EGU GENERAL ASSEMBLY 2023
Vienna, Austria, 23-28 April 2023

Stress Inversion and Forecast of Future Vent Locations in Calderas: Combining a Monte Carlo Algorithm with a Physics-based Model of Dike Propagation.

L. Mantiloni , E. Rivalta, T. Davis, L. Passarelli, K. Anderson, V. Pinel

1] Helmholtz Zentrum Potsdam – Deutsche GeoForschungsZentrum (GFZ), Potsdam, Germany; **2]** Institute for Mathematics, University of Potsdam, Potsdam, Germany; **3]** Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
4] Department of Earth Sciences, University of Oxford, Oxford, UK; **5]** Istituto Nazionale di Geofisica e Vulcanologia INGV, Bologna, Italy; **6]** United States Geological Survey USGS, Moffett Field, CA, USA; **7]** Institut des Sciences de la Terre ISTerre, Le Bourget du Lac, France

1) INTRODUCTION

Regions of distributed volcanism: where will the next eruption occur?

Many approaches are purely statistical:

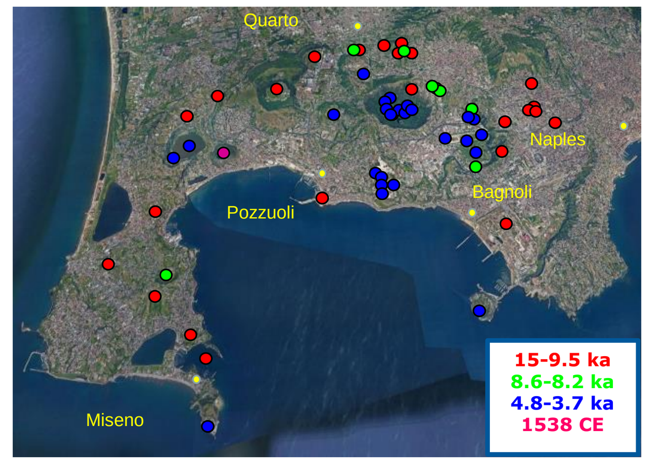
Spatial density of past vents + surface features → Probability maps

Challenges:

Limited data records.
Scarce and scattered past eruptive vents.
Vent distribution patterns changing over time.

Alternative approach?

What controls magma propagation?
Physics-based models may help …



Campi Flegrei caldera, Italy
(modified after *Google Earth, earth.google.com/web/*)

2) A NEW FORECAST STRATEGY

Rivalta et al. (2019) [1]

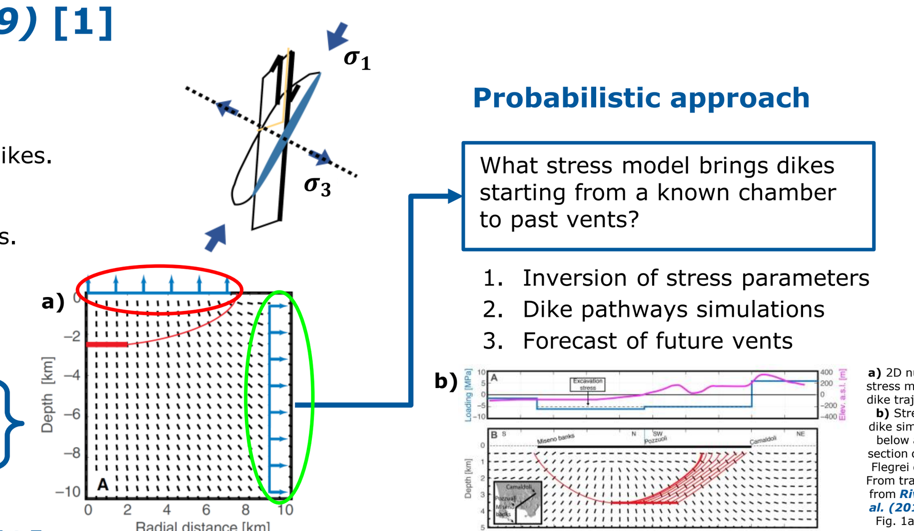
Mechanical model

- Magma propagation mechanism: dikes.
- 2D approach.
- Driving mechanism: external stress.
  - Dikes open against σ_3
  - Dikes propagate along σ_1
- Stress Sources:
  - Topographic load/unload
  - Tectonic stress

Probabilistic approach

What stress model brings dikes starting from a known chamber to past vents?

