Thermo-poro-elastic effects induced by fluid flow can explain the recent seismicity and deformation at Campi Flegrei (Italy)

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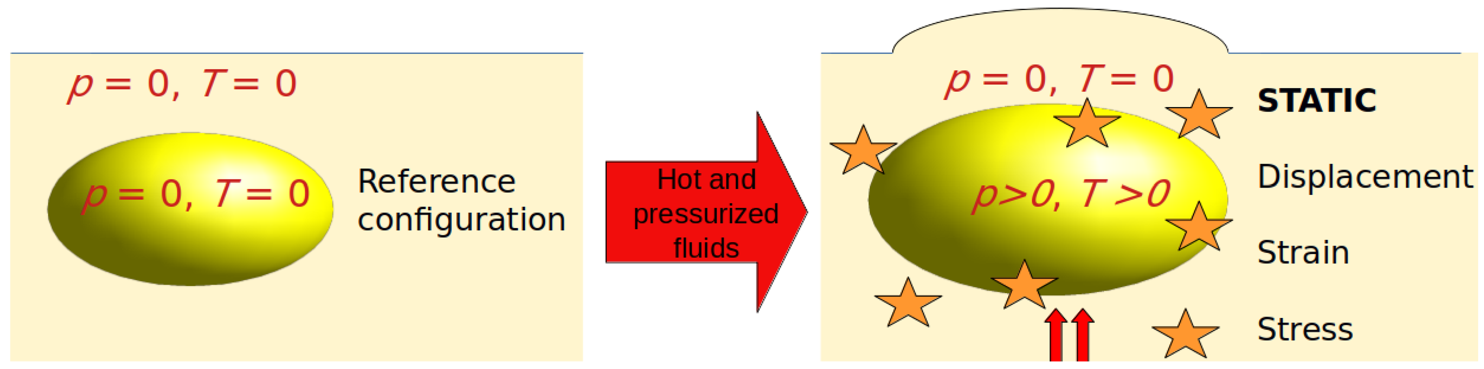
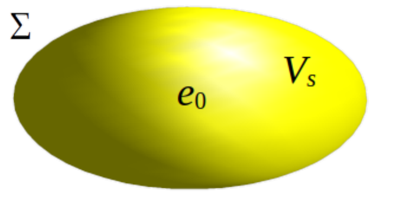
1. What are TPE inclusions ?

Thermo-Poro-Elastic (**TPE**) deformation sources allow to explain **seismicity** and **deformation** induced by pore-pressure, *p* and temperature, *T* changes in **geothermal** and **volcanic** environments.



2. How are they modeled ?

The **inclusion method** (Eshelby, 1957) allows us to model the static TPE effects of pore-pressure and temperature changes occurring inside a **closed volume,** *Vs* (i.e. an inclusion) enclosed by a surface, *Σ* and embedded in an elastic medium.



$$e_0 = \frac{1}{3H}p + \frac{1}{3}\alpha_s T$$ **TPE inclusion potency**

H: Poroelastic, Biot's constant
α_s: Thermal expansion

Displacement

$$u_i(\mathbf{x}) = \oint_{\Sigma} 3K\epsilon_0 n_k G_{ik}(\mathbf{x},\mathbf{x}')d\Sigma'$$

