Inflation or deflation? New results for Mayon volcano applying elastic-gravitational modeling

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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, the observed changes of the deformation and gravity fields are interpreted separately, not in a joint inversion. It can be difficult, if not impossible, to interpret the data coherently or correctly in terms of the characteristics of the intrusion or the deflation derived from the gravity changes with purely elastic models, as in the case of Mayon Volcano, Philippines. We show that elastic-gravitational models can be used to interpret these cases simultaneously leading to a result that is more plausible on the basis of the available information. Thus, we may need to change the philosophy normally used to interpret geodetic observations. Interpretation as proposed in this work can significantly improve the possibility of predicting future eruptions.

1. Introduction

Volcanic activity almost inevitably produces geodetic effects such as deformation and gravity changes before, during, and after the activity, as well as between 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 McTigue*, 1994; *Rymer*, 1996; *Dvorak and Dzurisin*, 1997; *Massonnet and Feigl*, 1998; *Dzurisin et al.*, 1999; *Fernández et al.*, 1999; *Stein et al.*, 2000; *Rymer and Williams-Jones*, 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 [e.g., *Rundle*, 1982; *Fernández and Rundle*, 1994; *De Natale and Pingue*, 1996; *Dvorak and Dzurisin*, 1997] are a basic, essential tool for the latter task.

Quantitative mathematical models cannot purport to cover all different physical and chemical aspects of volcanoes and

we must select and focus on key phenomena. 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 centre of dilatation (point pressure source) in an elastic half-space to interpret the ground deformation produced in volcanic areas. *Mogi's* model has been extensively applied in modelling ground deformation and has been successful in explaining primarily the vertical component of the deformation. However, this model often poses difficulties in simultaneously modelling observed displacements and gravity changes [*Rymer et al.*, 1993; *Rymer*, 1996], and there is a large body of evidence for ground deformation and seismicity at calderas and other volcanic areas that cannot be modelled by these purely elastic effects [e.g., *Bonafede*, 1991; *De Natale et al.*, 1997; *Gaeta et al.*, 1998; *Jahr et al.*, 1998; *Battaglia et al.*, 1999; *Jentzsch et al.*, 2001].

Rundle [1980, 1982] presented an elastic-gravitational model that considers a stratified half-space of homogeneous layers and 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 system. It has been shown theoretically [*Fernández and Rundle*, 1994; *Fernández et al.*, 1997; *Fernández et al.*, 1999] 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. This fact is very important as it can serve to explain observations in active zones where major gravity changes appear without any significant deformation, or vice versa.

The following is a practical comparison of these theoretical results with the modeling of geodetic data observed at Mayon volcano in the Philippines, where there are gravity changes without significant deformation. Furthermore, while gravity change data and displacement data generally are interpreted separately, we will see in the modeling of deformation and gravity change data that this can lead to different and maybe 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; *McTigue*, 1987; *Davis*, 1986; *Yang et al.*, 1988].

2. Background & Data

Mayon volcano is part of the Bicol volcanic chain southeast of the island of Luzon, Philippines (see Figure 1). Part of the Legaspi Lineament of the central Philippine fault system runs NW-SE across Legaspi City, southwest of

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Figure 1. Location of Mayon Volcano.

Mayon. The shape of the volcano is a nearly perfect cone with an altitude of 2462 m. Nearly one million people live in the vicinity of Mayon volcano, and Legaspi City is situated only 12 km away from the crater. The activity of Mayon is quasiperiodic: during the last century it erupted nearly every 10 years [Jentzsch *et al.*, 2001]. The last eruption was in early 2000.

A small eruption took place in February/March 1993, just after the start of gravity and GPS measurements in December 1992 [Völksen and Seiber, 1995; Jahr *et al.*, 1998; Jentzsch *et al.*, 2001]. Therefore, a second campaign was carried out in May 1993 to monitor the decrease in activity. Height control is provided by simultaneous Global Positional System (GPS) measurements; in all, the network consists of 25 points. There are two profiles towards the summit (one of them up to an elevation of 850 m), that are connected to a local and a regional network around the volcano with an extension of 40 km by 50 km. Two points at the opposite side of the Legaspi lineament are also connected to the reference network. The errors of the gravity differences [Jentzsch *et al.*, 2001] between the points derived from a least squares adjustment of the data of each campaign are around $\pm 12 \mu\text{Gal}$.

Five microgravity and differential GPS campaigns were carried out over the next four years. There was no significant gravity change between the first and the second campaign (December 1992, May 1993), although Mayon was active in February/March 1993. The increase in gravity along the profiles in the slope was significant between May 1993 and December 1996, reaching around $150 \mu\text{Gal}$ ($\pm 14 \mu\text{Gal}$), increasing with elevation and as the distance from the crater decreases. The variation is $30 \mu\text{Gal}$ per year if a continuous process is assumed. It should be noted that the volcanic activity at Mayon subsided during that time and the volcano remained inactive up until late 1999.

All the data show that gravity changes are restricted to the area around the volcano within a radius of about 8 km from

the summit. The differential GPS measurements carried out with three simultaneous receivers revealed no significant changes of elevation within the accuracy range ± 3 to 4 cm between all campaigns.

The connection between the variation of gravity and elevation due to mass and/or density changes is usually interpreted in relation with two gradients: if gravity follows the free air gradient (FAG), no subsurface change in the mass has occurred, while data following the gradient after the standard Bouguer correction (BCFAG) implies mass changes [see e.g., Brown and Rymer, 1991; Rymer *et al.*, 1993; Rymer, 1996]. Any departures from these gradients are used to model volcanic processes. In this case, however, the results at Mayon cannot be related to the gravity gradients FAG and BCFAG because the gravity changes drawn against height differences from one campaign to the next show no gradient [Jentzsch *et al.*, 2001]. Furthermore, it is unusual for gravity to increase with decreasing activity, as it does during this particular time period at Mayon.

