

## Inflation of Long Valley caldera, California, Basin and Range strain, and possible Mono Craters dike opening from 1990-94 GPS surveys

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**Abstract.** Five years of annual Global Positioning System (GPS) surveys of a network centered on Long Valley, California, constrain displacement rates for these stations relative to a central station in the network. These observations are consistent with recent models of resurgent dome inflation in Long Valley (Langbein *et al.*, 1995) and have sufficient signal to detect the presence of Basin and Range strain in the Long Valley region. The data also allow for the possibility of dike inflation beneath the Mono Craters; dike intrusion is consistent with the Mono Craters' recent geologic history of ash eruptions, with seismic tomography, leveling data, and geologic studies of these volcanic domes and flows.

### Introduction

Global Positioning System (GPS) equipment and techniques provide a unique opportunity for earth scientists to study regional and local tectonic plate motions and conduct natural hazards monitoring. Modern low-cost, light-weight systems, that can be used in all weather conditions, provide geodetic precision (1-4 mm) with post-processed solutions on baselines that are tens to hundreds of kilometers long (Blewitt, 1993). Many researchers have used GPS to monitor volcanic deformation; interesting articles include Owen *et al.*, (1995), Shimada *et al.*, (1990), and Sigmundsson *et al.*, (1992). Utilizing these techniques, we began, in 1990, to monitor a network of points in and around Long Valley caldera, a site of volcanic and tectonic unrest that includes a high level of seismic strain release, rapid ground deformation, and an unusually high flux of magmatic carbon dioxide (Langbein *et al.*, 1993; Farrar *et al.*, 1995). Each summer for five years (1990-94) we reoccupied 31 stations. Our objectives were to measure horizontal deformation rates, confirm recent models of deformation, and establish GPS as a useful tool for long-term volcano-hazard monitoring.

Geodetic measurements show two episodes of rapid deformation in Long Valley caldera. The first episode began sometime after 1976 (Savage *et al.*, 1987) with strain accumulation slowing to background rates (a few parts in 10<sup>7</sup>/yr) by 1988 (Langbein, 1989; Savage, 1988). Savage *et al.* (1987) inferred the principal deformation source to be 0.02

km<sup>3</sup>/yr inflation of a 10-km-deep magma chamber located under the resurgent dome in Long Valley caldera. The second episode began in October 1989 (Langbein *et al.*, 1993; Dixon *et al.*, 1993) and continued through at least 1995 (Langbein *et al.*, 1995). Using trilateration and leveling data, Langbein *et al.* (1995) derived a refined model for inflation of the Long Valley caldera that included a primary ellipsoidal inflation source 5.5 km beneath the resurgent dome and a secondary ellipsoidal inflation source 10 to 20 km beneath the south moat of the caldera.

Most geodetic monitoring has focused on the inflating magma chamber beneath the resurgent dome in Long Valley caldera. Relatively few measurements have been made around the domes and flows of the Mono-Inyo Volcanic Chain, where magma has erupted at the surface as recently as 500-600 years ago (Bailey, 1989). Our GPS observations provide both broad-scale areal coverage of Long Valley caldera and dense coverage of the Mono Craters volcanic chain near Mono Lake. Our intent in installing a dense array of GPS stations, around the Mono Craters, was to monitor the ascent of magma towards the surface if intrusive activity occurred. The proximity of the Sierran front to the west of the Mono Chain limited the west extent of our network, thus many of our stations are located in close proximity to the volcanic features themselves. This limitation, and the absence of more stations to the east of the Chain, means that this GPS network can detect shallow dike inflation, but deeper inflation sources are indistinguishable from uniaxial strain. Our annual GPS surveys between 1990 and 1994 define deformation rates that are consistent with Langbein *et al.*'s (1995) model of resurgent-dome inflation, detect regional Basin and Range strain, and allow for the possibility of dike inflation beneath the Mono Craters. The large area covered by our GPS network provides the basis for an improved understanding of this volcano-tectonic system, which will lead to better hazard mitigation in the future.

