Spatiotemporal gravity changes on volcanoes: Assessing the importance of topography

Maria Charco,1 Antonio G. Camacho,2 Kristy F. Tiampo,3 and José Fernández2

Received 17 January 2008; revised 2 March 2009; accepted 13 March 2009; published 24 April 2009.

[1] Mass redistribution and deformation cause spatiotemporal gravity changes in active volcano areas. The ability of the gravity measurements to detect subsurface magma movement as a precursor to volcanic eruptions is greatly enhanced if gravity changes are analyzed and modeled jointly with ground deformation data. One effective tool for this analysis is provided by the gravity and elevation change ratio. The proposed numerical formulation allows to simulate a wide range of pressures and mass loads. However, the assessment of gravity changes is especially important when they occur without measurable ground deformation. In such a case it is very difficult to relate the gravity/uplift ratio to changes in subsurface mass movements by using classical models. In this work, we study the role played by pressure and mass sources in the interpretation of observed gravity/uplift ratio when deformation is negligible in volcanic areas associated with rough topographic relief. Citation: Charco, M., A. G. Camacho, K. F. Tiampo, and J. Fernández (2009), Spatiotemporal gravity changes on volcanoes: Assessing the importance of topography, Geophys. Res. Lett., 36, L08306, doi:10.1029/2009GL037160.

1. Introduction

[2] Spatiotemporal gravity changes on volcanoes, excluding temporal changes as a result of solid Earth tides, ocean tides and variations in atmospheric pressure which are not of primary interest for volcano monitoring, are caused by mass redistributions and the free-air effect of elevation changes. In this way, repeated microgravity surveys have the potential to provide information on both surface displacements related to inflation/deflation cycles and subsurface mass changes (∆M). This can be caused by a variety of processes which include the filling and draining of magma reservoirs, surface and subsurface magma movement, changes in the density of magma bodies, and changes in surface and groundwater reservoirs. Nevertheless, the capability of gravity measurements to detect subsurface mass flow is greatly enhanced if gravity measurements are analyzed and modeled jointly with ground deformation data. Deformation measurements are sensitive to changes in medium volume, as well as changes in pressure. Using ground deformation, the change in edifice volume (∆V_e) of the volcano can be estimated by integrating the observed elevation over the observation area. Assuming the medium behaves elastically, measured or estimated values for the elastic properties of the country rock and the effective modulus of the magma stored within the reservoir can then be used to estimate the volume of magma intruded (∆V_magma) which is accommodated by a combination of expansion of the chamber (∆V_chamber) and compression of stored magma (∆V_compression) [Detaney and McTigue, 1994; Johnson et al., 2000]. In this way, simultaneous gravity and deformation measurements provide an estimate of ∆M and ∆V_chamber, so that changes in the average density of the reservoir may be deduced, providing insights into chamber dynamics. Therefore, gravity-height change data have been shown to be a key tool for mid- to long-term hazard assessment since they allow subsurface mass redistribution to be detected long before other eruption precursors appear [e.g., Berrino et al., 1984; Rymer, 1994; Battaglia et al., 2008].

[3] In order to perform the joint interpretation of both changes in gravity and displacement, mathematical models are required to understand the internal volcano processes. Attempts to model gravity changes which are expected to accompany crustal deformation have been proposed by using half-space solutions [e.g., Hagiwara, 1977; Okubo, 1992]. While such models have been quite successful at fitting surface measurements, it is clear that local topographic relief in volcanic areas can produce significant difference between observed and calculated deformation and gravity changes, that results in misinterpretation of source characteristics estimations [Charco et al., 2007]. Although several studies have been performed to assess how medium topography can influence the deformation field in a volcanic area [e.g., Cayol and Cornet, 1998; Williams and Wadge, 1998, 2000], few investigations have been carried out on gravity fields. While in the past Currenti et al. [2007] and Charco et al. [2007] evaluated both ground deformation and gravity changes using numerical models, we investigate the ratio between gravity and elevation change (vertical gravity gradient) as a means of inferring subsurface mass/volume changes.

