + r(\mathbf{u})$$

The kriging equation would provide the smoothly varying estimator $s(\mathbf{u})$. To restore the full variance of our geostatistical model, one may think of simulating a realization of the error with zero mean and the correct variance and variogram (Deutsch and Journel, 1998, p. 127). The simulated value of the variable would be the sum of the unique estimate and a simulated error value

$$s^{(s)}(\mathbf{u}) = s(\mathbf{u}) + r^{(s)}(\mathbf{u})$$

We applied a sequential Gaussian simulation algorithm to simulate the variable of interest $s$ (Deutsch and Journel, 1998, p. 127). The standard deviation of the simulated variable is taken as measure of the interpolation error (Battaglia and others, 2003).

The Gaussian simulation works with data that follow a normal distribution. Even though most Earth science data do not follow a normal distribution, a nonlinear transformation can convert the original data distribution (fig. 8) into a normal distribution (fig. 10). The transformed data set is also called "normal score." The simulation is performed in the normal space and repeated 500 times, and all the simulated values are back-transformed (Deutsch and Journel, 1998, p. 141). At any sampled point, the simulation algorithm returns the exact experimental value.

Just as in kriging, the variogram model is the key to any Gaussian simulation. Two models (hole and gaussian) fit the experimental normal score variogram (fig. 11). Although cross-validation (table 8) indicates that two models have practically identical performances, a statistical analysis of the simulation shows that the gaussian model better reproduces the overall statistics of the experimental data (fig. 10).

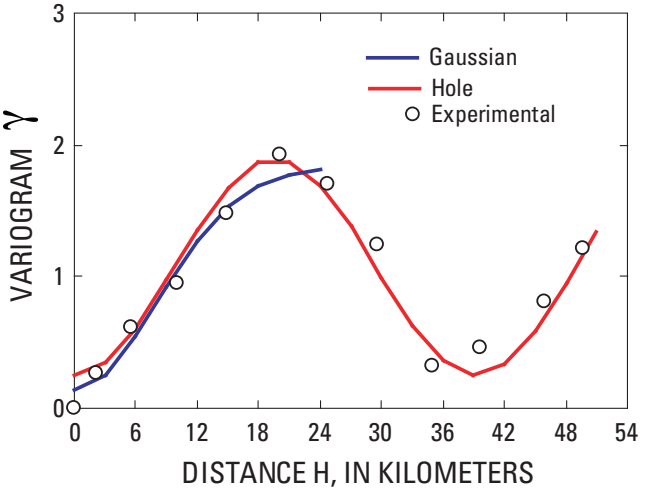


**Figure 11.** The normal score variogram inferred from the 25 measured values. Hole effect model defined by a length a to the first peak and positive variance contribution c; Gaussian model defined by an effective range a and a positive variance contribution c; and n is the nugget effect (Deutsch and Journel, 1998, p. 28).

**Table 8.** Cross-validation of the variogram model the normal score.

| | Data | Gaussian model | Hole model |
|---|---|---|---|
| Mean | -0.0000 | -0.0466 | -0.0394 |
| Standard deviation | 0.09951 | 0.8715 | 0.8913 |
| Correlation | | 0.5922 | 0.6011 |

- Hole (a, c, n: 19.5746 0.8188 0.2543 - $\gamma_H(h) = c \cdot \left[1 - \cos\left(\pi\, h/a\right)\right]$
- Gaussian (a, c, n: 34.3768 1.6947 0.1340) - $\gamma_P(h) = c \cdot \left[1 - \exp\left(-9\, h^2/a^2\right)\right]$
- Note that Gaussian model fit the data only for a limited distance. This is not a problem, because the best variogram model is chosen by cross-validation (see fig. 10).

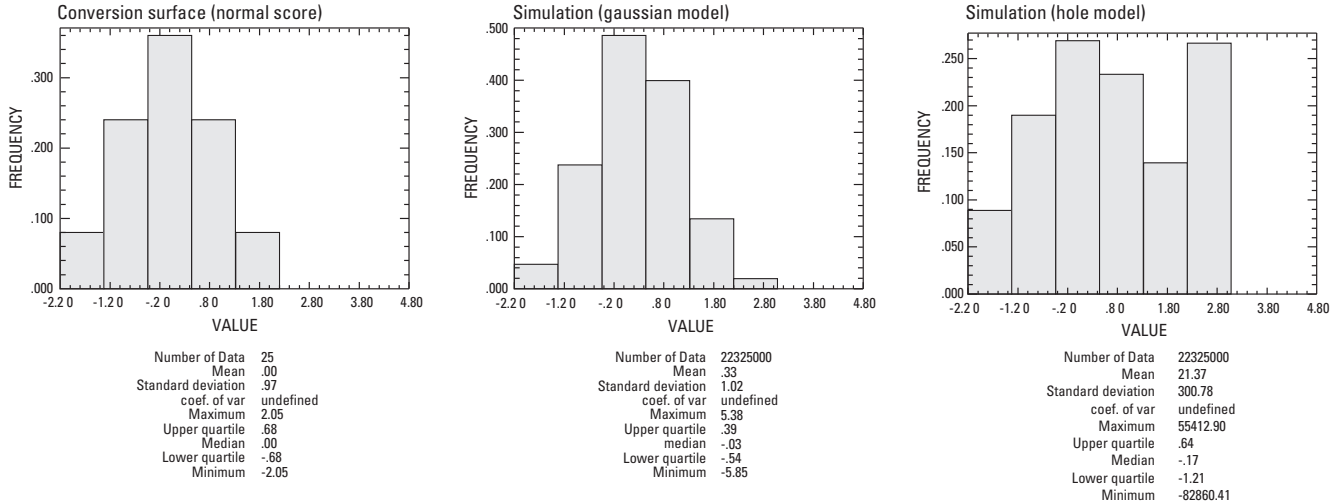


**Figure 10.** Histograms of the conversion surface (normal score) and the simulations. The gaussian model best reproduces the overall statistics of the normal score data set. The number of simulation data corresponds to 500 realizations of the conversion surface (normal score) on a grid of 190x235 cells, covering the Long Valley region from Lee Vining to Tom's Place. Each cell is 0.2x0.2 km in size.

# Tables 1–5

**Table 1.** Leveling heights for the Long Valley region (see fig. 1*B* for bench mark locations).

| BM ID | Distance | NAD 27 | | | | NAD 83 | | 2006 leveling heights (m) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | LAT (°) | W LONG (°) | X (UTM) | Y (UTM) | LAT (°) | LONG (°) | raw | ortho | σ |
| Hw 395 | | | | | | | | | | |
| C916 | 0 | 37.945556 | 119.103889 | 315132 | 4201661 | 37.94553 | -119.10488 | 2072.542 | 2073.909 | 0.000 |
| U123 | 1.18 | 37.934444 | 119.101111 | 315350 | 4200413 | 37.93433 | -119.10208 | 2066.386 | 2067.759 | 0.001 |
| Q916 | 4.67 | 37.906389 | 119.094444 | 315869 | 4197293 | 37.90633 | -119.09538 | 2081.839 | 2083.219 | 0.002 |
| DIABLO | 5.87 | 37.895000 | 119.091944 | 316060 | 4196023 | 37.89493 | -119.09288 | 2093.084 | 2094.467 | 0.002 |
| V123 | 6.71 | 37.888611 | 119.091944 | 316045 | 4195313 | 37.88853 | -119.09288 | 2091.156 | 2092.542 | 0.002 |
| JUCTION | 7.22 | 37.886667 | 119.089722 | 316233 | 4195097 | 37.88663 | -119.09068 | 2101.939 | 2103.324 | 0.002 |
| W123 RESET | 9.72 | 37.863333 | 119.086944 | 316421 | 4192495 | 37.86323 | -119.08788 | 2155.200 | 2156.603 | 0.002 |
| N916 | 11.07 | 37.853333 | 119.082778 | 316757 | 4191378 | 37.85323 | -119.08378 | 2190.014 | 2191.423 | 0.002 |
| BM7 | 12.29 | 37.842500 | 119.077500 | 317197 | 4190169 | 37.84243 | -119.07848 | 2220.981 | 2222.401 | 0.002 |
| M916 | 13.87 | 37.831389 | 119.070833 | 317759 | 4188924 | 37.83133 | -119.07178 | 2273.714 | 2275.144 | 0.003 |
| 5 RESET | 16.66 | 37.811111 | 119.050833 | 319470 | 4186632 | 37.81103 | -119.05178 | 2351.603 | 2353.077 | 0.003 |
| J916 | 20 | 37.804167 | 119.037500 | 320624 | 4185841 | 37.80413 | -119.03848 | 2403.222 | 2404.711 | 0.003 |
| 16DOR | 20.44 | 37.790000 | 119.029444 | 321303 | 4184250 | 37.78993 | -119.03038 | 2421.198 | 2422.707 | 0.003 |
| K916 | 21.9 | 37.780000 | 119.019444 | 322160 | 4183121 | 37.77993 | -119.02038 | 2437.253 | 2438.777 | 0.003 |
| T2SR | 21.91 | | | 322099 | 4183201 | 37.78064 | -119.02109 | 2436.417 | 2438.180 | 0.003 |
| BM2 | 23.43 | 37.770833 | 119.007778 | 323160 | 4182078 | 37.77073 | -119.00878 | 2450.858 | 2452.376 | 0.003 |
| B1391 | 24.18 | 37.766667 | 119.001667 | 323687 | 4181612 | 37.76663 | -119.00268 | 2420.170 | 2421.685 | 0.003 |
| A1391 | 24.64 | 37.763333 | 118.998056 | 323996 | 4181228 | 37.76323 | -118.99908 | 2394.960 | 2396.478 | 0.003 |
| B1383 | 25.6 | 37.759722 | 118.989444 | 324754 | 4180812 | 37.75963 | -118.99038 | 2354.398 | 2355.902 | 0.004 |
| CAL TRAN88 | 27.43 | 37.752222 | 118.979722 | 325591 | 4179962 | 37.75213 | -118.98068 | 2285.610 | 2287.095 | 0.004 |
| A1383 | 27.76 | 37.744444 | 118.976389 | 325864 | 4179090 | 37.74433 | -118.97738 | 2280.117 | 2281.611 | 0.004 |
| X123 | 28.29 | 37.740278 | 118.973333 | 326127 | 4178629 | 37.74023 | -118.97427 | 2280.484 | 2281.984 | 0.004 |
| Z911 | 29.17 | 37.734444 | 118.968333 | 326554 | 4177965 | 37.73433 | -118.96927 | 2292.204 | 2293.712 | 0.004 |
| Y911 | 30.45 | 37.723056 | 118.960000 | 327259 | 4176696 | 37.72303 | -118.96097 | 2343.482 | 2345.025 | 0.004 |
| B13 | 31.57 | 37.715833 | 118.953889 | 327780 | 4175875 | 37.71573 | -118.95487 | 2332.277 | 2333.842 | 0.004 |
| EAL15 | 32.37 | 37.709167 | 118.950833 | 328038 | 4175137 | 37.70913 | -118.95177 | 2306.170 | 2307.738 | 0.004 |
| EAL33 | 32.99 | 37.704444 | 118.949722 | 328124 | 4174602 | 37.70433 | -118.95067 | 2320.826 | 2322.397 | 0.004 |
| D916 | 33.09 | 37.703056 | 118.950000 | 328095 | 4174459 | 37.70303 | -118.95097 | 2312.192 | 2313.766 | 0.004 |
| Z1382 RESET | 33.96 | 37.696667 | 118.946667 | 328371 | 4173742 | 37.69663 | -118.94767 | 2323.264 | 2324.842 | 0.004 |
| Y123 | 34.91 | 37.689167 | 118.941389 | 328821 | 4172901 | 37.68913 | -118.94237 | 2315.532 | 2317.110 | 0.004 |
| 13DOR | 35.25 | 37.688056 | 118.938333 | 329092 | 4172773 | 37.68803 | -118.93927 | 2310.754 | 2312.335 | 0.004 |
| 12DOR | 36.27 | 37.680278 | 118.932778 | 329559 | 4171897 | 37.68023 | -118.93377 | 2311.056 | 2312.641 | 0.004 |
| BM12 | 37.33 | 37.671111 | 118.930833 | 329714 | 4170873 | 37.67103 | -118.93177 | 2309.546 | 2311.116 | 0.004 |
| W911 | 38.81 | 37.660556 | 118.925833 | 330131 | 4169699 | 37.66053 | -118.92677 | 2242.584 | 2244.130 | 0.004 |
| 1EGE | 39.12 | 37.657222 | 118.923889 | 330291 | 4169318 | 37.65713 | -118.92487 | 2233.810 | 2235.359 | 0.004 |

