Rheological and topographical controls on deformation due to a shallow magma reservoir

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Introduction: Most surface deformation models of volcanoes approximate the volume as a linearly elastic, homogeneous half-space, with point sources of pressure. The point source estimation breaks down when the reservoir is shallow, and the presence of heterogeneous materials and high temperatures in volcanic regions affects the rheological behaviour of the medium surrounding the magmatic source.

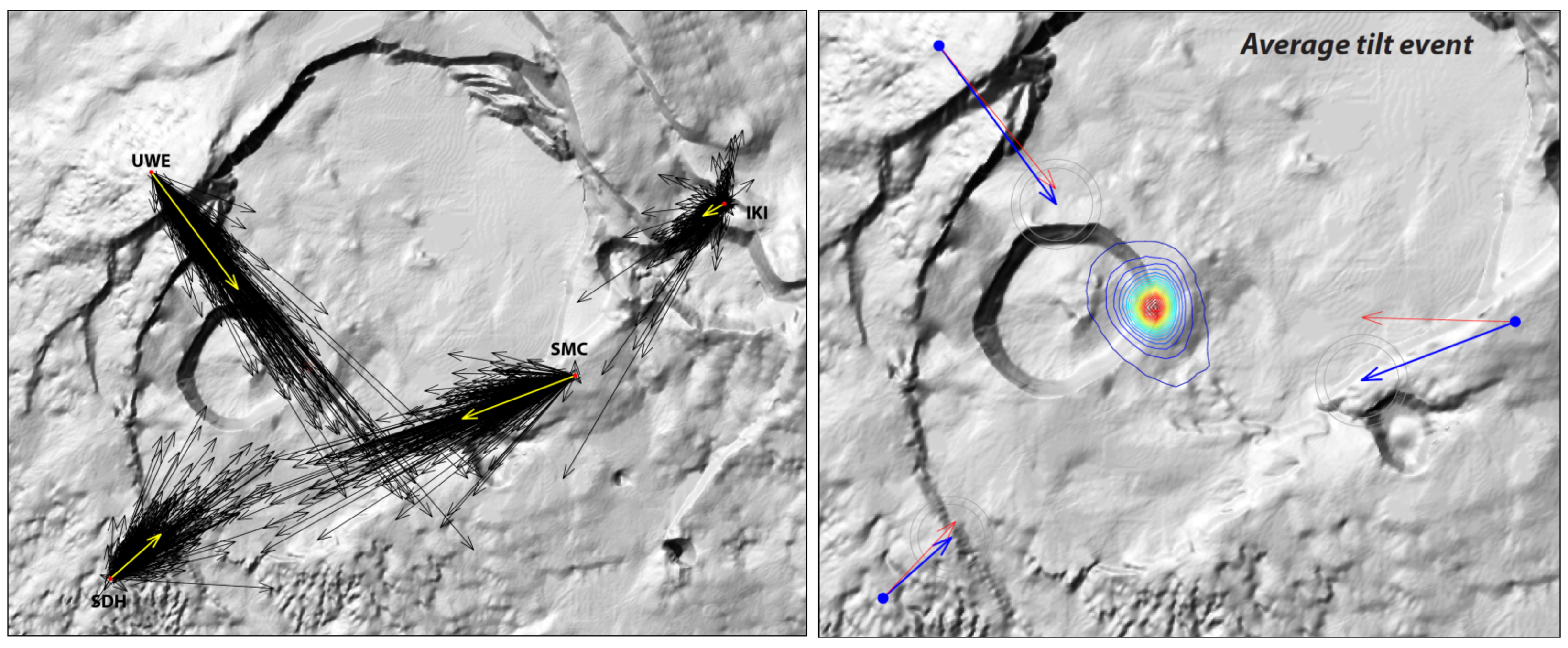

***Figure 1**. Deformation at Kilauea Volcano. Left: Tilt vectors of DI events in black, average vector in yellow. Right: Average tilt vector in blue, calculated tilt vector from best fit model using traditional analytical methods in red. Contours display best fit model.*

At Kilauea Volcano in Hawaii, repeated ground deformation is measured using ground and space based geophysical methods. The repeating deformation is thought to be caused by cycles of pressurisation in a shallow (~1 km depth), well-established magma reservoir. However, the extreme topography of the caldera, the thermal effect of the reservoir, and the proximity of the reservoir to the surface mean that traditional models may not be appropriate (Figure 1, after (1)).

