The search for magma reservoirs in Long Valley Caldera: single versus distributed sources

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Abstract: Long Valley Caldera and the Mono–Inyo Craters chain form a large volcanic complex in eastern California that has experienced persistent earthquake activity and ground uplift over the past 25 years. The central part of Long Valley Caldera (an area of more than 100 square km) has been slowly rising since 1980 at an average rate of 3 cm a^{-1}. Inversion of micro-gravimetry and deformation data using a single vertical prolate ellipsoid source has helped to define the existence of a relatively shallow (5–8 km) silicic magma intrusion of 0.11–0.19 km^3 beneath the caldera's resurgent dome. We use the information from the single-source inversion to constrain a more general three-dimensional distribution of volume changes in the subsurface. The distributed inversion identifies two main inflation areas beneath the resurgent dome: one following the regional trend of north–south faults, and another in the dome's southern section, parallel to a strike-slip fault that is responsible for most of the seismic activity in the caldera's south moat.

The Long Valley volcanic area (Fig. 1) has been active for the past 3 Ma (Hildreth 2004). Rhyolite lava eruptions from 2.1 to 0.8 Ma formed Glass Mountain on the northeast rim of the present caldera (Metz & Mahood 1985). The Glass Mountain eruptions, which were fed by a large, chemically evolving magma chamber in the shallow crust (van den Bogaard & Schirnick 1995), culminated 0.76 Ma ago in a cataclysmic caldera-forming eruption (Hildreth 2004). This massive eruption resulted in the deposition of 600 cubic kilometres of Bishop Tuff and the simultaneous subsidence of the magma-chamber roof, creating the present 17 × 32 km, oval depression of the Long Valley Caldera. Between 0.76 and 0.6 Ma ago, uplift of the caldera floor and the eruption of flows of rhyolite lava formed the resurgent dome (Bailey 1989). The most recent eruptive activity occurred 600 years ago along the Mono–Inyo Craters volcanic chain (Sieh & Bursik 1986). In May of 1980, a strong earthquake swarm struck the southern margin of Long Valley Caldera, marking the onset of the current period of unrest (Bailey & Hill 1990). This ongoing unrest includes recurrent earthquake swarms and uplift of the resurgent dome within the central section of the caldera. After a sharp increase in the deformation rate during the summer to autumn of 1997, the caldera was relatively inactive, with no significant deformation since the spring of 1998 (Fig. 2; Langbein 2003).

Several sources of deformation have been identified in Long Valley Caldera (Sorey *et al.* 2003). Surveys of two-colour EDM and levelling networks indicate that the principal sources of deformation are the intrusion of a magma body beneath the resurgent dome, and right-lateral strike-slip within the south moat of the caldera (Langbein *et al.* 1995; Langbein 2003). Radar interferometry (Thatcher & Massonet 1997; Fialko *et al.* 2001), GPS surveys (Marshall *et al.* 1997) and gravity measurements (Battaglia *et al.* 2003*b*) confirm the intrusion beneath the resurgent dome. In addition, there is evidence for fluid intrusion beneath the caldera's south moat and Mammoth Mountain (Sorey *et al.* 1993; Hill *et al.* 2003).

Single versus distributed sources

Single-source models, like the well-known point source of dilation (Mogi's source) in an elastic, homogeneous and isotropic half-space, are widely used to interpret geodetic and gravity data in active volcanic areas. In particular, they are used to determine the location and volume of a magma intrusion, and thus to help anticipate the onset of an eruption and mitigate its damage (Dvorak & Dzurisin 1997). Choosing the right source model is critical in the geological interpretation of the geodetic and gravity data. For

