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Thermo-Poro-Elastic effects as hidden drivers of gravity signals in volcanic systems

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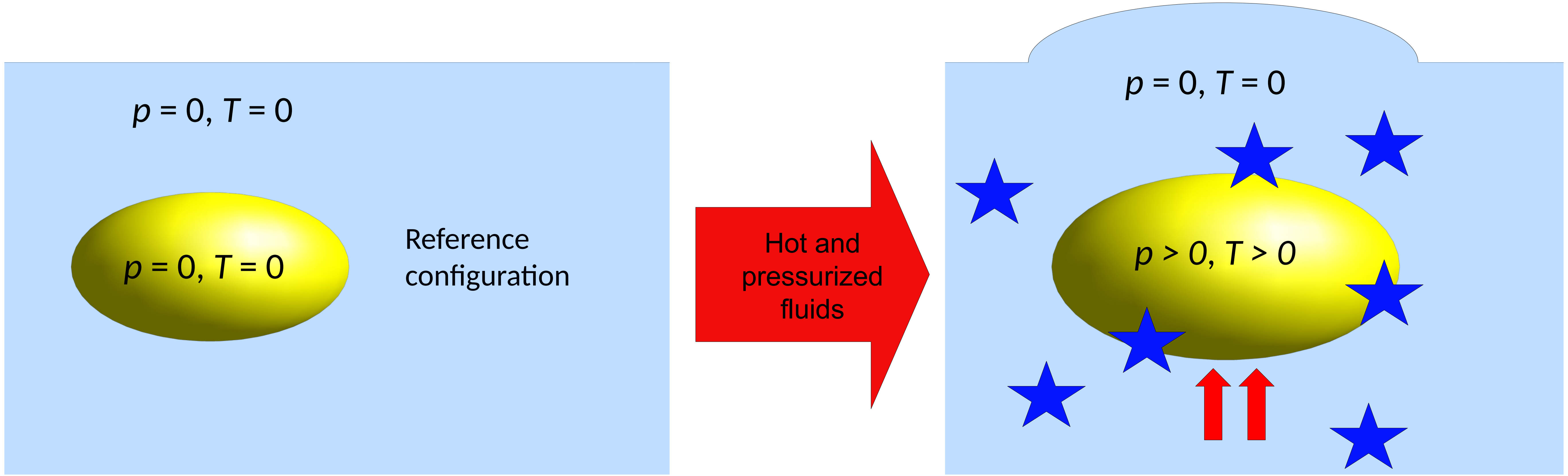
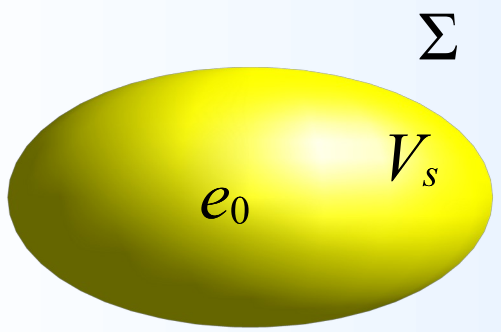
EGU General Assembly 2026 - Vienna, Austria & Online | 3–8 May 2026

Thermo-Poro-Elastic (**TPE**) inclusions allow to model the mechanical effects induced by **pore-pressure, *p*** and **temperature, *T*** changes occurring in closed volumes (e.g. reservoirs).



The mechanical fields can be computed analytically or numerically starting from the **inclusion method** (Eshelby, 1957)



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

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

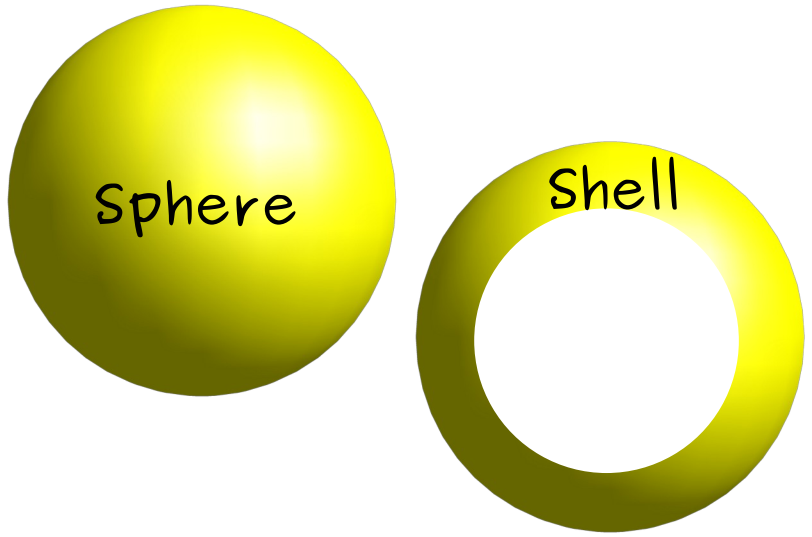
$$u_i(\mathbf{x}) = \oint_{\Sigma} 3K\epsilon_0 n_k G_{ik}(\mathbf{x}, \mathbf{x}')d\Sigma'$$

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

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

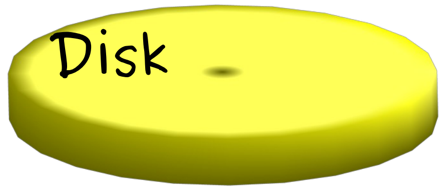
$$\tau_{ij}(\mathbf{x}) = \begin{cases} \lambda e_{kk}\delta_{ij} + 2\mu e_{ij} - 3Ke_0\delta_{ij}, & \mathbf{x} \in V_S \\ \lambda e_{kk}\delta_{ij} + 2\mu e_{ij}, & \mathbf{x} \notin V_S \end{cases}$$

Available geometries
of TPE inclusions

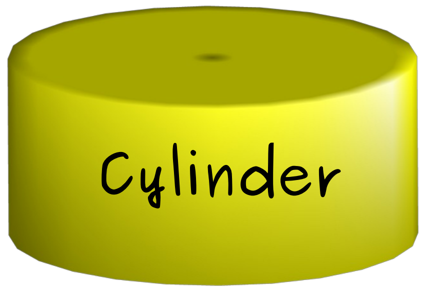


Belardinelli et al. (2019)
Battolini et al. (2026)