Computational Methods: To assess the control of varying rheology and topography on surface deformation due to a shallow magma reservoir, a 3D finite element model was constructed using COMSOL Multiphysics®. The model geometry includes topography from high-resolution digital elevation models with anchored features for areas needing a finer mesh (Figure 2). All boundaries (other than the surface) were fixed and thin infinite element domains were used at the edges.

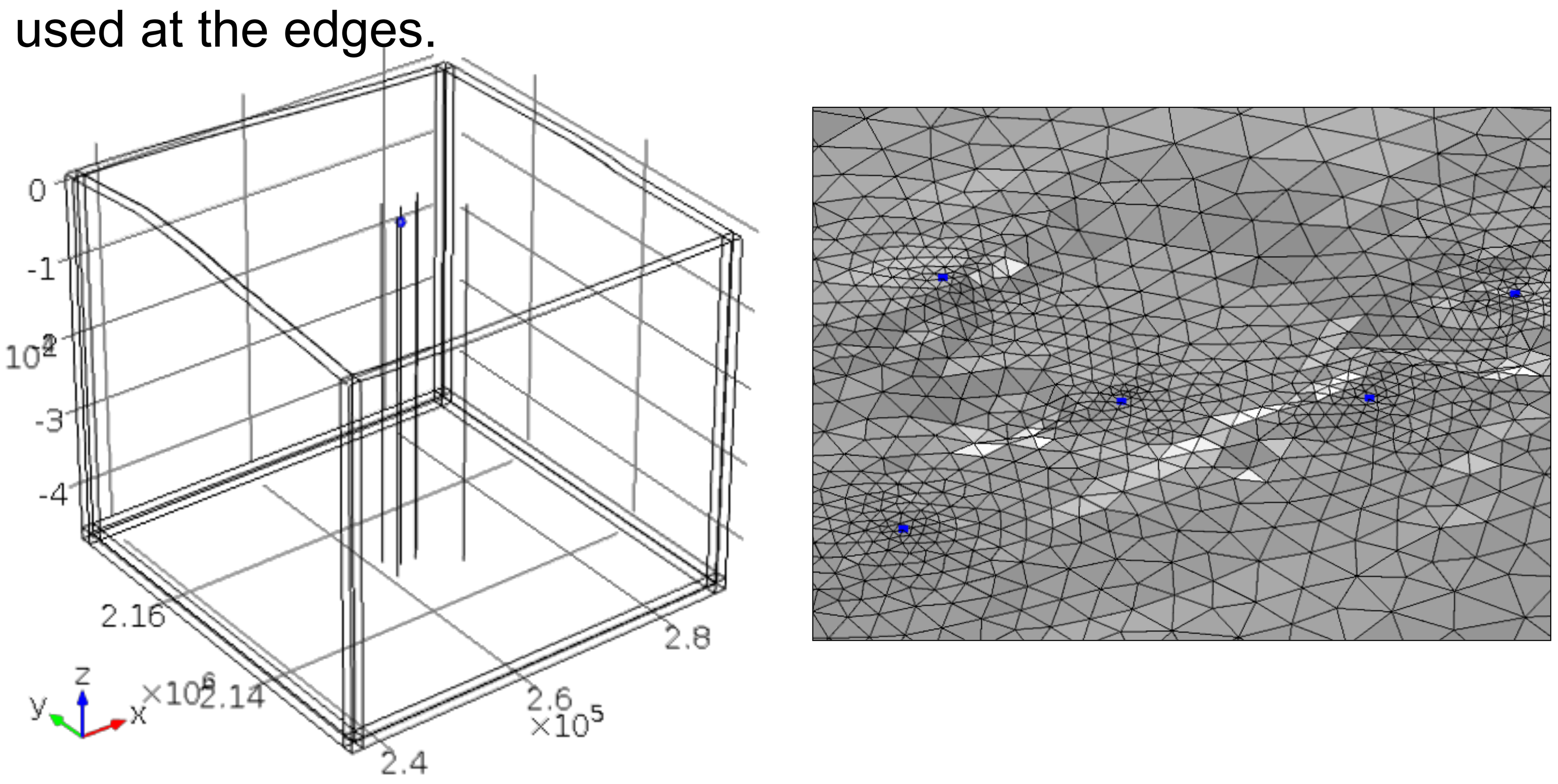

***Figure 2**. Model geometry. Left: Frame of geometry showing sphere surfaces with applied load (purple) and infinite element edges. Right: mesh around Kilauea Caldera showing anchored points (blue).*

Solutions of surface deformation (tilt) and stress distribution due to a pressurised sphere were calculated for different rheologies including homogeneous and heterogeneous elastic, heterogeneous visco-elastic and temperature dependent visco-elastic media. The effect of the depth of the reservoir was also tested in each case.

