Numerical Inversion of Surface Deformation at Long Valley Caldera (California) By Using 3D Mechanical Models

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Abstract: We use 3D numerical models to analyze the ground deformation observed at Long Valley Caldera (LVC) between 1992 and 2000 via space-based geodetic techniques. More specifically, we implement a complex model that includes the topography and the material heterogeneities information of LVC. The 3D heterogeneous models are implemented in a Genetic Algorithm optimization to constrain the pressure of the source that caused the surface displacements measured at LVC.

Keywords: Ground deformation, Earth Science, Optimization.

1. Introduction

The interactions between tectonic and magmatic stresses may often cause surface deformations in active volcanic areas. Such ground displacements can be nowadays measured with centimeter accuracy. However, despite the complexities of active volcanic environments, the interpretation of ground displacements is still performed with simplified models, which can be misleading.

In this paper, we present the impact of the mechanical heterogeneities and real topography on the 3D solution of the deformation field.

In particular, being the volcanoes geological environments where lateral variations of mechanical heterogeneity are dominant is necessary to consider this characteristic in order to obtain a more realist representation of the active physical processes. More specifically, in the case of caldera system the eruptive mechanism usually produce an internal softer basin surrounded by stiffer material. In this context, Finite Element approach allows us to implement the models with material heterogeneities and mechanical discontinuities.

Recent studies on Long Valley Caldera, California (LVC) have shown that by considering heterogeneous geometries and the simplified topographic relief within axisymmetric Finite Element (FE) models may affect on the interpretation of source parameters (Magni et al., 2008). We extend the work of Magni et al., 2008, by considering 3D FE models of LVC. First, we include realistic topography obtained by Shuttle Radar Topography Mission (SRTM) data. Moreover, we include the 3D models within a Genetic Algorithm (GA) optimization procedure, in order to constrain the parameters of the causative source of ground displacements observed at LVC between 1992 and 2000 via space-based geodetic techniques.

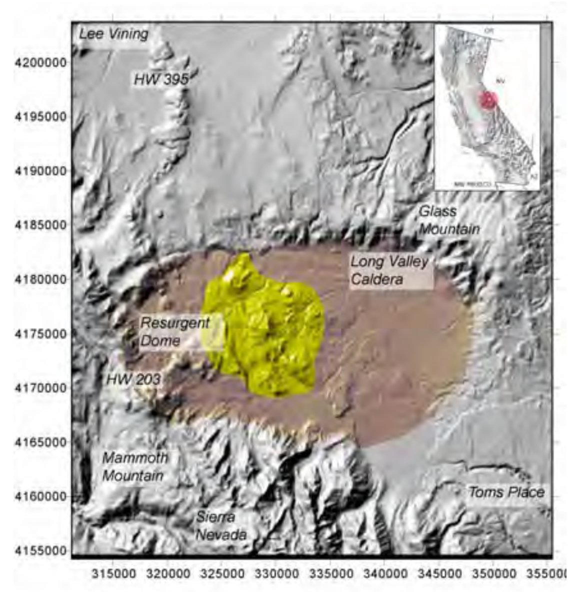

Figure 1. Shaded relief map of Long Valley caldera and monitoring sites. Brown-caldera; yellow—resurgent dome. Coordinates are in UTM NAD27. Inset in upper right corner shows location of study area.

2. Geological Background

The LVC formed ~760,000 yr ago following the massive eruption of the Bishop Tuff. Post caldera volcanism includes lava domes as young as 650 yr. The recent geological unrest is characterized by uplift of the resurgent dome in the central section of the caldera (75 cm in the past 33 yr) and earthquake activity followed by periods of relative quiescence (Tizzani et al., 2009). To measure the deformation of the entire caldera floor and its surroundings in Tizzani et al., 2007 a data set composed of 21 descending orbit SAR images (track 485, frame 2845), acquired by the European Space Agency ERS-1/2 satellites, spanning the time interval from June 1992 to August 2000, has been considered. The ERS-1/2 satellite data were processed using the Small Baseline Subset (SBAS)–DInSAR algorithm (Berardino et al., 2002).