The estimated maximum effect due to water level changes in the zone on gravity is about $50 \mu\text{Gal}$. Since some of the points with strong gravity changes are located in consolidated rock, ground water level changes cannot be responsible for the observed gravity variations. Further, the steep slope of the

Figure 2. a. Gravity changes for Tumpa-Lahar-Channel profile, observed vs. Modelled for epochs 4-1. b. The same for epochs 5-1. Dotted lines represent gravity changes modelled considering density changes within a vent system [Jahr *et al.*, 1998; Jentzsch *et al.*, 2001]. Dashed lines show results of modelling using elastic-gravitational deformation model via genetic algorithm (GA) inversion technique.

Mayon Resthouse profile does not seem to permit any discussion of a prevailing water table. Only the small gravity change at the foot of the Mayon Resthouse profile of up to 30 μGal can be associated to changes in the local water level [Jentzsch *et al.*, 2001].

As a result, the observed gravity increase, unaccompanied by significant changes in elevation, cannot be explained with the classical Mogi model, which primarily models surface deformation as a result of inflation. In a first step, it is explained [Jahr *et al.*, 1998; Jentzsch *et al.*, 2001] by density changes within a vent system. This model adjusts about 50% of the observed signal and explains the pattern of observed gravity changes (see the computed results shown in dotted lines in Figure 2). This model is based on a redistribution of mass down the vent system. However, the inability of this model to account for a large part of the observed gravity change prompted further analysis using a more complicated elastic-gravitational model.

3. Results

The recent eruption of Mayon volcano and the intermediate small activities give rise to the assumption that the opposite process might have taken place: injection instead of deflation. We test this hypothesis by modeling the observed gravity changes without deformation using a genetic algorithm (GA) inversion technique [e.g., Michalewicz, 1994; Tiampo *et al.*, 2000] and considering elastic-gravitational Earth models [Rundle, 1980, 1982; Fernández and Rundle, 1994; Fernández *et al.*, 1997; Fernández *et al.*, 1999]. The elastic-gravitational model provides a much better solution than either the simple Mogi source or the vent magma model, emphasizing the importance of considering gravitational effects in modeling magmatic sources. The characteristics obtained for the intrusion are: a depth of 1.95 km below the base of the volcano, 0.21 kbar pressure, a radius of 1.65 km, and 0.474 MU for mass (1 MU = 1 Mass Unit = 10^{12} kg) for epoch 4-1; and a depth of 1.82 km, 0.31 kbar pressure, a radius of 1.71 km, and 0.841 MU for mass for epoch 5-1. Figure 2 compares the results for this elastic-gravitational inversion (dashed line) with the actual measurements for the Tumpa-Lahar-Channel profile (solid line), as well as that for the model which redistributes magma down the volcanic vent (dotted line). The results for the Mayon-Resthouse profile for the same epochs reproduce the total magnitude and character of the measured signal, but do not extend as far from the vent. Further study is needed to determine if this is due to asymmetries in the source itself, or baseline inaccuracies along that particular profile [Jahr *et al.*, 1998; Jentzsch *et al.*, 2001]. Interpretation of these results suggests that the gravity changes at Mayon are better explained by reinjection of magma below the volcano following the 1993 eruption rather than mass redistribution in the volcanic vent.

More importantly, the elastic-gravitational model, which accounts for the interaction of the mass of the intrusion with the ambient gravity field and redistribution of densities inside the crust, is demonstrated to be a very powerful tool for interpreting geodetic measurements in volcanic zones and distinguishing between pressure and mass effects, unlike the purely elastic models which are primarily used to analyze volcanic systems, but which are unable to explain gravity changes without displacements or vice-versa. It is also clear that gravity and displacement data must be interpreted at the same time in order to model magmatic sources correctly.

4. Conclusions

The first conclusion from the results obtained above is that interpreting deformations and gravity changes by using purely elastic models sometimes can lead to results that are clearly incorrect in terms of the location and characteristics of the intrusion. On the other hand, the interpretation of gravity changes alone may be not sufficient, as can be seen at Mayon volcano, where only about 50% of the observed changes can be explained [Jahr *et al.*, 1998; Jentzsch *et al.*, 2001]. Here, additional constraints are needed. Taking into account different processes in the magma system like pressure changes in the intrusion or magma recharge, elastic-gravitational models should be used. Especially in cases where gravity changes exist without deformation, and vice versa, the interpretation should include adequate mass and pressure combinations for the intrusion. This approach accounts for the effect of opposite signs for both types of source.

Finally, our 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. Very often the interpretation using purely elastic models that are both simplistic and inappropriate, gives rise to false alarms based on insufficient assumptions. Displacements and gravity changes must be interpreted together wherever possible. This will allow us to distinguish between the different cases and to discriminate between the roles played by pressure changes and by mass displacements, which are otherwise very hard to interpret correctly. A correct interpretation of the observed geodetic signals will have implications in the improving and development of monitoring and alert systems for the mitigation of hazards, as well as direct socio-economic implications as it affects urban and industrial infrastructure planning. Remembering that many sources can be represented as masses or pressure changes, similar to the volcanic case, our results and conclusions are generally applicable to the monitoring and interpretation of other kinds of natural hazards and man-made activities (mining, pumping, tunneling, etc.) which induce both displacements and gravity changes and pose a clear risk to human activity.

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