**Table 1.** Leveling heights for the Long Valley region (see fig. 1*B* for bench mark locations)—Continued.

| BM ID | Distance | NAD 27 | | | | NAD 83 | | 2006 leveling heights (m) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | LAT (°) | W LONG (°) | X (UTM) | Y (UTM) | LAT (°) | LONG (°) | raw | ortho | σ |
| 2EGE | 39.42 | 37.655000 | 118.922778 | 330383 | 4169072 | 37.65493 | -118.92377 | 2230.182 | 2231.734 | 0.004 |
| 3EGE | 39.73 | 37.652500 | 118.921111 | 330527 | 4168791 | 37.65243 | -118.92207 | 2230.089 | 2231.641 | 0.004 |
| 4EGE | 40.03 | 37.650556 | 118.919444 | 330673 | 4168578 | 37.65053 | -118.92037 | 2232.357 | 2233.906 | 0.004 |
| 5EGE | 40.33 | 37.648056 | 118.917222 | 330862 | 4168296 | 37.64803 | -118.91817 | 2238.275 | 2239.818 | 0.004 |
| 6EGE | 40.6 | 37.646667 | 118.915000 | 331052 | 4168137 | 37.64663 | -118.91597 | 2235.115 | 2236.654 | 0.004 |
| Z123 | 40.79 | 37.645833 | 118.913333 | 331200 | 4168034 | 37.64573 | -118.91427 | 2221.979 | 2223.518 | 0.004 |
| 7EGE | 41.04 | 37.644722 | 118.910833 | 331419 | 4167907 | 37.64463 | -118.91177 | 2216.631 | 2218.169 | 0.004 |
| CASA AZ | 41.27 | 37.643611 | 118.908056 | 331654 | 4167780 | 37.64353 | -118.90907 | 2209.634 | 2211.173 | 0.004 |
| DBR11 | 41.35 | 37.643889 | 118.908333 | 331637 | 4167814 | 37.64383 | -118.90927 | 2209.989 | 2211.529 | 0.005 |
| DBR8 | 41.53 | 37.643056 | 118.906111 | 331830 | 4167721 | 37.64303 | -118.90707 | 2208.597 | 2210.136 | 0.005 |
| DBR7 | 41.59 | 37.642778 | 118.905556 | 331873 | 4167687 | 37.64273 | -118.90657 | 2208.757 | 2210.296 | 0.005 |
| DBR6 | 41.65 | 37.642222 | 118.905000 | 331925 | 4167620 | 37.64213 | -118.90597 | 2207.724 | 2209.263 | 0.005 |
| DBR5 | 41.82 | 37.642222 | 118.904444 | 331978 | 4167619 | 37.64213 | -118.90537 | 2207.446 | 2208.985 | 0.005 |
| DBR2 | 42 | 37.641389 | 118.902778 | 332117 | 4167527 | 37.64133 | -118.90377 | 2201.828 | 2203.370 | 0.005 |
| DBR1 | 42.05 | 37.641111 | 118.902500 | 332143 | 4167493 | 37.64103 | -118.90347 | 2198.549 | 2200.092 | 0.005 |
| 9EGE | 42.14 | 37.641944 | 118.902500 | 332145 | 4167582 | 37.64183 | -118.90347 | 2205.811 | 2207.354 | 0.005 |
| MGB20 | 42.68 | 37.639722 | 118.897500 | 332581 | 4167329 | 37.63963 | -118.89847 | 2193.343 | 2194.898 | 0.005 |
| MGB19 | 42.73 | 37.639444 | 118.896667 | 332651 | 4167294 | 37.63933 | -118.89767 | 2193.317 | 2194.870 | 0.005 |
| MGB18 | 42.78 | 37.639444 | 118.896389 | 332677 | 4167294 | 37.63933 | -118.89737 | 2192.796 | 2194.349 | 0.005 |
| 11EGE | 42.83 | 37.639167 | 118.895833 | 332730 | 4167270 | 37.63913 | -118.89677 | 2192.376 | 2193.926 | 0.005 |
| MGB13 | 43.12 | 37.637778 | 118.893056 | 332965 | 4167110 | 37.63773 | -118.89407 | 2190.744 | 2192.276 | 0.005 |
| 10DOR | 44.96 | 37.632778 | 118.875278 | 334524 | 4166524 | 37.63273 | -118.87626 | 2174.661 | 2176.196 | 0.005 |
| A124 RESET | 46.04 | 37.629444 | 118.863333 | 335576 | 4166125 | 37.62933 | -118.86426 | 2168.642 | 2170.171 | 0.005 |
| S911 RESET | 47.53 | 37.625833 | 118.848333 | 336892 | 4165700 | 37.62573 | -118.84926 | 2174.444 | 2175.963 | 0.005 |
| 9DOR RESET | 48.38 | 37.623333 | 118.838611 | 337742 | 4165406 | 37.62323 | -118.83956 | 2165.434 | 2166.948 | 0.005 |
| T911 RESET | 49.11 | 37.620833 | 118.830833 | 338425 | 4165115 | 37.62073 | -118.83176 | 2158.041 | 2159.550 | 0.005 |
| 8DOR | 50 | 37.618611 | 118.822222 | 339180 | 4164856 | 37.61853 | -118.82316 | 2145.381 | 2146.883 | 0.005 |
| CONVICT | 51.16 | 37.614722 | 118.810000 | 340248 | 4164402 | 37.61463 | -118.81096 | 2150.912 | 2152.398 | 0.005 |
| 7DOR | 52.54 | 37.603611 | 118.803611 | 340789 | 4163160 | 37.60353 | -118.80456 | 2099.466 | 2100.944 | 0.005 |
| V911 | 53.87 | 37.593889 | 118.794444 | 341581 | 4162068 | 37.59383 | -118.79536 | 2087.225 | 2088.710 | 0.005 |
| 6DOR | 55.35 | 37.586111 | 118.783333 | 342545 | 4161184 | 37.58603 | -118.78426 | 2108.880 | 2110.367 | 0.005 |
| U911 | 56.23 | 37.581667 | 118.770278 | 343683 | 4160674 | 37.58163 | -118.77126 | 2108.727 | 2110.208 | 0.005 |
| D124 | 57.99 | 37.573056 | 118.758889 | 344672 | 4159701 | 37.57303 | -118.75986 | 2112.663 | 2114.139 | 0.005 |
| C1433 | 60.29 | 37.561944 | 118.738611 | 346442 | 4158425 | 37.56183 | -118.73956 | 2142.561 | 2144.043 | 0.005 |
| E124 | 61.49 | 37.564167 | 118.725556 | 347595 | 4158659 | 37.56413 | -118.72656 | 2196.710 | 2198.206 | 0.005 |
| P911 RESET | 62.79 | 37.556111 | 118.716111 | 348418 | 4157745 | 37.55603 | -118.71706 | 2149.444 | 2150.944 | 0.006 |

**Table 1.** Leveling heights for the Long Valley region (see fig. 1*B* for bench mark locations)—Continued.

| BM ID | Distance | NAD 27 | | | | NAD 83 | | 2006 leveling heights (m) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | LAT (°) | W LONG (°) | X (UTM) | Y (UTM) | LAT (°) | LONG (°) | raw | ortho | σ |
| CROWLEY AZ | 64.05 | 37.558611 | 118.702222 | 349651 | 4158000 | 37.55853 | -118.70316 | 2133.982 | 2135.442 | 0.006 |
| F124 | 64.67 | 37.560278 | 118.696111 | 350193 | 4158179 | 37.56023 | -118.69706 | 2134.573 | 2136.026 | 0.006 |
| Hw 203 | | | | | | | | | | |
| CASA AZ | 41.27 | 37.643611 | 118.908056 | 331654 | 4167780 | 37.64353 | -118.90907 | 2209.634 | 2211.173 | 0.004 |
| DBR15 | 41.53 | 37.642778 | 118.910556 | 331432 | 4167696 | 37.64273 | -118.91157 | 2215.042 | 2216.579 | 0.005 |
| DBR16 | 41.58 | | | | | | | 2218.106 | 2219.890 | 0.005 |
| DBR17 | 41.63 | 37.642222 | 118.911389 | 331360 | 4167631 | 37.64213 | -118.91237 | 2220.713 | 2222.248 | 0.005 |
| DBR19 | 41.77 | 37.641944 | 118.913056 | 331209 | 4167601 | 37.64183 | -118.91407 | 2227.385 | 2228.921 | 0.005 |
| DBR20 | 41.82 | 37.641667 | 118.913889 | 331138 | 4167580 | 37.64163 | -118.91487 | 2229.134 | 2230.670 | 0.005 |
| DBR21 | 41.86 | 37.641389 | 118.914444 | 331093 | 4167548 | 37.64133 | -118.91537 | 2230.209 | 2231.746 | 0.005 |
| 1LRM | 42.48 | 37.640000 | 118.920556 | 330543 | 4167404 | 37.63993 | -118.92157 | 2239.175 | 2240.724 | 0.005 |
| 34EGE | 42.58 | 37.640278 | 118.921111 | 330500 | 4167438 | 37.64023 | -118.92207 | 2242.761 | 2244.311 | 0.005 |
| 35EGE | 43.6 | 37.639167 | 118.932222 | 329518 | 4167336 | 37.63913 | -118.93317 | 2288.375 | 2289.941 | 0.005 |
| 36EGE | 43.88 | 37.639167 | 118.935000 | 329271 | 4167341 | 37.63913 | -118.93597 | 2300.971 | 2302.537 | 0.005 |
| 37EGE | 44.22 | 37.640000 | 118.938611 | 328955 | 4167436 | 37.63993 | -118.93957 | 2316.878 | 2318.445 | 0.005 |
| 38EGE | 44.43 | 37.640833 | 118.940278 | 328807 | 4167528 | 37.64073 | -118.94127 | 2326.490 | 2328.057 | 0.005 |
| 2JCM | 44.68 | 37.641667 | 118.940278 | 328809 | 4167628 | 37.64163 | -118.94127 | 2331.964 | 2333.530 | 0.005 |
| 39EGE | 44.98 | 37.643056 | 118.945278 | 328371 | 4167792 | 37.64303 | -118.94627 | 2332.273 | 2333.844 | 0.005 |
| 3LRM | 45.79 | 37.646111 | 118.953056 | 327689 | 4168140 | 37.64603 | -118.95407 | 2357.627 | 2359.202 | 0.005 |
| STA907 | 45.88 | 37.646111 | 118.953611 | 327645 | 4168141 | 37.64603 | -118.95457 | 2357.469 | 2359.046 | 0.005 |
| 3JCM | 46.4 | 37.647500 | 118.958611 | 327207 | 4168305 | 37.64743 | -118.95957 | 2373.041 | 2374.622 | 0.005 |
| K1383 | 47.49 | 37.648333 | 118.970556 | 326150 | 4168416 | 37.64823 | -118.97157 | 2395.076 | 2396.670 | 0.005 |
| J1383 | 48.54 | 37.648611 | 118.981944 | 325154 | 4168470 | 37.64854 | -118.98287 | 2444.373 | 2445.984 | 0.005 |
| H1383 | 49.39 | 37.653611 | 118.986944 | 324725 | 4169034 | 37.65353 | -118.98787 | 2473.767 | 2475.391 | 0.005 |
| 5JCM | 49.95 | 37.656111 | 118.991389 | 324334 | 4169320 | 37.65603 | -118.99237 | 2505.020 | 2506.653 | 0.005 |
| G1383 | 50.69 | 37.653611 | 118.994167 | 324081 | 4169048 | 37.65354 | -118.99517 | 2545.448 | 2547.083 | 0.005 |
| F1383 | 51.42 | 37.650556 | 118.999167 | 323633 | 4168725 | 37.65054 | -119.00017 | 2582.893 | 2584.539 | 0.005 |
| 6JCM | 51.6 | 37.651667 | 119.000278 | 323538 | 4168849 | 37.65164 | -119.00127 | 2596.167 | 2597.814 | 0.005 |
| E1383 | 52.27 | 37.650833 | 119.006667 | 322971 | 4168761 | 37.65074 | -119.00767 | 2632.094 | 2633.745 | 0.005 |
| 7JCM | 52.82 | 37.648056 | 119.010833 | 322603 | 4168469 | 37.64804 | -119.01177 | 2654.897 | 2656.551 | 0.005 |
| 8JCM | 53.85 | 37.650000 | 119.021667 | 321646 | 4168701 | 37.64994 | -119.02267 | 2690.411 | 2692.077 | 0.005 |
| JEE17 | 55.07 | 37.653333 | 119.032778 | 320675 | 4169088 | 37.65324 | -119.03377 | 2688.590 | 2690.272 | 0.005 |
| PM14 | 55.57 | | | 320472 | 4168980 | 37.65222 | -119.03604 | 2705.347 | 2707.054 | 0.005 |
| 9JCM | 55.66 | 37.651667 | 119.037778 | 320230 | 4168920 | 37.65164 | -119.03877 | 2715.027 | 2716.705 | 0.005 |
| PM15 | 55.77 | | | | | | | 2724.494 | 2726.198 | 0.005 |
| 42EGE | 56.88 | 37.651667 | 119.050833 | 319083 | 4168945 | 37.65164 | -119.05177 | 2759.282 | 2760.943 | 0.005 |

