Modelling Gravity changes and crustal deformation in active volcanic areas

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ABSTRACT
Elastic half-space models are widely used to interpret displacements and gravity changes in active volcanic areas. Those models usually compute the displacement response to dilatational sources that simulate a change in pressure of the magma chamber. However, elastic-gravitational model allows one to compute gravity, deformation and potential changes due to pressurized cavities and intruded masses together. First, we interpret deformation and gravity change data in Long Valley caldera, California, by using both a classical elastic and an elastic-gravitational model. Our results show that intruded mass can not be neglected for interpretation of gravity changes while displacements are mainly caused by pressurization. Therefore, the intrusion mass together with the associated pressurization produces distinctive changes in gravity that could be used to interpret gravity changes without ground deformation or viceversa depending on what is the source playing the main role in modelling. Second, we model the source of inflation at Long Valley caldera using a Genetic Algorithm inversion technique and microgravity data (1982-1998). The results of the performed inversions fit gravity anomaly centered under the resurgent dome. The two source inversion suggest that the gravity change could be caused by a more spatially distributed source under the resurgent dome.

Key words. Elastic-gravitational model, volcanic source, gravity, displacement and Genetic Algorithm

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1. INTRODUCTION

The effects associated with crustal intrusion that can be used in monitoring volcanic activity are those that can be detected on the ground surface before an eruption. These effects include gravity changes and ground deformation that usually form part of geodetic monitoring in active areas (see e.g., Fernández et al. 1999; Rymer and Williams-Jones, 2000; Stein et al. 2000; Gottsmann and Rymer, 2002; Dzurisin, 2003). The analysis and interpretation of this geodetic signals is a classical tool for researches involved in volcanological studies. Since the pioneering work by Mogi (1958), several mathematical formulations, generally based on elastostatic analysis, have been developed in order to simulate theoretical changes due pressure sources in volcanic areas. Within the elastic frame there are models that include spherical and ellipsoidal point sources, vertical and horizontal magma migration, finite sources, collapse structures and fluid migration (e.g., Rundle, 1980; Davis, 1986; McTigue, 1987; Bonafede, 1990 and De Natale and Pingue, 1996). Rundle (1980) studied the effect of the medium properties in modelling and solved the equations that represent the coupled elastic-gravitational problem for a stratified half-space of homogeneous layers. This type of model goes one step further than classical elastic model since it allows for numerical experiments considering jointly the effects of a pressurized chamber cavity and mass intrusion.

Exploration in geophysics to obtain the properties of the Earth's interior or information pertaining to sources causing a local geodynamic phenomena like gravity changes and/or ground deformation is performed by different techniques. Traditionally this kind of inversion procedures has been approached by using local optimization techniques such as steepest descent, conjugate gradients or the simultaneous iterative reconstruction methods. Recently, Genetic Algorithm (GA) methods have been proposed in geophysics (e.g., Beauducel et al. 2000; Billings et al. 1994; Boschetti et al. 1996; Stofa and Sen, 1991; Montesinos, 2002). Genetic algorithms use random processes to locate a near optimal solution and require no derivative information as some methodologies mentioned above.

The combination of GA inversion with the elastic-gravitational model allows for the efficient solution of detailed and realistic magmatic sources at a variety of volcanic areas (Tiampo et al. 2004a). This paper analyzes the elastic-gravitational model through the interpretation of deformation and gravity changes observed at Long Valley caldera, California, USA. The results show that displacements and changes in gravity must be interpreted together whenever possible. The combination between mass and pressurization that elastic-gavitational model allows can be used to joint interpretations.

2. ELASTIC-GRAVITATIONAL MODEL

Elastic-gravitational model provides a complete solution of the problem of calculating gravity, deformation and potencial changes arising from volcanic crustal loading that includes the directly coupled effects of gravity and elastic displacement. We begin by reviewing the coupled elastic-gravitational model. The generalized static Navier equations for an elastic self-graviting uniform medium are (Love, 1911):

$$\rho_0 g \nabla(\mathbf{u}\cdot\mathbf{e}_z) - \rho_0 \nabla\phi - \rho_0 g \mathbf{e}_z \cdot \nabla\cdot\mathbf{u} + \nabla\cdot\boldsymbol{\sigma} + \mathbf{F}_p = 0 \quad (1)$$

$$\nabla^2\phi = -4\pi G\rho_0 \nabla\cdot\mathbf{u} + \mathbf{F}_m \quad (2)$$

Here, **u** is the vector displacement in a local cylindrical coordinate system (r,θ,z) with the origin at the surface and with the z-axis pointing down into the medium, ϕ is the gravitational potential, ϱ_0 is the unperturbed density, G is the gravitational constant and g is the acceleration of gravity.