### Data

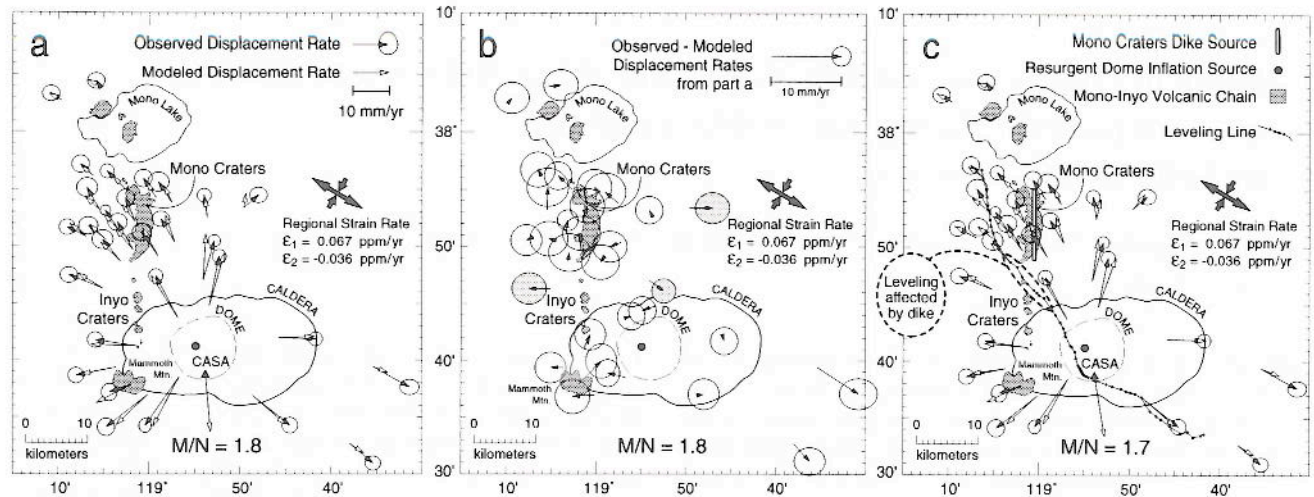
Our annual GPS campaigns included 31 stations occupied over a period of five days during late July or August. We recorded dual-frequency carrier-phase and C/A-code pseudorange data at 30-second intervals for at least six hours at each site. Up to seven receivers were deployed each day. At least one local station, usually CASA, was observed every day to provide a tie between stations occupied on different days. Relative station positions were computed with the Bernese 3.0 software using methods described by Davis *et al.* (1989). We computed integer-ambiguity, ionosphere-free, improved-orbit solutions in the ITRF global reference frame by including simultaneous data from several tracking stations within North America. Length-change rates were computed,

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**Figure 1.** (a) Observed (solid arrows) and modeled (hollow arrows) displacement-rate vectors for an ellipsoidal Long Valley inflation source plus regional strain. (b) Residual displacement rates from (a). Note that residual vectors are drawn with a different vector scale than in (a). Displacements away from the Mono-Inyo chain axis are apparent at three stations with shaded ellipses. (c) Observed and modeled rates from ellipsoidal Long valley inflation, regional strain, and Mono-Inyo dike inflation. Error ellipses indicate the 95% confidence level. M/N, Weighted RMS misfit-to-noise. Dots and line, location of leveling line (data shown in figure 2).

by least-squares, for baselines formed with the reference station at CASA. These length-change rate vectors are shown with 95% confidence error ellipses in Figure 1. The inflation-model-computed displacement rate of CASA has been added to the observed displacement rates so that they are presented in the model reference frame; in this frame, the character of the volcanic inflation source is easily recognized from the displacement pattern. The network spans both the Long Valley caldera and the Mono-Inyo volcanic chain, and the observed displacement rates indicate that while the largest deformations are occurring inside the caldera, significant displacements exist adjacent to the caldera to the north and east.

We used Savage's (1988) principal component analysis technique to examine the spatial and temporal character of deformation within our GPS network. We found that the position changes relative to the reference station CASA were dominated (95 percent of the data variance) by a single spatially coherent deformation mode that accumulated at a relatively steady rate. A steady rate of deformation during the 1990 to 1994 interval is consistent with length changes observed in the frequently sampled two-color electronic distance measurement (EDM) network (Langbein *et al.*, 1993) and with continuous GPS data collected at CASA since early 1993 (Webb *et al.*, 1995). Although minor changes in the rate of deformation were observed in the two-color EDM network and in our GPS network, the fact that we found the deformation to be spatially coherent during this interval means that the observed changes do not arise from changes in the location of the source, but from small inflation-rate changes. In our analysis we use average length-change rates computed from our GPS data; therefore, our computed inflation rates represent average rates during the 1990-94 interval.

Our discussion will focus on the horizontal component of the deformation. In picking our 6-hour periods for data collection, we choose to look for time windows that minimized the horizontal dilution of precision (the reduction of precision due to the geometry of the satellite constellation) with the inevitable tradeoff of permitting some periods of high vertical

dilution of precision. The resulting vertical displacement rates have uncertainties approximately 6 to 7 times that of the horizontal displacement rates. We include the GPS vertical displacements in our inversions for deformation source parameters but, because all observations are weighted by their uncertainty, they have little influence. We include no further discussion of the GPS measured vertical deformation other than to note that the observed vertical changes are always consistent in sign and nearly always in magnitude with the model vertical displacement rates.