**Table 1.** Leveling heights for the Long Valley region (see fig. 1*B* for bench mark locations)—Continued.

| BM ID | Distance | NAD 27 | | | | NAD 83 | | 2006 leveling heights (m) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | LAT (°) | W LONG (°) | X (UTM) | Y (UTM) | LAT (°) | LONG (°) | raw | ortho | σ |
| D1383 | 57.68 | 37.654167 | 119.056667 | 318568 | 4169234 | 37.65414 | -119.05767 | 2796.339 | 2797.979 | 0.005 |
| 20JD | 57.73 | 37.654167 | 119.056944 | 318551 | 4169234 | 37.65414 | -119.05787 | 2796.461 | 2798.097 | 0.005 |
| RET | 58.11 | 37.656667 | 119.059722 | 318310 | 4169517 | 37.65664 | -119.06067 | 2823.587 | 2825.176 | 0.005 |
| Antelope Valley Rd | | | | | | | | | | |
| 3EGE | 39.73 | 37.652500 | 118.921111 | 330527 | 4168791 | 37.65243 | -118.92207 | 2230.089 | 2231.641 | 0.004 |
| 12EGE | 40.01 | 37.654167 | 118.918611 | 330752 | 4168976 | 37.65413 | -118.91957 | 2236.042 | 2237.591 | 0.004 |
| 13EGE | 40.28 | 37.651944 | 118.916111 | 330967 | 4168716 | 37.65183 | -118.91707 | 2249.094 | 2250.638 | 0.004 |
| 24JCM | 40.55 | 37.654167 | 118.914722 | 331096 | 4168969 | 37.65413 | -118.91567 | 2272.126 | 2273.669 | 0.004 |
| 14EGE | 40.96 | 37.655833 | 118.914444 | 331126 | 4169146 | 37.65573 | -118.91537 | 2276.599 | 2278.144 | 0.004 |
| 15EGE | 41.27 | 37.657500 | 118.911111 | 331421 | 4169328 | 37.65743 | -118.91207 | 2289.307 | 2290.857 | 0.004 |
| 16EGE | 41.95 | 37.660000 | 118.909722 | 331550 | 4169603 | 37.65993 | -118.91067 | 2307.087 | 2308.640 | 0.005 |
| 23JCM | 42.01 | 37.664167 | 118.906667 | 331824 | 4170064 | 37.66413 | -118.90767 | 2328.435 | 2329.995 | 0.005 |
| 17EGE | 42.27 | 37.664167 | 118.906667 | 331824 | 4170064 | 37.66413 | -118.90767 | 2338.736 | 2340.294 | 0.005 |
| 18EGE | 42.67 | 37.666111 | 118.906389 | 331855 | 4170274 | 37.66603 | -118.90737 | 2327.664 | 2329.226 | 0.005 |
| 19EGE | 42.96 | 37.668889 | 118.904167 | 332055 | 4170581 | 37.66883 | -118.90517 | 2330.719 | 2332.285 | 0.005 |
| 20EGE | 43.22 | 37.671389 | 118.903611 | 332114 | 4170857 | 37.67133 | -118.90457 | 2336.381 | 2337.947 | 0.005 |
| 22JCM | 43.83 | 37.673333 | 118.902500 | 332215 | 4171066 | 37.67323 | -118.90347 | 2340.491 | 2342.057 | 0.005 |
| 22EGE | 44.14 | 37.674722 | 118.899722 | 332465 | 4171216 | 37.67463 | -118.90067 | 2340.094 | 2341.661 | 0.005 |
| 23EGE | 44.53 | 37.675000 | 118.897222 | 332687 | 4171245 | 37.67493 | -118.89817 | 2343.340 | 2344.906 | 0.005 |
| 21JCM | 44.83 | 37.674167 | 118.893889 | 332976 | 4171150 | 37.67413 | -118.89487 | 2326.433 | 2328.001 | 0.005 |
| 24EGE | 45.23 | 37.673333 | 118.890556 | 333265 | 4171045 | 37.67323 | -118.89157 | 2320.305 | 2321.872 | 0.005 |
| 25EGE | 45.57 | 37.673611 | 118.886944 | 333592 | 4171071 | 37.67353 | -118.88787 | 2301.172 | 2302.739 | 0.005 |
| 26EGE | 45.94 | 37.676111 | 118.886667 | 333615 | 4171348 | 37.67603 | -118.88767 | 2279.865 | 2281.432 | 0.005 |
| 27EGE | 46.27 | 37.679167 | 118.885833 | 333701 | 4171691 | 37.67913 | -118.88677 | 2256.428 | 2257.992 | 0.005 |
| KWH5 | 47.12 | 37.679167 | 118.877778 | 334407 | 4171677 | 37.67913 | -118.87877 | 2198.973 | 2200.516 | 0.005 |
| KWH6 | 47.17 | 37.679167 | 118.877222 | 334460 | 4171676 | 37.67913 | -118.87817 | 2199.125 | 2200.666 | 0.005 |
| 18JCM RESET | 47.75 | 37.681944 | 118.871944 | 334933 | 4171966 | 37.68183 | -118.87287 | 2202.042 | 2203.568 | 0.005 |
| 25JCM | 49.36 | 37.687222 | 118.858889 | 336091 | 4172531 | 37.68713 | -118.85987 | 2211.396 | 2212.922 | 0.005 |
| 26JCM | 50.99 | 37.683611 | 118.841389 | 337627 | 4172101 | 37.68353 | -118.84237 | 2157.287 | 2158.812 | 0.005 |
| 27JCM | 52.3 | 37.679722 | 118.828333 | 338774 | 4171646 | 37.67963 | -118.82927 | 2128.954 | 2130.478 | 0.005 |
| 28JCM RESET | 53.19 | 37.676667 | 118.819167 | 339570 | 4171297 | 37.67663 | -118.82016 | 2122.305 | 2123.831 | 0.005 |
| 43DOR | 54.49 | 37.684167 | 118.810556 | 340344 | 4172115 | 37.68413 | -118.81156 | 2111.871 | 2113.400 | 0.005 |
| 44DOR | 55.79 | 37.675000 | 118.805833 | 340748 | 4171086 | 37.67493 | -118.80676 | 2120.750 | 2122.281 | 0.005 |
| 29JCM | 55.85 | 37.675000 | 118.805278 | 340792 | 4171085 | 37.67493 | -118.80626 | 2123.125 | 2124.655 | 0.005 |
| Long Valley | | | | | | | | | | |
| 43DOR | 54.49 | 37.684167 | 118.810556 | 340344 | 4172115 | 37.68413 | -118.81156 | 2111.871 | 2113.400 | 0.005 |

**Table 1.** Leveling heights for the Long Valley region (see fig. 1*B* for bench mark locations)—Continued.

| BM ID | Distance | NAD 27 | | | | NAD 83 | | 2006 leveling heights (m) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | LAT (°) | W LONG (°) | X (UTM) | Y (UTM) | LAT (°) | LONG (°) | raw | ortho | σ |
| 44DOR | 55.79 | 37.675000 | 118.805833 | 340748 | 4171086 | 37.67493 | -118.80676 | 2120.750 | 2122.281 | 0.005 |
| 29JCM | 55.879 | 37.675000 | 118.805278 | 340792 | 4171085 | 37.67493 | -118.80626 | 2123.125 | 2124.655 | 0.005 |
| 49DOR | 57.094 | 37.685556 | 118.798333 | 341432 | 4172249 | 37.68553 | -118.79926 | 2117.673 | 2119.201 | 0.005 |
| T3S R29E | 58.191 | 37.687500 | 118.789167 | 342238 | 4172445 | 37.68743 | -118.79016 | 2098.894 | 2100.422 | 0.005 |
| 3JD | 58.359 | 37.688333 | 118.787778 | 342363 | 4172531 | 37.68823 | -118.78876 | 2108.117 | 2109.642 | 0.005 |
| 50DOR | 59.832 | 37.687778 | 118.772778 | 343685 | 4172450 | 37.68773 | -118.77376 | 2080.458 | 2081.980 | 0.005 |
| 4JD | 61.963 | 37.699444 | 118.762222 | 344644 | 4173720 | 37.69933 | -118.76316 | 2077.896 | 2079.386 | 0.006 |

**Table 2.** Long Valley region GPS-on-Bench Mark survey for 2006 (http://quake.wr.usgs.gov/research/deformation/gps/auto/MammothLevel/index.html).

