



## A digital twin for volcanic unrest at Mount Etna

Rebecca Bruni<sup>1</sup>, Erica De Paolo<sup>2</sup>, Deepak Garg<sup>1</sup>, Martina Allegra<sup>2</sup>, Flavio Cannavò<sup>2</sup>, **Chiara Paola Montagna**<sup>1</sup>, Paolo Papale<sup>1</sup>, and Michele Carpenè<sup>3</sup>

<sup>1</sup>INGV (Istituto Nazionale di Geofisica e Vulcanologia), Italy

<sup>2</sup>Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Osservatorio Etneo, Italy

<sup>3</sup>Italian Supercomputing Centre (CINECA), Italy

Surface deformation at active volcanoes is often a direct consequence of magma movements at depth. These dynamics create pressure changes within magmatic systems, altering the stress state of the surrounding rocks. The resulting deformation signals propagate to the surface, where they are captured by monitoring networks, offering a potential for valuable insights into the magmatic activity.

To improve near-real-time detection and response during volcanic unrest, we are developing a digital twin for volcanic unrest induced by dike intrusions at Mount Etna. This innovative framework integrates 3D numerical simulations with artificial intelligence (AI) to enhance early warning capabilities and crisis management.

The project involves two interconnected AI modules: the first (AI1) scans multi-parametric monitoring data to identify signs of unrest, while the second (AI2) analyzes surface deformation patterns to infer the distribution of probability for the underlying pressure forces. The AI2 model is trained on a dataset derived from an order of 10 million numerical simulations of dyke intrusions beneath Mount Etna, performed using the open-source, multi-physics finite element software GALEs on the HPC Leonardo pre-exascale machine at CINECA. These simulations account for a distribution of dyke characteristics - size, location, orientation, and dip - replicating the variability observed at Mount Etna. The 3D computational framework incorporates the latest DEM topography and heterogeneous rock properties from recent seismic tomography surveys. By solving elastostatic equations, the simulations establish input-output relationships between source parameters and deformation patterns. The trained AI2 is designed to reconstruct the probability distribution of source parameters from deformation datasets as recorded by the real GNSS stations on the volcano. The whole workflow, triggered by AI1, instructed by GALEs, analysed by AI2, and automatically fed by real data every 30 – 60 minutes, provides a near-real-time picture of dyke propagation allowing a quick and robust interpretation of ground deformation data and assisting in early warning and volcanic crisis management.

All of the software and procedures will be available open source for direct use as well as for replicating the approach at other volcanoes.