The elastic-gravitational model allows for geologically meaningful solutions given by the superposition of a pressurized cavity with no mass change or mass intrusion with no magma chamber overpressure. In this way, $\mathbf{F}_p$ represents the body force equivalent to the dilatation source and $\mathbf{F}_m$ the gravitational source of mass. Therefore, it is theoretically possible to interpret changes in gravity without any significant deformation or viceversa since total uplift can be made to vanish without total gravity changes vanishing when mass plays the principal role in modelling and viceversa if the pressure source is the principal one. The right combination between mass and pressurization could be used to interpret unusual geodetic measurements. In this way, elastic-gravitational model is a refinement in the elastic models that could give more accurate interpretations.

Rundle (1980) solved the model equations using the propagator matrix technique (Thompson, 1950; Haskell, 1953) in a layered half-space to obtain surface gravity, deformation and potential changes arising from volcanic loading. Rundle (1981) developed the numerical formulation for the case of a single layer in welded contact with an infinite half-space. Expressions in the case of two layers may be seen in Fernández and Rundle (1994). Fernández et al. (1997) gave the appropiate formulation for a medium composed of up to four layers over half-space. These authors suggested, through the numerical comparison of an elastic-gravitational solution with that for a purely elastic medium, that the complete solution for deformation and gravity changes should include the coupling between elastic and gravitational effects. More recently, Charco et al. (2002) have obtained the analytical expressions to compute vertical deflection and geoid changes. Charco (2004) showed theoretically through dimensional and scaling analysis of equations (1) and (2) that the consideration of gravity effects can be important for the proper explanation of gravity changes in certain volcanic regions.

3. LONG VALLEY CALDERA

Over the last 20 years in Long Valley caldera, located to the east of the Sierra Nevada (California), there have been three episodes of rapid inflation of the central resurgent dome, accompanied by seismicity inside and around the caldera, without any eruptions or deflations between these episodes. The first episode began in 1976, although it peaked in the middle of 1979 and continued into the eighties (e.g., Langbein et al. 1995). The second episode started in October 1989 after several years of relative calm (see e.g., Tiampo et al. 2000). The most recent episode of inflation and uplift of the resurgent dome within the caldera occurred in 1997-1998.

The Long Valley Caldera, elliptical in shape, extends 32 km in east-west direction and 17 km north to south, with an average elevation of 2200 m (Fig. 1). The caldera itself was formed in an explosive eruption of rhyolitic magma 0.7 m.y. ago, producing about 500 km^3 of Bishop tuff both within and outside the caldera and about 300 km^3 of ash dispersed over much of the western United States (Abers, 1985). Bailey et al. (1976) give a detailed description of caldera development and post-caldera volcanism.

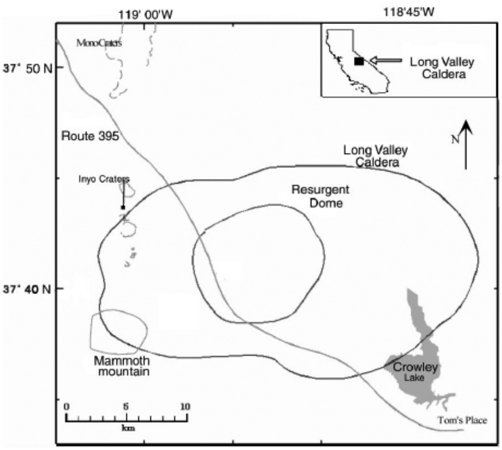

Figure 1. Long Valley Geology (Tiampo et al. 2000). Much of Long Valley is covered by rocks formed during volcanics eruptions in the past 2 million years. A cataclysmic eruption 760,000 ma formed Long Valley and ejected flows of hot glowing ash, which cooled to form the Bishop tuff.

Between July 1982 and July 1998, gravity within the caldera decreased substantially (the precise relative gravity measurements reveal a decrease in gravity of as much as -107±6 mGal centered on the uplifting resurgent dome) whereas the control stations showed no substantial change. The largest gravity decrease is located on the resurgent dome. After correcting by elevation differences using the free-air gradient and water table effect, the residual gravity field or free-air gravity change shows a peak of 64±16 mGal centered on the resurgent dome. A density value for the intruded material of 3300 kgm^{-3} is obtained by assuming that the chamber volume change is equal to the volume of mass that enters or leaves the cavity. Their results require an intrusion of silicate magma and exclude in situ thermal expansion or pressurization of the hydrothermal system.