Nespoli et al. (2022)

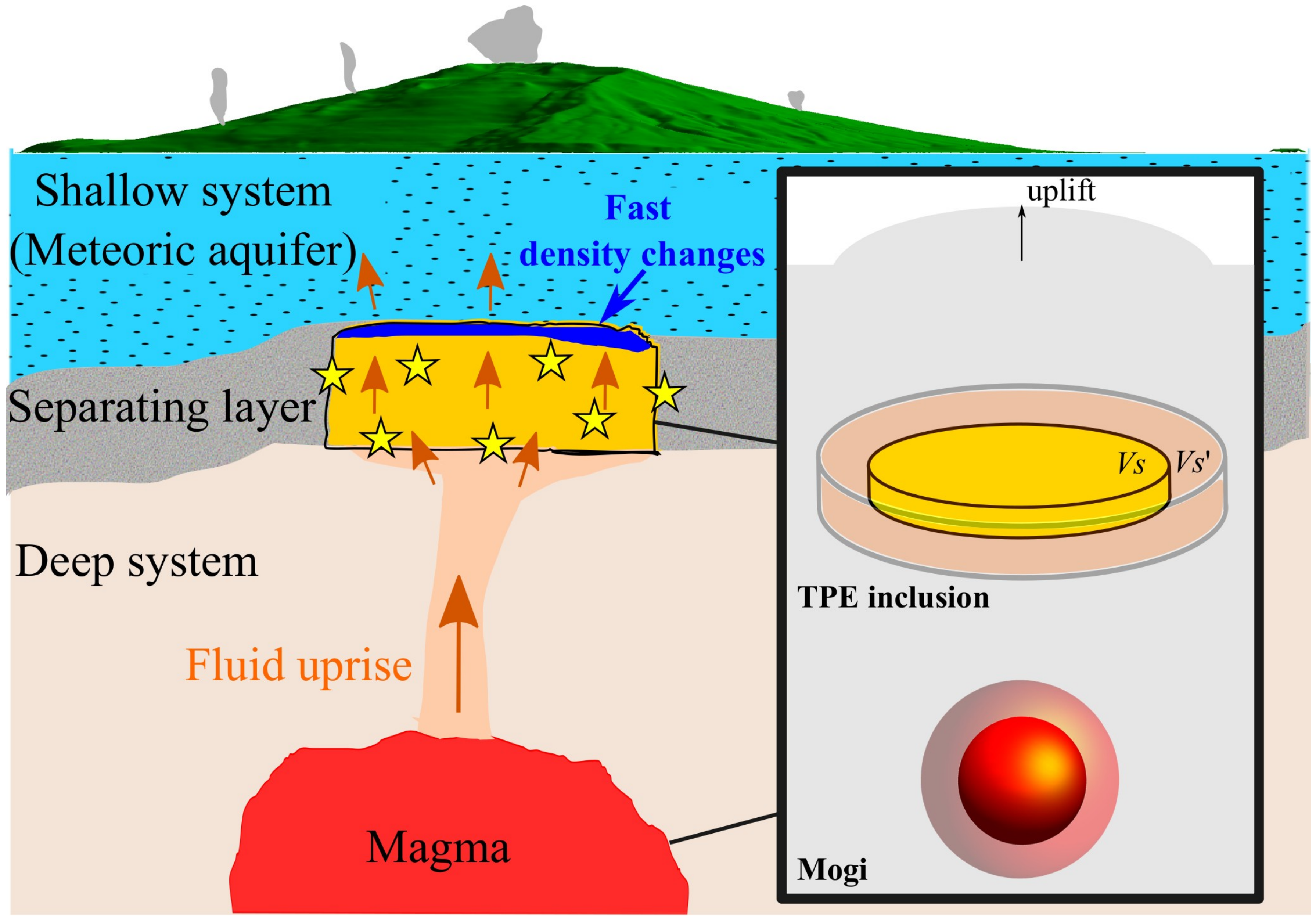


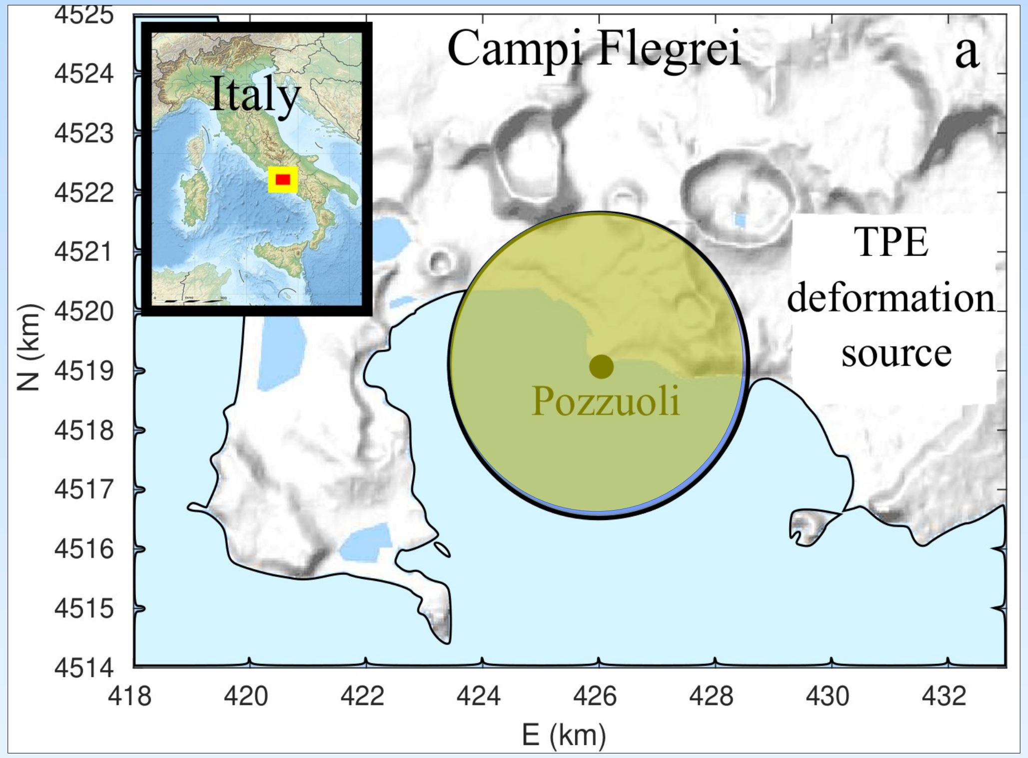
Belardinelli et al. (2022)
Mantiloni et al. (2021)