| | ITRF00 | | | | | | | | NAD83 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **BM ID** | **X (m)** | **Y (m)** | **Z (m)** | **LAT (dms)** | **LONG (dms)** | **height (m)** | **σ (m)** | | **LAT (dd)** | **LONG (dd)** | **height (m)** | **σ (m)** |
| **Hw 395** | | | | | | | | | | | | |
| C916 | -2450419.145 | -4401717.603 | 3901862.070 | 37 56 40.7939 | -119 6 16.2618 | 2048.888 | 0.018 | | 37.94466 | -119.10450 | 2049.495 | 0.018 |
| JUCT | -2451311.907 | -4405770.894 | 3896805.613 | 37 53 12.2367 | -119 5 27.5163 | 2078.324 | 0.018 | | 37.88673 | -119.09096 | 2078.932 | 0.018 |
| BM07 | -2451833.960 | -4409032.959 | 3893006.686 | 37 50 33.2118 | -119 4 41.3230 | 2197.436 | 0.013 | | 37.84255 | -119.07813 | 2198.046 | 0.013 |
| T2SR | -2449570.806 | -4415305.648 | 3887707.705 | 37 46 50.3230 | -119 1 15.9916 | 2412.830 | 0.015 | | 37.78064 | -119.02109 | 2413.442 | 0.015 |
| X123 | -2447236.056 | -4419592.030 | 3884073.818 | 37 44 25.2129 | -118 58 27.7323 | 2256.680 | 0.017 | | 37.74033 | -118.97436 | 2257.295 | 0.017 |
| EA15 | -2446539.834 | -4422417.572 | 3881355.677 | 37 42 33.1483 | -118 57 7.0136 | 2282.240 | 0.018 | | 37.70920 | -118.95193 | 2282.856 | 0.018 |
| D916 | -2446675.900 | -4422826.693 | 3880817.210 | 37 42 10.9301 | -118 57 3.7904 | 2288.246 | 0.018 | | 37.70303 | -118.95104 | 2288.863 | 0.018 |
| 13DO | -2446236.824 | -4424196.403 | 3879538.797 | 37 41 18.5810 | -118 56 21.0628 | 2286.816 | 0.019 | | 37.68849 | -118.93917 | 2287.433 | 0.019 |
| 1EGE | -2446147.210 | -4426593.686 | 3876751.808 | 37 39 26.3398 | -118 55 30.5551 | 2209.887 | 0.021 | | 37.65731 | -118.92514 | 2210.505 | 0.021 |
| A124 | -2442387.554 | -4430783.175 | 3874244.940 | 37 37 45.3173 | -118 51 53.7879 | 2144.692 | 0.018 | | 37.62925 | -118.86493 | 2145.312 | 0.018 |
| CONV | -2438694.463 | -4433914.285 | 3872968.372 | 37 36 53.5008 | -118 48 40.3435 | 2126.971 | 0.013 | | 37.61486 | -118.81119 | 2127.593 | 0.013 |
| V911 | -2438236.020 | -4435715.037 | 3871102.288 | 37 35 38.7132 | -118 47 48.6101 | 2063.397 | 0.020 | | 37.59408 | -118.79682 | 2064.020 | 0.020 |
| D124 | -2436073.169 | -4438579.376 | 3869234.977 | 37 34 21.6729 | -118 45 35.1857 | 2088.882 | 0.012 | | 37.57268 | -118.75976 | 2089.505 | 0.012 |
| CROA | -2432179.496 | -4441819.302 | 3868009.583 | 37 33 31.0159 | -118 42 12.6637 | 2110.124 | 0.020 | | 37.57268 | -118.75976 | 2110.749 | 0.020 |
| **Hw 203** | | | | | | | | | | | | |
| 2JCM | -2448139.275 | -4426795.549 | 3875434.378 | 37 38 29.9317 | -118 56 37.6672 | 2308.123 | 0.018 | | 37.64164 | -118.94378 | 2308.740 | 0.018 |
| K138 | -2450061.872 | -4425273.250 | 3876057.839 | 37 38 53.8817 | -118 58 16.3161 | 2371.290 | 0.026 | | 37.64830 | -118.97118 | 2371.907 | 0.026 |
| 5JCM | -2451481.682 | -4423984.601 | 3876807.417 | 37 39 21.8251 | -118 59 32.4275 | 2481.347 | 0.042 | | 37.65606 | -118.99233 | 2481.963 | 0.042 |
| PM14 | -2455059.681 | -4422479.395 | 3876592.227 | 37 39 8.0001 | -119 2 9.7977 | 2681.712 | 0.020 | | 37.65222 | -119.03604 | 2682.327 | 0.020 |
| RETT | -2456867.244 | -4421287.068 | 3876999.297 | 37 39 21.7108 | -119 3 37.8439 | 2800.002 | 0.013 | | 37.65603 | -119.06050 | 2800.616 | 0.013 |
| **Antelope Valley Rd** | | | | | | | | | | | | |
| 18EG | -2444518.478 | -4426901.440 | 3877576.656 | 37 39 57.7769 | -118 54 26.3383 | 2303.678 | 0.029 | | 37.66605 | -118.90730 | 2304.296 | 0.029 |
| 25EG | -2442785.387 | -4427263.227 | 3878207.757 | 37 40 24.2927 | -118 53 17.3162 | 2277.133 | 0.021 | | 37.67341 | -118.88813 | 2277.751 | 0.021 |
| KWH6 | -2441775.218 | -4427266.572 | 3878668.793 | 37 40 45.7358 | -118 52 41.1673 | 2175.047 | 0.019 | | 37.67937 | -118.87809 | 2175.665 | 0.019 |
| 25JC | -2440123.372 | -4427570.743 | 3879376.437 | 37 41 14.4222 | -118 51 36.1584 | 2187.269 | 0.022 | | 37.68734 | -118.86003 | 2187.888 | 0.022 |
| 26JC | -2438889.595 | -4428453.656 | 3879057.484 | 37 41 2.7103 | -118 50 34.6865 | 2133.127 | 0.019 | | 37.68408 | -118.84295 | 2133.746 | 0.019 |
| 44DO | -2436384.951 | -4430499.056 | 3878240.950 | 37 40 30.1741 | -118 48 24.9339 | 2096.536 | 0.016 | | 37.67504 | -118.80691 | 2097.156 | 0.016 |
| 29JC | -2436349.096 | -4430535.028 | 3878226.400 | 37 40 29.5184 | -118 48 22.9451 | 2098.917 | 0.018 | | 37.67486 | -118.80636 | 2099.537 | 0.018 |
| **Long Valley** | | | | | | | | | | | | |
| T3SR | -2434676.129 | -4430438.460 | 3879339.680 | 37 41 15.7376 | -118 47 25.0312 | 2074.636 | 0.020 | | 37.68770 | -118.79027 | 2075.256 | 0.020 |
| 4JDD | -2432186.508 | -4430876.515 | 3880359.537 | 37 41 58.0532 | -118 45 47.3840 | 2053.676 | 0.019 | | 37.69946 | -118.76315 | 2054.296 | 0.019 |

**Table 3.** Experimental hybrid geoid height (N+s) for the Long Valley region.

| BM ID | Distance | UTM NAVD 27 | | NAD83 GPS | | NAVD88 leveled | | measured geoid | | GEOID03 | | Geoids difference | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | X | Y | height (m) | σ (m) | height (m) | σ (m) | N+s (m) | σ (m) | N+s (m) | σ (m) | Δ (m) | σ (m) |
| **Hw 395** | | | | | | | | | | | | | |
| C916 | 0 | 315132 | 4201661 | 2049.495 | 0.018 | 2073.909 | 0.000 | -24.414 | 0.018 | -24.408 | 0.024 | -0.006 | 0.030 |
| JUCTION | 7.22 | 316233 | 4195097 | 2078.932 | 0.018 | 2103.324 | 0.002 | -24.392 | 0.018 | -24.374 | 0.024 | -0.018 | 0.030 |
| BM7 | 12.29 | 317197 | 4190169 | 2198.046 | 0.013 | 2222.401 | 0.002 | -24.355 | 0.013 | -24.364 | 0.024 | 0.009 | 0.027 |
| T2SR | 21.91 | 322099 | 4183201 | 2413.442 | 0.015 | 2438.180 | 0.003 | -24.738 | 0.015 | -24.454 | 0.024 | -0.284 | 0.028 |
| X123 | 28.29 | 326127 | 4178629 | 2257.295 | 0.017 | 2281.984 | 0.004 | -24.689 | 0.017 | -24.624 | 0.024 | -0.065 | 0.030 |
| EAL15 | 32.37 | 328038 | 4175137 | 2282.856 | 0.018 | 2307.738 | 0.004 | -24.882 | 0.018 | -24.750 | 0.024 | -0.132 | 0.030 |
| D916 | 33.09 | 328095 | 4174459 | 2288.863 | 0.018 | 2313.766 | 0.004 | -24.903 | 0.018 | -24.754 | 0.024 | -0.149 | 0.030 |
| 13DOR | 35.25 | 329092 | 4172773 | 2287.433 | 0.019 | 2312.335 | 0.004 | -24.902 | 0.019 | -24.778 | 0.024 | -0.124 | 0.031 |
| 1EGE | 39.12 | 330291 | 4169318 | 2210.505 | 0.021 | 2235.359 | 0.004 | -24.854 | 0.021 | -24.749 | 0.024 | -0.105 | 0.032 |
| A124 RESET | 46.04 | 335576 | 4166125 | 2145.312 | 0.018 | 2170.171 | 0.005 | -24.859 | 0.019 | -24.723 | 0.024 | -0.136 | 0.030 |
| CONVICT | 51.16 | 340248 | 4164402 | 2127.593 | 0.013 | 2152.398 | 0.005 | -24.805 | 0.014 | -24.727 | 0.024 | -0.078 | 0.028 |
| V911 | 53.87 | 341581 | 4162068 | 2064.020 | 0.020 | 2088.710 | 0.005 | -24.690 | 0.021 | -24.608 | 0.024 | -0.082 | 0.032 |
| D124 | 57.99 | 344672 | 4159701 | 2089.505 | 0.012 | 2114.139 | 0.005 | -24.634 | 0.013 | -24.558 | 0.024 | -0.076 | 0.027 |
| CROWLEY AZ | 64.05 | 349651 | 4158000 | 2110.749 | 0.020 | 2135.442 | 0.006 | -24.693 | 0.021 | -24.662 | 0.024 | -0.031 | 0.032 |
| **Hw 203** | | | | | | | | | | | | | |
| 2JCM | 44.68 | 328809 | 4167628 | 2308.740 | 0.018 | 2333.530 | 0.005 | -24.790 | 0.019 | -24.668 | 0.024 | -0.122 | 0.030 |
| K1383 | 47.49 | 326150 | 4168416 | 2371.907 | 0.026 | 2396.670 | 0.005 | -24.763 | 0.026 | -24.657 | 0.024 | -0.106 | 0.036 |
| 5JCM | 49.95 | 324334 | 4169320 | 2481.963 | 0.042 | 2506.653 | 0.005 | -24.690 | 0.042 | -24.651 | 0.024 | -0.039 | 0.049 |
| PM14 | 55.57 | 320472 | 4168980 | 2682.327 | 0.020 | 2707.054 | 0.005 | -24.727 | 0.021 | -24.593 | 0.024 | -0.134 | 0.032 |
| RET | 58.11 | 318310 | 4169517 | 2800.616 | 0.013 | 2825.176 | 0.005 | -24.560 | 0.014 | -24.543 | 0.024 | -0.017 | 0.028 |
| **Antelope V.** | | | | | | | | | | | | | |
| 18EGE | 42.67 | 331855 | 4170274 | 2304.296 | 0.029 | 2329.226 | 0.005 | -24.930 | 0.029 | -24.808 | 0.024 | -0.122 | 0.038 |
| 25EGE | 45.57 | 333592 | 4171071 | 2277.751 | 0.021 | 2302.739 | 0.005 | -24.988 | 0.022 | -24.851 | 0.024 | -0.137 | 0.032 |
| KWH6 | 47.17 | 334460 | 4171676 | 2175.665 | 0.019 | 2200.666 | 0.005 | -25.001 | 0.020 | -24.866 | 0.024 | -0.135 | 0.031 |
| 25JCM | 49.36 | 336091 | 4172531 | 2187.888 | 0.022 | 2212.922 | 0.005 | -25.034 | 0.023 | -24.899 | 0.024 | -0.135 | 0.033 |
| 26JCM | 50.99 | 337627 | 4172101 | 2133.746 | 0.019 | 2158.812 | 0.005 | -25.066 | 0.020 | -24.923 | 0.024 | -0.143 | 0.031 |
| 44DOR | 55.79 | 340748 | 4171086 | 2097.156 | 0.016 | 2122.281 | 0.005 | -25.125 | 0.017 | -24.962 | 0.024 | -0.163 | 0.029 |
| 29JCM | 55.85 | 340792 | 4171085 | 2099.537 | 0.018 | 2124.655 | 0.005 | -25.118 | 0.019 | -24.962 | 0.024 | -0.156 | 0.030 |
| **Long Valley** | | | | | | | | | | | | | |
| T3S R29E | 58.191 | 342238 | 4172445 | 2075.256 | 0.020 | 2100.422 | 0.005 | -25.166 | 0.021 | -24.981 | 0.024 | -0.185 | 0.032 |
| 4JD | 61.963 | 344644 | 4173720 | 2054.296 | 0.019 | 2079.386 | 0.006 | -25.090 | 0.020 | -24.959 | 0.024 | -0.131 | 0.031 |