Strain

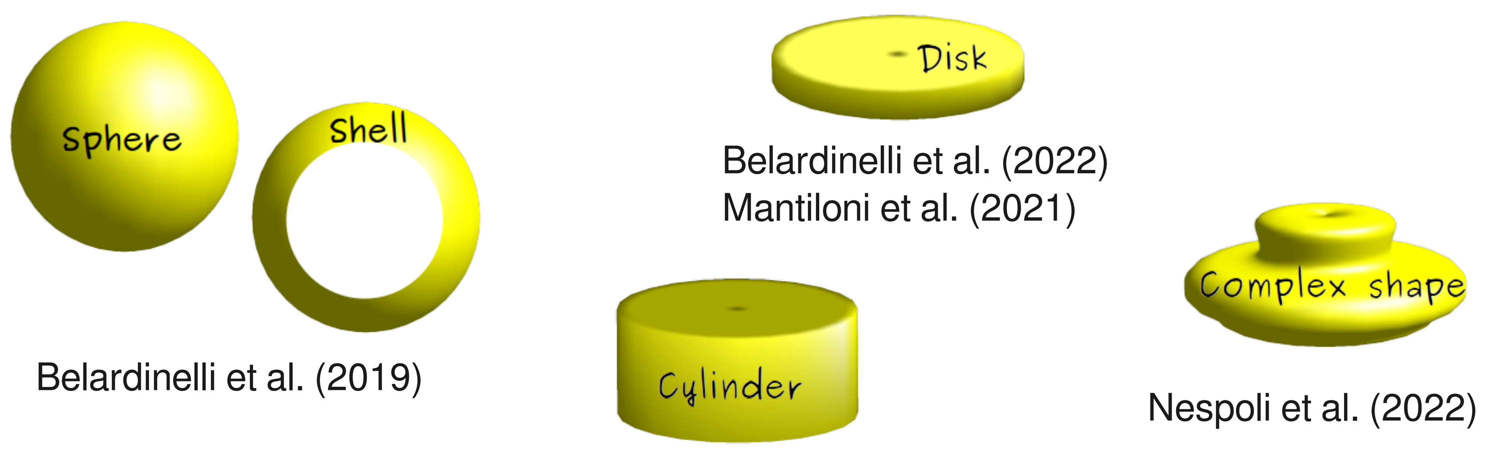
$$e_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Stress

$$\tau_{ij}(\mathbf{x}) = \begin{cases} \lambda e_{kk}\delta_{ij} + 2\mu e_{ij} - 3Ke_0\delta_{ij}, & \mathbf{x} \in V_S \\ \lambda e_{kk}\delta_{ij} + 2\mu e_{ij}, & \mathbf{x} \notin V_S \end{cases}$$

G_{ik}: Drained-isothermal Green's function

3. Different geometries are available



Belardinelli et al. (2022)
Mantiloni et al. (2021)

Belardinelli et al. (2019)

Nespoli et al. (2022)

Nespoli et al. (2021)

In the literature **analytical** and/or **numerical solutions** are available for **different geometries** of TPE deformation sources

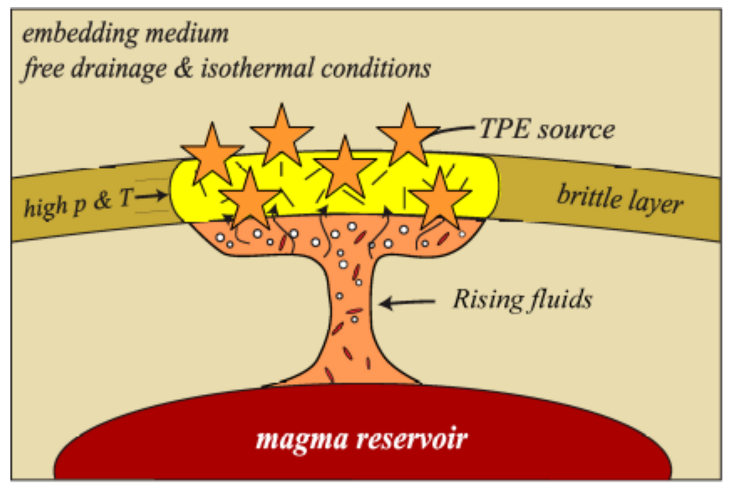
4. They are useful because ...