We apply the elastic-gravitational model to the second period of inflation at Long Valley caldera as Tiampo et al. (2000). Therefore, we use the same medium and sources parameters. We try two spherical point source model in a homogeneous crust. The larger spherical source located at 9.9 km has a volume increment (ΔV) of 0.036 km^3 while the second at only 0.008 km^3 is located at 7.3 depth. Taking into account the initial source radii of 4 km for the deeper magma chamber (Elbring and Rundle, 1985) located beneath the resurgent dome and of 1.5 km for the shallowest chamber located beneath the south moat (Sanders, 1984) that arose during the first inflation period, and the magma density pointed above, Fernández et al. (2001) obtained the pressure increase and the final masses of the intrusions. The volume increments resulted in the pressure and mass increments of 6.9 MPa and 0.1188 MU for the source beneath the resurgent dome and 29.0 MPa and 0.0264 MU for the shallowest source.

Fig. 2 shows the displacements and gravity changes caused by two dilatation sources within an elastic and homogeneous half-space with Poisson's ratio σ = 0.25. Thus, we consider pressure effects without taking into account the intrusion mass. Vertical displacements are similar to those observed during the second period of inflation (Langbein et al. 1993; Langbein et al. 1995; Tiampo et al. 2000) although free-air gravity changes are null since changes in gravity are due to uplift for this kind of sources, as Rundle (1978) and Walsh and Rice (1979) pointed out.

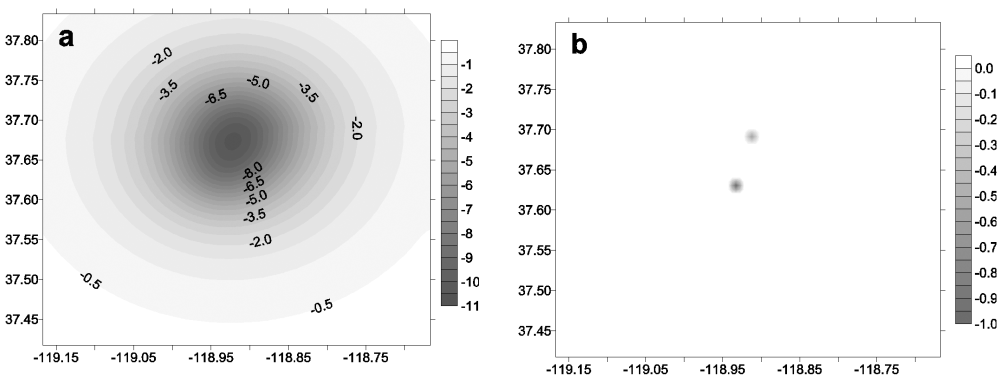

Figure 2. Results obtained for Long Valley Caldera and the second inflation period considering a homogeneous elastic crust and two Mogi sources. a. Vertical displacements in cm. b. Free-Air gravity changes in μGal (1 μGal = 10^{-8} m/s^2) (Fernández et al. 2001).

Numerical experiments are carried out considering the effects on gravity changes and uplift due to the supersposition of a pressurized magma chamber cavity and a gravitational source (intruded mass). The interaction between mass and self-gravitation of the medium is simulated through elastic displacements and gravity coupling. Fig. 3 displays the vertical displacements and the free air gravity change (residual gravity) for Long Valley caldera considering the sources described above within a elastic-gravitational homogeneous half-space. The vertical displacement field (Fig. 3a) is similar to those computed by using a elastic half-space while changes in gravity (Fig. 3b) have a similar pattern to the ones showed by Battaglia et al. (1999) with a maximum located at the resurgent dome. Nevertheless, the predicted maximun is around 13 μGal while the residual gravity change observed at Long Valley shows a peak of 64±16 μGal. The diferences in magnitude could be due to the fact that we are modelling the second period of inflation (1989-1992) and gravity changes were observed at Long Valley between 1982 and 1998, a longer period. Furthermore, the source parameter estimation pointed above could be not totally correct since it come from modelling in which deformation and gravity changes are treated separately. The results show that during the second period of inflation there may have been some magma recharge together with a certain overpressure. The contribution of the intrusion mass is almost null compare to pressurization contribution in displacement calculation while the emplacement of a mass at some depth is significant for changes in gravity. In this way, elastic-gravitational model provides realistic results without assuming that the change in volume of the magma chamber is the volume of magma which enters or leaves the chamber during an injection or removal proces.