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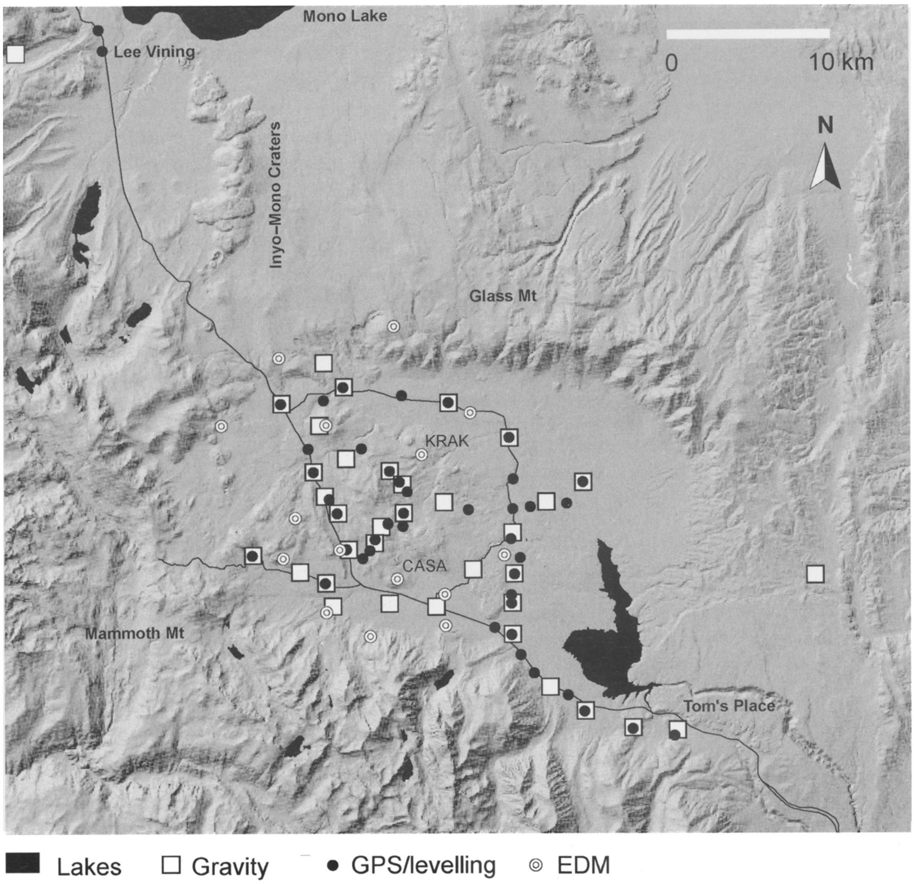


Fig. 1. Map of Long Valley Caldera. The resurgent dome is the broad, dome-shaped highland of post-caldera lava domes about 9 km in diameter that stands at the centre of the caldera, about 500 m above the surrounding lowlands that form the caldera 'moat'. Mammoth Mountain is a cumulo-volcano formed by repeated eruptions of dacite and rhyodacite from vents on the southwest rim of the caldera 220 000–50 000 years ago (Hildreth 2004). The map shows the levelling routes, the two-colour EDM geodetic network, the levelling sites occupied with GPS, and the gravity network.

example, if the actual source does not possess spherical symmetry, the standard approach of using a point source to invert uplift data will lead to biased estimates of the source parameters (e.g. a deeper location), resulting in considerable uncertainty about the nature of the magma chamber and intruding fluid (Battaglia & Segall 2004). Furthermore, a point-source model appears at odds with the real geology of volcanic regions, since magma bodies are not single point-like sources.

In this paper, we analyse geodetic and gravity data without assuming an initial source model. This means being able to determine a range of values for the depth, geometry, volume change, mass change and density of the intruding fluid by resolving a three-dimensional model of subsurface volume and mass change. To test whether this approach can provide a more realistic description of the source of uplift, we evaluate the bounds on the intrusion obtained using a distributed source, against the results from the inversion of geodetic and gravity data using standard point-source models.

Magma intrusion beneath the resurgent dome

Among the most fundamental questions with regard to Long Valley geodynamics is the cause of the ongoing unrest at the caldera. Combining geodetic and micro-gravity data can provide important constraints on the source of inflation.