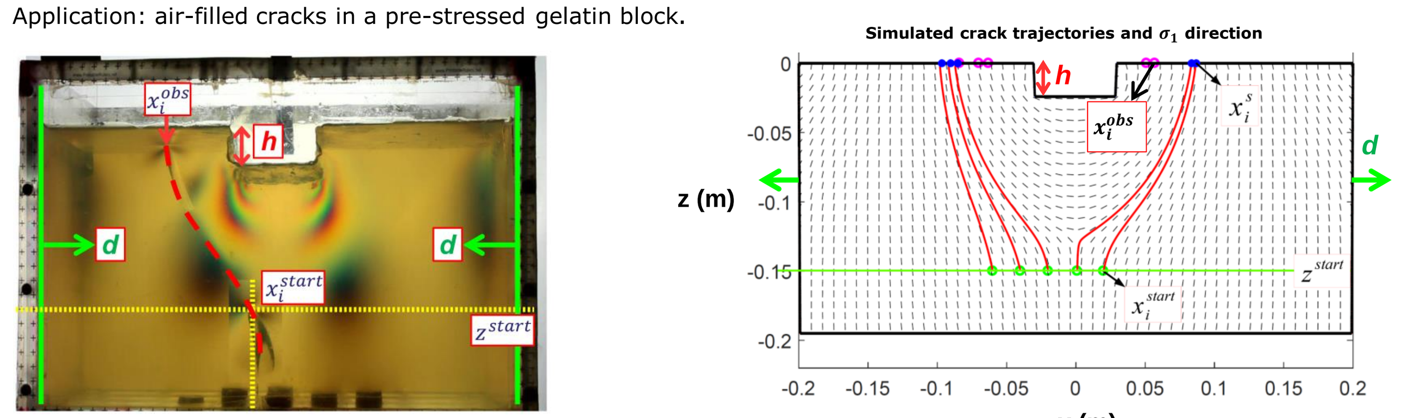
1. Inversion of stress parameters
2. Dike pathways simulations
3. Forecast of future vents



a) 2D numerical stress model and dike trajectories. b) Stress and dike simulations below a cross section of Campi Flegrei caldera. From trajectories from *Rivalta et al. (2019) [1]*, Fig. 1a and 5, respectively.

Mantiloni et al. (2021) [2]

Application: air-filled cracks in a pre-stressed gelatin block.



3) ADDRESSING THE LIMITATIONS

Let's expand the strategy to 3D

- Dike propagation model
- Stress model: realistic topographies
- 3D stress optimization method

→ We look for a model that:

- Can reproduce complex 3D pathways → Eruptive scenarios
- Depends on few parameters → Simple
- Is computationally efficient → Fast

4) NUMERICAL STRESS MODEL

Stress model

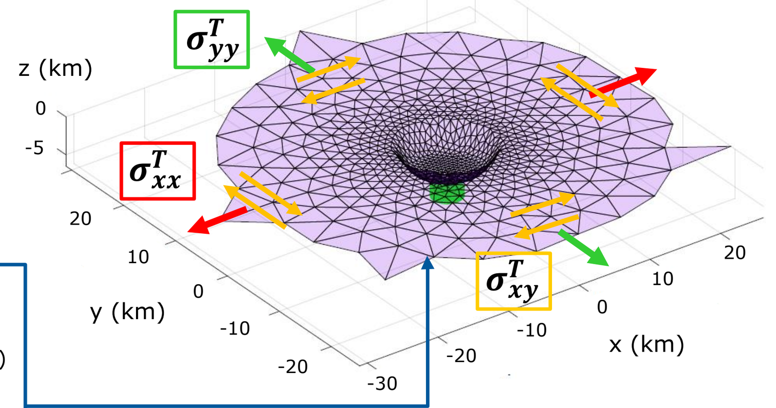
Superposition of:

- Background (lithostatic) stress
- Tectonic stress -> σ^T_{xx}, σ^T_{yy}, σ^T_{xy}
- Gravitational loading / unloading due to topography

Method by *Martel & Muller, 2000* [3]

Topography → Triangular dislocations mesh
(*Persson & Strang, 2004* [4], *Nikkhoo & Walter, 2015* [5])

Boundary Element numerical model
(**Cut&Displace**, *Davis et al., 2017* [6])



