Surface loading effects complicate the derivation of internal pressure source characteristics from volcano deformation signals

R. Grapenthin[1*], F. Sigmundsson[2], R. Pedersen[2] and V. Pinel[3]

[1] Humboldt-University Berlin, Germany (now at Geophysical Institute, Univ. Alaska, Fairbanks, USA)
[2] Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland
[3] IRD, UMR5559, Laboratoire de Geophysique Interne et Tectonophysique, Chambery, France
*contact: ronni@gi.alaska.edu

AGU – V53C-1421

AGU – V53C-1421

Abstract

Modeling a circular lava flow on top of a deflating magma chamber shows that the crust will adjust to the load towards final relaxed response. During this process gradual subsidence may mistakenly be interpreted as due to pressure decrease in the magma chamber only; both processes show a very similar deformation pattern. This poses a problem when characteristics of a magma chamber are to be derived.
In this study the Mogi model and Green's functions are used to compare the crustal response to a deflating hypothetical magma chamber to the deformation pattern emerging due to the final relaxed response to lava flows at the surface. We find that ongoing adjustment to surface loads can be misinterpreted as subsidence due to a deflating magma chamber. To avoid misleading interpretations, we suggest that both the horizontal and vertical displacements should be examined carefully.

1. Introduction

An increasing number of crustal deformation studies relate volcano deformation to internal pressure sources (e.g., magma chambers). Surface loads such as lava flows do, however, provide an additional source of deformation. The initial elastic response due to a load on the surface of the Earth is followed by a visco-elastic response of the ductile crust below the uppermost elastic layer (see Fig. 1c,d). Hence, a deformation a deformation signal recorded in the vicinity of a volcano is likely to be due to a combination of an internal pressure source and a surface load (a composition of previously erupted lava flows - at the extreme the volcano edifice itself).

2. Model Configurations

To model the final relaxed response to a surface load we use the framework CrusDe [Grapenthin, 2007] which implements Green's functions that approximate a flat Earth as thick elastic plate over an inviscid fluid as derived by Pinel *et al.* [2007]. We assume 5 km as elastic thickness of the lithosphere, a Young's modulus of 40 GPa [Grapenthin *et al.*, 2006], a Poisson's ratio of 0.25, and a density of 3100 $kg\,m^{-3}$ for the fluid, i.e. upper mantle. The load is an approximation of the Hekla 2000 lava in Iceland (Fig. 1a,b).