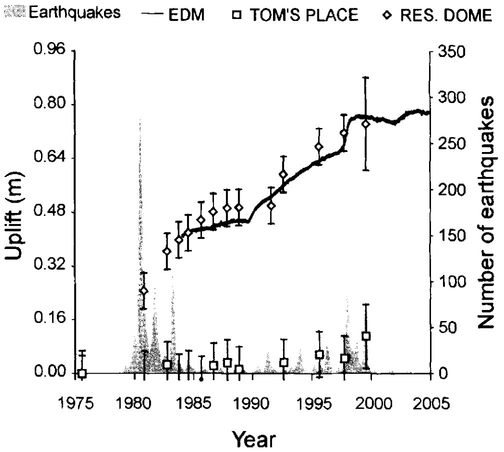


Fig. 2. Long Valley Caldera unrest. The plot shows the number of $M > 3.0$ earthquakes, the uplift at the resurgent dome (benchmark W911) and at Tom's Place (several km outside the caldera), and the extension of the CASA–KRAK baseline (EDM), a proxy of resurgent dome vertical deformation. Levelling data were provided by the USGS Cascades Volcano Observatory (D. Dzurisin, pers. comm.). Two-colour EDM data are courtesy of the USGS Long Valley Observatory (http://lvo.wr.usgs.gov). Earthquake data are provided by the Northern California Earthquake Data Center (NCEDC – http://quake.geo.berkeley.edu).

The United States Geological Survey (USGS) started an intensive geodetic monitoring programme in Long Valley in 1980 (Bailey & Hill 1990). Data collected by the USGS include levelling surveys from 1980 to 1997 (Savage *et al.* 1987; Langbein *et al.* 1995), and measurements of horizontal deformation using a two-colour geodimeter from 1985 (Langbein *et al.* 1995) and GPS from 1994 (Marshall *et al.* 1997). The last complete levelling of Long Valley Caldera occurred in July–August 1992. Crustal deformation within the caldera is monitored by a network of continuously operating GPS receivers (Dixon *et al.* 1997). The US Geological Survey occupied the Long Valley gravity network six times from 1980 to 1985 (Jachens & Roberts 1985).

In an effort to update the vertical deformation measurements within the caldera, we resurveyed 44 of the existing levelling monuments in Long Valley in July 1999 (Fig. 1) using dual-frequency GPS receivers (Battaglia *et al.* 2003*a*). The gravity network (Fig. 1) was occupied twice, in the summers of 1998 and 1999 (Battaglia *et al.* 2003*b*). Because sources with different geometries can have similar vertical deformation profiles but distinct horizontal deformation (Dieterich & Decker 1975), we invert both vertical and horizontal displacements. In order to improve the signal-to-noise ratio, we model the inflation using a two-step approach (Battaglia *et al.* 2003*a*, 2003*b*). First, we invert geodetic data from 1985 to 1999, the longest time interval for which both horizontal and vertical deformation data are available, to determine the geometry and location of the source (Figs 3 & 4). Then, we invert both the uplift and gravity data from 1982 to 1999, in order to determine the volume and density of the intrusion.

The best-fitting inflation source is a vertical prolate ellipsoid located beneath the resurgent dome (Fig. 4). A bootstrap method was employed to estimate 95% confidence bounds for the parameters of the inflation model. We obtained a range of 0.25–0.65 for the source geometric aspect ratio, 4.9–7.5 km for the depth, 0.105–0.187 km^3 for the 1982–1999 volume change, and 1180–2330 kg m^{-3} for the density. Our results support the intrusion of silicate melts, but there is still uncertainty about the geometry of the magma chamber and the nature of the intruding fluid. For example, is the ellipsoidal model truly representative of the actual geological structure (e.g. a neck or volcanic plug intruding into the shallow crust) or are we simply recovering the average properties? If we are measuring average properties, then the low-density estimate for the intrusion (1180–2330 kg m^{-3}) could point to a hybrid source composed of both