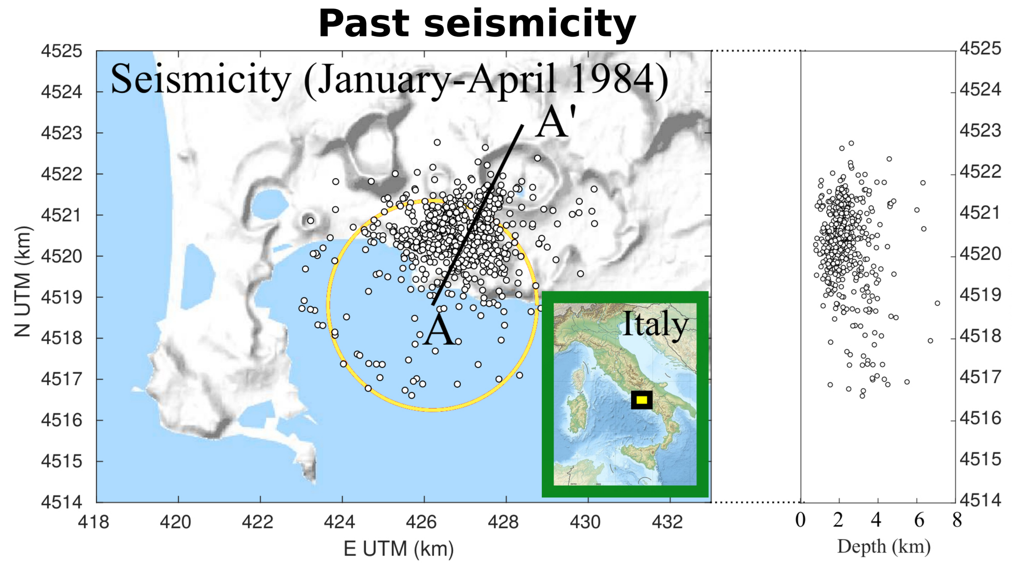
- explain deformation and stress due to the **injection or withdrawal** of hydrothermal fluids
- create a **strong deviatoric stress** field even within them
- explain deformations even in if there are **no evidences** of shallow large **magmatic** bodies
- explain the **heterogeneity of fault mechanisms** of induced earthquakes

5. Applications to the Campi Flegrei caldera

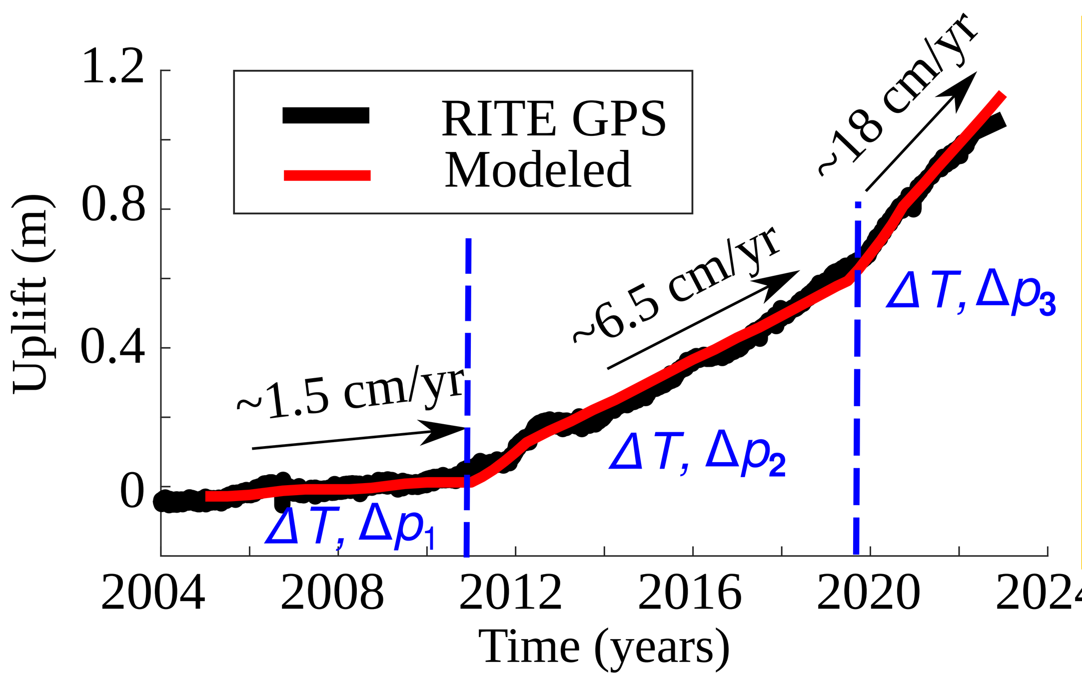
TPE inclusions have been mostly applied to model the **displacement** and the **stress field** in the caldera of **Campi Flegrei** (Italy), where pore-pressure and temperature changes are assumed to derive from the **exsolution of fluids** from a deep magmatic chamber.