5) SAM: A NEW 3D DIKE MODEL

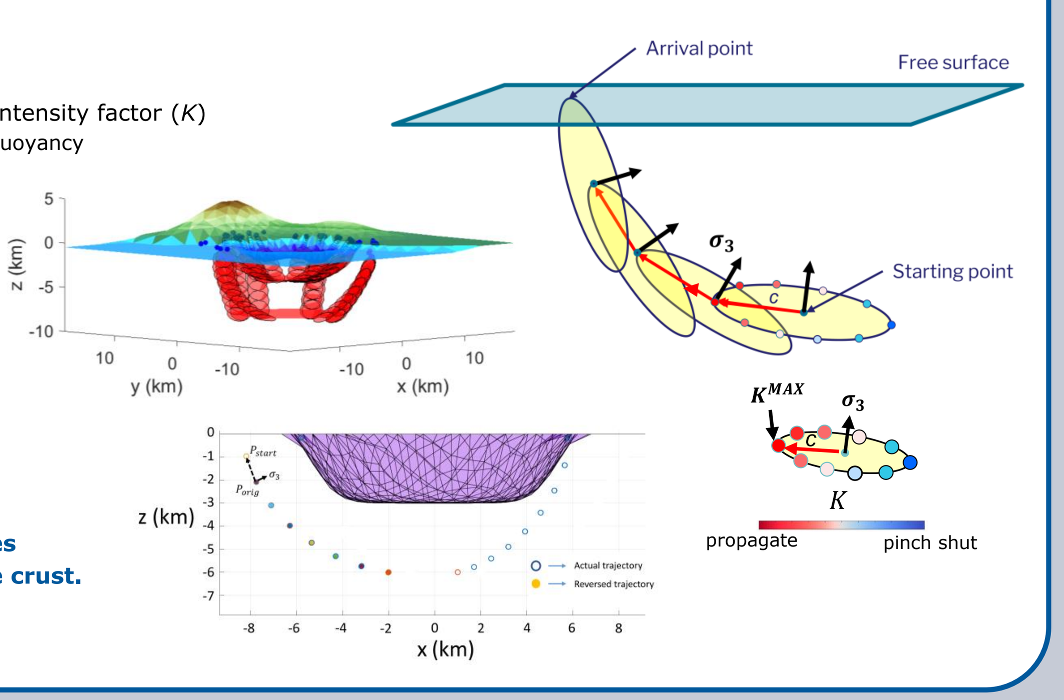
SAM: Simplified Analytical Model of 3D dike pathways (*Mantiloni et al. (2023) [7]*)

Dike: penny-shaped crack
Dike opening surface: σ_3
Direction of propagation: stress intensity factor (K)
$K \propto$ external stress gradient + dike buoyancy

It needs:
Magma density
Dike radius (c)

Limitations:
Dike volume neglected.
Fixed dike shape.

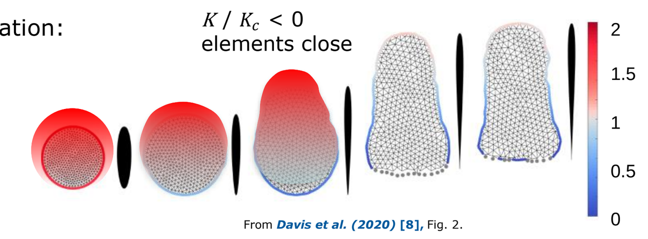
Advantages:
Fast.
Captures 3D problem.
Can backtrack dike trajectories from a vent down through the crust.