Nespoli et al. (2021)

In the last years, TPE inclusions have been mostly applied to 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.**

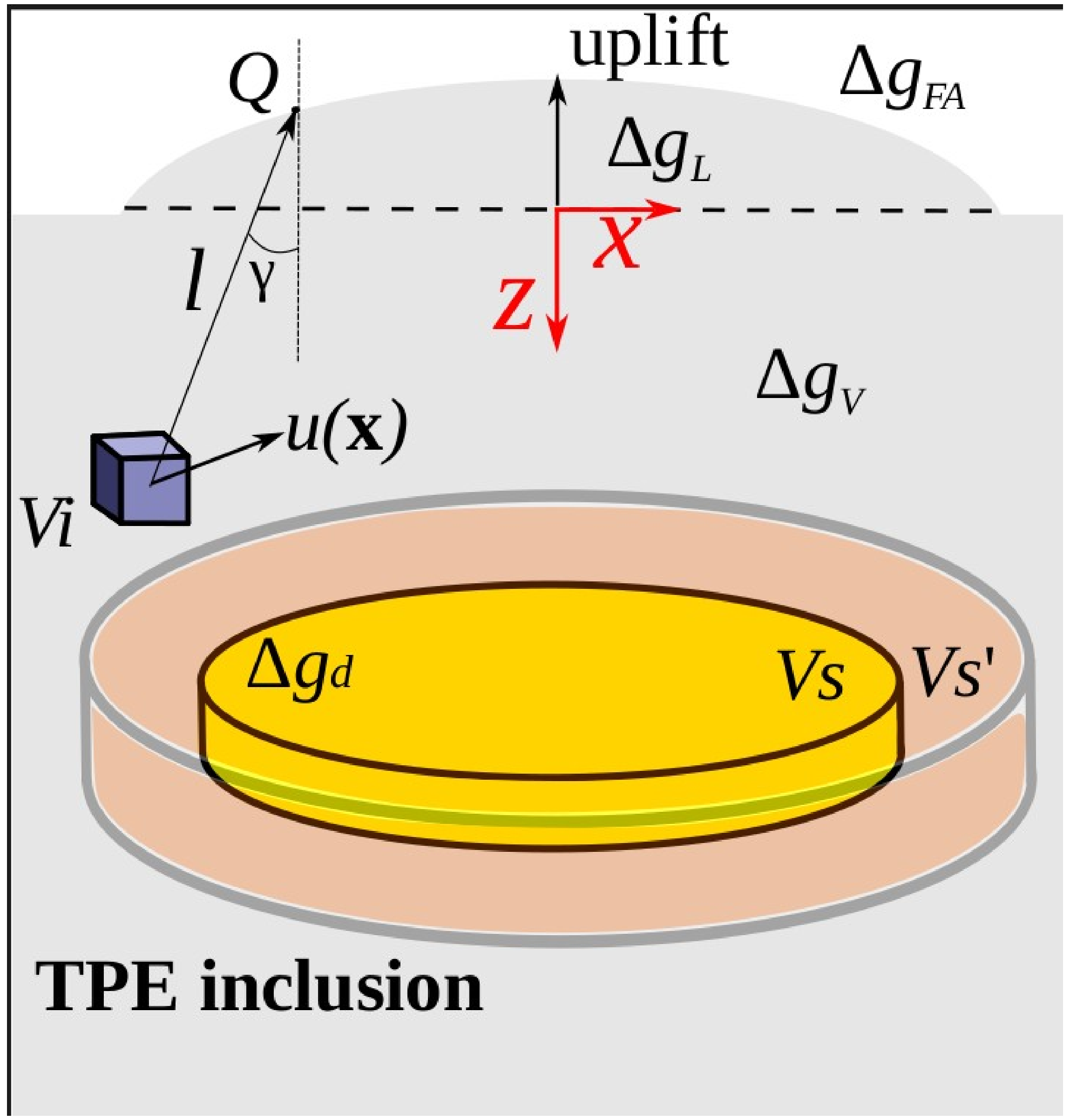




Geometry and location of the TPE source inferred by Nespoli et al. (2021) from the **inversion** of geodetic data of the 82-84 unrest phase. At about **2 km of depth.**

Recent studies (Nespoli et al., 2021 and 2023) demonstrate that this source can effectively account for the seismicity and uplift patterns observed during both the **past** (1982–1984) and the **current unrest phases**.

Differently from previous work we compute the **gravity variations induced by disk-shaped inclusions** and quantify the contributions associated with **solid** and **fluid compressibility**, **thermal expansion**, and **deformation-related density changes**.



Free-air **Residuals** due to mass redistribution

$$\Delta g_{TOT} = \Delta g_{FA} + \Delta g_R$$

$$\Delta g_R = G \int_V \Delta\rho \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV = \Delta g_L + \Delta g_V + \Delta g_d$$

$$\Delta g_L = G \int_V \mathbf{u} \cdot \nabla \rho \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV$$

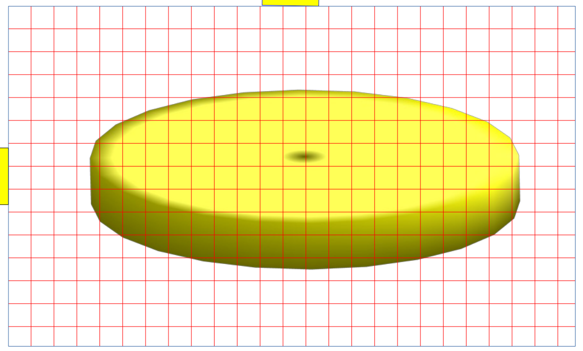
Bouguer correction

$$\Delta g_V = -G \int_V \rho e_{kk} \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV$$