The **geometry and location** of the TPE source was inferred by Nespoli et al. (2021) from the **inversion of geodetic data** of the '82-'84 unrest phase. They found that a cylindrical TPE inclusion with a **radius** of about 2.5 km, placed at a **depth** of 2 km can explain both the observed displacement and seismicity.



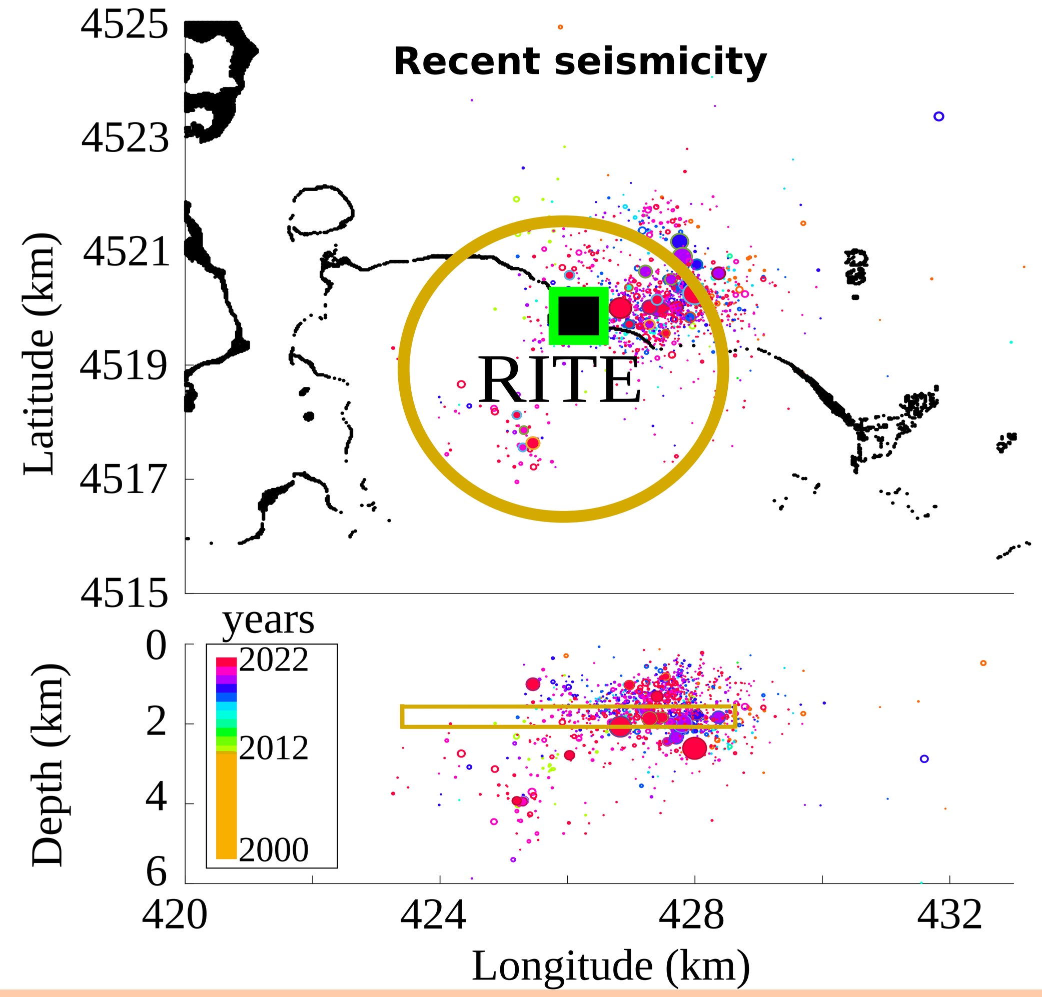


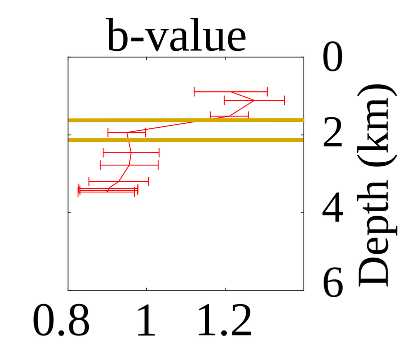
We show that the **time-series of soil uplift** observed in the last years can be reproducedby assuming the rising of hot and pressurized fluids, possibly exsolved by a deep magmatic source, within the **same deformation source** responsible of the '82-'84 unrest.