**Table 4.** Experimental conversion surface s for the Long Valley region.

| | NAD83 GPS | | NAVD88 leveled | | USGG2003 | s | |
|---|---|---|---|---|---|---|---|
| **BM ID** | **height (m)** | **σ (m)** | **height (m)** | **σ (m)** | **height (m)** | **height (m)** | **σ (m)** |
| | | | **Hw 395** | | | | |
| C916 | 2049.495 | 0.018 | 2073.909 | 0.000 | -24.320 | -0.094 | 0.024 |
| JUCTION | 2078.932 | 0.018 | 2103.324 | 0.002 | -24.299 | -0.093 | 0.024 |
| BM7 | 2198.046 | 0.013 | 2222.401 | 0.002 | -24.300 | -0.055 | 0.024 |
| T2SR [1] | 2413.442 | 0.015 | 2438.180 | 0.003 | -24.419 | -0.319 | 0.024 |
| X123 | 2257.295 | 0.017 | 2281.984 | 0.004 | -24.610 | -0.079 | 0.024 |
| EAL15 | 2282.856 | 0.018 | 2307.738 | 0.004 | -24.749 | -0.133 | 0.024 |
| D916 | 2288.863 | 0.018 | 2313.766 | 0.004 | -24.755 | -0.148 | 0.024 |
| 13DOR | 2287.433 | 0.019 | 2312.335 | 0.004 | -24.785 | -0.117 | 0.024 |
| 1EGE | 2210.505 | 0.021 | 2235.359 | 0.004 | -24.767 | -0.087 | 0.024 |
| A124 RESET | 2145.312 | 0.018 | 2170.171 | 0.005 | -24.762 | -0.097 | 0.024 |
| CONVICT | 2127.593 | 0.013 | 2152.398 | 0.005 | -24.776 | -0.029 | 0.024 |
| V911 | 2064.020 | 0.020 | 2088.710 | 0.005 | -24.663 | -0.027 | 0.024 |
| D124 | 2089.505 | 0.012 | 2114.139 | 0.005 | -24.620 | -0.014 | 0.024 |
| CROWLEY AZ | 2110.749 | 0.020 | 2135.442 | 0.006 | -24.730 | 0.037 | 0.024 |
| | | | **Hw 203** | | | | |
| 2JCM | 2308.740 | 0.018 | 2333.530 | 0.005 | -24.686 | -0.104 | 0.024 |
| K1383 | 2371.907 | 0.026 | 2396.670 | 0.005 | -24.665 | -0.098 | 0.024 |
| 5JCM | 2481.963 | 0.042 | 2506.653 | 0.005 | -24.652 | -0.038 | 0.024 |
| PM14 [1] | 2682.327 | 0.020 | 2707.054 | 0.005 | -24.584 | -0.143 | 0.024 |
| RET | 2800.616 | 0.013 | 2825.176 | 0.005 | -24.527 | -0.033 | 0.024 |
| | | | **Antelope V.** | | | | |
| 18EGE | 2304.296 | 0.029 | 2329.226 | 0.005 | -24.828 | -0.102 | 0.024 |
| 25EGE | 2277.751 | 0.021 | 2302.739 | 0.005 | -24.873 | -0.115 | 0.024 |
| KWH6 | 2175.665 | 0.019 | 2200.666 | 0.005 | -24.889 | -0.112 | 0.024 |
| 25JCM | 2187.888 | 0.022 | 2212.922 | 0.005 | -24.925 | -0.109 | 0.024 |
| 26JCM | 2133.746 | 0.019 | 2158.812 | 0.005 | -24.954 | -0.112 | 0.024 |
| 44DOR | 2097.156 | 0.016 | 2122.281 | 0.005 | -25.001 | -0.124 | 0.024 |
| 29JCM | 2099.537 | 0.018 | 2124.655 | 0.005 | -25.001 | -0.117 | 0.024 |
| | | | **Long Valley** | | | | |
| T3S R29E | 2075.256 | 0.020 | 2100.422 | 0.005 | -25.021 | -0.145 | 0.024 |
| 4JD | 2054.296 | 0.019 | 2079.386 | 0.006 | -25.001 | -0.089 | 0.024 |

[1] This point is an outlier and has not been included in the final interpolation.

**Table 5.** Geoid heights at leveling benchmarks for the Long Valley region (see fig. 1*B* for benchmark location).

| BM | UTM NAD27 | | LVGEOID (m) | | Conversion surface s (m) | | USGG2003 |
|---|---|---|---|---|---|---|---|
| | X | Y | height | σ | height | σ | height (m) |
| **LINE 1: HIGHWAY 395** | | | | | | | |
| F124 | 350193 | 4158179 | -24.721 | 0.028 | 0.038 | 0.027 | -24.759 |
| CROWLEY AZ [1] | 349651 | 4158000 | -24.693 | 0.021 | 0.037 | 0.000 | -24.73 |
| P911 | 348423 | 4158055 | -24.654 | 0.030 | 0.027 | 0.030 | -24.681 |
| P911 RESET | 348418 | 4157745 | -24.638 | 0.027 | 0.028 | 0.027 | -24.666 |
| E124 | 347595 | 4158659 | -24.662 | 0.029 | 0.016 | 0.029 | -24.678 |
| C1433 | 346442 | 4158425 | -24.619 | 0.030 | 0.007 | 0.030 | -24.626 |
| BMQ | 346317 | 4158371 | -24.613 | 0.029 | 0.006 | 0.029 | -24.619 |
| Q911 | 346128 | 4158619 | -24.617 | 0.028 | 0.003 | 0.029 | -24.62 |
| D124 [1] | 344672 | 4159701 | -24.634 | 0.013 | -0.014 | 0.000 | -24.62 |
| U911 | 343683 | 4160674 | -24.665 | 0.031 | -0.020 | 0.031 | -24.645 |
| C124 | 342588 | 4161150 | -24.656 | 0.029 | -0.023 | 0.030 | -24.633 |
| 6DOR | 342545 | 4161184 | -24.658 | 0.029 | -0.024 | 0.030 | -24.634 |
| V911 [1] | 341581 | 4162068 | -24.690 | 0.021 | -0.027 | 0.000 | -24.663 |
| B124 | 340910 | 4163002 | -24.727 | 0.029 | -0.027 | 0.029 | -24.7 |
| 7DOR | 340789 | 4163160 | -24.733 | 0.030 | -0.027 | 0.030 | -24.706 |
| CONVICT [1] | 340248 | 4164402 | -24.805 | 0.014 | -0.029 | 0.000 | -24.776 |
| 8DOR | 339180 | 4164856 | -24.822 | 0.031 | -0.044 | 0.031 | -24.778 |
| T911 RESET | 338425 | 4165115 | -24.833 | 0.030 | -0.056 | 0.030 | -24.777 |
| 9DOR | 337742 | 4165406 | -24.845 | 0.029 | -0.067 | 0.029 | -24.778 |
| 9DOR RESET | 337742 | 4165406 | -24.845 | 0.029 | -0.067 | 0.029 | -24.778 |
| S911 RESET | 336892 | 4165700 | -24.854 | 0.028 | -0.080 | 0.028 | -24.774 |
| A124 | 335522 | 4166104 | -24.857 | 0.000 | -0.097 | 0.019 | -24.76 |
| A124 RESET [1] | 335576 | 4166125 | -24.859 | 0.019 | -0.097 | 0.000 | -24.762 |
| 10DOR | 334524 | 4166524 | -24.857 | 0.021 | -0.101 | 0.021 | -24.756 |
| R911 | 334603 | 4166456 | -24.854 | 0.021 | -0.100 | 0.021 | -24.754 |
| 11DOR | 333018 | 4167142 | -24.848 | 0.021 | -0.099 | 0.021 | -24.749 |
| MGB13 | 332965 | 4167110 | -24.844 | 0.021 | -0.098 | 0.021 | -24.746 |
| MGB14 | 332895 | 4167145 | -24.843 | 0.020 | -0.097 | 0.020 | -24.746 |
| MGB16 | 332852 | 4167201 | -24.845 | 0.020 | -0.097 | 0.020 | -24.748 |
| MGB17 | 332773 | 4167236 | -24.844 | 0.021 | -0.096 | 0.022 | -24.748 |
| 11EGE | 332730 | 4167270 | -24.844 | 0.021 | -0.096 | 0.022 | -24.748 |
| MGB18 | 332677 | 4167294 | -24.844 | 0.022 | -0.096 | 0.022 | -24.748 |
| MGB19 | 332651 | 4167294 | -24.843 | 0.022 | -0.096 | 0.022 | -24.747 |
| MGB20 | 332581 | 4167329 | -24.843 | 0.022 | -0.096 | 0.022 | -24.747 |
| MGB21 | 332528 | 4167330 | -24.842 | 0.022 | -0.096 | 0.022 | -24.746 |
| 10EGE | 332335 | 4167400 | -24.841 | 0.022 | -0.096 | 0.022 | -24.745 |
| 9EGE | 332145 | 4167582 | -24.848 | 0.020 | -0.096 | 0.020 | -24.752 |
| DBR1 | 332143 | 4167493 | -24.841 | 0.020 | -0.096 | 0.020 | -24.745 |
| DBR2 | 332117 | 4167527 | -24.842 | 0.021 | -0.096 | 0.021 | -24.746 |
| DBR3 | 332047 | 4167562 | -24.842 | 0.021 | -0.096 | 0.021 | -24.746 |
| DBR4 | 331995 | 4167585 | -24.844 | 0.021 | -0.095 | 0.021 | -24.749 |
| DBR5 | 331978 | 4167619 | -24.845 | 0.020 | -0.095 | 0.020 | -24.75 |
| 8EGE | 331952 | 4167686 | -24.847 | 0.020 | -0.095 | 0.020 | -24.752 |
| DBR6 | 331925 | 4167620 | -24.844 | 0.020 | -0.095 | 0.020 | -24.749 |
| DBR7 | 331873 | 4167687 | -24.845 | 0.021 | -0.095 | 0.021 | -24.75 |
| DBR8 | 331830 | 4167721 | -24.846 | 0.021 | -0.095 | 0.021 | -24.751 |
| DBR9 | 331759 | 4167745 | -24.845 | 0.021 | -0.095 | 0.021 | -24.75 |
| DBR10 | 331707 | 4167779 | -24.842 | 0.019 | -0.095 | 0.019 | -24.747 |

**Table 5.** Geoid heights at leveling benchmarks for the Long Valley region (see fig. 1*B* for benchmark location)—Continued.