Due to the dilation of the surrounding medium

$$\Delta g_d = G \int_V \delta\rho_d \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV$$

Due to the density variations inside the inclusion



Fine grid with small elements *Vi*

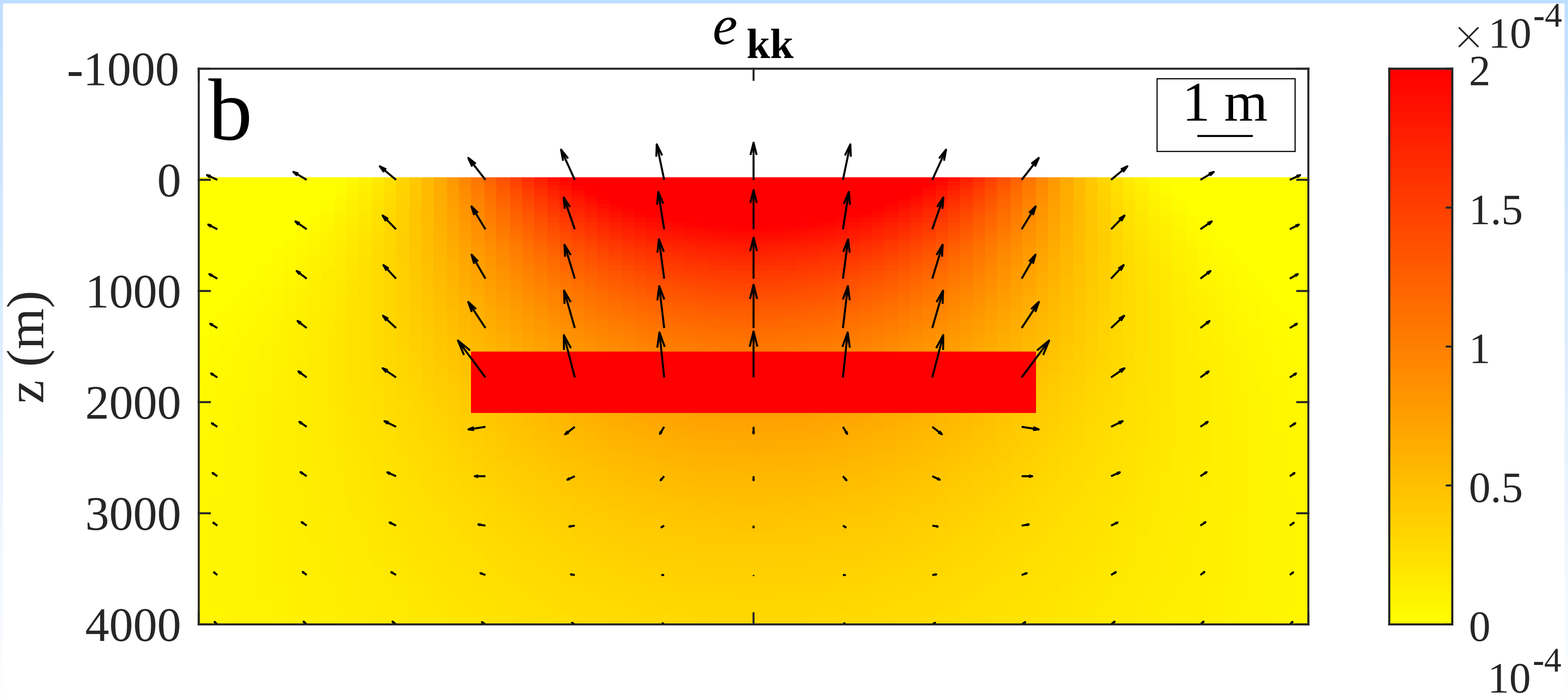
$$\Delta g_R = G\int_V \Delta\rho \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV = \Delta g_L + \Delta g_V + \Delta g_d$$

The contribution is mostly related to the **dilation of the medium** induced by the TPE inclusion

$$\Delta g_V = -G\int_V \rho e_{kk} \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV$$

Due to the dilation of the surrounding medium

Displacements (black arrows) and dilation (colorbar) induced by increments of *p* and *T*



$$\Delta g_R = G \int_V \Delta\rho \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV = \Delta g_L + \Delta g_V + \Delta g_d$$

In **conventional** magmatic models, a **volume increase** is linked to **mass addition** and **positive gravity changes**, whereas TPE inclusions are less trivial.

$$\Delta g_d = G \int_V \delta\rho_d \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV$$

Due to the density variations inside the inclusion

$\delta\rho_d$

Density variations within the source depend on changes of:

V_i*, *p and ***T***

- TPE parameters
- Porosity
- Solid thermal expansion
- Solid bulk modulus
- Fluid thermal expansion
- Fluid bulk modulus

Case C1 to C4

- The same geometry of the **disk-shaped TPE** inclusion of Campi Flgerei
- **C1 to C4 cases** with different thermodynamical transformation of the pore fluid, but leading to **the same mechanical fields**
- C1 and C2 start with **liquid water**; C3 and C4 start with **vapor**