The DInSAR measurements have a spatial resolution of ~100 m and an accuracy of ~2 mm/yr for the deformation velocity and ~10 mm for surface displacements.

The best-fitting source solution for the DInSAR data proposed by Tizzani et al., 2009 is a tilted prolate spheroid, the center of which is located beneath the resurgent dome.

3. FE Modeling Strategy

In order to improve the interpretation achieved by considering classic analytical models, we propose to use within the optimization a FE model, which includes complexities as the topographic relief and the material heterogeneities (Figure 2). This approach is in agreement with the procedures implemented by Manconi et al., 2009, and Tizzani et al., 2010, and is used to fill the gap between the accuracy achieved on the deformation field and the models used for its interpretation.

3.1 Inclusion of Realistic Topography

We have considered the information supplied by independent geological and geophysical studies and we build up our LVC model. For what concerns the introduction of a realistic topography, we have used a procedure that jointly exploits two modules of COMSOL Multiphysics, the Moving mesh (ALE) and the Structural Mechanics module.

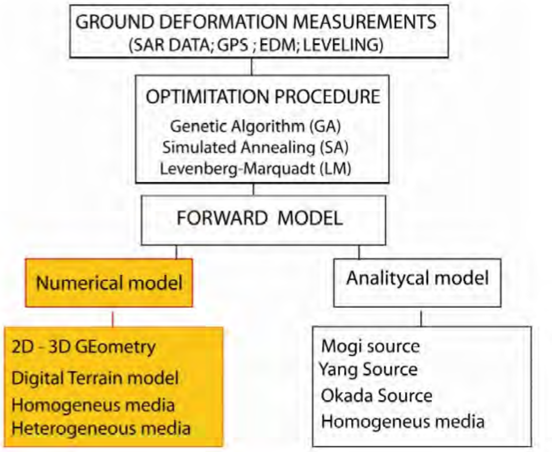

Figure 2. Flow chart of the numerical optimization procedure used in the analysis of surface deformation data measured in volcanic areas. We consider the procedure highlighted in yellow, where numerical models, which might include several complexities, are used instead of the standard analytical models.

The topography information is obtained by Shuttle Radar Topography Mission (SRTM) data.

The inclusion of real topography of the area in the FE environment was performed by means of the following steps. First of all, by using a the Solid, deformation – stress procedure inside to Structural Mechanics Module we build up a 3D block. Then, we apply to the block particular boundary conditions: roller and fixed constrains the lateral and at the bottom of the block, respectively, and a prescribed displacement at its upper face. More specifically, the displacement field is imposed as a function defined in a grid of points relevant to the SRTM digital elevation model. Moreover, we impose in the sub-domain setting of the ALE module that the mesh should be physically driven by displacement field resulting after the simulation. Thus, the deformed mesh is used to generate a new geometry. In this way we have obtained a 3D geometry that includes the topography information of the investigated area and will be used for the following modeling steps (Figure 3). The last part of the procedure (create a geometry form a deformed mesh) is still not available in the version 4.0a of COMSOL, but will be re-integrated in the version 4.1.

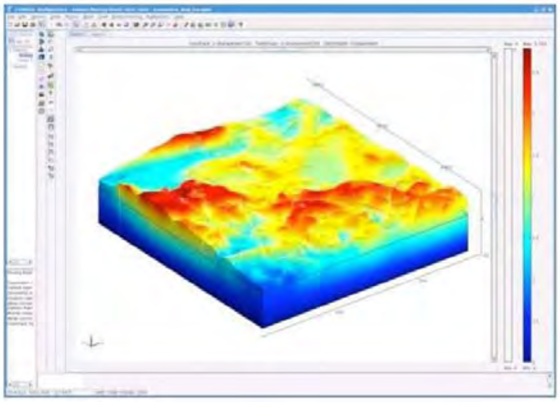

Figure 3. Finite Element model including the topography information of the area of LVC.

