Joint interpretation of displacement and gravity data in volcanic areas. A test example: Long Valley Caldera, California

J. Fernández,¹ M. Charco,¹ K. F. Tiampo,² G. Jentzsch,³ and J. B. Rundle²

Abstract. Volcanic activity produces deformation and gravity changes that many times can be used as precursors of future eruptions. Applying geodetic techniques to monitoring activity involves interpretation using deformation models. Usually gravity change data and displacement data are interpreted separately. We show, using modeling of deformation and gravity change data in Long Valley Caldera, California, USA, that this can lead to incorrect interpretations. The results obtained show that displacements and gravity changes must be interpreted together whenever possible and that elastic-gravitational models can be a far more appropriate approximation to problems of volcanic load in the crust than the more commonly used purely elastic models. Therefore it is necessary to change the philosophy normally used to interpret geodetic observations, improving the possibility of predicting future eruptions.

1. Introduction

Volcanic activity almost inevitably produces deformation and gravity changes before, during, between and after the events. On the basis of this fact and the high levels of precision attainable, different geodetic techniques are proving to be a powerful tool in the monitoring of volcanic activity, making it possible to detect ground motion and gravity changes that reflect magma rising from depth, sometimes months or weeks before the magma flow leads to earthquakes or other eruption precursors [e.g.: Delaney and McGlue, 1994; Rymer, 1996; Dvorak and Dzurisin, 1997; Massonnet and Feigl, 1998; Fernández et al., 1999; Rymer and Williams-Jones, 2000; Stein et al., 2000]. Geodetic monitoring thus complements seismic monitoring by extending the study of volcanic phenomena from seconds to years and providing details on the growth of magma bodies within the volcano [Stein et al., 2000]. Applying such longer-term monitoring techniques to volcanically active zones inevitably involves data processing and the subsequent final interpretation of observed deformations and gravity changes. Mathematical deformation models are a basic, essential tool for the latter task.

Present knowledge on critical stages of volcanoes prior to eruption is mostly based on elastostatic views; by studying volcanic unrest in terms of mechanical models involving overpressure in magma chambers and conduits. Reaching eruptive conditions is interpreted, in this framework, as overcoming the mechanical rock strength in large volumes, from the top of a magma chamber to the surface. Mogi [1958] applied a center of dilatation (point pressure source) in an elastic space to interpret the ground deformation produced in volcanic areas. Mogi's model has been extensively applied in modeling ground deformations in volcanic areas and has been successful in explaining primarily vertical ground deformations. This model often poses difficulties in simultaneously modeling observed displacements and gravity changes [e.g.: Rymer et al., 1993; Rymer, 1996; Jentzsch et al., 2000] and there is a large body of evidence for ground deformations and seismicity at calderas that can not be modelled by these purely elastic effects [e.g.: Bonafede, 1990; De Natale et al., 1997; Gaeta et al., 1998]. Rundle [1980, 1982] obtains and solves the equations that represent the coupled elastic-gravitational problem for a stratified half-space of homogeneous layers. The magmatic intrusion is considered a point intrusion located at depth c. This model [Rundle, 1980, 1982; Fernández and Rundle, 1994; Fernández et al., 1997] takes into account the interaction between the mass of the intrusion and the ambient gravity field and the effect caused by the change of pressure in the magmatic chamber (due to overfilling or temperature changes). It has been shown theoretically [Fernández et al., 1997] that consideration of gravity effects can be fundamental for adjusting and properly explaining gravity changes measured in active zones. Vertical displacements and gravity changes produced by pressure increases and the mass of the intrusion have different signs [Rundle, 1982, Fernández et al., 1997]. This is very important because the right combinations of mass, radius and pressure in the intrusion can serve to explain observations in active zones where major gravity changes appear without any significant deformation, or vice versa [see e.g., Rundle, 1982; Rymer, 1996; Jentzsch et al., 2000]. Furthermore, while gravity change data and displacement data generally are interpreted separately, or vertical displacement data are used only for correction of observed gravity values, we will see in the modeling of deformation and gravity change data in the Long Valley Caldera, California, USA that this can lead to incorrect interpretations. The results obtained will show that elastic-gravitational models can be a far more appropriate approximation to problems of volcanic load in the crust than the more commonly used purely elastic models [e.g.: Mogi, 1958; McGlue, 1987; Davis, 1986; Yang et al., 1988]. We must take into account that a correct interpretation of the observed geodetic signals will have implications for the improvement and development of monitoring and alert systems for the mitigation of hazards, as well as direct socioeconomic implications as it affects urban and industrial infrastructure planning.
2. A Test Example: Long Valley Caldera, California, USA

The elliptical-shaped Long Valley Caldera extends 32 km in east-west direction and 17 km north to south, with an average elevation of 2200 m (Figure 1). Information about its formation and evolution are easy to find in the literature [see e.g.: Bailey et al., 1976; Hill, 1984; Abers, 1985]. Over the last 20 years in the Long Valley caldera, located to the east of the Sierra Nevadas (California), there have been two episodes of rapid inflation of the central resurgent dome, accompanied by seismicity inside and around the caldera, without any eruptions between these two episodes. The first episode [Hill, 1984] began in the late 1970s and continued through the mid 1980s. The second episode [Langbein et al., 1993; Langbein et al., 1995; Tiampo et al., 2000] started in October 1989 after several years of relative calm. The models used in previous studies [e.g.: Rundle and Whitcomb, 1984; Langbein et al., 1995; Battaglia et al., 1999; Tiampo et al., 2000] use point sources beneath the resurgent dome. These models are normally purely elastic and do not consider displacements and gravity changes together in the inversion. Normally they also consider a homogeneous half-space. Previous works [Langbein et al., 1995; Tiampo et al., 2000] showed that additional sources of deformation are needed to model the available geodetic observations properly.