| BM | UTM NAD27 | | LVGEOID (m) | | Conversion surface s (m) | | USGG2003 |
|---|---|---|---|---|---|---|---|
| | X | Y | height | σ | height | σ | height (m) |
| DBR11 | 331637 | 4167814 | -24.842 | 0.021 | -0.095 | 0.022 | -24.747 |
| CASA AZ | 331654 | 4167780 | -24.841 | 0.019 | -0.095 | 0.019 | -24.746 |
| 7EGE | 331419 | 4167907 | -24.839 | 0.022 | -0.094 | 0.022 | -24.745 |
| Z123 | 331200 | 4168034 | -24.837 | 0.021 | -0.093 | 0.021 | -24.744 |
| 6EGE | 331052 | 4168137 | -24.838 | 0.020 | -0.093 | 0.020 | -24.745 |
| 5EGE | 330862 | 4168296 | -24.838 | 0.021 | -0.092 | 0.021 | -24.746 |
| 4EGE | 330673 | 4168578 | -24.843 | 0.021 | -0.091 | 0.021 | -24.752 |
| 3EGE | 330527 | 4168791 | -24.845 | 0.020 | -0.089 | 0.020 | -24.756 |
| 2EGE | 330383 | 4169072 | -24.850 | 0.018 | -0.088 | 0.019 | -24.762 |
| 1EGE [1] | 330291 | 4169318 | -24.854 | 0.021 | -0.087 | 0.000 | -24.767 |
| W911 | 330131 | 4169699 | -24.863 | 0.018 | -0.089 | 0.019 | -24.774 |
| BM12 | 329714 | 4170873 | -24.886 | 0.013 | -0.099 | 0.013 | -24.787 |
| X911 | 329346 | 4171003 | -24.882 | 0.014 | -0.101 | 0.014 | -24.781 |
| 12DOR | 329559 | 4171897 | -24.901 | 0.014 | -0.108 | 0.014 | -24.793 |
| 13DOR [1] | 329092 | 4172773 | -24.902 | 0.019 | -0.117 | 0.000 | -24.785 |
| Y123 | 328821 | 4172901 | -24.902 | 0.013 | -0.121 | 0.013 | -24.781 |
| 14DOR | 328464 | 4173552 | -24.905 | 0.014 | -0.135 | 0.014 | -24.77 |
| Z1382 | 328371 | 4173742 | -24.905 | 0.014 | -0.138 | 0.014 | -24.767 |
| Z1382 RESET | 328371 | 4173742 | -24.905 | 0.014 | -0.138 | 0.014 | -24.767 |
| D916 [1] | 328095 | 4174459 | -24.903 | 0.018 | -0.148 | 0.000 | -24.755 |
| EAL33 | 328124 | 4174602 | -24.901 | 0.013 | -0.146 | 0.013 | -24.755 |
| EAL15 [1] | 328038 | 4175137 | -24.882 | 0.018 | -0.133 | 0.000 | -24.749 |
| B13 | 327780 | 4175875 | -24.854 | 0.014 | -0.123 | 0.014 | -24.731 |
| 69.97RT | 327524 | 4176280 | -24.830 | 0.014 | -0.116 | 0.014 | -24.714 |
| Y911 | 327259 | 4176696 | -24.797 | 0.014 | -0.109 | 0.014 | -24.688 |
| Z911 | 326554 | 4177965 | -24.730 | 0.017 | -0.089 | 0.017 | -24.641 |
| 15DOR | 326407 | 4178102 | -24.718 | 0.019 | -0.086 | 0.019 | -24.632 |
| X123 [1] | 326127 | 4178629 | -24.689 | 0.017 | -0.079 | 0.000 | -24.61 |
| CRESTVIEW | 326127 | 4178629 | -24.689 | 0.000 | -0.079 | 0.017 | -24.61 |
| A1383 | 325864 | 4179090 | -24.662 | 0.023 | -0.076 | 0.023 | -24.586 |
| CAL TRAN88 | 325591 | 4179962 | -24.632 | 0.025 | -0.072 | 0.025 | -24.56 |
| L916 | 325345 | 4179967 | -24.621 | 0.026 | -0.070 | 0.026 | -24.551 |
| L916 RESET | 325345 | 4179967 | -24.621 | 0.026 | -0.070 | 0.026 | -24.551 |
| B1383 | 324754 | 4180812 | -24.593 | 0.028 | -0.069 | 0.028 | -24.524 |
| KUSE | 324365 | 4181165 | -24.570 | 0.028 | -0.067 | 0.028 | -24.503 |
| A1391 | 323996 | 4181228 | -24.555 | 0.030 | -0.065 | 0.030 | -24.49 |
| B1391 | 323687 | 4181612 | -24.539 | 0.029 | -0.064 | 0.029 | -24.475 |
| BM2 | 323160 | 4182078 | -24.517 | 0.030 | -0.062 | 0.030 | -24.455 |
| T2SR | 322099 | 4183201 | -24.478 | 0.033 | -0.059 | 0.033 | -24.419 |
| K916 | 322160 | 4183121 | -24.481 | 0.032 | -0.060 | 0.032 | -24.421 |
| 16DOR | 321303 | 4184250 | -24.447 | 0.034 | -0.057 | 0.034 | -24.39 |
| J916 | 320624 | 4185841 | -24.429 | 0.033 | -0.056 | 0.033 | -24.373 |
| H916 | 320553 | 4185809 | -24.426 | 0.034 | -0.055 | 0.034 | -24.371 |
| BM5 | 319470 | 4186632 | -24.401 | 0.034 | -0.053 | 0.034 | -24.348 |
| 5 RESET | 319470 | 4186632 | -24.401 | 0.034 | -0.053 | 0.034 | -24.348 |
| BM6 | 318614 | 4187762 | -24.378 | 0.032 | -0.052 | 0.032 | -24.326 |
| M916 | 317759 | 4188924 | -24.360 | 0.029 | -0.052 | 0.029 | -24.308 |
| BM7 [1] | 317197 | 4190169 | -24.355 | 0.013 | -0.055 | 0.000 | -24.3 |
| N916 | 316757 | 4191378 | -24.356 | 0.030 | -0.064 | 0.030 | -24.292 |

**Table 5.** Geoid heights at leveling benchmarks for the Long Valley region (see fig. 1*B* for benchmark location)—Continued.

| BM | UTM NAD27 | | LVGEOID (m) | | Conversion surface s (m) | | USGG2003 |
|---|---|---|---|---|---|---|---|
| | X | Y | height | σ | height | σ | height (m) |
| W123 | 316514 | 4192316 | -24.360 | 0.030 | -0.071 | 0.030 | -24.289 |
| W123 RESET | 316421 | 4192495 | -24.359 | 0.030 | -0.073 | 0.030 | -24.286 |
| R916 | 316393 | 4193584 | -24.376 | 0.028 | -0.082 | 0.028 | -24.294 |
| JUCTION [1] | 316233 | 4195097 | -24.392 | 0.018 | -0.093 | 0.000 | -24.299 |
| V123 | 316045 | 4195313 | -24.385 | 0.026 | -0.093 | 0.026 | -24.292 |
| DIABLO | 316060 | 4196023 | -24.394 | 0.026 | -0.095 | 0.026 | -24.299 |
| DIABLO RESET | 316060 | 4196023 | -24.394 | 0.026 | -0.095 | 0.026 | -24.299 |
| Q916 | 315869 | 4197293 | -24.397 | 0.028 | -0.095 | 0.028 | -24.302 |
| P916 | 315774 | 4198560 | -24.407 | 0.028 | -0.095 | 0.028 | -24.312 |
| U123 | 315350 | 4200413 | -24.407 | 0.024 | -0.094 | 0.024 | -24.313 |
| C916 [1] | 315132 | 4201661 | -24.414 | 0.018 | -0.094 | 0.000 | -24.32 |
| **LINE 2: HIGHWAY 203** | | | | | | | |
| CASA AZ | 331654 | 4167780 | -24.841 | 0.019 | -0.095 | 0.019 | -24.746 |
| DBR11 | 331637 | 4167814 | -24.842 | 0.021 | -0.095 | 0.022 | -24.747 |
| DBR12 | 331584 | 4167782 | -24.839 | 0.019 | -0.095 | 0.019 | -24.744 |
| DBR13 | 331512 | 4167750 | -24.836 | 0.021 | -0.095 | 0.021 | -24.741 |
| DBR14 | 331485 | 4167728 | -24.835 | 0.021 | -0.095 | 0.021 | -24.74 |
| DBR15 | 331432 | 4167696 | -24.832 | 0.021 | -0.095 | 0.021 | -24.737 |
| DBR17 | 331360 | 4167631 | -24.828 | 0.021 | -0.095 | 0.021 | -24.733 |
| DBR18 | 331289 | 4167599 | -24.825 | 0.022 | -0.095 | 0.022 | -24.73 |
| DBR19 | 331209 | 4167601 | -24.823 | 0.022 | -0.095 | 0.022 | -24.728 |
| DBR20 | 331138 | 4167580 | -24.820 | 0.022 | -0.095 | 0.022 | -24.725 |
| DBR21 | 331093 | 4167548 | -24.818 | 0.020 | -0.095 | 0.020 | -24.723 |
| 33EGE | 330819 | 4167520 | -24.812 | 0.021 | -0.095 | 0.021 | -24.717 |
| 1LRM | 330543 | 4167404 | -24.803 | 0.021 | -0.096 | 0.021 | -24.707 |
| 34EGE | 330500 | 4167438 | -24.803 | 0.022 | -0.096 | 0.022 | -24.707 |
| 1JCM | 330084 | 4167380 | -24.795 | 0.021 | -0.097 | 0.022 | -24.698 |
| 2LRM | 329712 | 4167332 | -24.789 | 0.021 | -0.099 | 0.021 | -24.69 |
| 35EGE | 329518 | 4167336 | -24.787 | 0.022 | -0.100 | 0.022 | -24.687 |
| 36EGE | 329271 | 4167341 | -24.784 | 0.019 | -0.101 | 0.019 | -24.683 |
| 37EGE | 328955 | 4167436 | -24.784 | 0.020 | -0.103 | 0.020 | -24.681 |
| 38EGE | 328807 | 4167528 | -24.786 | 0.019 | -0.104 | 0.019 | -24.682 |
| 2JCM [1] | 328809 | 4167628 | -24.790 | 0.019 | -0.104 | 0.000 | -24.686 |
| 39EGE | 328371 | 4167792 | -24.790 | 0.018 | -0.104 | 0.018 | -24.686 |
| 40EGE | 328084 | 4168009 | -24.791 | 0.021 | -0.104 | 0.021 | -24.687 |
| 3LRM | 327689 | 4168140 | -24.788 | 0.023 | -0.104 | 0.023 | -24.684 |
| STA907 | 327645 | 4168141 | -24.788 | 0.023 | -0.104 | 0.023 | -24.684 |
| 41EGE | 327374 | 4168235 | -24.786 | 0.020 | -0.104 | 0.020 | -24.682 |
| 3JCM | 327207 | 4168305 | -24.785 | 0.021 | -0.103 | 0.021 | -24.682 |
| K1383 [1] | 326150 | 4168416 | -24.763 | 0.026 | -0.098 | 0.000 | -24.665 |
| 4JCM | 325038 | 4168839 | -24.714 | 0.024 | -0.062 | 0.024 | -24.652 |
| J1383 | 325154 | 4168470 | -24.714 | 0.026 | -0.069 | 0.026 | -24.645 |
| H1383 | 324725 | 4169034 | -24.702 | 0.027 | -0.051 | 0.027 | -24.651 |
| 5JCM [1] | 324334 | 4169320 | -24.690 | 0.042 | -0.038 | 0.000 | -24.652 |
| G1383 | 324081 | 4169048 | -24.681 | 0.028 | -0.038 | 0.028 | -24.643 |
| F1383 | 323633 | 4168725 | -24.669 | 0.030 | -0.037 | 0.030 | -24.632 |
| 6JCM | 323538 | 4168849 | -24.669 | 0.029 | -0.036 | 0.029 | -24.633 |
| E1383 | 322971 | 4168761 | -24.659 | 0.031 | -0.034 | 0.031 | -24.625 |

**Table 5.** Geoid heights at leveling benchmarks for the Long Valley region (see fig. 1*B* for benchmark location)—Continued.