[4] From the point of view of volcano monitoring, the assessment of gravity changes is especially important when they occur without measurable ground deformation, [e.g., Rymer et al., 1993; Fernández et al., 2001; Carbone et al., 2003]. In such cases, the vertical gravity gradients tend to infinity and it is difficult to relate them to changes in subsurface mass and/or density. As a result, the observed changes in gravity are difficult to explain with the classical models, which primarily consider surface deformation as a result of inflation. Following the methodologies developed by Fernández et al. [2005] and Charco et al. [2007],

Copyright 2009 by the American Geophysical Union.
0094-8276/09/2009GL037160S05.00

1Departamento de Matemática Aplicada, E. U. Arquitectura Técnica de Madrid, Universidad Politécnica de Madrid, Madrid, Spain.
2Instituto de Astronomía y Geodesia, Facultad de Ciencias Matemáticas, CSIC-UCM, Madrid, Spain.
3Department of Earth Sciences, University of Western Ontario, London, Ontario, Canada.
2. Changes in Gravity

[5] Interpretation of measured displacements and gravity changes in volcanic areas often assumes that the deformation source is embedded in a homogeneous and isotropic elastic half-space. A model first proposed by Mogi [1958], based on the analytical solution for the elastic field arising from a spherical dilatation source in a half-space, is commonly used to calculate the uplift due to inflation/contraction of a magma chamber. This kind of model neglects the mass of the intruded magma (thus they are not able to distinguish between $\Delta V_{\text{chamber}}$ and $\Delta V_{\text{compression}}$) and its interaction with the pre-existing gravity field of the Earth. However, it has been shown that, for prominent volcanoes with high relief, the rough topography has a greater effect on changes in gravity and deformation than medium pre-existing gravity [Charco et al., 2007]. In such cases, a purely elastic field that incorporates the topographic features of the medium and both the mass and pressurization of the source can be used to compute surface displacements and gravity changes. Starting from these theoretical results, displacement and gravity changes produced by volcanic loading and perturbed by topographic features can be computed.

[6] The anomalous gravity field associated with density changes of the medium detected during inflation/deflation episodes can be related to the Poisson differential equation:

$$\nabla^2 \phi = -4\pi G \Delta \rho, \tag{1}$$

where $\phi$ is the perturbed gravitational potential, $G$ is the gravitational constant and $\Delta \rho$ is the change in density that can be accounted for by three main terms [Bonafede and Mazzanti, 1998]:

$$\Delta \rho = -u \cdot \nabla \rho_0 + \rho_1 - \rho_0 \nabla \cdot u, \tag{2}$$

with $u$ is the displacement field, $\rho_0$ is the medium density and $\rho_1$ is the density due to an intrusive mass. The first term is due to the displacement of density boundaries in a heterogeneous medium and to the displacement produced by adding a rock layer in uplifted regions of a homogeneous medium. Currenti et al. [2007] pointed out that a heterogeneous medium generates gravity anomalies quite similar to those generated by a homogeneous one: when the medium is elastic, the deformation and gravity changes depend almost entirely on the average rigidity and the density of the medium surrounding the source. Considering this aspect and the need to isolate topographic effects on vertical gravity gradients, we neglect the effects due to medium heterogeneities. The second term originates from density due to the introduction of new mass into the pressurized volume. The third term is the contribution due to volume change arising from the total pressure applied by the magma, which comprises the reservoir pressure and the weight of the magma. Each term contributes in the total gravity change observed at the ground surface.

[7] The total gravity change observed with an instrument fixed at Earth’s surface has four components:

$$\Delta g = \Delta g^\text{FA} + \Delta g^\text{B} + \Delta g^\text{D} + \Delta g^\text{M}. \tag{3}$$

$\Delta g^\text{FA}$ is the free-air component and it is added to the integral of the Poisson equation in order to take into account the free-air effect of the vertical movement, $u_z$. Deformation also causes gravity to change as the mass elements comprising the medium are displaced relative to the gravimeter. This change corresponds to the first and last terms of the right-hand-side of equation (2) and, from the observational point of view, is divided into two components: the Bouguer component, $\Delta g^\text{B}$, and the deformation component, $\Delta g^\text{D}$. A simple Bouguer correction due to expansion of the initial mass above the initial volume can be calculated assuming the mass distributed as an infinite slab with thickness equal to $u_z$. The component $\Delta g^\text{D}$ is caused by displacements of the initial mass within the initial volume, $\nabla \cdot u$. $\Delta g^\text{B}$ arises from the input/output of mass. The gravity change $\Delta g^\text{M}$ due to the net mass of magma, $\Delta M$, entering or leaving the magma chamber, is given by:

$$\Delta g^\text{M} = G \Delta M \frac{c}{(r^2 + c^2)^{3/2}}, \tag{4}$$

for a system of coordinates with the origin located just above the source and the $Z$-axis pointing down into the medium. $r$ is the horizontal distance to the source and $c$ is its depth. The elastic analysis performed by Rundle [1978] and Walsh and Rice [1979] shows that the ratio $\frac{\Delta g}{\gamma u_z}$ due to the inflation/deflation of a spherical magma chamber should be given by the free-air effect assuming no magma transfer into the chamber, i.e., the deformation component $\Delta g^D$ exactly cancels the Bouguer component $\Delta g^B$ and so the net change in gravity is reduced to:

$$\Delta g = -\gamma u_z + G \Delta M \frac{c}{(r^2 + c^2)^{3/2}}. \tag{5}$$

where $\gamma$ is the free-air gravity gradient ($\gamma = 308.6 \mu\text{Gal m}^{-1}$, $1 \mu\text{Gal} = 10^{-8} \text{ m s}^{-2}$). We are interested in identifying fast geodetic changes associated with volcanic activity. The topographic contribution to the gravitational potential is numerically implemented by using the Indirect Boundary Element Method (IBEM) through the change in vertical displacement induced by pressurization of the medium and mass load effects [Charco et al., 2007]. Since gravity is strongly height dependent, the gravitational attraction of mass primarily depends on the distance between the computation point and the magma chamber, rather than the local shape of the free surface. In order to approximate the topographic effect over $\Delta g^\text{FA}$, it is considered as an extra layer in the same way as the Bouguer correction. Thus, including topographic effects, surface gravity change can be calculated by:

$$\Delta g = -\gamma u_z + G \Delta M \frac{c'}{(r^2 + c'^2)^{3/2}}, \tag{6}$$
where $c' = c + f(r, \theta)$, $f(r, \theta)$ is a function of the horizontal location and represents the elevation above mean sea level of the calculation point $(r, \theta)$. $u_z$ caused by both pressurization and mass effects is numerically implemented by IBEM.

3. Vertical Gravity Gradients: Results

[8] We performed some numerical experiments in order to examine topographic effects on vertical gravity gradients by considering a wide range of parameter space (see auxiliary material), which could be of interest to researchers studying the interpretation of spatiotemporal subsurface density changes. For this purpose, we used a model capable of combining pressurization and mass load effects in order to obtain geologically meaningful solutions. The effect of topography is represented by axisymmetrical volcanoes of altitude $H$ and average slope of the flanks of $\alpha = 0^\circ$, $10^\circ$, $20^\circ$ and $30^\circ$. The height of the volcanoes is $H = 0, 881, 1820$, and $2886$ m, respectively, corresponding to a radius of $5$ km for the volcano base. The elastic behavior of the medium (topography and the underlying half-space) is represented by Lamé parameters $\lambda = \mu = 30$ GPa, i.e., a Poisson ratio of 0.25. The effect of different volcano heights is compared with the case of a flat free-surface ($\alpha = 0^\circ$, $H = 0$ m). The results obtained prompted us to thoroughly study the case in which vertical displacements are close to zero, where classical models cannot be used to relate gravity with deformation. In such cases deformations are negligible compared to instrument resolution, but they are where topographic effects are likely to be most important. Considering the expressions (5) and (6), it is possible to reproduce unusual geodetic data that lead to surprisingly high or low gravity gradients or a nonlinear gravity-height relationship observed at certain volcanoes: combining the gravitational load of magma and the pressure of the reservoir in a suitable way, total uplift may vanish without total gravity change vanishing or vice versa. Thus we can include pressurization together with mass injection while taking into account that the increase of the chamber volume may not be equal to the volume of magma recharge and that mass load counteracts the pressurization effects.