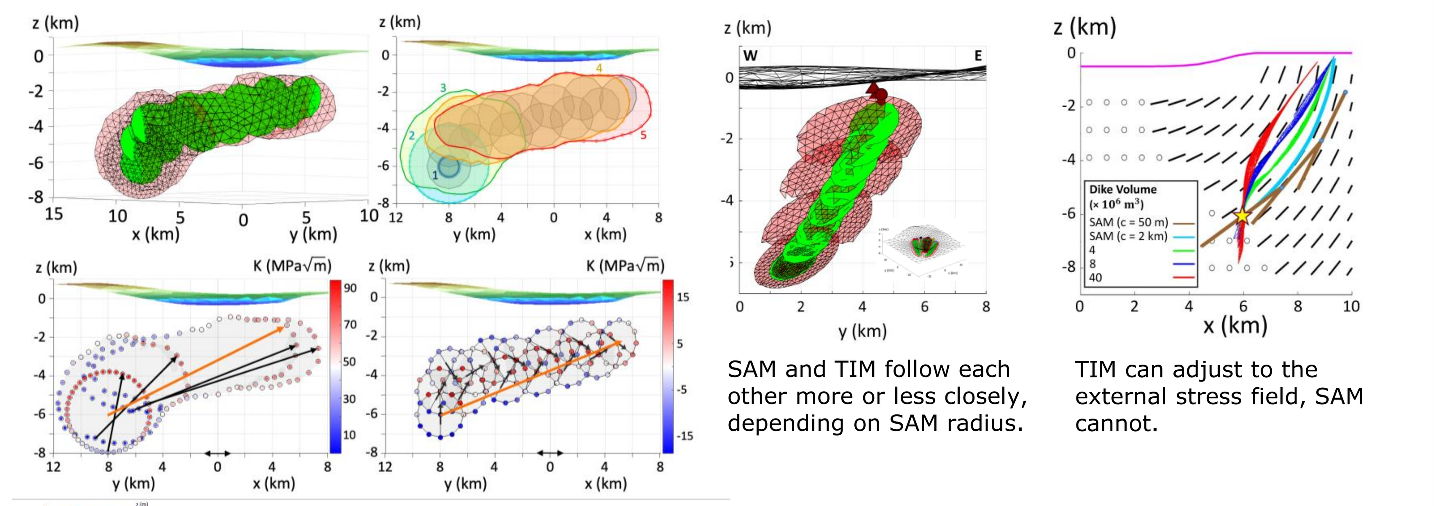
6) TESTING SAM

Let's compare SAM to a numerical model of 3D dike propagation:
TIM - Three-dimensional Intrusion Model
(*Davis et al., 2020* [8]; *Davis et al., 2021* [9])

Driving mechanism: K / K_c
K -> stress intensity factor
K_c -> fracture toughness of hosting medium
$K \propto$ internal pressure + external stress gradient

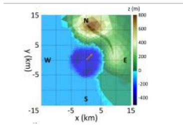


From *Davis et al. (2020)* [8], Fig. 2.



SAM and TIM follow each other more or less closely, depending on SAM radius.

TIM can adjust to the external stress field, SAM cannot.



K values are different,
SAM trajectory is zigzagged.
Overall trajectories are compatible.

SAM and TIM dikes are compatible, if both start oriented to the external stress.

7) STRESS INVERSION

Backtrack dikes from known past vents with SAM: what stress model brings them to a known magma chamber?

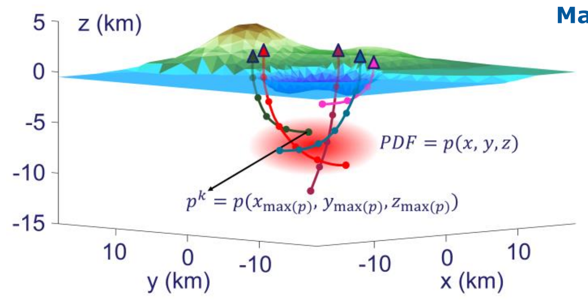
Mantiloni et al., in preparation

Inputs:

- Data (N vents)
- PDF for magma chamber location, shape and size

Free stress parameters:

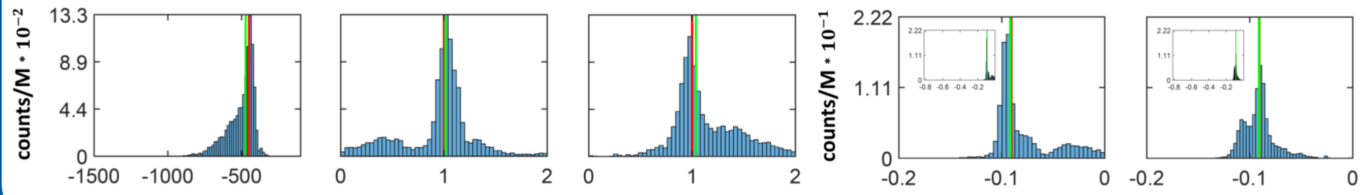
- ***d*** (caldera depth)
- ***h*** (resurgent dome height)
- σ^T_{xx} σ^T_{yy} σ^T_{xy} (tectonic stress components)



Markov Chain Monte Carlo algorithm

For each step:

1. Sample values of stress parameters.
2. For each vent:
   Backtrack the *k-th* dike.
   Evaluate $p^k = \max(p)$ along the trajectory.
3. Cost function: $-2*\sum_{k=1}^{N} log(p^k)$.
   What stress parameters minimize it?