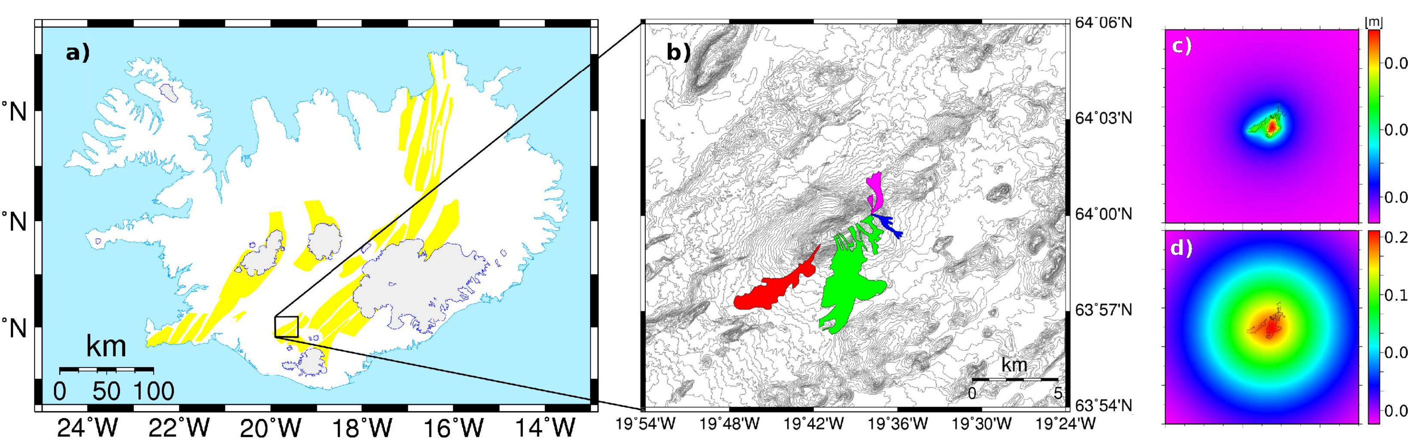

FIG. 1: **a)** A map of Iceland (volcanic zones in yellow. The rectangle marks the model area. **b)** Blow up of the model area showing the topography around Mt. Hekla and the approximate Hekla 2000 lava flows, **mean thickness: pink - 3 m, blue - 3 m, green - 12 m, red - 10 m**. **c)** Instantaneous vertical displacement and d) final relaxed vertical displacement due to the lava.

The deformation due to surface load has an exponential evolution with relaxation time related to viscosity. The transition from instantaneous (Fig. 1c) to relaxed response (Fig. 1d) takes on the order of tens to hundreds of years [Pinel et al., 2007]. The final relaxed response is close to being axisymmetric (Fig. 1d) and equivalent to that of a disk load. Hence, we approximate the lava flows (Fig. 1b) as a disk with height 9.82 m, radius 2.5 km, and density 2900 $kg\,m^{-3}$.