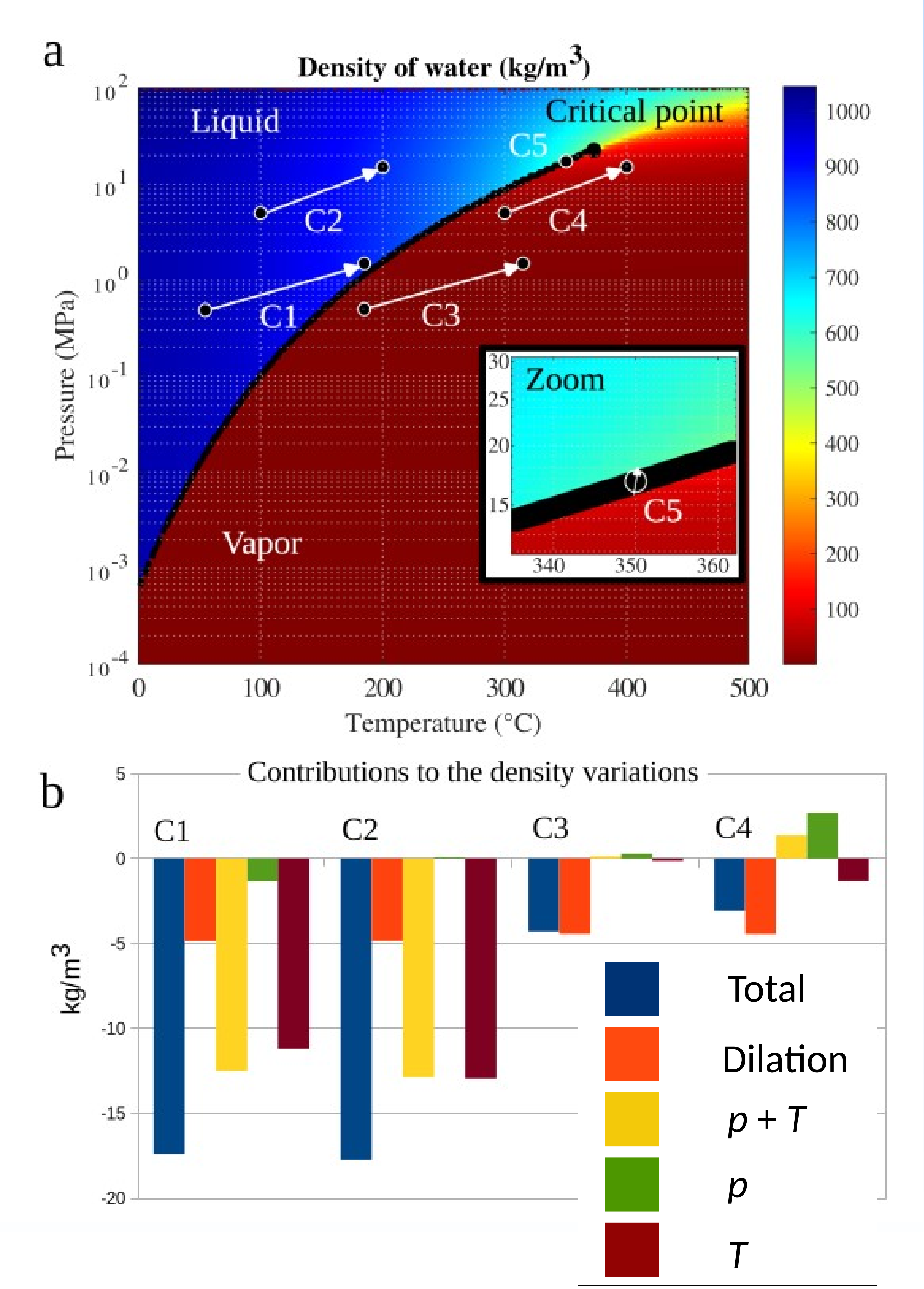
Density variations are generally **negative** or **very small**

<u>In C1 and C2 (water):</u>

65 % due to the **temperature**
(Different expansion of solid and fluid)

