Effects of topography on the interpretation of the deformation field of prominent volcanoes-Application to Etna

Valérie Cayol, François Henri Cornet

GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.11, PAGES 1979-1982, JUNE 1, 1998

Effects of topography on the interpretation of the deformation field of prominent volcanoes - Application to Etna

Valérie Cayol [1] and François H. Cornet

Institut de Physique du Globe de Paris, France

Abstract. We have investigated the effects of topography on the surface-deformation field of volcanoes. Our study provides limits to the use of classical half-space models. Considering axisymmetrical volcanoes, we show that interpreting ground-surface displacements with half-space models can lead to erroneous estimations of the shape of the deformation source. When the average slope of the flanks of a volcano exceeds 20°, tilting in the summit area is reversed to that expected for a flat surface. Thus, neglecting topography may lead to misinterpreting an inflation of the source as a deflation. Comparisons of Mogi's model with a three-dimensional model shows that ignoring topography may lead to an overestimate of the source-volume change by as much as 50% for a slope of 30°. This comparison also shows that the depths calculated by using Mogi's solution for prominent volcanoes should be considered as depths from the summit of the edifices. Finally, we illustrate these topographic effects by analyzing the deformation field measured by radar interferometry at Mount Etna during its 1991-1993 eruption. A three-dimensional modeling calculation shows that the flattening of the deflation field near the volcano's summit is probably a topographic effect.

Introduction

Measurements of surface deformations and displacements of volcanoes are used to understand their plumbing systems, as well as their eruptive mechanisms. Volcanoes, as agents of mountain building, are commonly associated with significant topographic relief; however, most mechanical models of volcanoes [*Mogi*, 1958; *Okada*, 1985] consider the Earth's surface as flat and use half-space solutions. This approximation can lead to erroneous interpretations of the deformation data. Making a plane-symmetric approximation, *McTigue and Stein* [1984] and *McTigue and Segall* [1988] investigated the effects of topography on surface displacements. Most subaerial volcanoes, however, are associated with more axisymmetrical geometries. In this paper, we determine the effects of topography on the deformation field created at the surface of prominent volcanoes, and we investigate the artifacts that might arise from the use of half-space models for these volcanoes. The modeling method used for our study is a three-dimensional boundary element method [*Cayol and Cornet*, 1997].

[1] Now at U.S. Geological Survey, Menlo Park, Calif.

Paper number 98GL51512.
0094-8534/98/98GL-51512$05.00

Effects of topography on surface deformations of prominent volcanoes

We consider the surface displacements created by spherical pressurized sources located beneath axisymmetrical volcanoes with average slopes of their flanks of 0°, 10°, 20° and 30° (Figure 1). The volcano models with slopes of 10° and 20° are representative of basaltic shield volcanoes, such as Mauna Loa (Hawaii, Pacific Ocean) or Piton de la Fournaise (Reunion Island, Indian Ocean), whereas the volcano models with slopes of 30° are representative of andesitic volcanoes, such as Merapi (Indonesia) or Sakurajima (Japan).

The comparison between vertical and horizontal displacements is shown in Figure 2. It appears that the steeper the volcano, the lower the central uplift. For volcanoes with an average slope of 30°, the summit of the edifice is the locus of a local minimum of vertical displacements, while maximums of vertical displacements are located at a distance $r = 3a$ from the summit.

This result has several consequences for the determination of the shape of the pressure source. If half-space solutions are used to interpret the displacements measured on volcanoes with average slopes of 10° to 20°, the deformation source might be supposed to be a circular horizontal disk [*Dieterich and Decker*, 1975], when it is actually spherical. For volcanoes with an average slope of 30°, use of a half-space solution might lead to inferring a vertically elongated ellipsoidal source instead of a spherical one.

When the average slope is larger than 20°, tilt signs are also affected by topography. Indeed, when the tiltmeter is located at a distance $r < 3a$ from the summit, the radial tilt $\partial U_z / \partial r$ is opposite in sign to what would be expected for a flat topography. Thus, neglecting topography might lead

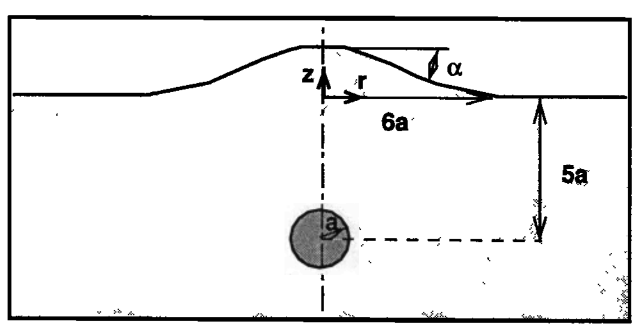

Figure 1. Characteristics of model used to determine influence of topography of volcanoes on surface displacements.