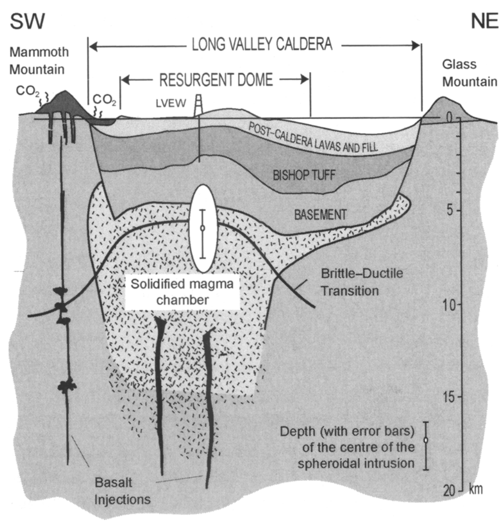
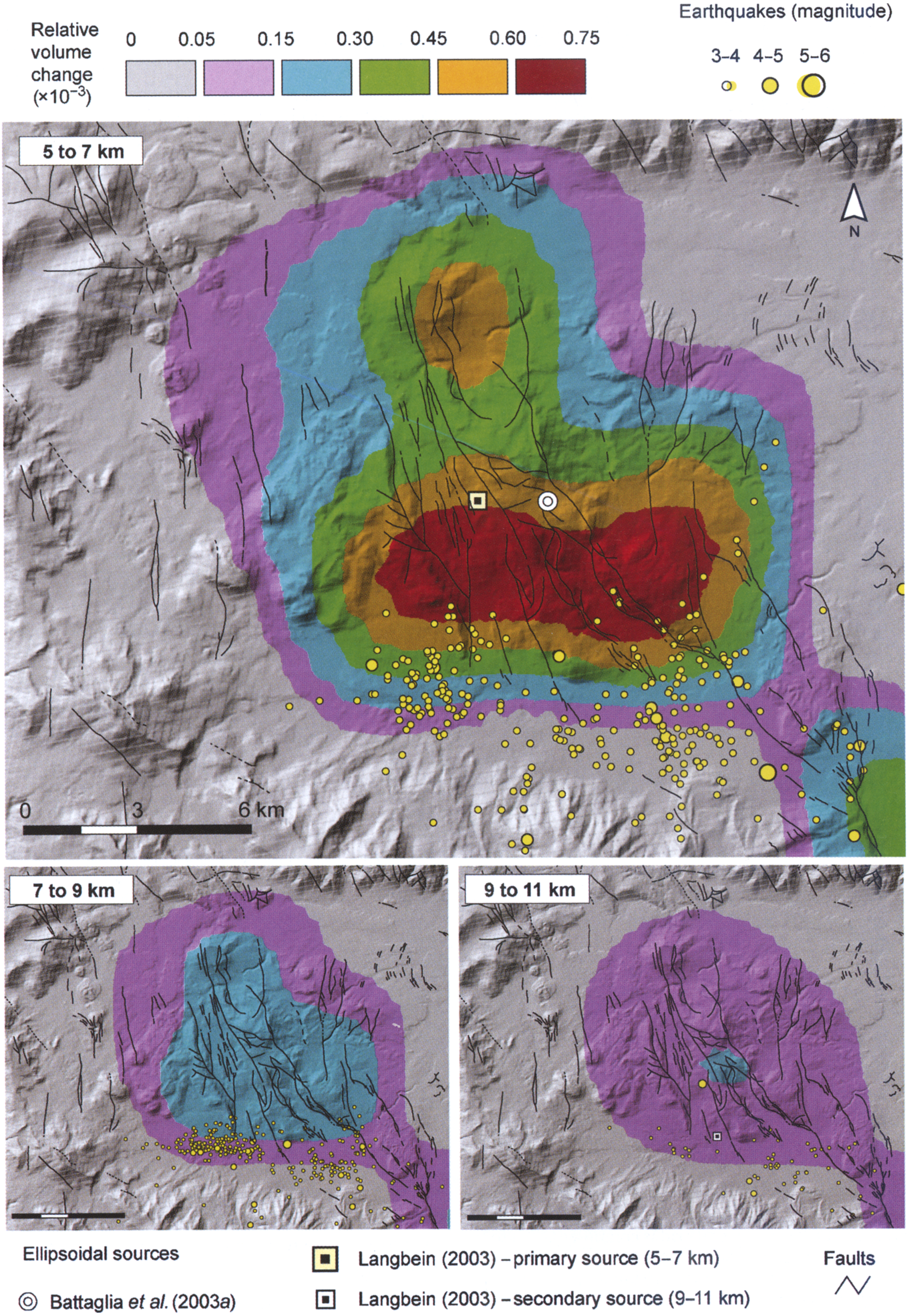


Fig. 3. Simple-source model of the intrusion beneath the resurgent dome. The source is a prolate ellipsoid with aspect ratio 0.25–0.65 (95% bounds), depth 4.9–7.5 km, volume change 0.105–0.187 km^3 and density 1180–2330 kg m^{-3}. Cross-section modified from Sackett *et al.* (1999, fig. 1).