3.1 Inclusion of Realistic 3D Mechanical Properties

Concerning the implementation of available geophysical data (in the specific case, a 3D seismic tomography), we considered the inclusion of 3D function within the subdomain settings of the LVC models. We defined the material properties in a grid of points, and we let COMSOL interpolate over the whole domain considering the “nearest neighbor” algorithm. Thus, the material properties are defined as heterogeneous, however, avoiding the creation of sub-domains separated by geometrical discontinuities. In this context, our procedure allows achieving a more realistic spatial representation of the mechanical discontinuities derived by a priori information, avoid the problems of meshing while sharp sub-domains are present, and assuring a constant resolution of the displacement results in the whole domain. In Figure 4 we show a slice cutting the 3D model at about 1 km depth, where is evidenced the lateral variation of mechanical properties.

4. Results

In order to test the validity of our 3D numerical optimization model we have performed a set of experiments over homogeneous and heterogeneous conditions. Subsequently, we compare our best-fit solution with the deformation field computed via analytical procedure (see Figure 5).

To this end, we consider the deformation source responsible of the 97-99 unrest phenomena at LVC as proposed by Tizzani et al., 2009, in the case of homogeneous elastic half space conditions of the crust beneath the caldera region. More specifically, the analytical best-fit solution is characterized by a depth source at a depth between 6.6 and 8.7 km. The spheroid has a geometrical aspect ratio (ratio between the semi-minor and semi-major axis) of 0.56–0.84, with a strike angle ranging from 196° to 302° and tilted of 63° from the horizontal axis.

The source obtained in this study is very similar to this proposed by Tizzani et al., 2007.

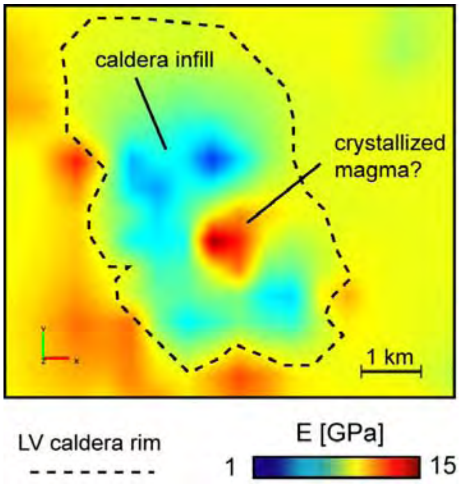

Figure 4. Map view at 1km of depth of the mechanical properties included within the heterogeneous model of Long Valley caldera. The values of Young's modulus (E) are derived from a 3D seismic tomography. The consideration of the mechanical contrast between the caldera infill (lower E) and the crystallized magma present in the caldera center (higher E) causes difference in the stress and strain field due to a source inflation at depth.

However, the inclusion of realistic topography and the mechanical properties of the crust produced an significantly improvement of SAR best fit signal, especially in the zone of maximum uplift were the analytical solution show high residual values (see Figure 5). In addition, we notice a significant reduction (30%) of the source pressure value. Finally, we point out that the high value of residual founded in the area a SW of caldera boundary in the region of McGeeCrk (Sierra Nevada) would confirm the tectonic origin of the detected deformation pattern, in this case the proposed volcanic source is unable to model this pattern; however we remark the possibility to model in future also this deformation trend using the capability of FEM approach, and introduce a range of mechanical discontinuities as well as several physical processes in future advanced models.