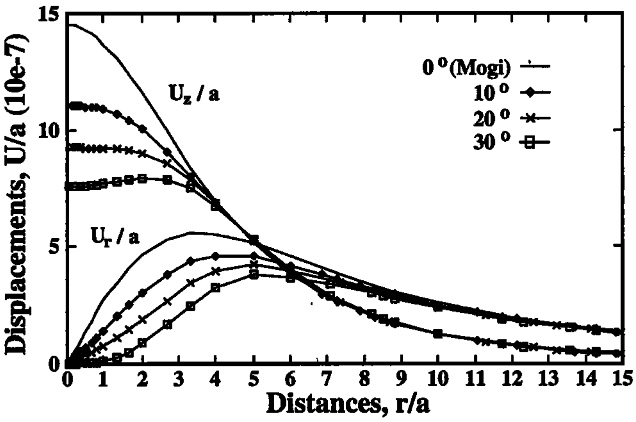

Figure 2. Surface displacements created by a spherical pressure source beneath volcanoes with average slopes of 0°, 10°, 20° and 30°. Poisson's ration is 0.21, and Young's modulus is 50 GPa. Displacements and distances are normalized by source radius.

to a misinterpretation of the volume change of the source, which might be supposed to undergo deflation when inflation is actually occurring.

It can also be noticed that topographic effects tend to diminish with increasing distance ($r > 6a$). This observation implies that half-space solutions could be used if the data are recorded sufficiently far from the volcano's summit. However, at such distances the volcano-related deformation might be indiscernible from the background noise.

These results remain valid for sources at larger or smaller depths than those considered here. Similar effects were noticed by *McTigue and Segall* [1988] for a line of inflation beneath a volcanic ridge. They attributed the central subsidence of the ridge to a horizontal extension created by the source.

Artifacts introduced by using Mogi's solution for prominent volcanoes

Using simplified volcano topographies and spherical sources of pressure, one can show that the depth and the volume variation of the source can be determined independently, similar to Mogi's model [*Cayol*, 1996]. We use this property to determine the characteristics of the source. Three steps are followed (Figure 3). In a forward problem, we compute the displacements created by a spherical source of pressure on the surface of a prominent volcano. Then, this displacement field is taken as an input to the inverse problem of determining the source characteristics with Mogi's solution. Finally, the initial source characteristics (depth D_0 and volume variation ΔV_0) and those determined using Mogi's solution (depth D and volume variation ΔV) are compared. Figure 3 describes the model characteristics used in this study.

For volcanoes with an average slope of 20°, we find (Figure 4) that Mogi's solution gives the right depth if we consider this depth as a depth from the summit; however, the volume variation of the source is overestimated by 15% to 20%. The minimum overestimation corresponds to the case where data are recorded close to the summit ($r < 2a$), and the maximum overestimation to the case where data are recorded farther on the flanks ($2a < r < 6a$). Similarly, for volcanoes with slopes of 10° and 30°, the source depth given by Mogi's solution should be considered as a depth from the volcano's summit. Table 1 shows that the steeper the volcano, the larger the volume overestimation resulting from the use of Mogi's solution. For volcanoes with a 10° slope, considering the precision of deformation data, topographic effects can be neglected, and Mogi's solution can be used; however, for volcanoes with a 30° slope, neglecting topography may lead to overestimating the source-volume variation by as much as 50%. These results remain valid for sources at depths as shallow as $2a$ below the volcano's base or for deeper sources.

Example: interferometric data from Mount Etna

Massonnet et al. [1995] used radar interferometry to calculate the deflation of Mount Etna related to its 1991-1993 eruption. The interferogram shown in Figure 5(a) records the displacements that occurred between October 1992 and October 1993 on a 45- by 45-km area of the volcano. Considering that every fringe represents 28 mm of displacement along the line-of-sight between the satellite and the ground site, a maximum deflation of 112 to 140 mm is estimated.

