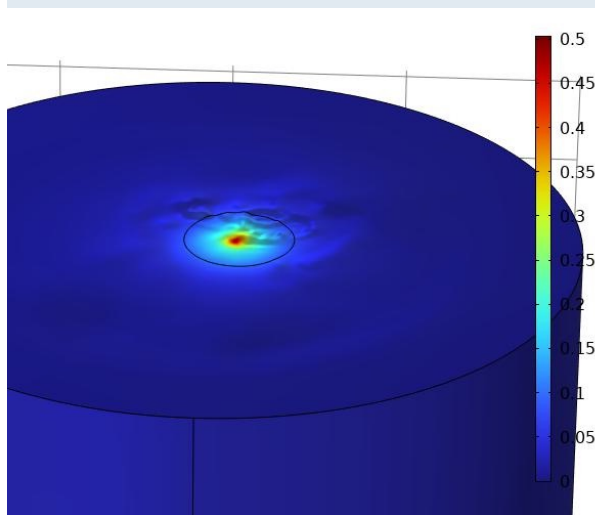




Geomechanical Workflow in COMSOL Multiphysics® to Evaluate Hydrothermal Unrest at Campi Flegrei

Beyond pressure: how thermal expansion contributes to bradyseism at the Campi Flegrei caldera

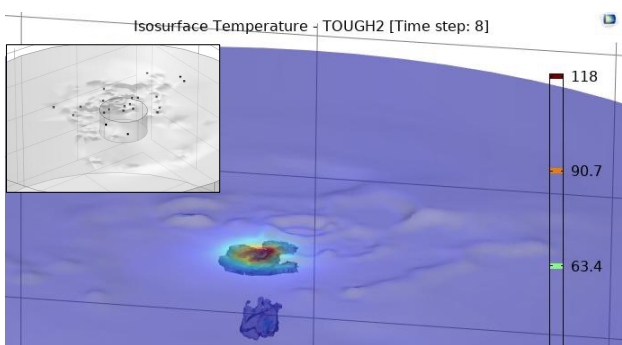
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Abstract

The ongoing unrest at the Campi Flegrei caldera (Italy), characterized by intense ground uplift and seismicity, reflects the coupled response of a mechanically heterogeneous crust to pressure and temperature perturbations associated with the magmatic-hydrothermal system. Modeling surface deformations requires coupling fluid-dynamic scenarios with the mechanical response of the volcanic structure. Here we present an advanced 3D finite element model developed in COMSOL Multiphysics® to evaluate the geomechanical response of the caldera to spatio-temporal variations in subsurface pressure and temperature.

The 3D finite element model spans a 20 km radius domain down to 20 km depth, integrates high-resolution topography and heterogeneous elastic properties from seismic tomography, and employs a two-step computational strategy—first computing in-situ stress, then importing 4D pressure-temperature anomalies from TOUGH2 via one-way coupling. The resulting thermo-poroelastic displacements are compared with GNSS observations. The framework is now being extended toward dynamic data assimilation and parameter calibration.



Modeled temperature-anomaly isosurfaces at the final simulation time step, showing the three-dimensional extent of the thermally perturbed region beneath Campi Flegrei. The inset shows the DEM-resolved surface and the locations of the virtual GNSS sites.

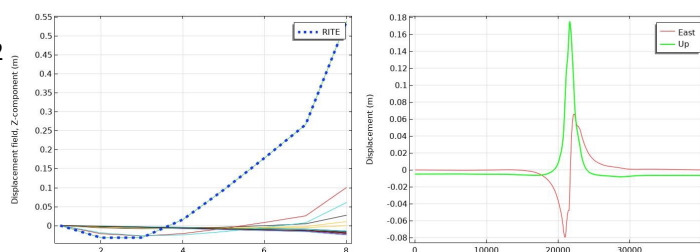
Methodology

We developed a 3D FEM in COMSOL with heterogeneous elastic properties from seismic tomography, a high-resolution DEM-resolved free surface, and a two-step workflow: first computing the lithostatic in-situ stress field to establish a pre-stressed equilibrium state, then importing 4D pressure and temperature anomalies from TOUGH2 via one-way coupling to drive crustal deformation, where pore pressure reduces effective stress and thermal expansion generates volumetric strain ($\epsilon_v^{th} = 3\alpha_s \Delta T$), with surface displacements compared with GNSS observations.

Results

The modeled surface displacement captures the first-order bell-shaped pattern observed in the GNSS data. For the adopted TOUGH2 scenario, separate simulations driven by pressure and temperature changes indicate that pore pressure provides the dominant mechanical contribution, whereas direct solid thermal expansion produces a non-negligible contribution to the modeled uplift and locally modifies its spatial distribution.

Future developments will focus on refining the geometrical representation of the hydrothermal source, improving the spatial resolution of ground elastic parameters, and enhancing the fidelity of TOUGH2 outputs through better constraints on multiphase flow properties, enabling more accurate predictions and a deeper understanding of the processes governing caldera unrest.



Deformation recorded at RITE GNSS site: left, compared with Z-component recorded at each other site; right, sixth temporal step, comparing East and Up components

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