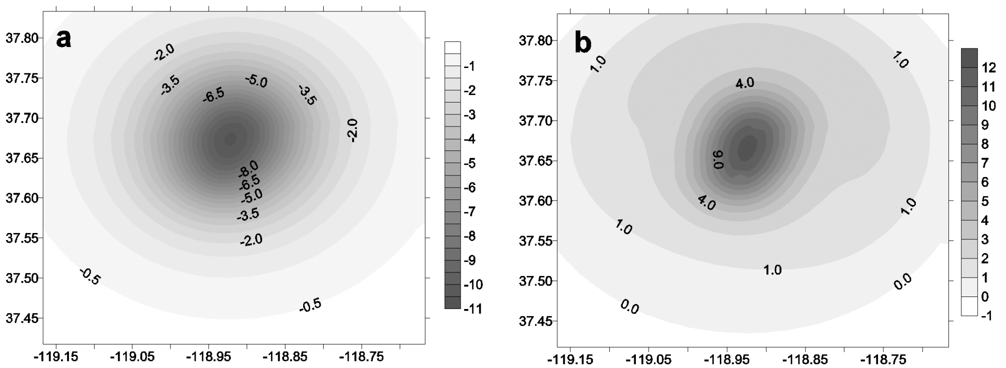

Figure 3. Results obtained for Long Valley Caldera and the second inflation period considering a homogeneous elastic-gravitational crust and pressure and mass effects of the two sources. a. Vertical displacements in cm. b. Free Air gravity changes in μGal (Fernández et al. 2001).

We use now the elastic-gravitational deformation model to perform the inversion of the temporal free air gravity changes between 1982-1998 in Long Valley caldera. This inversion provides the parameters of the gravitational source causing those changes and allow us to interpret them without taking into account the parameters estimated in other works.

4. INVERSION TECHNIQUE. QUALITATIVE DESCRIPTION OF GENETIC ALGORITHM

The branch of mathematics known as optimization has found significant use in many geophysical applications. One of the objectives of geophysical inversion is to find Earth models that explain the geophysical measurements. The inversion of geophysical data is complicated by the fact that observed data are contaminated by noise and are acquired at a limited number of observation points. Although Genetic algorithms (GA) have been adapted and applied to a variety of applications they have proven to be an attractive global search tool suitable for irregular functions tipically observed in nonlinear optimization problems in the physical sciences (see e.g., Stoffa and Sen, 1991, Boschetti et al. 1996, Yu and Rundle, 1995; Yu et al. 1998).

The idea of a GA is based on the evolutionary process of biological organism in nature, i.e., individuals which are more successful in adapting to their environment will have a better chance of surviving and reproducing, while individuals which are less "fit" will be eliminated. This means that genes from highly fit individuals will spread to an increasing number of individuals in each successive generation. The combination of good characteristics from highly adapted ancestors, through mating, may produce even more fit offspring.

The inverse problem looks for the parameters that control the geophysical response we measure. This set of parameters constitutes the optimal model parameters. Using GA the parameters to be inverted are coded as genes. Each gene represents a possible solution to the problem. Starting with an initial range of parameters, these algorithms progressively modify the solution by incorporating evolutionary operators - selection, crossover and mutation, that alter the composition of the parameter set. The fitness of an individual is evaluated with respect to a given objective function that plays the role of the environment. The fittest members of each population are combined using probabilistic transition rules to form a new offspring population. Highly fit individuals are given opportunities to reproduce by exchanging pieces of their genetic information in the crossover procedure, with other highly fit individuals. This produces new offspring solutions that share some characteristics taken from both parents. Mutation is often applied after crossover by altering some parameters in the strings. This procedure is introduced to ensure against the occasional loss of valuable genetic material (Tiampo et al. 2000). The offspring will then replace some members of the existing population. This cycle is repeated until a satisfactory solution is found or some termination criteria is met.

Our program is schematically shown in Fig. 4. Specific features include real valued genes, an elitist function and windowing fitness function (Tiampo et al. 2000). In classical GA the coding genes are usually represented as strings of binary alphabet. It has some drawbacks when applied to multidimensional, high-precision numerical problems (Michalewicz, 1992). The implementation used in this work increases the efficiency of the algorithm, because the need to convert bit strings to real values in every fitness evaluation is eliminated. Each model parameter is forced to be within a desired range, and the operators were carefully designed to preserve this requirement. There is no loss of precision as a result of a binary representation, while crossover and mutation subroutines can be customized for the specific real parameter representation of the inversion (Wright, 1991). Of course, we can always extend the precision of the binary representation by introducing more bits, but this considerably slows down the algorithm.