Relative volume change (×10^{-3})
0
0.05
0.15
0.30
0.45
0.60
0.75
Earthquakes (magnitude)
3–4
4–5
5–6
5 to 7 km
N
0
3
6 km
7 to 9 km
9 to 11 km
Ellipsoidal sources
Battaglia et al. (2003a)
Langbein (2003) – primary source (5–7 km)
Langbein (2003) – secondary source (9–11 km)
Faults

melt and an aqueous phase (Battaglia *et al.* 2003*b*).

Distributed source

As noted above, a distributed source allows for a more general model in which the geometry is not prescribed a priori. As such, a distributed model may be considered to be exploratory in nature. That is, the geometry of the resulting model can provide information on the geological structures controlling magmatic and hydrothermal processes within the caldera. One can view our distributed source as a first step in deciphering the kinematics of fluid movement beneath Long Valley Caldera.

We will construct a distributed source by subdividing the volume beneath the caldera into a set of non-overlapping cells or grid-blocks, as described in Vasco *et al.* (1988) and Vasco *et al.* (2000). Each grid block may undergo a distinct fractional volume change. The displacement at any point on the surface is the combined response due to the volume change of each grid block. The background medium is assumed to behave elastically over the duration of the observation interval. As noted in Vasco *et al.* (1988), this does not preclude local inelastic behaviour within each grid block. Rather, we are solving for an effective elastic source, as is done in seismic source modelling (Aki & Richards 1980). Because surface deformation observations typically cannot resolve detailed volume change variations as a function of depth (Dieterich & Decker 1975), we prescribe the depth boundaries of our grid. Based upon earlier point-source modelling and physical considerations, we adopted a three-layer grid with depth boundaries: 5–7 km, 7–9 km, and 9–11 km. Each layer was subdivided into a 41 (east–west) by 41 (north–south) grid of cells. The observed surface deformation is linearly related to the fractional volume change of each grid block. Thus, each observation provides a linear constraint on the subsurface volume change in the grid of cells (Vasco *et al.* 1988).

Fig. 4. Three-dimensional distribution of relative subsurface volume changes, and earthquakes hypocentres. The inversion grid is composed of three layers; each layer is divided into a 41 × 41 grid. We show results for layers 6, 8 and 10 km deep, and the location of the ellipsoidal sources after Battaglia *et al.* (2003*a*) and Langbein (2003). Earthquake data were provided by the Northern California Earthquake Data Center (NCEDC – http://quake.geo.berkeley.edu).

Given an adequate distribution of data, we may estimate the volume-change distribution within the grid. That is, using a regularized, linear least-squares procedure we can solve for the distribution of volume change at depth (Vasco *et al.* 2000). Using both the vertical deformation and the line length changes provided by the two-colour EDM measurements (Battaglia *et al.* 2003*a*), we estimate the fractional volume change beneath the Long Valley Caldera. The resulting distribution of fractional volume change in the three layers of the model is shown in Figure 4. Dark red and light brown in this figure signify greater fractional volume changes. The largest fractional volume change forms a dominantly east–west body in the depth range 5–7 km. In addition, a north–south-trending component of fractional volume change roughly parallels a system of NNW-trending faults within the caldera. This feature extends northward from the east–west anomaly to the northern edge of the caldera. The volume change in the deeper layers (7–9 km, 9–11 km) is much smaller in amplitude and similar in pattern to the overlying layer. This is most likely due to the poor depth resolution provided by the surface deformation data.

We tried various parameterizations in depth, e.g. various numbers of layers and layer boundaries. We observed that the pattern of volume change was fairly robust, but the detailed depth distribution was not. We should note that separate inversions of just the EDM data, or the GPS observations, did not result in deformation being distributed along the caldera fault system. Rather, only the joint inversion of GPS and EDM data produced subsurface volume change correlated with the fault network. This suggests that the pattern is needed to reconcile the two datasets.