Using Mogi's solution, *Massonnet et al.* [1995] determined that this displacement field was created by a source located at a depth of 16 ± 3 km, with a volume variation of $(130 \pm 10) \times 10^6$ m^3 (Figure 5(b)). However, with a half-space solution, the reference altitude of the source depth is unknown, leading to an uncertainty as large as the volcano height. It can also be noticed that Mogi's solution only roughly accounts for the displacement pattern. In particular, the flattening of the displacement field in the summit area (larger fringe spacing toward the summit), the similarity of the fringe pattern to the topographic relief, and the opening of the fringes to the west are not explained. Because Mount Etna has an average slope of 15°, we postulate that some characteristics of this fringe pattern are attributable to the topography. We have constructed a model of the volcano in which the ground relief is realistic and the source is spherical. The mesh of the ground surface was generated from a digital elevation model of the volcano and, to avoid edge effects, the surface of this mesh is 8 times larger than that of the interferogram. A Poisson's ratio of 0.21 was used, but a Poisson's ratio of 0.25 would change the results by only 2% [*Mogi*, 1958]. Young's modulus can take any value because we seek the determination of volume variations from

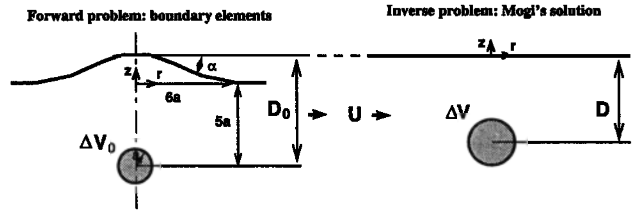

Figure 3. Method used to estimate effects of topography when interpreting surface displacements of volcanoes with Mogi's solution. Source depths, D_0 and D, are depths measured from volcano summit.

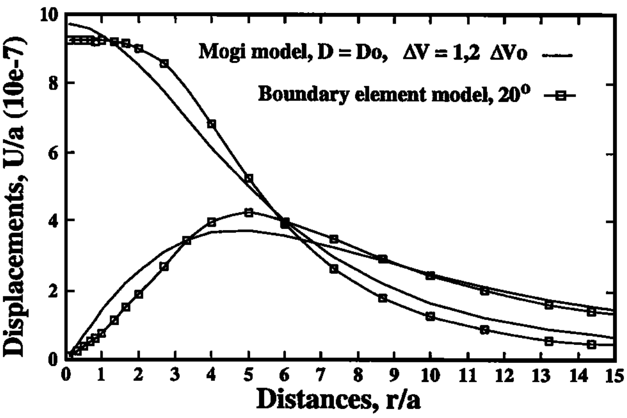

Figure 4. Effect of an average slope of 20° when interpreting surface displacements with Mogi's solution. Displacements and distances are normalized by source radius.

surface displacements. Interferometric data were inverted for the source characteristics by trial and error. The best agreement (Figure 5(c)) was found for a source located at a depth of 16 ± 1 km below the summit and with a volume variation of $(128 \pm 7) \times 10^6$ m^3.

The depth determined is the same as, and the volume change slightly smaller than those calculated from Mogi's solution. This result confirms those found previously for simplified volcano topographies: when using Mogi's solution, the depths determined correspond to depths below the summit of edifices, and volume variations are overestimated. For Mount Etna, the volume overestimation is small (8%) because the area over which displacements are computed is large enough to enclose the volcano and the surrounding flatter surface where topographic relief is negligible. This three-dimensional modeling also permitted us to decrease the uncertainties in estimating the source depth and the volume variation, respectively, by 66% and 30%. Most strikingly, however, the interferogram calculated with a realistic three-dimensional model shows a flattening of the deflation field toward the volcano's summit. This flattening, which we also noticed previously (Figure 2), is a topographic effect. Nonetheless, our model fails to account for all details of the fringe pattern. The similarity of the fringes to the topography is attributable to time varying properties of the atmosphere, homogeneous over the interferogram area (D. Massonnet personal communication, 1997). The opening of the fringes to the west also remains unexplained. This feature might be related to winds creating atmospheric perturbations around the volcano, or might be explained by a different source shape or inhomogeneous mechanical properties of the volcano, such that the rigidity is less to the west than to the east of the volcano.

Table 1. Bias in source volume variations induced by the use of Mogi's solution for analyzing the displacement fields of volcanoes.

Average slope	10°	20°	30°
Overestimation of ΔV	10%	15-20%	35-50%

Conclusion

This study has shown some errors that might be introduced into the interpretation of volcano deformations when their topography is neglected. For spherical sources beneath axisymmetrical volcanoes, the steeper the volcano, the flatter the vertical-displacement field, leading to possible misinterpretations of source geometry. For slopes larger that 20°, the tilting in the summit area is reversed, leading to possible erroneous estimation of magma movements. Using Mogi's solution to interpret the displacement data of prominent volcanoes, the depths determined should be considered as depths from the summit, and corrective factors should be applied to account for the volume overestimation in this model.