Battaglia et al. [1999] study and model gravity changes observed at Long Valley for the period from 1982 to 1998. They compare two source inversions for both spherical Mogi point sources and the finite prolate ellipsoid [Davis, 1986; Yang et al., 1988]. The spherical sources are well constrained, the larger located at 9.9 km beneath the resurgent dome, with a volume of 0.036 km$^3$, while the second with only 0.008 km$^3$, is located at a depth of 7.3 km beneath the south moat. The depths to the ellipsoidal sources are switched, with the larger source at 9.6 km and the smaller at 11.8 km, with volumes of 0.037 and 0.002 km$^3$ respectively. Tiampo et al. [2000] found that the spherical source solution has a better fitness than the ellipsoidal model, yet the ellipsoidal model solution is not spherical. This lead them to conclude that additional sources, in particular the existing normal faulting in the northwest of the caldera, which they do not model in their study, are needed to provide a better solution. They do not use gravity measurements for the correction of uplift effects. Their results would corresponds with the first model described by Rymer and Williams-Jones [2000]. Tiampo et al. [2000] model the second inflation period at Long Valley using genetic algorithm techniques and high-quality geodetic measurements of elevation and baseline extension changes. They compare two source inversions for both spherical Mogi point sources and the finite prolate ellipsoid [Davis, 1986; Yang et al., 1988]. The spherical sources are well constrained, the larger located at 9.9 km beneath the resurgent dome, with a volume of 0.036 km$^3$, while the second with only 0.008 km$^3$, is located at a depth of 7.3 km beneath the south moat. The depths to the ellipsoidal sources are switched, with the larger source at 9.6 km and the smaller at 11.8 km, with volumes of 0.037 and 0.002 km$^3$ respectively. Tiampo et al. [2000] found that the spherical source solution has a better fitness than the ellipsoidal model, yet the ellipsoidal model solution is not spherical. This lead them to conclude that additional sources, in particular the existing normal faulting in the northwest of the caldera, which they do not model in their study, are needed to provide a better solution. They do not use gravity data in their study.

We apply our elastic-gravitational model to the second inflation period at Long Valley caldera like Tiampo et al.
[2000] as a test. Therefore we used the same characteristics for both the medium and the number and location of sources. We try the two spherical point source model in a homogeneous crust. The volume increment values obtained, which represent the volumes of expansion for the two sources considered, can be used to obtain the pressure and masses increment of the intrusions, by only taking into account the initial source radii of 4 km for the deep magmatic chamber [Elbringer and Rundle, 1986] and 1.5 Km for the shallowest, located beneath the south moat [Sanders, 1984] that arose during the first period of inflation in Long Valley caldera. Using the relation between pressure and volume changes for spherical intrusions [see McTigue, 1987] and the density value of 3300 kg m$^{-3}$ [Battaglia et al., 1999], the pressure changes and the masses increments obtained are 6.9 MPa and 0.1188 MU for the source beneath the south moat and the density

3. Conclusions

From the results obtained in previous theoretical works and from applying the model to Long Valley Caldera the first conclusion we obtain is that interpreting deformations and gravity changes by using purely elastic models often can lead to results that are clearly incorrect in terms of the location and/or characteristics of the intrusion. This easily occurs if the effects on the intrusion are not due primarily to pressure changes in the intrusion, but instead there is a considerable amount of magma recharge in the intrusion. Elastic-gravitational models, which accounts for the interaction of the mass of the intrusion with the ambient gravity field and redistribution of densities inside the crust, can be used reasonably to interpret cases where gravity changes exist without deformation, and vice versa, considering adequate mass and pressure combinations for the intrusion, taking into account that the effects for both types of source are of opposite signs. Furthermore, displacements and gravity changes must be interpreted together whenever possible, because this will allow us to distinguish between the possible cases and to discriminate between the role played by pressure
changes and that played by mass displacements. It can be done using elastic-gravitational models, but is otherwise very hard to be done correctly with purely elastic models that do not consider the mass of the intrusion and its interaction with the surrounding medium and the gravity field. Therefore the results clearly show the need to change the philosophy normally used to interpret geodetic observations in volcanism, in which displacement data and gravity change data are not interpreted together, and very often are interpreted using purely elastic models that are both simplistic and inappropriate, giving rise to false alarms based in incorrect interpretations. In order to properly compare our model with the elastic model, we have not considered layering or viscoelastic properties of the media in this work, although both of them can be important in modelling geodetic observations [see e.g., Bonafede et al., 1990; Fernández et al., 1997]

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