[9] Figure 1 displays vertical displacement, changes in gravity and vertical gravity gradient caused by a spherical pressurized point source located at 4 km depth considering a pressure increment of 10 MPa and a mass load of 1 MU (1 MU = $10^{12}$ kg). We employ these pressure and mass values in order to ensure the displacements caused by the source become zero for the half-space case but to single out the topographic effect for gravity changes. The assumption of topographic relief involves some variations in the magnitude and pattern of the changes in deformation and gravity. However, the vertical gravity gradient caused by pressure (Figure 1a) is still constant and equal to the free-air gradient as it was studied by Rundle [1978] and Walsh and Rice [1979] for the half-space models. The vertical gravity gradient caused by the mass load (Figure 1b) depends on the radial distance, i.e., the relationship between gravity and elevation is not linear. This is due to the fact that, in this case, the surface gravity change caused by mass is related to the change in volume of the magma chamber through the elastic parameters of the medium and the intrusion, and thus to vertical displacement, $u_z$. The reduction in magnitude caused by topographic relief is more noticeable in the gravity changes than in the vertical gravity gradients. This
is due to the reduction in magnitude of the vertical displacement. Topography has also a small but noticeable effect in changing the amplitude of the vertical gravity gradients. The curves are slightly flatter in the proximity of the symmetry axis. Pressurization of the magma chamber is responsible for the volcano edifice inflation while mass causes ground subsidence. However, when topography is taken into account, the high sensitivity of displacement to pressure changes creates a lower reduction of the magnitude of the vertical displacements caused by mass. Thus, the superposition of mass and pressure increases the magnitude of the ground subsidence with topographic relief (Figure 1c).

Therefore, the singularity that the vertical gravity gradients should show as $u_z \rightarrow 0$ disappears when topography height increases. In spite of this, the magnitude of the vertical displacements are below 1 cm, while gravity changes are significant and detectable within the attainable instrument precision (e.g., Rymer and Brown [1989] pointed out an accuracy of 10–15 μGal in microgravity surveys).

Figure 2a shows the gravity-height relationship for the example showed in Figure 1. This relationship is not a straight line as would be expected for the Mogi model. For the half-space case (solid curve), surface gravity changes reach almost 450 μGal as subsidence increases. At a certain point, the ground subsidence and gravity change start to decrease as mass effects are counteracted by pressure effects. When the topography is included (dashed, dotted, and dash-dotted curves) the gravity-height relationship shows a pattern variation that can be forecasted from the gravity gradients showed before: gravity decreases while subsidence increases due to the local maximum/minimum of gravity changes and vertical displacements in the proximity of the symmetry axis. Gravity decreases with pressure increment at constant mass, so the change produced by the topography indicates an increment of pressure effects. This can be explained by the fact that gravity changes are sensitive to both changes of mass and pressure while vertical displacements are more sensitive to pressure effects. This change in the pattern tends to diminish as the source depth decreases, since the topographic effect is significant for shallow sources, particularly when the lateral extension of the relief and the source depth are of the same order of magnitude [Charco et al., 2007].

Figure 2b shows the gravity-height relationship due to a spherical pressurized point source located at 4 km depth considering a pressure increment of 10 MPa and a mass load of 0.8 MU while Figure 2c shows the relationship for the point source considering a pressure increment of 8 MPa and a mass load of 1 MU. The curves are similar to those of the previous examples, showing changes in the pattern and magnitude of the gravity-height relationship. Nevertheless, when the subsidence magnitude tends to increase with topography, the increment of mass effects is more noticeable in the example showed in the Figure 2c.

4. Conclusions

Repeated or continuous deformation and gravity measurements can provide information on how the gravity-height relationship evolves and the associated spatiotemporal changes of mass and magma chamber volume within the medium. Considering a source that takes into account the combination of both pressurization and mass load effects, it is possible to explain different gravity-height relationships. We study the role played by pressure and mass in the interpretation of observed nonlinear gravity-height
Acknowledgments. The research of M. C., A. G. C., and J. F. was supported under MICINN projects CGL2005-05500-C02/BTE and PCI2006-A7-0660. The work of K. F. T. was performed under an NSERC discovery grant and MICINN research project PCI2006-A7-0660. Finally, we would like to thank two anonymous reviewers for their helpful comments.

References