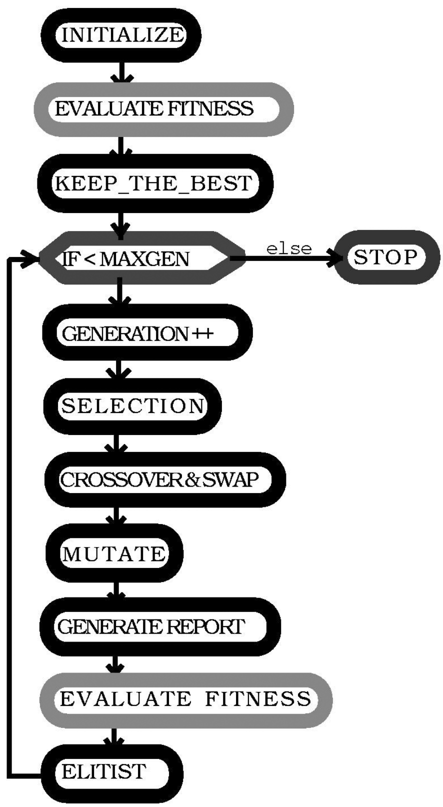

Figure 4. Schematic of genetic algorithm (GA) program (Tiampo et al. 2000).

There are two important factors in the evolution process of genetic search: population diversity and selective pressure (Whitley, 1989). These factors are strongly related: an increase in the selective pressure decreases the diversity of the population (Michalewicz, 1992). Thus, it is important to strike a balance between these two factors. The elitist function employed in the GA program is a sampling mechanism that attempts to achieve this goal. It enforces preservation of the best member of all populations, current and prior. Then, some parents are allowed to undergo selection with their offspring. Finally, a windowing function was added to prevent search stagnation and premature convergence. This function subtracts the fitness value of the worst member of the previous generation from every new population fitness, prior to selection of the next generation. This ensures that those members with a better relative fitness were included in a greater proportion in the next generation, despite the small absolute difference in their fitness (Tiampo et al. 2000).

5. FORWARD MODEL

To understand how the data are affected by the Earth behavior we must be able to compute synthetic data for an assumed Earth model. This constitutes the forward problem and involves deriving a mathematical relationship between data and model. Here, we used an elastic-gravitational layered Earth model to get the parameters of the source. The density and Lamé parameters have been obtained using the methodology described by Fernández and Díez (1995) and geological information from Hill et al. (1985) by Charco et al. (2004). GA code tries to find the parameters (x-y location, depth, radius, mass and pressure) that minimize the difference between model response and ground measurements. In this work we use the valu of chi-square to control that difference:

$$\chi^2 = \sum_k \frac{\left(y_k - f(x_k)\right)^2}{\sigma_k^2} \tag{3}$$

where y_k are the measured free air gravity changes, $f(x_k)$ are the calculated gravity changes from the model, σ_k is the standard deviation for each measurement and k is the total number of measurements (Taylor, 1982; Bevington and Robinson, 1992). If we assume that the observed data follows a Gaussian distribution the chi-square value permits evaluation to determine if the data has a media equal to the model predictions (Peña, 1994).

GA is a problem-solving method that seeks the fittest members of the population based upon maximum fitness value. Our optimization problem is to minimize the expression (1). This is equivalent to maximizing a function that we call the Fitness Value (*FV*):

$$FV = \frac{1}{\chi^2} \tag{4}$$

This expression converts the fitness to a continuously increasing function.

6. SENSITIVITY ANALYSIS

In order to evaluate the inversion results, sensitivity tests were conducted on two separate elastic-gravitational sources of varying sizes and depths. In each case, one parameter vary while the others remained fixed. Results are shown in Figs. 5 and 6. Sensitivity of deformation measurements was tested versus the sensitivity of the associated gravity measurements.The fitness is plotted against the normalized variable in question.