## Discussion

We analyze the data in the context of recently published studies of Long Valley caldera inflation, Basin and Range strain observations, and seismic tomography of Mono Craters. The GPS data have sufficient signal-to-noise, the ratio of the displacement rates to their uncertainties (RMS signal/noise = 14.2), to discriminate the existence of an inflation source beneath the caldera, and to detect Basin and Range strain; they have marginal detection capability for monitoring the expansion of a dike at depth.

The single ellipsoidal source (Davis, 1986) of Langbein *et al.*, (1995, model I, Table 2) explains 98% of the GPS signal variance, producing an RMS misfit, the ratio of the model residuals to the observation uncertainties, of 2.1 (Table 1). For this model, the source is fixed at the same location with the

**Table 1.** Summary of Model Fit

Model Sources	Weighted RMS Misfit
No source	14.1
Ellipsoidal Inflation (E. I.)	2.1
E. I. + uniaxial extension	1.6
E. I. + Basin & Range strain	1.8
E. I. + Basin & Range strain + Mono dike opening	1.7



same orientation as found by Langbein *et al.*, (1995, model I, Table 2), and it inflates at a rate of  $0.007 \text{ km}^3/\text{yr}$ , as determined by inversion of our GPS observations. Langbein *et al.* (1995) also found a second, deeper but poorly constrained, ellipsoidal source; this source did not improve the fit to our GPS observations. Langbein *et al.* (1995) also identified other shallow and peripheral sources of deformation because they modeled densely-spaced ( $\sim 1 \text{ km}$  spacing) leveling data throughout the caldera. Such sources can not be discerned with our GPS station coverage (5-10 km spacing) in Long Valley caldera. We chose an ellipsoidal source instead of a spherical source, because it provided a better fit to both the leveling and two-color EDM data in Langbein *et al.* (1995).

Situated at the west edge of the Basin and Range province, Long Valley caldera is subject to Basin and Range extensional strain. Contemporary strain rates for the western Basin and Range have been estimated from trilateration networks within the central Nevada seismic zone (Savage *et al.*, 1995). Accordingly, our GPS displacement-rate data should also be able to detect the regional strain. Thus, along with the rate of inflation, the GPS measurements detect uniaxial extension of  $0.15 \pm 0.03 \text{ ppm/yr}$  oriented  $\text{N}66^\circ\text{W} \pm 1$  (the strain rate normal to this component is  $0.02 \pm 0.02 \text{ ppm/yr}$ ). Using the uniform strain model with the model of inflation reduces the RMS misfit to 1.6 (Table 1).

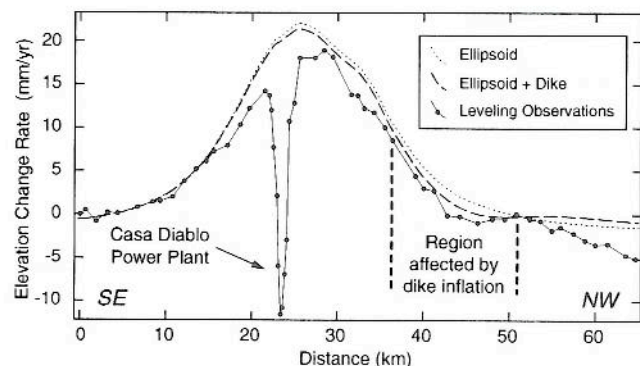
However, comparing our estimate of  $0.15 \text{ ppm/yr}$  of Basin and Range extension with the estimate derived from recent measurements of nearby trilateration networks indicates that our estimate is at least a factor of 2 too large. For instance, the strain rate estimated from Savage *et al.*'s (1995) Huntoon network, that lies just 60 km northeast of Long Valley and that has been measured six times between 1972 and 1994, has a major principal component of strain of  $0.07 \pm 0.01 \text{ ppm/yr}$  oriented  $\text{N}59^\circ\text{W} \pm 3$ .

Using Savage *et al.*'s (1995) strain rate for the Huntoon network, we remove this fixed strain rate and solve for the inflation rate that best fits the residual GPS displacements. Including Basin and Range strain in the model significantly improves the fit to the GPS data and produces an RMS misfit of 1.8 (Figure 1a and Table 1). While simply adding three more degrees of freedom to the model decreases the RMS misfit by 2%, adding the three strain components from the Huntoon network reduces the RMS misfit by 10%. At a distance of 60 km from Long Valley, the Huntoon network strain observations may or may not be representative of Basin and Range strain near Long Valley, but we note that Savage *et al.*'s (1995) observations indicate very little difference between strain rates measured in the Huntoon network and those measured more than 100 km further to the northeast in the central Nevada seismic zone. We find it not unreasonable to assume that these same strain rates might persist 60 km southwest of the Huntoon network near Long Valley. Our results suggest that there might be another source of east-west extension in addition to just Basin and Range strain and resurgent dome inflation in the Long Valley-Mono Craters area. One such source could be dike intrusion at depth beneath the Mono Craters. Dike intrusion beneath the Mono Craters is not unreasonable when considering the seismic and geologic evidence. Residuals, the observed minus the computed rates, for the model of ellipsoidal inflation plus Basin and Range strain are shown in Figure 1b. Three stations (shown with shaded ellipses in Figure 1b) that show marginal residual signal, indicate the possibility of deep dike inflation near the Mono Chain. The random and insignificant residuals

close to the volcanic domes are also consistent with deep inflation which would not produce significant displacements directly above the source.