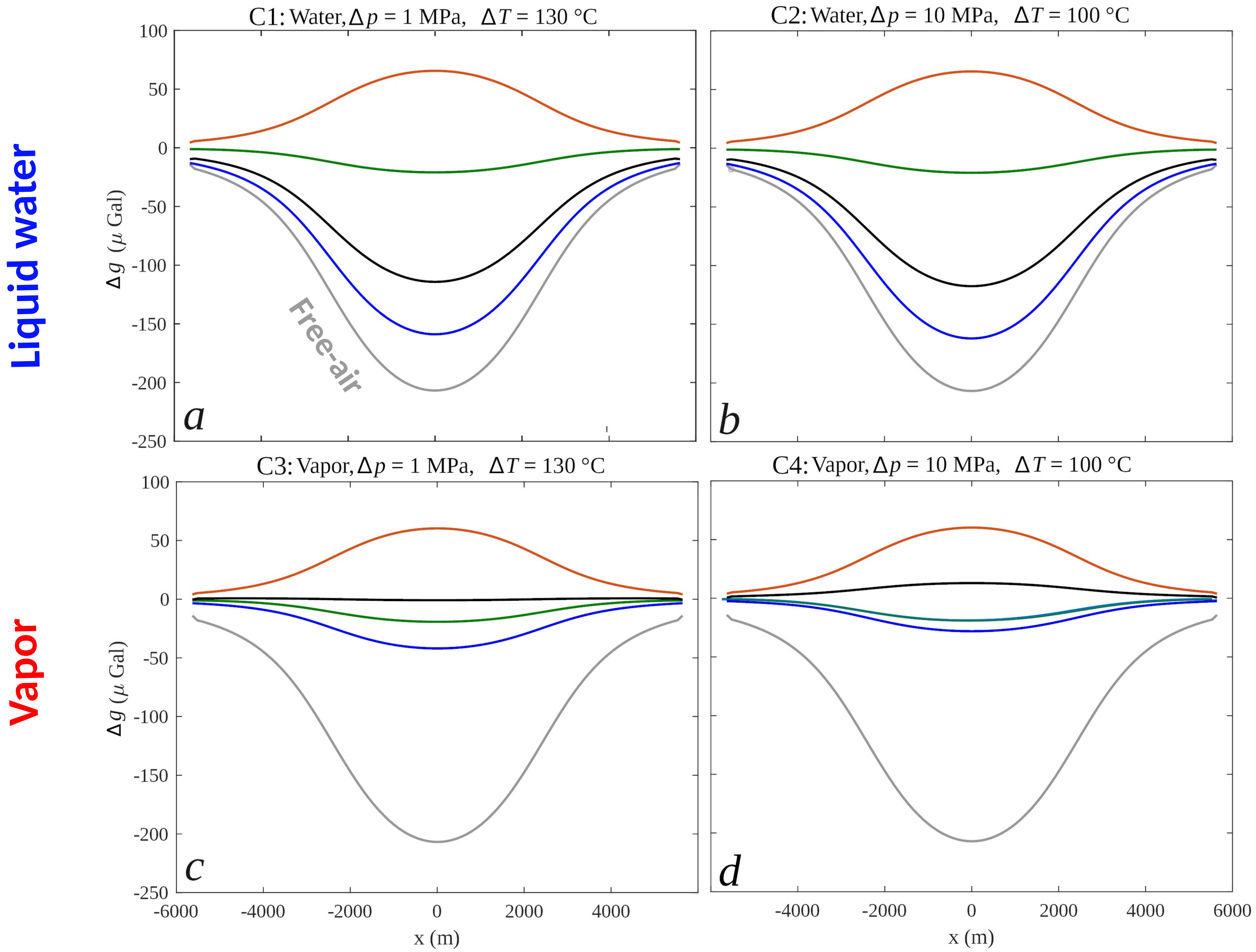
30 % volume change of the matrix

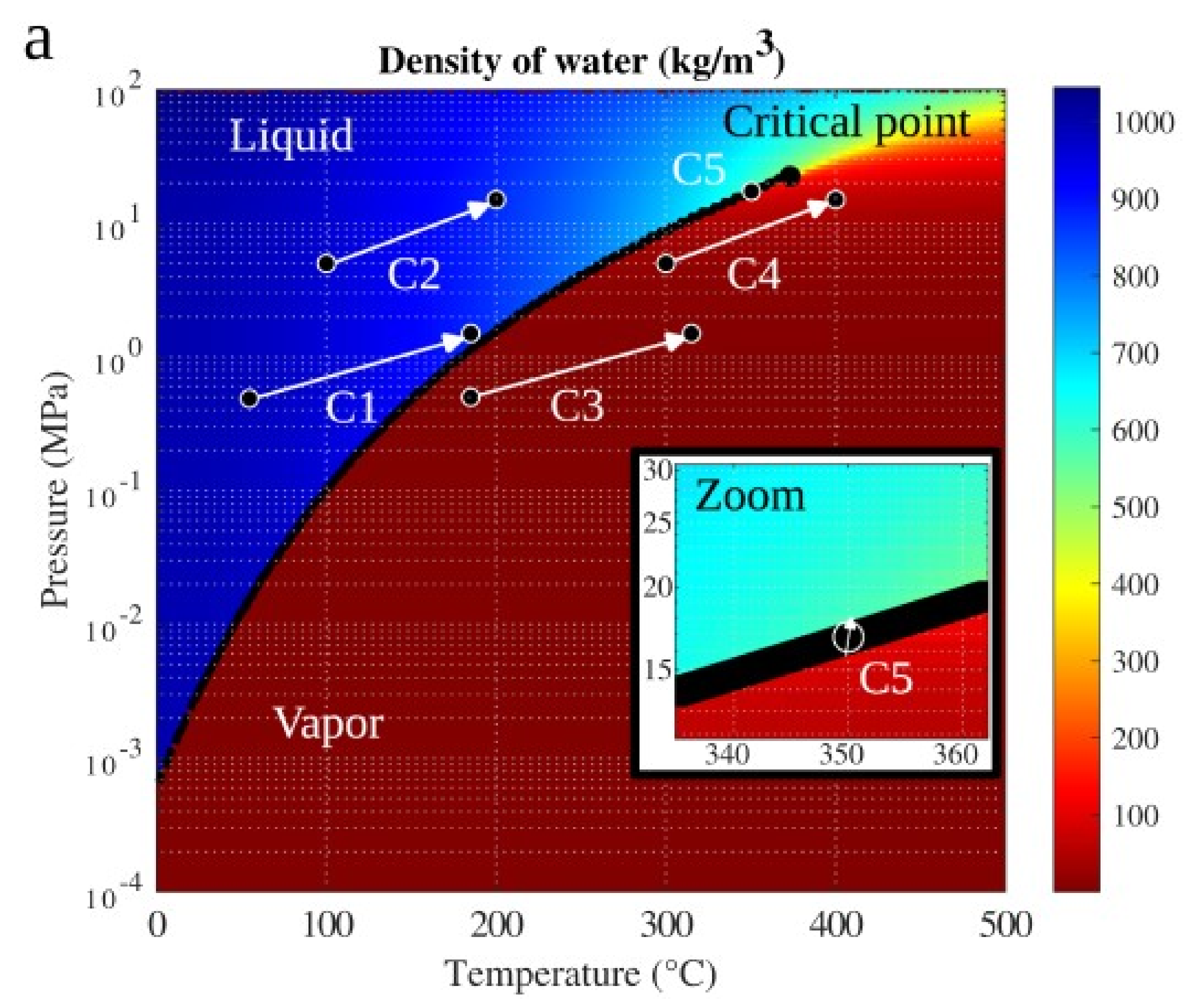
5 % pore-pressure
(Compressibility of solid and fluid)



Gravity residuals at the surface

$$\Delta g_R = G \int_V \Delta\rho \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV = \Delta g_L + \Delta g_V + \Delta g_d$$





While inducing a **significant uplift,** the **gravity residuals** are:

Liquid water ➡ **negative**

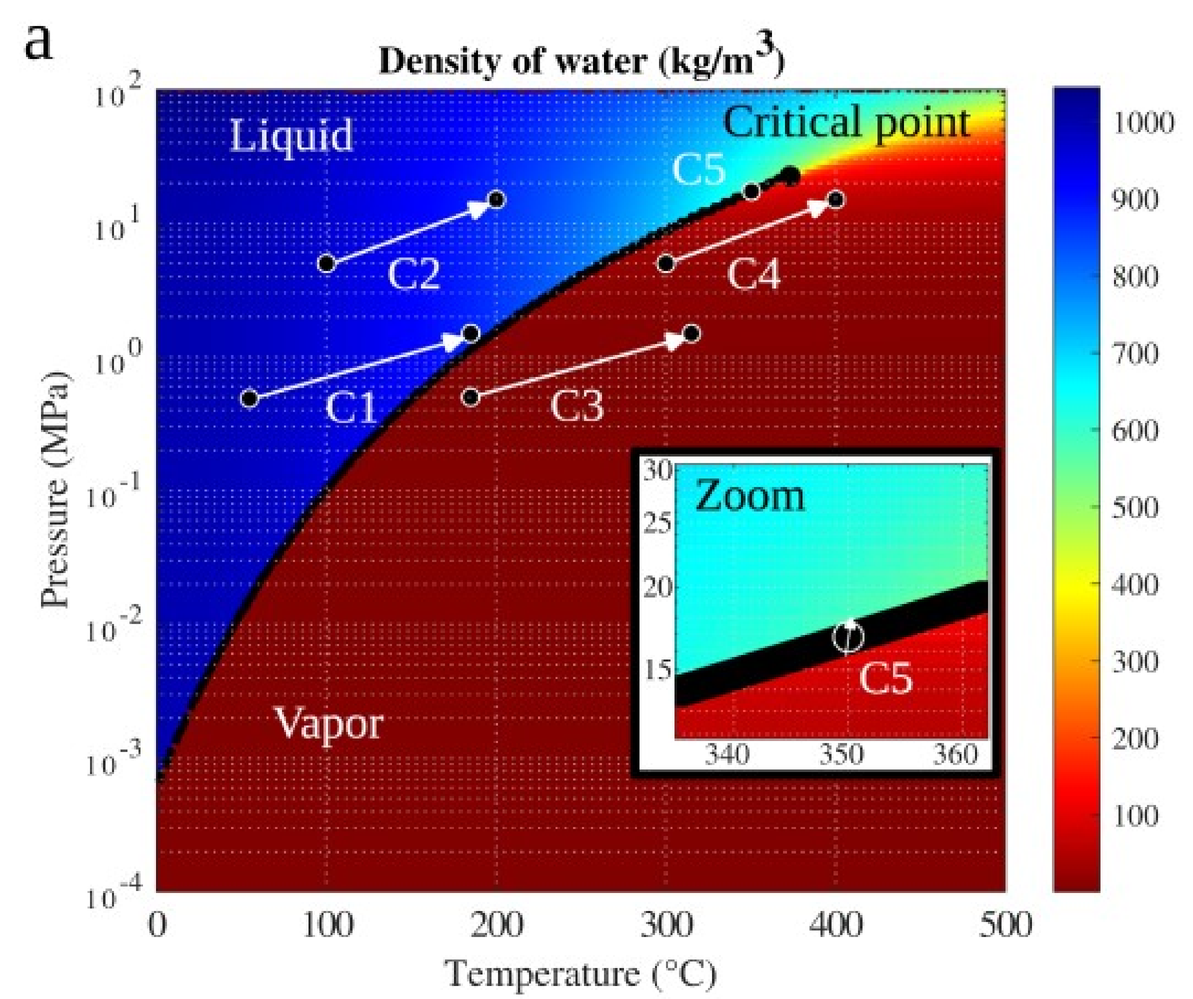
Vapor ➡ **very small**

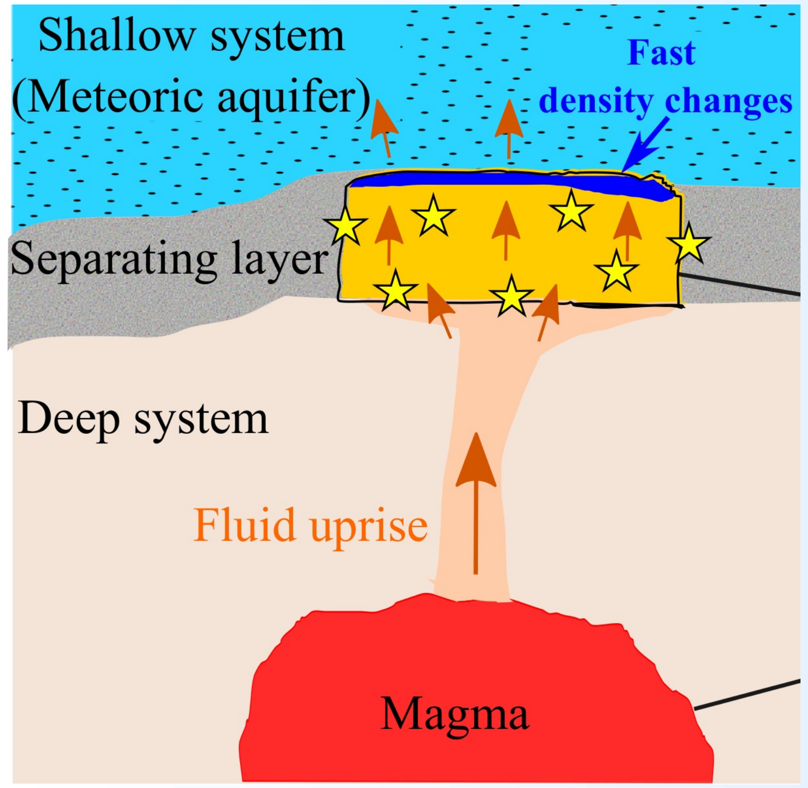
Case C5 - phase change

Small, transient **pressure** and/or **temperature** variations can produce large **density changes** (e.g. driven by fluid migration or seismic-related permeability changes)

Gravity anomalies **within a thin transition layer**

At constant pressure (17 MPa) and temperature (350 °C), 50% gas condensation causes a **density increase of ~480 kg/m³**