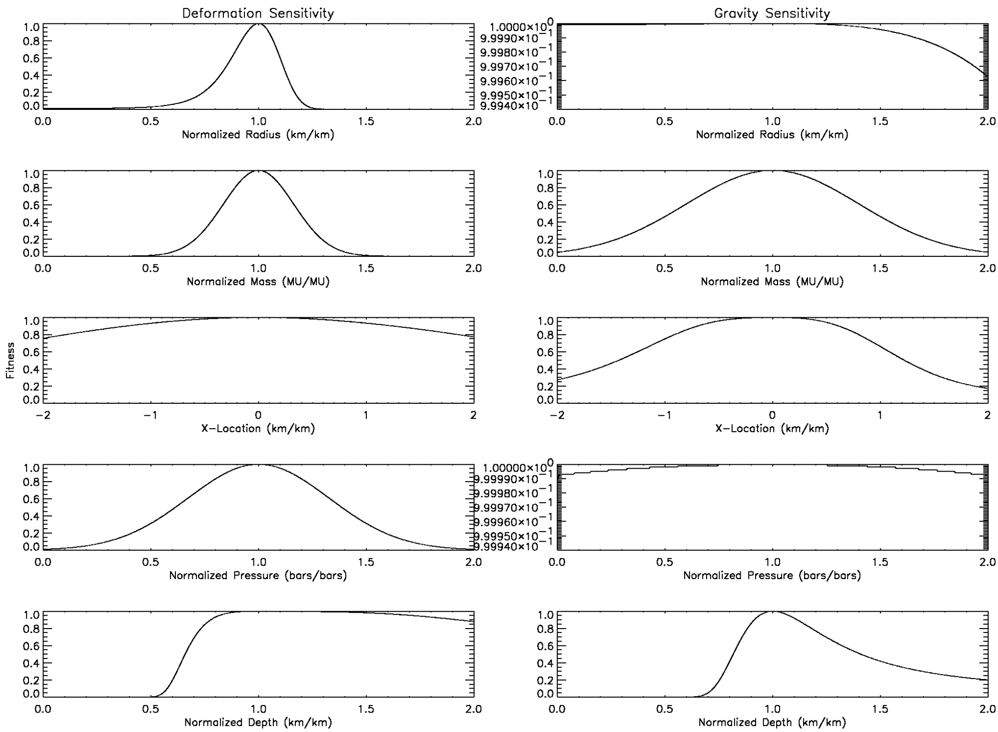

Figure 5. Sensitivity of the inversion fitness to the various elastic-gravitational model parameters, relative to both deformation, on the left, and gravity on the right. Smaller source, with a pressure of 80 bars and a radius of 0.75 km (centered at (0,0), depth of 2 km, mass of 1MU) (Tiampo et al. 2004b).