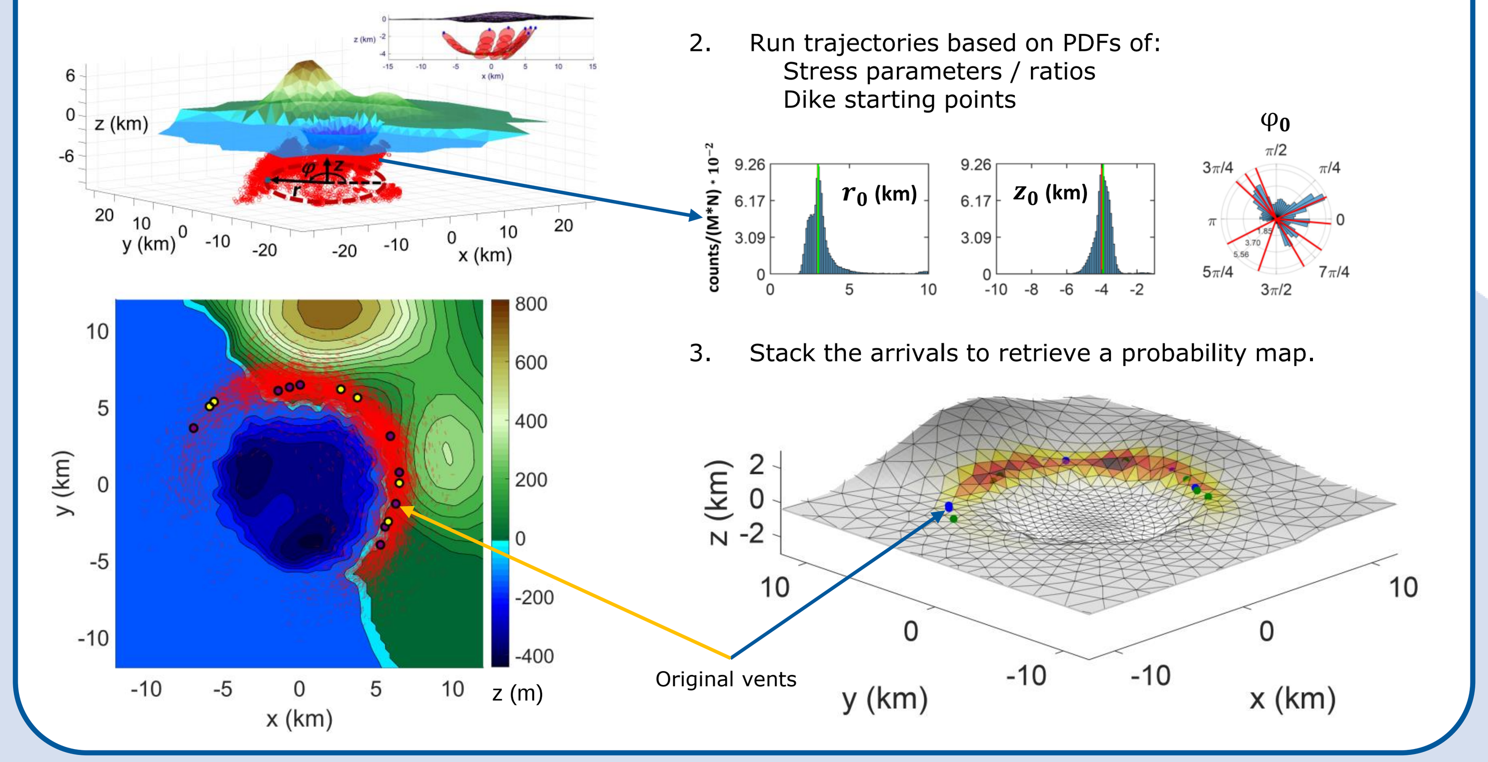
Posterior PDFs of stress parameters and their ratios (M=2e4)

8) VENT FORECAST

Mantiloni et al., in preparation

Let's test it on a synthetic scenario.

1. Run stress inversion.
2. Run trajectories based on PDFs of:
   Stress parameters / ratios
   Dike starting points
3. Stack the arrivals to retrieve a probability map.