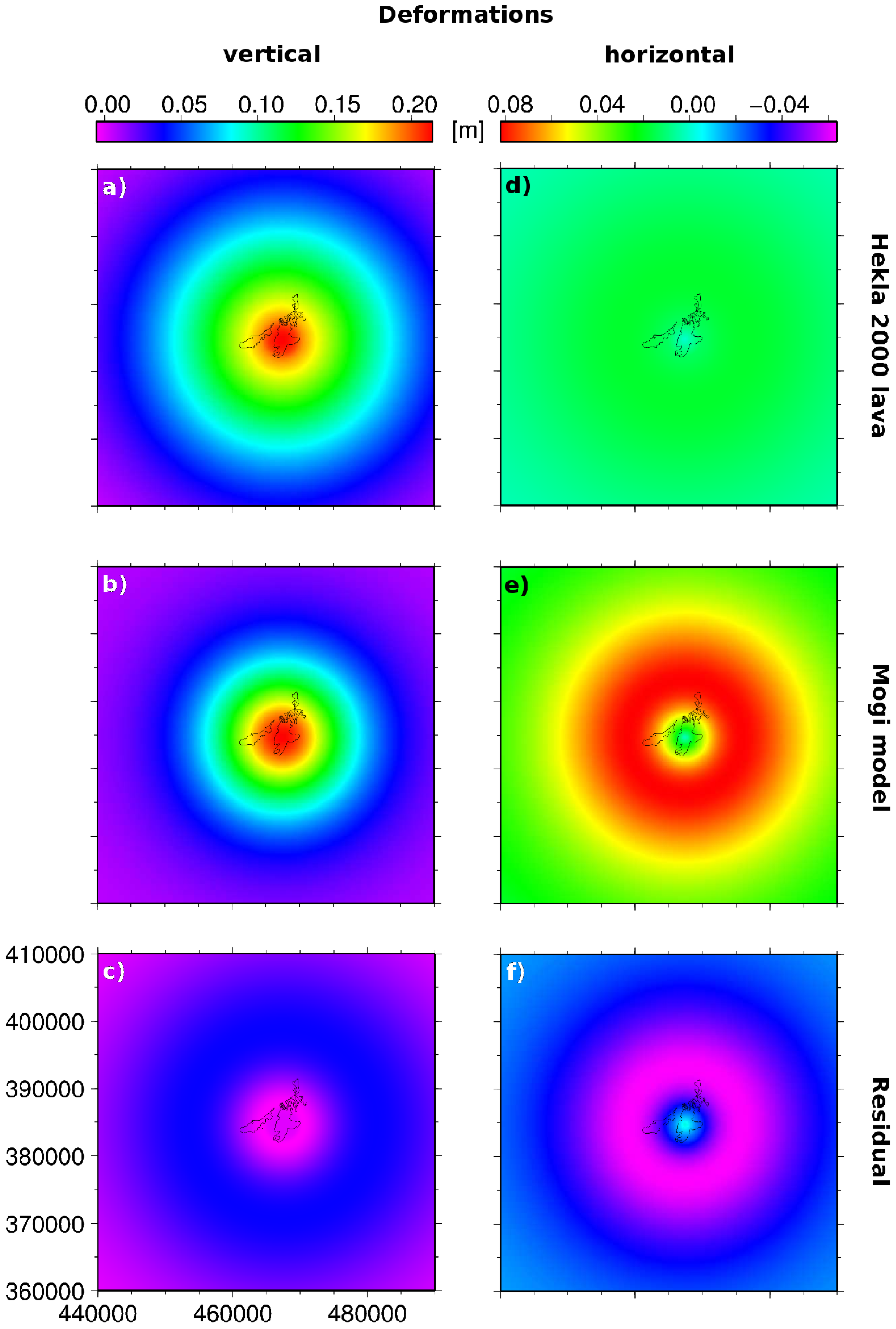

FIG. 2: Model results showing vertical and horizontal displacements due to the Hekla 2000 lava (disk, final relaxed response). Tickmarks in **c** are Lambert coordinates and describe the extend of the modeled area in meters. (**a,d**) and the Mogi model (**b,e**). The residuals (**c,f**) are calculated by subtracting the results of the Mogi model from the final relaxed response due to the Hekla lava. Note that the scale is similar in a column but not in a row.

To confine surface changes due to variations of a point source of pressure, we apply the Mogi model. Using the volume of the lava flow as volume of surface change, ΔV_e, we can calculate the source depth, d, underneath the point of maximum vertical displacement, h_0: $d = (\Delta V_e/(2\pi h_0))^{\frac{1}{2}}$ From this we can calculate the source strength: $C = h_0 d^2$ [Sigmundsson, 2006] and have all parameters of the Mogi model fixed.

3. Comparison of respones to different deformation sources

Figure 2 shows the simulated horizontal and vertical deformations for both the final relaxed response to the disk load and the Mogi model with a calculated source depth $d = 12\,km$ and a source strength $C = 0.031\,km^3$. The vertical displacement pattern and magnitude of the Mogi model are quite close to the final relaxed response (Fig. 2a,b) which is shown in the residual in Figure 2c. However, at about 12.5 km distance from the maximum vertical displacement ($h_0 = 0.21$ m), the difference between the Mogi model and the final relaxed response is 3.75 cm (a difference of 18%). Figure 3a displays a section from the center to the edge of Figure 2 and underlines these findings. For the horizontal displacement the difference is even more obvious as shown by Figure 2d,e,f. The Mogi model is always larger than the final relaxed response and the maximum difference is -6 cm at about 7.6 km from the center (Fig. 3c).