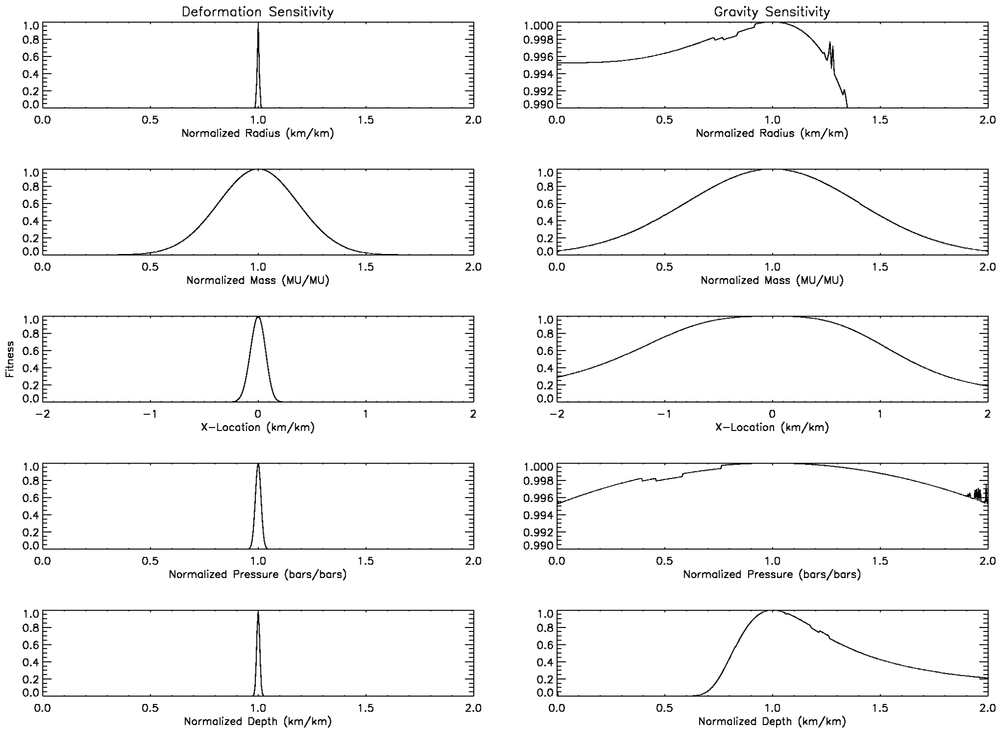

Figure 6. Sensitivity of the inversion fitness to the various elastic-gravitational model parameters, relative to both deformation, on the left, and gravity on the right. Larger source, with a pressure of 250 bars and a radius of 1.5 km (centered at (0,0), depth of 2 km, mass of 1MU) (Tiampo et al. 2004b).

The deformation sensitivity for pressure is a steeply varying parameter, with a single defined minimum that is highly peaked for a larger source. x (or y) distance is a steeply varying parameter, with a single, easily defined maximum, for both gravity and deformation measurements. This corresponds with the GAs ability to invariably locate the source in the x-y plane, as a result of the distinct location dependent pattern created by a magmatic source. However, for the smaller source, it is the gravity measurements that better define the x-location, while in the case of a larger source, the deformation measurements are more sensitive to the x-location.

In both cases, the normalized mass has a distinct, steeply varying signature for both gravity and deformation. However, the axisymmetric feature associated with the depth parameter, particularly for the smaller source, suggest that any inversion will tend to err more toward deeper sources than shallow. This is related to errors in the size of the source, as deeper sources neccessitate larger mass and/or volume to reproduce the correct magnitude of the geodetic signal. This illustrates the importance of incorporating both gravity and deformation measurements into the volcanic modeling process that it is independent of the method employed in the inversion.

Not surprisingly, while deformation measurements are very sensitive to pressure, the gravity measurements are not particularly at lower pressures. However, gravity sensitivity to the radius for larger sources suggest that the location of gravity measurements is of prime importance in the evaluation of the inversion ability to properly characterize the anomaly.

7. INVERSION RESULTS

Although the numerous published models of deformation of Long Valley caldera differ in detail, most have in common the following three sources: a primarily dilatational volume beneath the central part of the resurgent dome, centered at depth between 7-10 km, a secondary dilatational volume beneath the southern margin of the resurgent dome centered at depth between 4-8 km and a right lateral slip on a vertical west-northwest striking fault in the south moat.

First, we estimated the x-y location, the depth, the pressure change, the radius and the mass increment assuming a simple spherical point source located in a layered elastic-gravitational half-space. Taking into account prior models employed at Long Valley caldera, here we show the results of using two spherical point sources to represent both the deeper source beneath the resurgent dome and the south moat source (Langbein et al. 1995). Table 1 shows the parameters resulting from GA inversion. The free-air gravity changes computed using the elastic-gravitational model and the predicted parameters obtained from two sources GA inversion are shown in Fig. 7. The location of the maximum value is closer to the observed maximum residual gravity anomaly than those of one-source model we tested earlier. It seems as if the second gravity signal is coming from a bigger source and not from what is generally called the south moat intrusion.

Table 1. Parameters of the two- source inversion.

Parameters	Source 1	Source 2
x	118º 54’ 17’’W	118º55’22’’W
y	37º 41’23.8’’N	37º 37’ 51’’N
Depth c (km)	6.6	7.5
Increment magma pressure (Mpa) (DP)	9.6	23.7
Radius a (km)	0.5	0.2
Mass increment ($1MU=10^{12}$) (DM)	0.27 MU	0.2 MU