| BM | UTM NAD27 | | LVGEOID (m) | | Conversion surface s (m) | | USGG2003 |
|---|---|---|---|---|---|---|---|
| | X | Y | height | σ | height | σ | height (m) |
| 7JCM | 322603 | 4168469 | -24.658 | 0.032 | -0.034 | 0.032 | -24.624 |
| 8JCM | 321646 | 4168701 | -24.642 | 0.033 | -0.032 | 0.033 | -24.61 |
| JEE1 | 321481 | 4168826 | -24.637 | 0.033 | -0.032 | 0.033 | -24.605 |
| JEE3 | 321307 | 4168952 | -24.629 | 0.032 | -0.032 | 0.032 | -24.597 |
| JEE6 | 321142 | 4169078 | -24.623 | 0.032 | -0.032 | 0.032 | -24.591 |
| JEE9 | 320979 | 4169270 | -24.615 | 0.032 | -0.032 | 0.032 | -24.583 |
| JEE12 | 320871 | 4169184 | -24.616 | 0.031 | -0.032 | 0.031 | -24.584 |
| JEE15 | 320772 | 4169119 | -24.616 | 0.031 | -0.032 | 0.031 | -24.584 |
| JEE17 | 320675 | 4169088 | -24.616 | 0.032 | -0.032 | 0.032 | -24.584 |
| JEE19 | 320576 | 4169035 | -24.616 | 0.032 | -0.032 | 0.032 | -24.584 |
| JEE20 | 320479 | 4169003 | -24.616 | 0.032 | -0.032 | 0.032 | -24.584 |
| JEE22 | 320354 | 4168973 | -24.615 | 0.032 | -0.032 | 0.032 | -24.583 |
| PM14 | 320472 | 4168980 | -24.616 | 0.032 | -0.032 | 0.032 | -24.584 |
| 9JCM | 320230 | 4168920 | -24.616 | 0.030 | -0.032 | 0.030 | -24.584 |
| 42EGE | 319083 | 4168945 | -24.605 | 0.032 | -0.032 | 0.032 | -24.573 |
| D1383 | 318568 | 4169234 | -24.583 | 0.031 | -0.032 | 0.031 | -24.551 |
| 20JD | 318551 | 4169234 | -24.582 | 0.031 | -0.032 | 0.031 | -24.55 |
| RET [1] | 318310 | 4169517 | -24.560 | 0.014 | -0.033 | 0.000 | -24.527 |
| **LINE 3: LOOKOUT MTN-CASHBAUGH RANCH-WHITMORE HOT SPRINGS-CONVICT CREEK** | | | | | | | |
| 8DOR | 339180 | 4164856 | -24.822 | 0.031 | -0.044 | 0.031 | -24.778 |
| T911 RESET | 338425 | 4165115 | -24.833 | 0.030 | -0.056 | 0.030 | -24.777 |
| 9DOR RESET | 337742 | 4165406 | -24.845 | 0.029 | -0.067 | 0.029 | -24.778 |
| 1JD | 340232 | 4166312 | -24.934 | 0.028 | -0.057 | 0.028 | -24.877 |
| 48DOR | 340225 | 4166867 | -24.965 | 0.027 | -0.065 | 0.026 | -24.9 |
| 47DOR | 340417 | 4168129 | -25.026 | 0.020 | -0.082 | 0.020 | -24.944 |
| 46DOR | 340781 | 4169143 | -25.069 | 0.018 | -0.095 | 0.018 | -24.974 |
| 45DOR | 340212 | 4170297 | -25.093 | 0.014 | -0.109 | 0.014 | -24.984 |
| 2JD | 340272 | 4170662 | -25.102 | 0.013 | -0.113 | 0.013 | -24.989 |
| 29JCM [1] | 340792 | 4171085 | -25.121 | 0.019 | -0.120 | 0.000 | -25.001 |
| 44DOR [1] | 340748 | 4171086 | -25.121 | 0.017 | -0.120 | 0.000 | -25.001 |
| 43DOR | 340344 | 4172115 | -25.128 | 0.013 | -0.126 | 0.013 | -25.002 |
| 42DOR | 340072 | 4173108 | -25.127 | 0.014 | -0.127 | 0.014 | -25 |
| 41DOR | 340380 | 4173957 | -25.126 | 0.015 | -0.127 | 0.015 | -24.999 |
| 40DOR | 340648 | 4175062 | -25.107 | 0.017 | -0.120 | 0.017 | -24.987 |
| 39DOR | 340138 | 4176492 | -25.059 | 0.018 | -0.112 | 0.018 | -24.947 |
| 38DOR | 339911 | 4177551 | -25.015 | 0.021 | -0.108 | 0.021 | -24.907 |
| 26DOR | 339094 | 4178144 | -24.979 | 0.023 | -0.106 | 0.023 | -24.873 |
| 25DOR | 337403 | 4178211 | -24.957 | 0.020 | -0.106 | 0.020 | -24.851 |
| 24DOR | 336407 | 4178663 | -24.942 | 0.021 | -0.127 | 0.021 | -24.815 |
| 23DOR | 334991 | 4178847 | -24.891 | 0.023 | -0.095 | 0.023 | -24.796 |
| G916 | 333534 | 4179120 | -24.858 | 0.021 | -0.094 | 0.021 | -24.764 |
| F916 | 331752 | 4179501 | -24.813 | 0.020 | -0.095 | 0.020 | -24.718 |
| NUSE | 331505 | 4179506 | -24.808 | 0.021 | -0.095 | 0.020 | -24.713 |
| E916 | 329965 | 4179626 | -24.771 | 0.020 | -0.091 | 0.020 | -24.68 |
| MUSE | 328750 | 4178852 | -24.781 | 0.019 | -0.095 | 0.020 | -24.686 |
| LUSE | 327572 | 4177733 | -24.796 | 0.016 | -0.102 | 0.016 | -24.694 |
| 69.97RT | 327524 | 4176280 | -24.830 | 0.014 | -0.116 | 0.014 | -24.714 |
| B13 | 327780 | 4175875 | -24.854 | 0.014 | -0.123 | 0.014 | -24.731 |

**Table 5.** Geoid heights at leveling benchmarks for the Long Valley region (see fig. 1*B* for benchmark location)—Continued.

| BM | UTM NAD27 | | LVGEOID (m) | | Conversion surface s (m) | | USGG2003 |
|---|---|---|---|---|---|---|---|
| | X | Y | height | σ | height | σ | height (m) |
| **LINE 4: CASHBAUGH RANCH-LITTLE ANTELOPE VALLEY-CASA** | | | | | | | |
| 29JCM [1] | 340792 | 4171085 | -25.121 | 0.019 | -0.120 | 0.000 | -25.001 |
| 44DOR [1] | 340748 | 4171086 | -25.121 | 0.017 | -0.120 | 0.000 | -25.001 |
| 43DOR | 340344 | 4172115 | -25.128 | 0.013 | -0.126 | 0.013 | -25.002 |
| 28JCM | 339570 | 4171297 | -25.102 | 0.014 | -0.117 | 0.014 | -24.985 |
| 28JCM RESET | 339570 | 4171297 | -25.102 | 0.014 | -0.117 | 0.014 | -24.985 |
| 27JCM | 338774 | 4171646 | -25.086 | 0.014 | -0.115 | 0.014 | -24.971 |
| 26JCM [1] | 337627 | 4172101 | -25.066 | 0.020 | -0.112 | 0.000 | -24.954 |
| 25JCM [1] | 336091 | 4172531 | -25.034 | 0.023 | -0.109 | 0.000 | -24.925 |
| 18JCM | 334933 | 4171966 | -25.012 | 0.013 | -0.111 | 0.013 | -24.901 |
| 18JCM RESET | 334933 | 4171966 | -25.012 | 0.013 | -0.111 | 0.013 | -24.901 |
| KWH16 | 334854 | 4171967 | -25.010 | 0.013 | -0.111 | 0.013 | -24.899 |
| KWH15 | 334809 | 4171946 | -25.010 | 0.013 | -0.111 | 0.013 | -24.899 |
| KWH14 | 334782 | 4171880 | -25.009 | 0.013 | -0.111 | 0.013 | -24.898 |
| KWH13 | 334754 | 4171825 | -25.008 | 0.013 | -0.111 | 0.013 | -24.897 |
| KWH12 | 334727 | 4171792 | -25.006 | 0.013 | -0.111 | 0.013 | -24.895 |
| KWH11 | 334726 | 4171759 | -25.005 | 0.013 | -0.111 | 0.013 | -24.894 |
| KWH10 | 334709 | 4171759 | -25.005 | 0.013 | -0.111 | 0.013 | -24.894 |
| KWH9 | 334629 | 4171728 | -25.004 | 0.013 | -0.112 | 0.013 | -24.892 |
| KWH8 | 334558 | 4171729 | -25.003 | 0.013 | -0.112 | 0.013 | -24.891 |
| KWH7 | 334504 | 4171697 | -25.002 | 0.000 | -0.112 | 0.000 | -24.89 |
| KWH6 [1] | 334460 | 4171676 | -25.001 | 0.020 | -0.112 | 0.000 | -24.889 |
| KWH5 | 334407 | 4171677 | -25.000 | 0.000 | -0.112 | 0.000 | -24.888 |
| KWH4 | 334381 | 4171699 | -25.000 | 0.000 | -0.112 | 0.000 | -24.888 |
| 17JCM | 333626 | 4171903 | -24.996 | 0.013 | -0.116 | 0.013 | -24.88 |
| 27EGE | 333701 | 4171691 | -24.994 | 0.012 | -0.115 | 0.012 | -24.879 |
| 26EGE | 333615 | 4171348 | -24.989 | 0.013 | -0.115 | 0.013 | -24.874 |
| 25EGE [1] | 333592 | 4171071 | -24.988 | 0.022 | -0.115 | 0.000 | -24.873 |
| 24EGE | 333265 | 4171045 | -24.982 | 0.014 | -0.114 | 0.014 | -24.868 |
| 21JCM | 332976 | 4171150 | -24.980 | 0.012 | -0.113 | 0.012 | -24.867 |
| 23EGE | 332687 | 4171245 | -24.976 | 0.013 | -0.112 | 0.013 | -24.864 |
| 22EGE | 332465 | 4171216 | -24.970 | 0.014 | -0.110 | 0.014 | -24.86 |
| 21EGE | 332465 | 4171216 | -24.970 | 0.014 | -0.110 | 0.014 | -24.86 |
| 22JCM | 332215 | 4171066 | -24.961 | 0.013 | -0.109 | 0.014 | -24.852 |
| 20EGE | 332114 | 4170857 | -24.953 | 0.013 | -0.107 | 0.014 | -24.846 |
| 19EGE | 332055 | 4170581 | -24.944 | 0.014 | -0.105 | 0.014 | -24.839 |
| 18EGE [1] | 331855 | 4170274 | -24.928 | 0.029 | -0.100 | 0.000 | -24.828 |
| 17EGE | 331824 | 4170064 | -24.922 | 0.013 | -0.100 | 0.013 | -24.822 |
| 23JCM | 331824 | 4170064 | -24.922 | 0.013 | -0.100 | 0.013 | -24.822 |
| 16EGE | 331550 | 4169603 | -24.898 | 0.017 | -0.096 | 0.017 | -24.802 |
| 15EGE | 331421 | 4169328 | -24.886 | 0.018 | -0.094 | 0.019 | -24.792 |
| 14EGE | 331126 | 4169146 | -24.871 | 0.018 | -0.091 | 0.018 | -24.78 |
| 24JCM | 331096 | 4168969 | -24.865 | 0.019 | -0.091 | 0.019 | -24.774 |
| 13EGE | 330967 | 4168716 | -24.854 | 0.019 | -0.091 | 0.019 | -24.763 |
| 12EGE | 330752 | 4168976 | -24.855 | 0.019 | -0.089 | 0.019 | -24.766 |
| 3EGE | 330527 | 4168791 | -24.845 | 0.020 | -0.089 | 0.020 | -24.756 |

**Table 5.** Geoid heights at leveling benchmarks for the Long Valley region (see fig. 1*B* for benchmark location)—Continued.