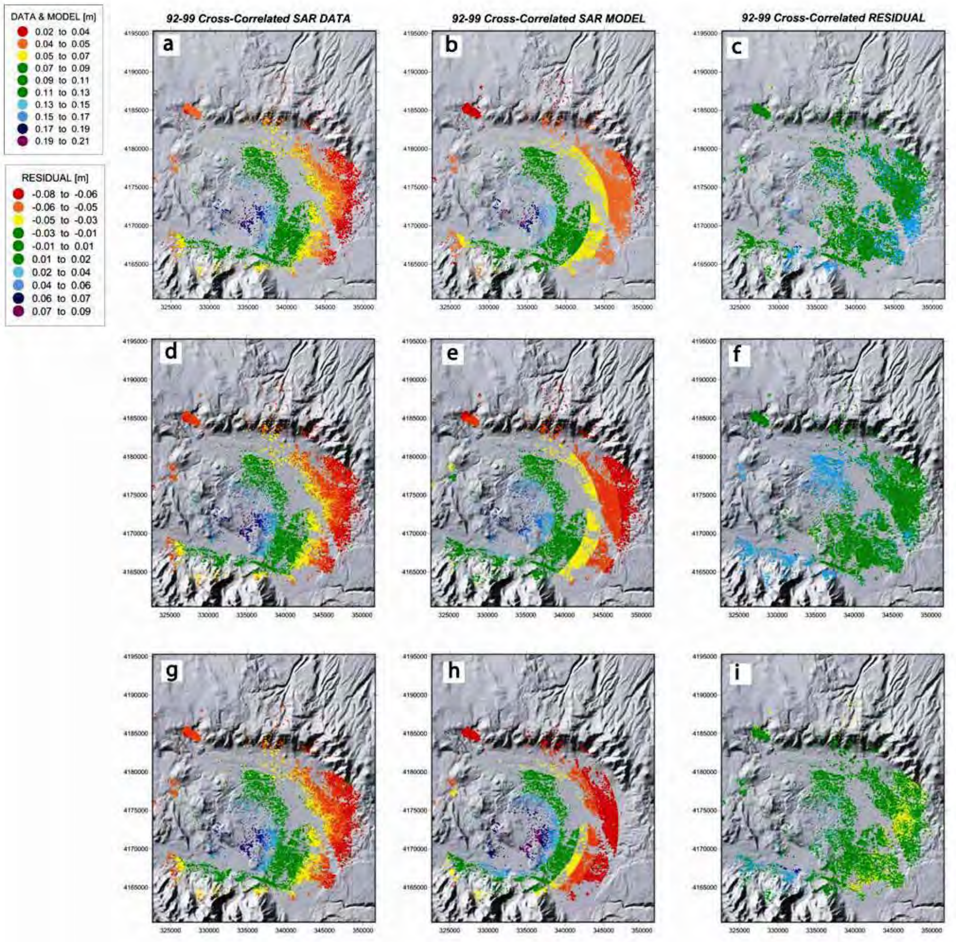

Figure 5. (a-c) Analytical solution of deformation field at LVC by fitting a spheroidal source in an elastic homogeneous half space with zero topography (Tizzani et al., 2009). (a) 1992–1999 synthetic aperture radar Interferometry (DInSAR) data, (b) model, and (c) residual. (d-f) Numerical modeling of deformation at LVC by fitting a spheroidal source in an elastic homogeneous media including DEM information. (g-h) Numerical modeling of deformation at Long Valley caldera in a case of spheroidal source included in a heterogeneous media with DEM information.

5. Conclusions

We presented an implementation of COMSOL models within Genetic Algorithm optimization procedures in order to interpret the ground deformation in active volcanic areas. We performed an application of this approach to analyze the unrest phenomenon characterizing the evolution of the deformation pattern at LVC. This analysis demonstrates the capability of FE model to simulate the 3D deformation pattern by using complex three-dimensional models, which take into account of the topographic relief of the area as well as the vertical and lateral variability of the material heterogeneities.

This approach is particularly suitable for a more accurate representation of physical processes occurring inner caldera region, as well as an appropriate interpretation of the measured deformation signals.

6. References

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