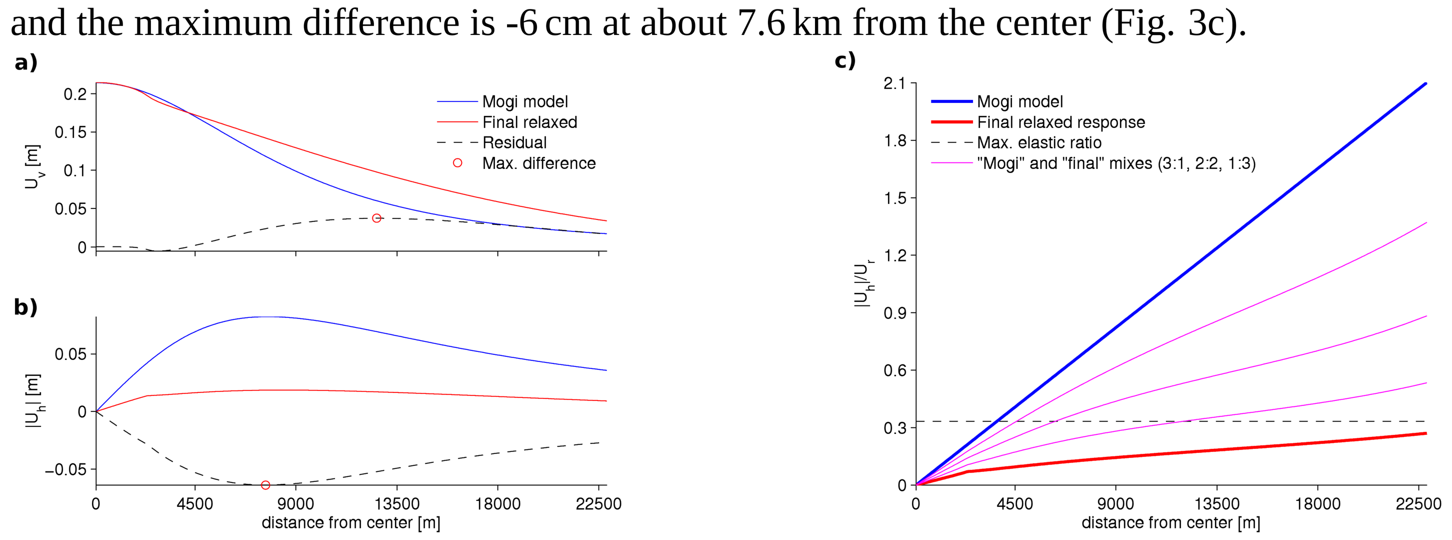

FIG. 3: Sections from center to edges of the plots in Fig. 2. **a)** Vertical displacement (U_r) coresponds to Fig. 2a (red), 2b (blue), 2c (black). **b)** Horizontal displacement ($|U_h|$), coresponds to Fig. 2d (red), 2e (blue), 2f (black). Red circle marks max. difference. **c)** Comparison of models in term of the ratio $|U_h|/U_r$. Pink lines are 'mixes' of the models. Black dashed line denotes the maximum elastic ratio due to a surface load.

Figure 3c directly compares the final relaxed response and the Mogi model using the ratio of horizontal and vertical displacement as suggested by Pinel *et al.* [2007] which clearly marks the different character in displacment depending on the source.

4. Discussion and Conclusions

The hypothetical source depth of $d = 12$ km is not supported by results of seismic studies at Hekla which would hint at a mixed deformation signal that would lead to a deeper source (Soosaloo *et al.* [2004] find no source between 4-14 km). Hence, our results show the significance of including surface loads (elastic and visco-elastic responses) in source studies. To identify whether elastic chamber pressure response or visco-elastic deformation due to surface loads is recorded in the data, we suggest carefully examining the horizontal displacement in addition to vertical displacement (i.e. the ratio with distance from the vent). A transition from instantaneous to relaxed response will clearly be distinguishable from the Mogi response (see Fig. 3c). We suggest that additional factors posed by the surface load must be considered and constrained by careful measurements and interpretations of observations and eruptions histories to correct the recorded data for composed signal sources.

REFERENCES: **Grapenthin, R.**, (2007), CrusDe: A plug-in based simulation framework for composable CRUStal DEformation simulation using Green's functions, *Diploma thesis*, Humboldt-University Berlin, Germany. **Grapenthin, R.**, F. Sigmundsson, H. Geirsson, T. Árnadóttir, and V. Pinel (2006), Icelandic rhythmics: Annual modulation of land elevation and plate spreading by snow load, *Geophys. Res. Lett.*, 33, L24,305, doi:10.1029/2006GL028081. **Pinel, V.**, F. Sigmundsson, E. Sturkell, H. Geirsson, P. Einarsson, M. T. Gudmundsson, and T. Högnadottir (2007), Discriminating volcano deformation due to magma movements and variable surface loads: Application to Katla subglacial volcano, Iceland, *Geophys. J. Int.*, 169(1), 325–338. **Sigmundsson, F.** (2006), Icelandic geodynamics, Crustal Deformation and Divergent Plate Tectonics, 228 pp., Springer-Praxis, Chichester, UK.