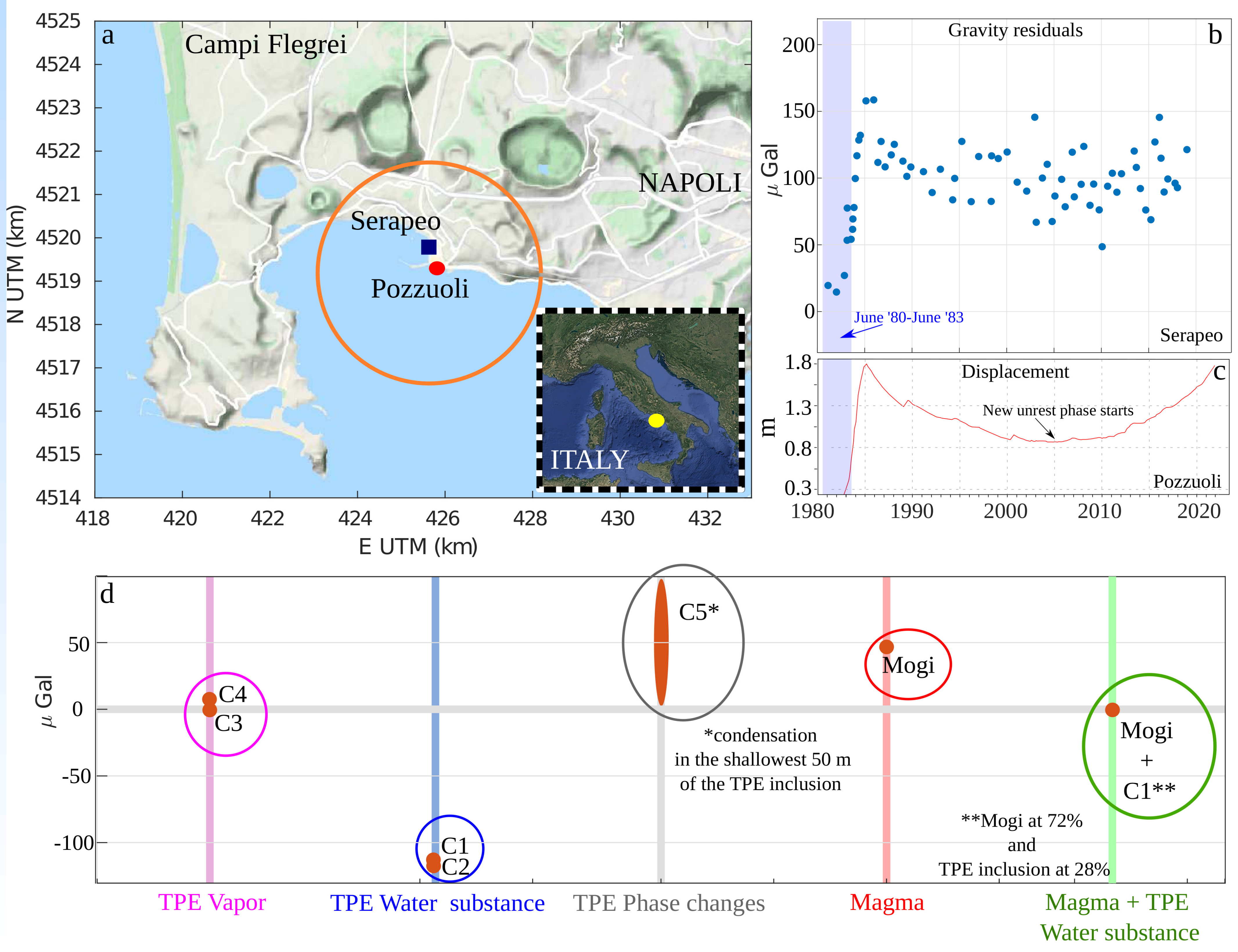




A 50 m thick layer is sufficient to produce **positive gravity residuals** (**~45 µGal**), even **without significant ground uplift**

All cases suggest a strong **de-correlation between deformation and gravity residuals**

Hints from the Campi Flegrei caldera



1982–84 unrest

Cases C1 and C2 (liquid water): negative residuals, which are opposite to the data

Cases C3 and C4 (vapor) very low residuals

Magma required

After 1985

Case C5 (phase changes) explains oscillations of gravity residuals without significant uplift

Case C3 and C4 (vapor) explain uplift without gravity residuals

What about TPE + magma?

A **combination** of a deep Mogi source (explaining the 72% of observed uplift) and a shallow liquid-filled TPE inclusion (28%) produces no net gravity residuals.

Conclusions

- **Residual gravity changes** of a TPE inclusion are **significant and strongly fluid-phase dependent**
- There is a **strong decorrelation** between uplift and gravity residuals
- TPE heating and pressurization can **mask or weaken gravity signals** from magma ascent
- This **complicates gravimetric interpretation** and calls for caution in hazard assessment when hydrothermal effects are not considered
- **The absence of gravimetric variations cannot be taken as evidence against magmatic intrusions.**

Thank you for your attention

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Link to our two most recent works on the subject!

Focus on gravity effects

https://doi.org/10.1016/j.epsl.2025.119762

Focus on TPE effects

https://doi.org/10.1016/j.earscirev.2024.104996

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$$\Delta g_R = G \int_V \Delta\rho \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV = \Delta g_L + \Delta g_V + \Delta g_d$$

$$\Delta g_L = G \int_V \mathbf{u} \cdot \nabla \rho \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV$$

$$\Delta g_L(z=0) = -2\pi G\rho u_z(z=0)$$

$$\rho = \rho_s(1-\phi) + \rho_f\phi$$

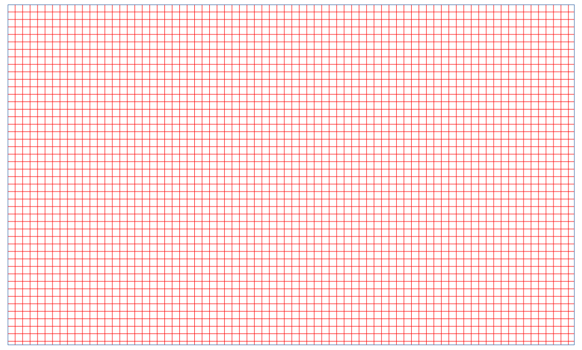
Bouguer correction

$$\Delta g_V = -G \int_V \rho e_{kk} \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV$$

$$\Delta g_V \approx -G\rho \sum_{i \notin V_s} e_{kk}^{(i)} \frac{\cos(\gamma_i)}{\ell_i^2} V_i$$

Due to the dilation of the surrounding medium

Fine grid with small elements *Vi*



$$\Delta g_d = G \int_V \delta\rho_d \frac{\cos\gamma}{|\boldsymbol{\ell}|^2} dV$$

$$\Delta g_d \approx G \sum_{i \in V_s} \left[\left(\frac{\rho'_{d(i)} - \rho}{\ell_i^2} \cos\gamma_i \right) V_i + \left(\frac{\rho'_{d(i)} - \rho}{\ell_i'^2} \cos\gamma'_i \right) e_{kk}^{(i)} V_i \right]$$

Due to the density variations inside the inclusion