We assume that **three different plumes** of fluids with increasing pore-pressure arrived **at the base** of the TPE inclusion in three different time windows:

$\Delta p_3 > \Delta p_2 > \Delta p_1$

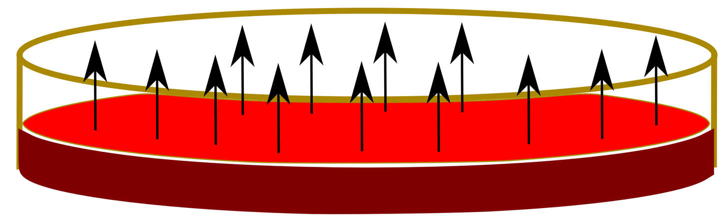




The **decrease of the b-values** is consistent with the fact that within the TPE inclusion the induced shear stress is maximum and the occurrence of larger earthquakes is favored

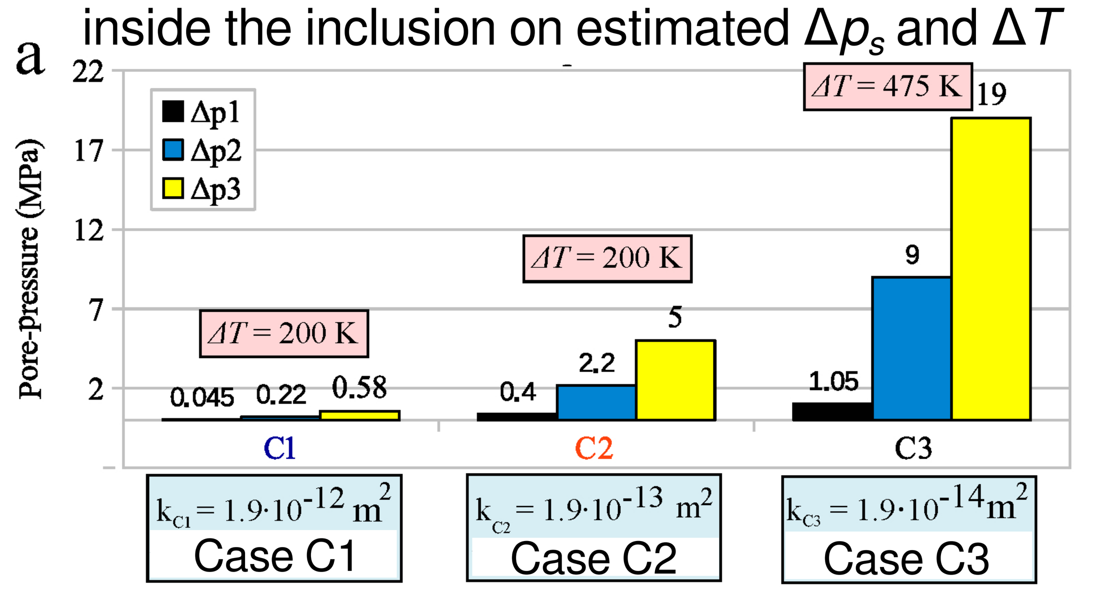
To model transient mechanical effects due to the fluid rising inside the inclusion, the TPE inclusion was represented by a **vertical superposition of 100 disk-like slices.** We first evaluate the effect of each slice on both deformation and stress field assuming a unitary TPE potency, *e0*, inside it.