Variable	Value	Units
Young's Modulus, E	70e^9	Pa
Density, ρ	8700	kg/m^3
Shear Modulus, G	4x10^9	Pa
Bulk Modulus, K	14e^9	Pa
Poisson's Ratio, ν	0.25	

***Table 1**. Material Properties from (2) and (3)*

Results: Results using a homogeneous elastic medium show that sharp topography can deflect the deformation field (Figure 3) and hence produce misleading tilt vectors. This effect is less pronounced with deeper pressure sources.

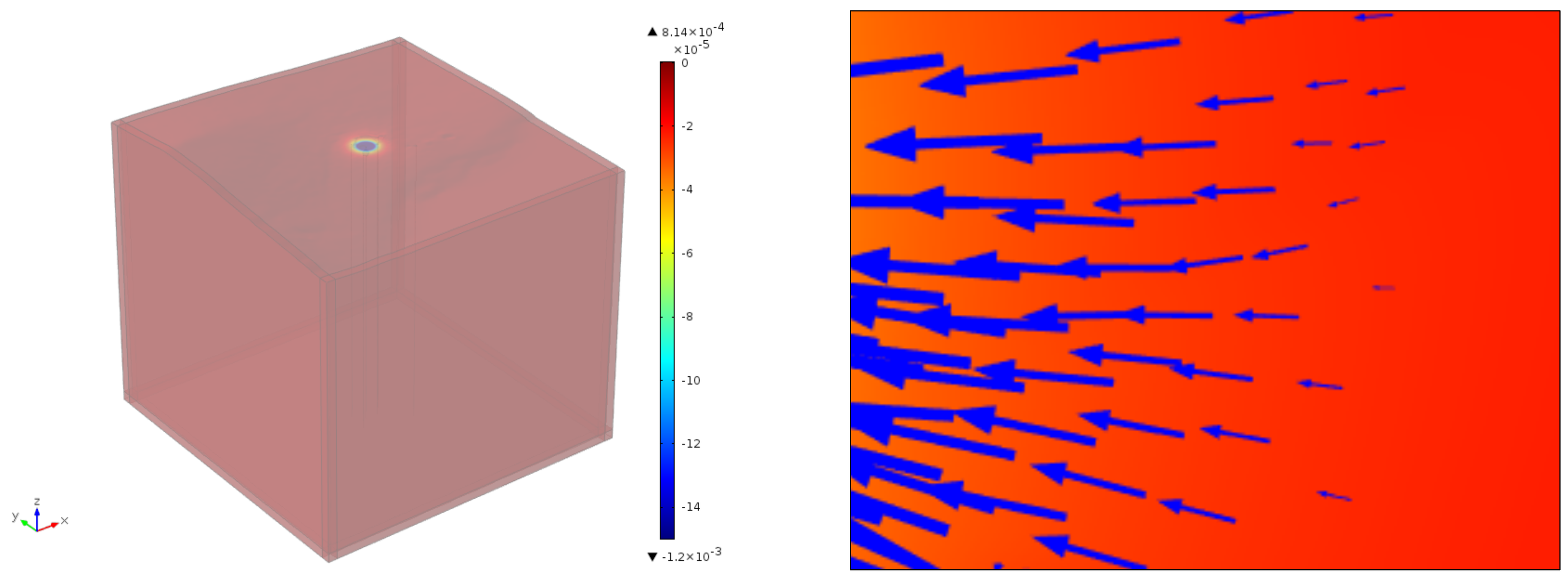

***Figure 3**. Deformation in an elastic medium. Left: Vertical displacement. Right: Tilt vectors show deflection around topography.*

The surface deformation is also affected by varying the rheology of the material inside the caldera. Figure 5 shows that the tilt azimuth changes with variation in Young's modulus. This effect can be seen at all of the tiltmeters, but is most dramatic at SMC.