Seismic tomography has been used to infer the existence of magma bodies beneath Long Valley and Mono Craters by locating regions of the crust that have unusually slow seismic-wave travel times. Using this technique, Dawson *et al.* (1990) inferred that a magma chamber, with a top at 10 km depth and a base at 20 km depth, lies beneath the Mono Craters. Since the geologic and geomorphic character of the Mono Craters suggest that they were fed by dike intrusions (Bursik and Sieh, 1989), we treat a probable inflation source there as a single vertical dike (Comminou and Dundurs, 1975) with the depth to its top at 10 km; this dike strikes north-south along  $119^\circ 00' 30'' \text{ W}$  and extends from  $37^\circ 49' \text{ N}$  to  $37^\circ 55' \text{ N}$ . Including a buried dike inflation source beneath the Mono Craters, with a geometry fixed a priori by the independent analyses, improves the fit to the GPS observations, and is qualitatively consistent with leveling data from 1988-92. In this model, we include Savage's (1995) Basin and Range strain rate from the Huntoon network and find an inflation rate of the resurgent dome of  $0.007 \text{ km}^3/\text{yr}$ , and a Mono Craters dike opening rate of  $6 \text{ cm/yr}$ . The model yields an RMS misfit of 1.7 (Figure 1c and Table 1). The greatest misfit is found at the southeast edge of the network; these residuals are insensitive to changes in the source parameters. The marginal improvement in fit means that while the dike is not required by the GPS data, it is not inconsistent with the data. Even if the two stations with the largest residuals in Fig. 1b are removed, the results are unchanged: the model variance is significantly reduced by including twice the extension that is observed in the adjacent networks, or by using the extension rate for the adjacent nets and introducing dike intrusion. If the dike geometry is treated as a priori, in which its inflation rate adds one degree of freedom to the model, adding the dike is significant at the 95% confidence level.

If the dike were in fact inflating, future measurements of our network would verify only shallower inflation; if the dike remains deep, its signal will continue to be indistinguishable from that of uniaxial extension. While the misfit of this model is not as low as that of the model of uniaxial extension, our model is consistent with previous studies and inferences about Basin and Range strain rates and geology of the Mono Craters. The model indicates that Dawson *et al.*'s (1990) inferred



**Figure 2.** Observed and modeled elevation change rate for the period 1988 through 1992. Dots, observed elevation change rate. Short dashes, ellipsoidal inflation and regional strain model. Long dashes, ellipsoidal inflation, regional strain and Mono Craters dike.



magma chamber, if it exists as a dike-like intrusion, opening at as much as 6 cm/yr is not inconsistent with these GPS data. If a volcanic crisis occurs, our network provides a baseline measurement from which to monitor future events.

Leveling observations, which illustrate the vertical deformation between 1988 and 1992, are shown in Figure 2 along with the predicted uplift pattern calculated from our models. When compared with model uplift, three main features of the vertical deformation pattern are found. Resurgent dome uplift dominates the vertical deformation along at least the first 50 km of the leveling line from the southeast. The striking departure from the model (at about 23 km) is caused by subsidence near the Casa Diablo geothermal power plant, which extracts steam from near-surface reservoirs (Sorey *et al.*, 1995). A somewhat more subtle feature that departs from the ellipsoid model can be seen between 37 and 50 km, where the leveling observations also show local subsidence. The model which includes dike inflation beneath the Mono Craters produces a qualitatively better fit to the leveling data in this region.

## Conclusion

Five years of annual GPS surveys provide well constrained displacement data over the active volcanic system at Long Valley caldera. These data are in good agreement with recently published models of resurgent dome uplift and detect Basin and Range strain in the Long Valley area that is twice as large as that measured in the nearby central Nevada seismic zone. Assuming that Basin and Range strain has the same magnitude in the Long Valley area, the GPS data allow for the possibility of dike intrusion beneath the Mono Craters to account for the additional east-west strain. The agreement between our GPS observations and other geodetic data demonstrate the usefulness of GPS as a monitoring tool. Such measurement campaigns can be used to develop models to improve our understanding of volcano-tectonic systems and the hazards they pose.

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