Discussion

We have presented two models of subsurface volume change which are compatible with observed surface deformation data. While the centroid of the volume change is similar for these models, the detailed distribution is distinctly different. As mentioned above, the distributed-source model is very general and we consider it to be exploratory in nature. The distribution of fractional volume change is suggestive in that it underlies some existing north-trending faults. In addition, the east–west component of volume change parallels a hypothesised east–west fault in the south moat region. Furthermore, the east–west component of volume change connects two sets of north–south trending faults. The more easterly set extends from the central caldera to the south, the other set cuts northward through the interior of the caldera (Fig. 4).

The fits to the EDM and GPS data are shown in Figure 5. Since the horizontal deformation uncertainties are much smaller than those of the vertical deformation, the best fit to the simple-source model is controlled by the fit to the EDM data. The measurements with the largest discrepancy from the model for the 1985–1999

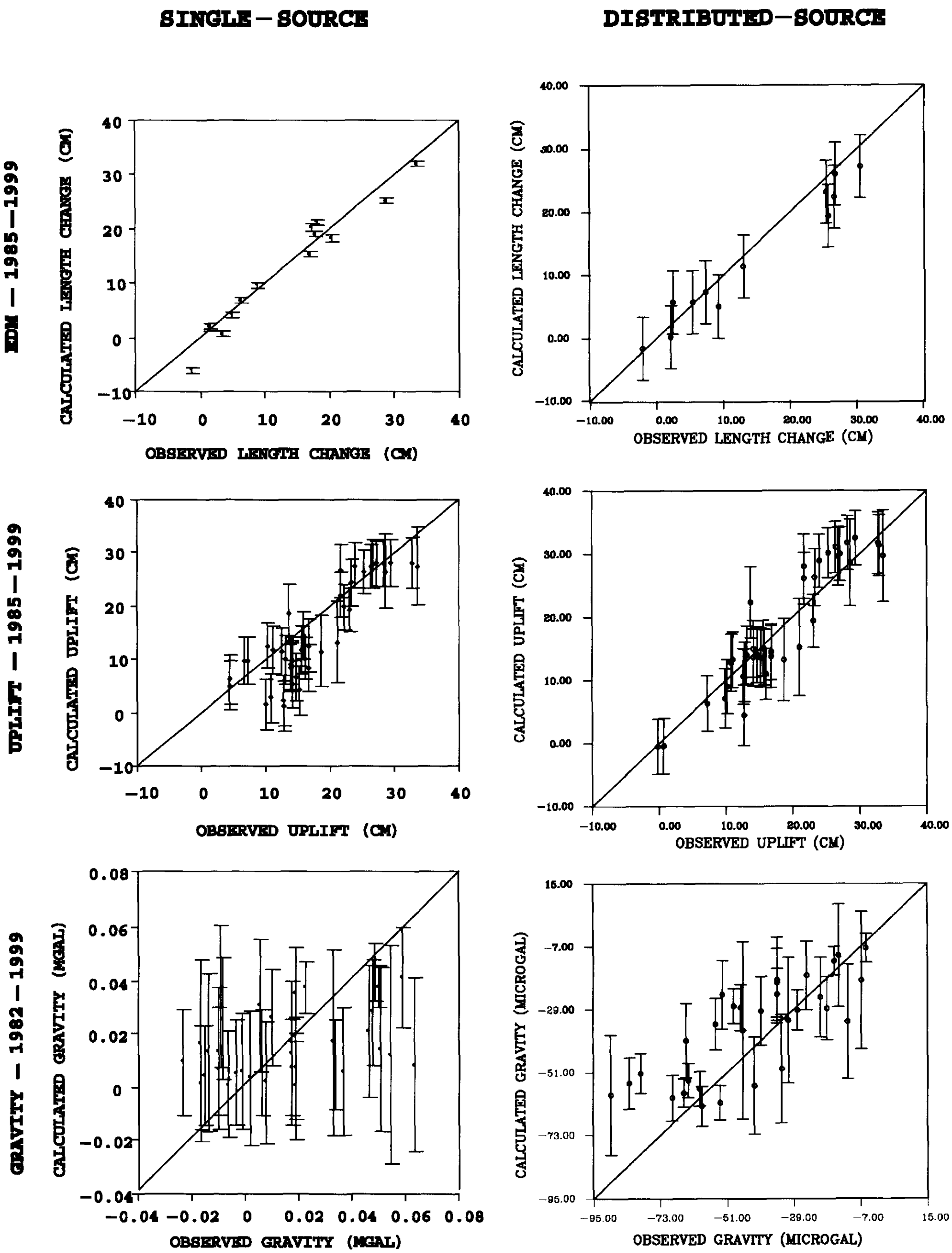


Fig. 5. Fit to data. Comparison between the single-source and distributed-source models.

period belong to geodetic points situated outside the caldera rim, close to Tom's Place (Fig. 1). The fit to the geodetic data is much better than the fit to the gravity data. This is due to the fact that deformation measurements at Long Valley Caldera show a strong radial symmetry, while gravity measurements do not possess such strong spatial symmetry (Battaglia *et al.* 2003*b*, fig. 6). Gravity changes measured in the field are the superposition of at least four different contributions (Battaglia *et al.* 2003*b*) and therefore are much noisier than geodetic measurements. For the time span investigated in this paper, where we consider gravity changes accumulated in a time interval 17 years long, only a few points show a significant signal-to-noise ratio, while all the others are within the background noise, probably much more influenced by local changes in the water table than by the mass intrusion modelled by our single source.

The fits due to the distributed source are slightly better than that provided by the point-source model. However, the improvement is marginal, given the extra degrees of freedom associated with the distributed source. To some degree, it is misleading to simply compare the misfit. By reducing the regularization weighting, it is possible to dramatically improve the fit to the data provided by the distributed model. Furthermore, by adjusting the depth boundaries we can also change the misfit significantly, but we believe that this would only over-model the data, without adding any new information on the source. Suffice it to say that both models fit the geodetic observations within their associated errors.