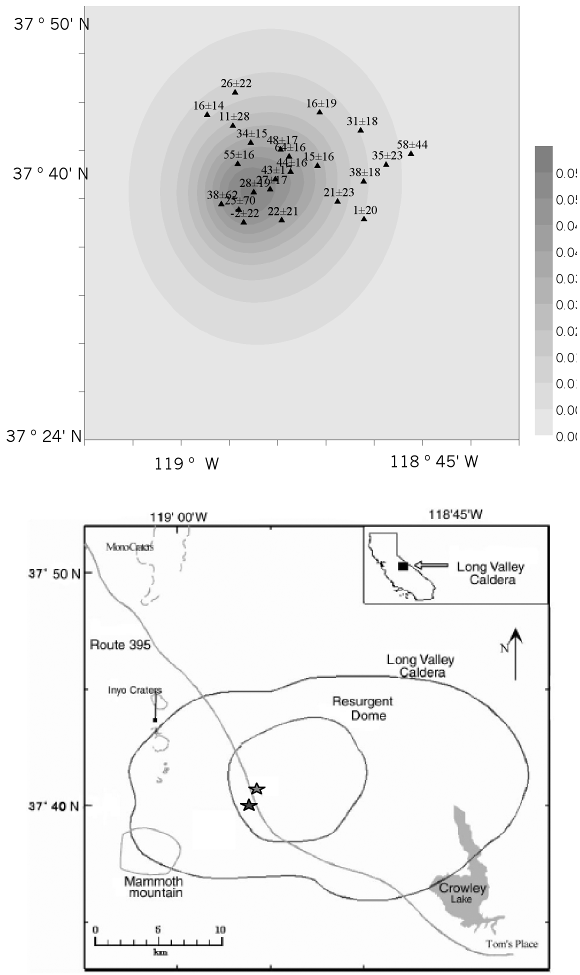

Figure 7. (a) Free-air gravity change in mGal predicted from the one source inversion. The location of the gravity stations is marked by a triangle. The numbers indicates the residual gravity change in the network stations in mGal. (b) The star marks the source x-y location.

Fialko et al. (2001) have performed a joint inversion of the InSAR and two color geodimeter data from Long Valley Caldera for the period between 1996 and 1998 that suggests that the deformation source has a shape of a steeply dipping prolate spheroid having a depth of 7 km and excess pressure of several MPa. The inferred location is in general agreement with a low velocity and high attenuation region beneath the resurgent dome revealed by seismic studies. Seismic evidence indicates that the main mass of Long Valley magma chamber is about 10 km in diameter and that its roof is 8-10 km deep with smaller cupolas as shallow as 4-5 km (Hill et al. 1985). Battaglia et al. (2004) modelled the source of inflation combining geodetic and microgravity data. The inflation source, a vertical prolate ellipsoid, is located at 5.9 km deep beneath the resurgent dome. The results of two sources inversion suggest that we can not rule out that the gravity changes could be caused by a single, more spatially distributed source, replacing the magma chamber under Casa Diablo that is represented by two point sources in the inverse problem.

The sensivity analysis of the elastic-gravitational model illustrates that, while the deformation measurements are very sensitive to the pressure and radius parameters, the gravity measurements are not. However with increasing pressure the gravity measurements become more sensitive to both parameters. That is the reason we have performed another inversion with a wider range on the pressure limits for the first source, and on mass and radius limits for the second one. The differences between pressure increments of both sources have diminished to 43.5 and 46.7 MPa, respectively. This could indicate that the free air gravity changes can be interpreted by using a more spatially distributed source and points out the necessity of a joint inversion of gravity and deformation measurements to discriminate the role played by the pressure and mass variations in the volume change of the magma chamber.

8. CONCLUSIONS

This paper reviews the application of the elastic-gravitational model for magmatic sources. This model provides a complete solution of the problem of calculating gravity, deformation and potential changes arising from volcanic crustal loading that includes the directly coupled effects of gravity and elastic displacement changes. Deformation and changes in gravity are obtained as a part of one solution.

It is standard to assume the chamber volume increase caused by overpressure in the magma chamber is equal to volume magma injection. First, we show that elastic-gravitational model provides realistic results without assuming that. Applying both a classical elastic and the elastic-gravitational model to interpret geodetic changes observed at Long Valley caldera between 1989 -1992 we obtain that the response of an elastic half-space to a point of dilatation can lead to error in the source parameter estimation since gravity changes caused by this kind of sources are due to uplift. The results show that during the second period of inflation there may have been some magma recharge together with a certain overpressure.

In the second step of our study into geodetic data interprtation, we invert the free air gravity changes observed at Long Valley caldera between 1982 -1998 by using a Genetic Algorithm inversion technique. This technique is a valuable tool for geophysical problems in which data are contaminaited by noised and are not continously distributed. A sensitivity analysis reveals important information about how initial measurements error and variations in the measurements scheme propagate into final inversion results. The results of the performed inversions fit the gravity anomaly centered under the resurgent dome. The two source inversion suggests that the gravity change could be caused by a more spatially distributed source under the resurgent dome.

The elastic-gravitational model considers pressurization together with the intrusion mass and gravity field interaction in order to interpret unusual geodetic measurements. So, the results demonstrate that the accuracy of a volcanic source parameter search can be increased by applying this kind of models that allow the joint interpretations of displacement and gravity changes without additional assumptions.

9. ACKNOWLEDGEMENTS

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