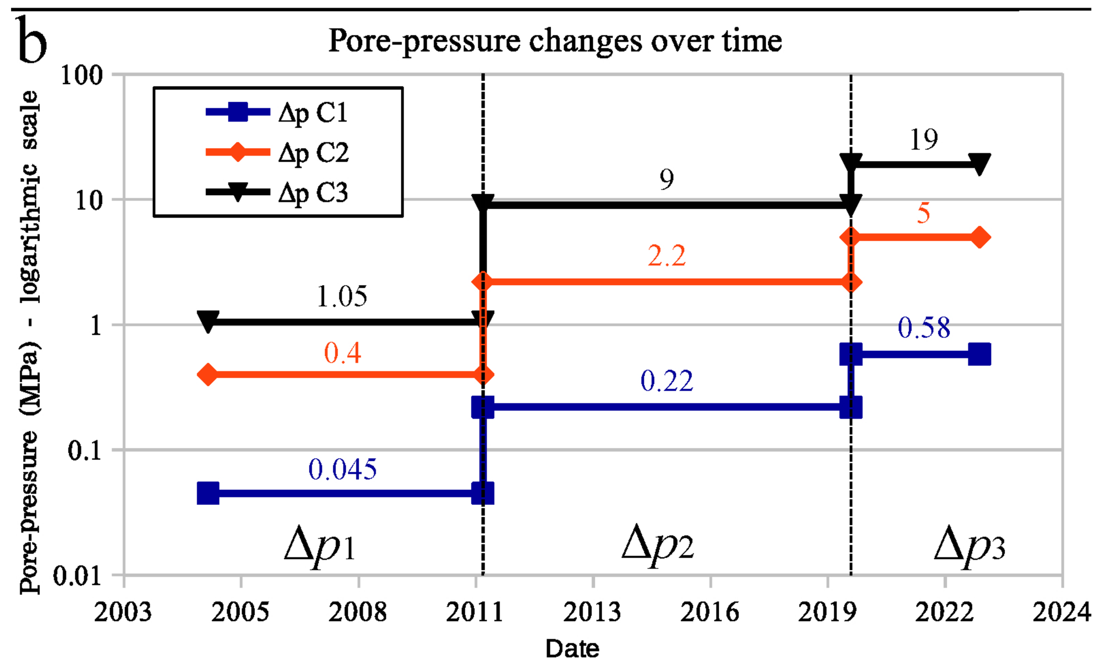
Following this procedure, we can compute a sort of Green's functions for each slice of the TPE inclusion. By **summing the effects of the slides** located at *z*, multiplied by the proper *e0*, computed from the analytical expression of *p(z,t)* and *T(z,t)* by Nespoli et al., (2021), we can model the effects of the **vertical distribution of** *p* **and** *T* for a given time *t* after the beginning of the exsolution of fluids inside the inclusion.



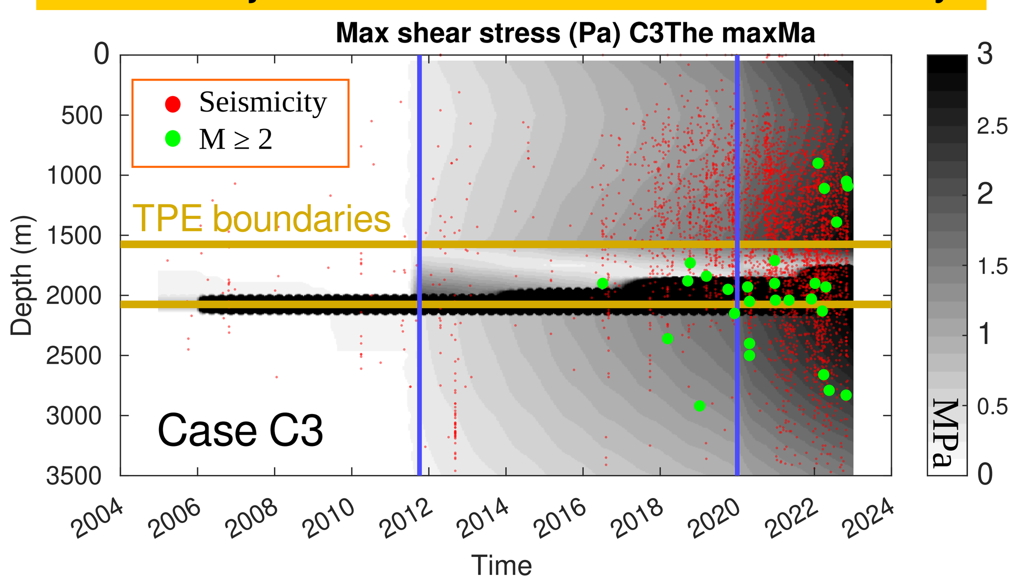
Rising hot and pressurized fluids

Parametric study: effecs of permeability (*k*) inside the inclusion on estimated Δp_s and ΔT





The increase of the maximum shear stress over time justifies the increase of the seismicity



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