| BM | UTM NAD27 | | LVGEOID (m) | | Conversion surface s (m) | | USGG2003 |
|---|---|---|---|---|---|---|---|
| | X | Y | height | σ | height | σ | height (m) |
| **LINE 5: SMOKEY BEAR FLAT-RESURGENT DOME-LITTLE ANTELOPE VALLEY** | | | | | | | |
| 17JCM | 333626 | 4171903 | -24.996 | 0.013 | -0.116 | 0.013 | -24.88 |
| 16PDI | 333724 | 4171935 | -24.996 | 0.012 | -0.115 | 0.012 | -24.881 |
| 15PDI | 333804 | 4171988 | -24.997 | 0.012 | -0.114 | 0.012 | -24.883 |
| 14PDI | 333977 | 4172240 | -25.002 | 0.013 | -0.115 | 0.013 | -24.887 |
| 4PDI | 333886 | 4172542 | -25.004 | 0.012 | -0.116 | 0.012 | -24.888 |
| 12PDI | 333792 | 4172699 | -25.005 | 0.013 | -0.117 | 0.013 | -24.888 |
| 31EGE | 333797 | 4172954 | -25.008 | 0.012 | -0.118 | 0.012 | -24.89 |
| 11PDI | 333873 | 4173197 | -25.013 | 0.013 | -0.119 | 0.013 | -24.894 |
| 10PDI | 333753 | 4173355 | -25.013 | 0.014 | -0.120 | 0.014 | -24.893 |
| 16JCM | 333520 | 4173659 | -25.014 | 0.014 | -0.122 | 0.014 | -24.892 |
| 9PDI | 333400 | 4173817 | -25.014 | 0.014 | -0.123 | 0.014 | -24.891 |
| 8PDI | 333160 | 4174133 | -25.006 | 0.015 | -0.115 | 0.015 | -24.891 |
| 32EGE | 332914 | 4174204 | -25.003 | 0.015 | -0.116 | 0.015 | -24.887 |
| 7PDI | 332748 | 4174263 | -25.001 | 0.015 | -0.116 | 0.015 | -24.885 |
| 15JCM | 332779 | 4174485 | -25.000 | 0.014 | -0.116 | 0.014 | -24.884 |
| 6PDI | 332678 | 4174731 | -24.997 | 0.013 | -0.117 | 0.013 | -24.88 |
| 5PDI | 332585 | 4174921 | -24.994 | 0.014 | -0.118 | 0.014 | -24.876 |
| 3PDI 1984 | 332567 | 4174922 | -24.994 | 0.014 | -0.118 | 0.014 | -24.876 |
| 2PDI 1984 | 332420 | 4175047 | -24.989 | 0.016 | -0.118 | 0.016 | -24.871 |
| 1PDI 1984 | 332231 | 4175295 | -24.982 | 0.014 | -0.119 | 0.014 | -24.863 |
| 2PDI 1983 | 332110 | 4175419 | -24.982 | 0.015 | -0.124 | 0.015 | -24.858 |
| 1PDI 1983 | 332088 | 4175631 | -24.977 | 0.016 | -0.124 | 0.016 | -24.853 |
| 14JCM | 332145 | 4175852 | -24.962 | 0.016 | -0.112 | 0.016 | -24.85 |
| 13JCM | 331088 | 4175907 | -24.937 | 0.015 | -0.115 | 0.015 | -24.822 |
| 12JCM | 330044 | 4175306 | -24.931 | 0.014 | -0.126 | 0.014 | -24.805 |
| L1383 | 330183 | 4174782 | -24.943 | 0.013 | -0.127 | 0.014 | -24.816 |
| 11JCM | 329670 | 4174726 | -24.930 | 0.014 | -0.130 | 0.014 | -24.8 |
| 10JCM | 329256 | 4173880 | -24.922 | 0.013 | -0.131 | 0.013 | -24.791 |
| 13DOR | 329092 | 4172773 | -24.902 | 0.000 | -0.117 | 0.000 | -24.785 |
| **LINE 6: LAKE CROWLEY TIE A** | | | | | | | |
| 43DOR | 340344 | 4172115 | -25.128 | 0.013 | -0.126 | 0.013 | -25.002 |
| 44DOR | 340748 | 4171086 | -25.121 | 0.000 | -0.120 | 0.000 | -25.001 |
| 29JCM | 340792 | 4171085 | -25.121 | 0.000 | -0.120 | 0.000 | -25.001 |
| 49DOR | 341432 | 4172249 | -25.154 | 0.013 | -0.140 | 0.013 | -25.014 |
| T3S R29E [1] | 342238 | 4172445 | -25.166 | 0.021 | -0.145 | 0.000 | -25.021 |
| 3JD | 342363 | 4172531 | -25.164 | 0.013 | -0.143 | 0.013 | -25.021 |
| 50DOR | 343685 | 4172450 | -25.136 | 0.015 | -0.115 | 0.015 | -25.021 |
| 4JD [1] | 344644 | 4173720 | -25.090 | 0.020 | -0.089 | 0.000 | -25.001 |
| 51DOR | 345725 | 4172590 | -25.087 | 0.024 | -0.083 | 0.024 | -25.004 |
| 52DOR | 346806 | 4171404 | -25.072 | 0.029 | -0.074 | 0.029 | -24.998 |
| 53DOR | 347664 | 4170090 | -25.052 | 0.031 | -0.066 | 0.031 | -24.986 |
| 54DOR | 348132 | 4169160 | -25.021 | 0.034 | -0.048 | 0.034 | -24.973 |
| 6JD | 347895 | 4168243 | -25.012 | 0.035 | -0.045 | 0.035 | -24.967 |
| 55DOR | 348436 | 4166934 | -24.971 | 0.037 | -0.033 | 0.038 | -24.938 |
| 56DOR | 348436 | 4166934 | -24.971 | 0.037 | -0.033 | 0.038 | -24.938 |
| LC4B | 348191 | 4167061 | -24.978 | 0.036 | -0.035 | 0.037 | -24.943 |
| LC4A | 347697 | 4166582 | -24.971 | 0.036 | -0.035 | 0.036 | -24.936 |

**Table 5.** Geoid heights at leveling benchmarks for the Long Valley region (see fig. 1*B* for benchmark location)—Continued.

| BM | UTM NAD27 | | LVGEOID (m) | | Conversion surface s (m) | | USGG2003 |
|---|---|---|---|---|---|---|---|
| | X | Y | height | σ | height | σ | height (m) |
| TBM LC4 | 347495 | 4166208 | -24.963 | 0.035 | -0.034 | 0.035 | -24.929 |
| **LINE 7: CONVICT LAKE SPUR** | | | | | | | |
| 9DOR RESET | 337742 | 4165406 | -24.845 | 0.029 | -0.067 | 0.029 | -24.778 |
| 30JCM | 337210 | 4164373 | -24.770 | 0.031 | -0.064 | 0.031 | -24.706 |
| 31JCM | 336668 | 4163307 | -24.678 | 0.031 | -0.064 | 0.032 | -24.614 |
| 32JCM | 336621 | 4162253 | -24.609 | 0.033 | -0.063 | 0.033 | -24.546 |
| 33JCM | 336370 | 4161614 | -24.555 | 0.034 | -0.062 | 0.034 | -24.493 |
| **LINE 8: DEADMAN SPUR** | | | | | | | |
| EAL15 | 328038 | 4175137 | -24.882 | 0.000 | -0.133 | 0.000 | -24.749 |
| EAL3 | 328038 | 4175137 | -24.882 | 0.000 | -0.133 | 0.000 | -24.749 |
| 34JCM | 327392 | 4175028 | -24.855 | 0.014 | -0.129 | 0.014 | -24.726 |
| EAL1 | 327392 | 4175028 | -24.855 | 0.014 | -0.129 | 0.014 | -24.726 |
| 35JCM | 326049 | 4174923 | -24.792 | 0.013 | -0.107 | 0.013 | -24.685 |
| 36JCM | 325473 | 4175624 | -24.751 | 0.016 | -0.095 | 0.016 | -24.656 |
| 37JCM | 324695 | 4175940 | -24.709 | 0.022 | -0.085 | 0.022 | -24.624 |
| 38JCM | 323759 | 4176704 | -24.642 | 0.025 | -0.073 | 0.025 | -24.569 |
| 39JCM | 322233 | 4176270 | -24.583 | 0.030 | -0.061 | 0.030 | -24.522 |
| 40JCM | 321591 | 4176351 | -24.560 | 0.032 | -0.057 | 0.032 | -24.503 |
| **LINE 9: SHERWIN CREEK-YMCA CAMP SPUR** | | | | | | | |
| MGB13 | 332965 | 4167110 | -24.844 | 0.021 | -0.098 | 0.021 | -24.746 |
| 11DOR | 333018 | 4167142 | -24.848 | 0.021 | -0.099 | 0.021 | -24.749 |
| MGB10 | 333040 | 4166920 | -24.837 | 0.023 | -0.098 | 0.023 | -24.739 |
| MGB9 | 333286 | 4166859 | -24.840 | 0.023 | -0.098 | 0.024 | -24.742 |
| MGB8 | 333036 | 4166709 | -24.827 | 0.022 | -0.098 | 0.022 | -24.729 |
| MGB7 | 332983 | 4166677 | -24.826 | 0.022 | -0.099 | 0.022 | -24.727 |
| MGB6 | 332955 | 4166611 | -24.822 | 0.022 | -0.099 | 0.022 | -24.723 |
| LC1 | 332937 | 4166611 | -24.822 | 0.022 | -0.099 | 0.022 | -24.723 |
| MGB5 | 332937 | 4166589 | -24.820 | 0.022 | -0.099 | 0.021 | -24.721 |
| MGB4 | 332936 | 4166556 | -24.819 | 0.022 | -0.099 | 0.021 | -24.72 |
| MGB3 | 332909 | 4166523 | -24.817 | 0.022 | -0.099 | 0.022 | -24.718 |
| MGB2 | 332855 | 4166491 | -24.814 | 0.022 | -0.099 | 0.022 | -24.715 |
| MGB1 | 332728 | 4166316 | -24.803 | 0.023 | -0.099 | 0.023 | -24.704 |
| 28EGE | 332610 | 4166129 | -24.792 | 0.024 | -0.099 | 0.024 | -24.693 |
| LC2 | 332480 | 4165821 | -24.774 | 0.024 | -0.099 | 0.024 | -24.675 |
| 29EGE | 332256 | 4165670 | -24.754 | 0.023 | -0.096 | 0.023 | -24.658 |
| 30EGE | 332007 | 4165587 | -24.746 | 0.024 | -0.096 | 0.024 | -24.65 |
| LC3 | 331812 | 4165557 | -24.741 | 0.025 | -0.096 | 0.025 | -24.645 |
| **LAKE CROWLEY TIE B** | | | | | | | |
| 1JD | 340232 | 4166312 | -24.934 | 0.028 | -0.057 | 0.028 | -24.877 |
| 48DOR | 340225 | 4166867 | -24.965 | 0.027 | -0.065 | 0.026 | -24.9 |
| 47DOR | 340417 | 4168129 | -25.026 | 0.020 | -0.082 | 0.020 | -24.944 |
| 46DOR | 340781 | 4169143 | -25.069 | 0.018 | -0.095 | 0.018 | -24.974 |
| LC3E | 342195 | 4168772 | -25.071 | 0.022 | -0.087 | 0.022 | -24.984 |
| LC3D | 342979 | 4168734 | -25.073 | 0.023 | -0.083 | 0.023 | -24.99 |
| LC3C | 344308 | 4169009 | -25.079 | 0.023 | -0.079 | 0.022 | -25 |
| LC3B | 345492 | 4169542 | -25.082 | 0.027 | -0.078 | 0.027 | -25.004 |
| LC3A | 345597 | 4168530 | -25.055 | 0.029 | -0.065 | 0.029 | -24.99 |
| TBM LC3 | 345623 | 4168529 | -25.054 | 0.029 | -0.064 | 0.029 | -24.99 |

**Table 5.** Geoid heights at leveling benchmarks for the Long Valley region (see fig. 1*B* for benchmark location)—Continued.

| BM | UTM NAD27 | | LVGEOID (m) | | Conversion surface s (m) | | USGG2003 |
|---|---|---|---|---|---|---|---|
| | X | Y | height | σ | height | σ | height (m) |
| **LAKE CROWLEY TIE C** | | | | | | | |
| 1JD | 340232 | 4166312 | -24.934 | 0.028 | -0.057 | 0.028 | -24.877 |
| LC2D | 341542 | 4166475 | -24.960 | 0.030 | -0.054 | 0.030 | -24.906 |
| LC2C | 342902 | 4166050 | -24.956 | 0.031 | -0.048 | 0.031 | -24.908 |
| LC2B | 344414 | 4165710 | -24.947 | 0.033 | -0.036 | 0.033 | -24.911 |
| LC2A | 345056 | 4164655 | -24.903 | 0.033 | -0.026 | 0.033 | -24.877 |
| TBM LC2 | 345054 | 4164533 | -24.898 | 0.032 | -0.026 | 0.032 | -24.872 |
| **MARY LAKE ROAD** | | | | | | | |
| J1383 | 325154 | 4168470 | -24.714 | 0.026 | -0.069 | 0.026 | -24.645 |
| CVO89-311 | 324483 | 4168018 | -24.682 | 0.027 | -0.056 | 0.027 | -24.626 |
| VISTA89 | 323772 | 4166990 | -24.652 | 0.032 | -0.052 | 0.032 | -24.6 |
| CVO89-310 | 323569 | 4166595 | -24.646 | 0.032 | -0.051 | 0.032 | -24.595 |
| CVO89-309 | 323181 | 4165770 | -24.636 | 0.033 | -0.050 | 0.034 | -24.586 |
| CVO89-308 | 323330 | 4164868 | -24.621 | 0.035 | -0.054 | 0.035 | -24.567 |
| CVO89-307 | 323397 | 4164289 | -24.611 | 0.035 | -0.055 | 0.036 | -24.556 |
| CVO89-306 | 323463 | 4164066 | -24.607 | 0.035 | -0.056 | 0.035 | -24.551 |
| CVO89-305 | 323529 | 4163854 | -24.597 | 0.038 | -0.056 | 0.038 | -24.541 |
| CVO89-304 | 323332 | 4163758 | -24.596 | 0.038 | -0.055 | 0.038 | -24.541 |
| CVO89-303 | 323171 | 4164072 | -24.608 | 0.038 | -0.053 | 0.038 | -24.555 |
| CVO89-302 | 322998 | 4164231 | -24.613 | 0.038 | -0.052 | 0.038 | -24.561 |
| CVO89-301 | 322516 | 4164397 | -24.624 | 0.038 | -0.048 | 0.038 | -24.576 |
| CVO89-300 | 321780 | 4164657 | -24.638 | 0.037 | -0.043 | 0.038 | -24.595 |

[1] Experimental sites (see also table 2).