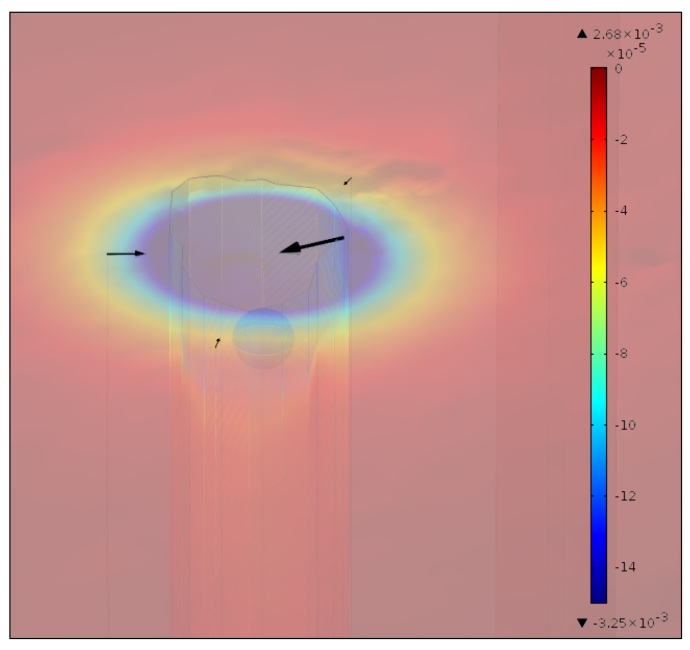

***Figure 4**. Tilt at tiltmeter locations and vertical displacement from negative pressure (deflation) of a sphere embedded in the caldera*

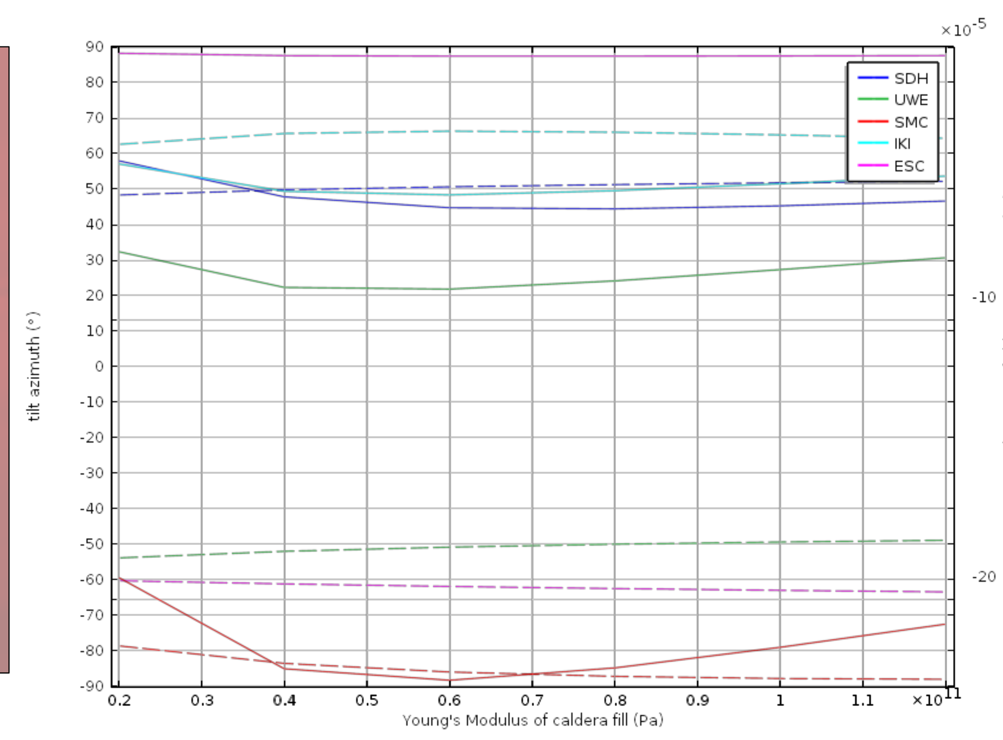

***Figure 5**. Plot of tilt azimuth (dashed) and vertical displacement (solid) at five tiltmeter sites with changing Young's modulus, E.*

Conclusions: The use of high-resolution topography in the finite element model has demonstrated that deformation from a shallow pressure source can be dramatically affected by overlying relief, not only in magnitude, but also in azimuth. This result is significant as it allows traditionally anomalous data to be evenly weighted during inversions for magma reservoir parameters.

The result that surface deformation may be either enhanced or subdued by varying the rheology of the medium in the model has profound consequences for the estimation of the depth and pressurisation of a magma reservoir from field data. It means that the rheological properties must be well known for the estimations of depth and pressurisation to be meaningful.

References:

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Excerpt from the Proceedings of the 2014 COMSOL Conference in Cambridge