9) SUMMARY & FUTURE STEPS

Two models for 3D dike propagation:

TIM: numerical, dike pathways and shape → Eruptive scenarios for individual dikes.
SAM: semi-analytical, dike pathways only, fast → Stress inversion, probability maps.

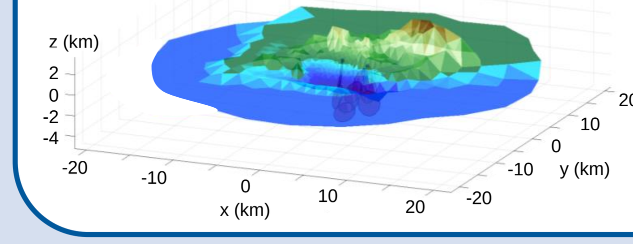
Stress inversion and forecast strategy:

It works in 2D (application to Campi Flegrei & analog models).
It works in 3D on synthetic tests …

Limitations

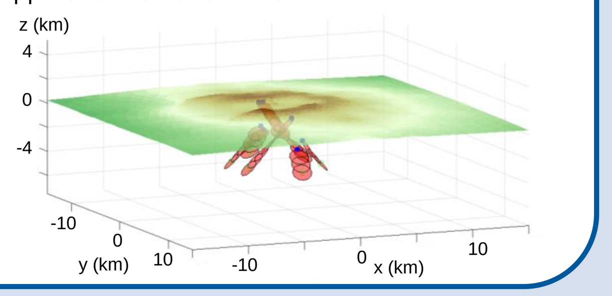
Our dike models neglect:	Neglected stress sources:	Host rock assumptions:
Magma viscosity (no dike velocity)	Magma reservoirs	Homogeneous medium
Dike-magma chamber coupling	Pre-existing faults and intrusions	Linear elasticity
Dike-dike interaction		

Near future:
Application to existing calderas.



Examples: SAM application to Campi Flegrei caldera, Italy (left) and Newberry Volcano, Oregon (right).

Long run:
Application to volcanic edifices.



References:

[1] Rivalta, E., Corbi, F., Passarelli, L., Acocella, V., Davis, T., & Di Vito, M. A. (2019). Stress inversions to forecast magma pathways and eruptive vent location. Science advances, 5(7), eaau9784.
[2] Mantiloni, L., Davis, T., Gaete Rojas, A. B., & Rivalta, E. (2021). Stress inversion in a gelatin box: testing eruptive vent location forecasts with analog models. *Geophysical Research Letters*.
[3] Martel, S. J., & Muller, J. R. (2000). A two-dimensional boundary element method for calculating elastic gravitational stresses in slopes. *Pure and Applied Geophysics*, *157*, 989-1007.
[4] Persson, P. O., & Strang, G. (2004). A simple mesh generator in MATLAB. *SIAM review*, *46*(2), 329-345.
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[6] Davis, T. (2017). A new open source boundary element code and its application to geological deformation: Exploring stress concentrations around voids and the effects of 3D frictional distributions on fault surfaces (M.Sc thesis. Aberdeen University)
[7] Mantiloni, L., Rivalta, E., & Davis, T. (2023). Mechanical modeling of pre-eruptive magma propagation scenarios at calderas. Journal of Geophysical Research: Solid Earth, 128 (3), e2022JB025956. doi: https://doi.org/10.1029/2022JB025956
[8] Davis, T., Rivalta, E., & Dahm, T. (2020). Critical fluid injection volumes for uncontrolled fracture ascent. *Geophysical Research Letters*, *47*(14), e2020GL087774.
[9] Davis, T., Bagnardi, M., Lundgren, P., & Rivalta, E. (2021). Extreme curvature of shallow magma pathways controlled by competing stresses: insights from the 2018 Sierra Negra eruption.

All software is open source!

- **SAM:** https://doi.org/10.5880/GFZ.2.1.2023.001 & https://github.com/LorenzoMantiloni/SAM-Simplified-Analytical-Model-of-Dyke-Propagation-in-Three-Dimensions
- **TIM:** https://doi.org/10.5281/zenodo.4726796 & https://doi.org/10.5281/zenodo.4727208
- **Cut&Displace:** https://doi.org/10.5281/zenodo.3694164

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Lorenzo Mantiloni
Helmholtz Zentrum Potsdam – Deutsches Geoforschungszentrum (GFZ)
Sektion 2.1
Helmholtzstraße 6/7 14467 Potsdam DE
lorenzo@gfz-potsdam.de