In this work, we describe the Earth's crust in the Long Valley volcanic region as a homogeneous, elastic half-space. This approach appears at odds with the complex geology of volcanic regions, since the crust is not a homogeneous medium. To determine the importance of vertical discontinuities in the Earth's density and elastic parameters when modelling displacement and gravity changes induced by a single source, Battaglia & Segall (2004) developed an Earth model for the Long Valley Caldera, including four elastic layers. The thickness, density and seismic velocities assigned to the four layers representing the crust have been estimated from published works on regional gravity, seismic tomography and geology of Long Valley. Their results suggested that for an elastic model appropriate to Long Valley Caldera, there were only minor differences between modelling the 1982–1999 caldera unrest using a single source in elastic, homogeneous half-spaces, or in layered half-spaces.

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The distributed-source model can also help to shed light on the relation between deformation and seismicity. According to the existing interpretation (e.g. Sorey *et al.* 2003), dominant sources contributing to the deformation and seismicity within the caldera include (Fig. 4): (1) aseismic inflation of a source centred at approximately 6 km beneath the resurgent dome; (2) seismic inflation of a deeper one (10–20 km) beneath the South Moat Seismic Zone (SMSZ); and (3) right-lateral strike-slip motion on a series of WNW-striking faults in the 10-km-wide SMSZ (Langbein 2003). Data from the NCEDC catalogue and high-accuracy earthquake hypocentres relocation (Prejean *et al.* 2002) suggest that most of the caldera seismic activity of magnitude 3 or greater is concentrated approximately between 4 and 8 km depth, just south of the area with the greatest volume change (Fig. 4). The association of subsurface volume change with mapped faults and earthquakes may be due to existing faults acting as conduits for fluid and gas movement beneath the caldera. That is, the faults represent high-permeability zones. Alternatively, the faults may represent zones of weakness which concentrate deformation: in essence, a mechanical heterogeneity which concentrates deformation. Or both processes may be operating in concert, and faults may concentrate fluid and gas flow as well as concentrating deformation.

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