Acknowledgments. We thank P. Briole for suggesting the study of topographic effects on Mount Etna. We thank A. Gudmundsson, D. Massonnet, P. Segall, and D.D. Pollard for their comments and discussions, and W. Thatcher and J.C. Savage for reviewing this manuscript. This research was founded in part by the 4th European Community program for natural hazards reduction (Pre-erupt project contract ENV4-CT96-0259).

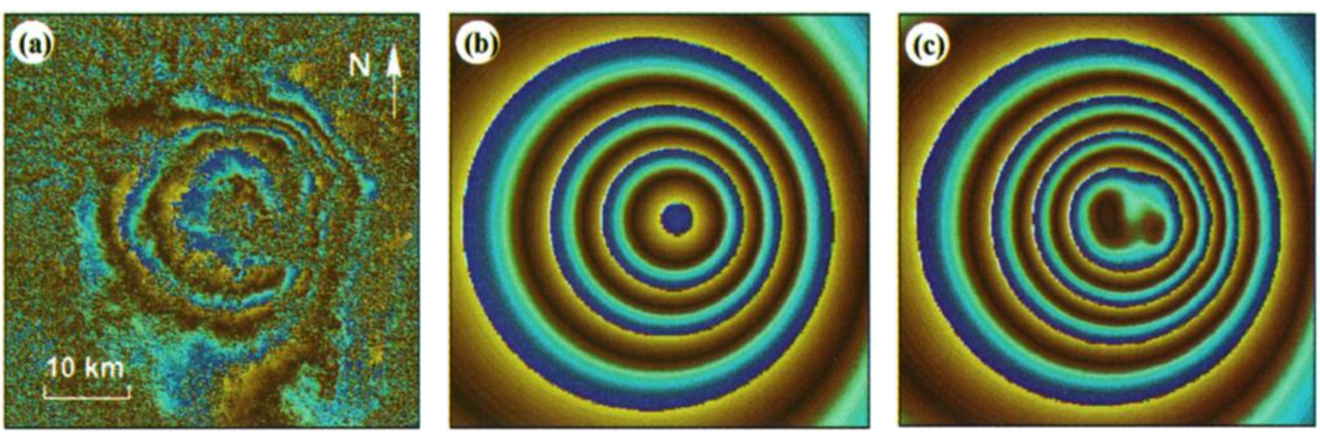

Figure 5. Actual and modeled interferograms for 1991-1993 eruption of Mount Etna. One fringe goes from blue to yellow and represents 28 mm of displacement. (a) Actual interferogram calculated by *Massonnet et al.* [1995]. (b) Best-fit interferogram calculated by *Massonnet et al.* [1995] using Mogi's solution. (c) Best-fit interferogram found by using a fully three-dimensional model.

References

Cayol, V., Analyse élastostatique tridimensionnelle du champ de déformations des édifices volcaniques par éléments frontières mixtes, *Thèse de doctorat de l'Université de Paris VII,* 1996.

Cayol, V., and F. H. Cornet, 3D mixed boundary elements for elastostatic deformation field analysis, *Int. J. Rock Mech. Min. Sci.*, *34*, 275-287, 1997.

Dieterich, J. H., and R. W. Decker, Finite element modeling of surface deformation associated with volcanism, *J. Geophys. Res.*, *80*, 4094-4102, 1975.

Massonnet, D., P. Briole and A. Arnaud, Deflation of Mount Etna monitored by spaceborne radar interferometry, *Nature*, *375*, 567-570, 1995.

McTigue, D. F., and P. Segall, Displacements and tilts from dip-slip faults and magma chambers beneath irregular surface topography, *Geophys. Res. Lett.*, *15*, 601-604, 1988.

McTigue, D. F., and R. S. Stein, Topographic amplification of tectonic displacement: implications for geodetic measurement of strain changes., *J. Geophys. Res.*, *89*, 1123-1131, 1984.

Mogi, K., Relations between the eruptions of various volcanoes and the deformation of the ground surfaces around them. *Bull. Earthquake Res. Inst., Univ. Tokyo*, *36*, 99-134, 1958.

Okada, Y., Surface deformation due to shear and tensile faults in a half-space, *Bull. Seismol. Soc. Am.*, *75*, 1135-1154, 1985.

V. Cayol, U.S. Geological Survey, 345 Middlefield Road, MS 977, Menlo Park, CA 94025. (e-mail: cayol@swave.wr.usgs.gov)

F. H. Cornet, Laboratoire de mécanique des roches, Département de sismologie URA CNRS 195, IPGP, 4 place Jussieu, Boite 89, 75252 Paris Cedex 05, France. (e-mail: cornet@ipgp.jussieu.fr)

(Received September 23, 1997; revised December 12, 1997; accepted December 30, 1997.)