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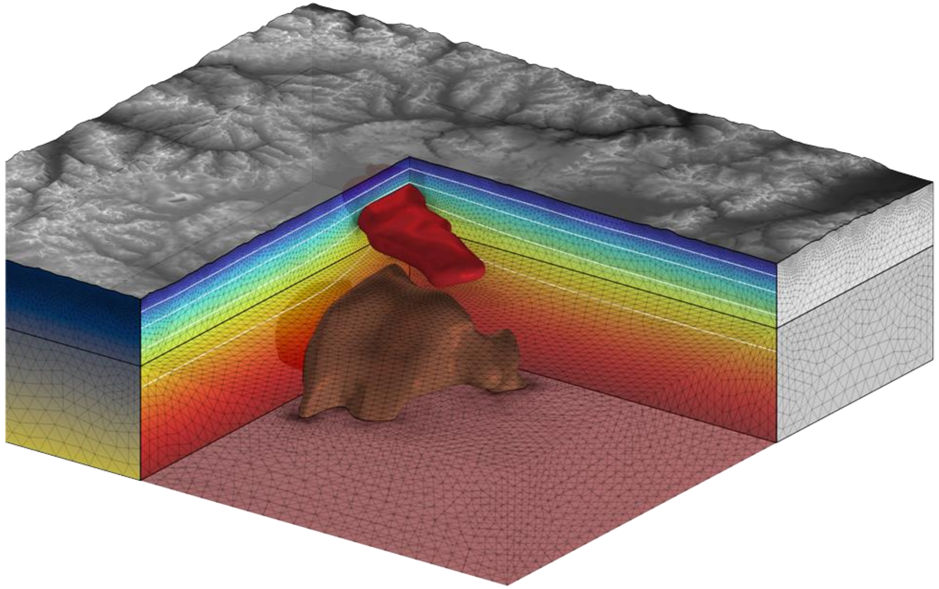

Thermo-Rheological Modelling of the Yellowstone Caldera: Insights into Volcanic Processes

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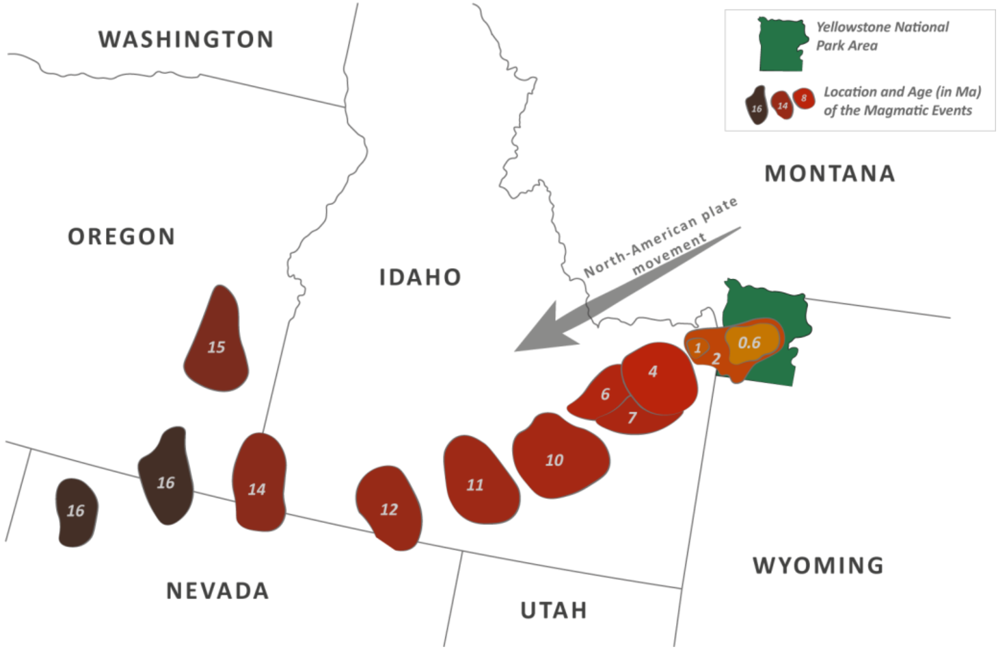
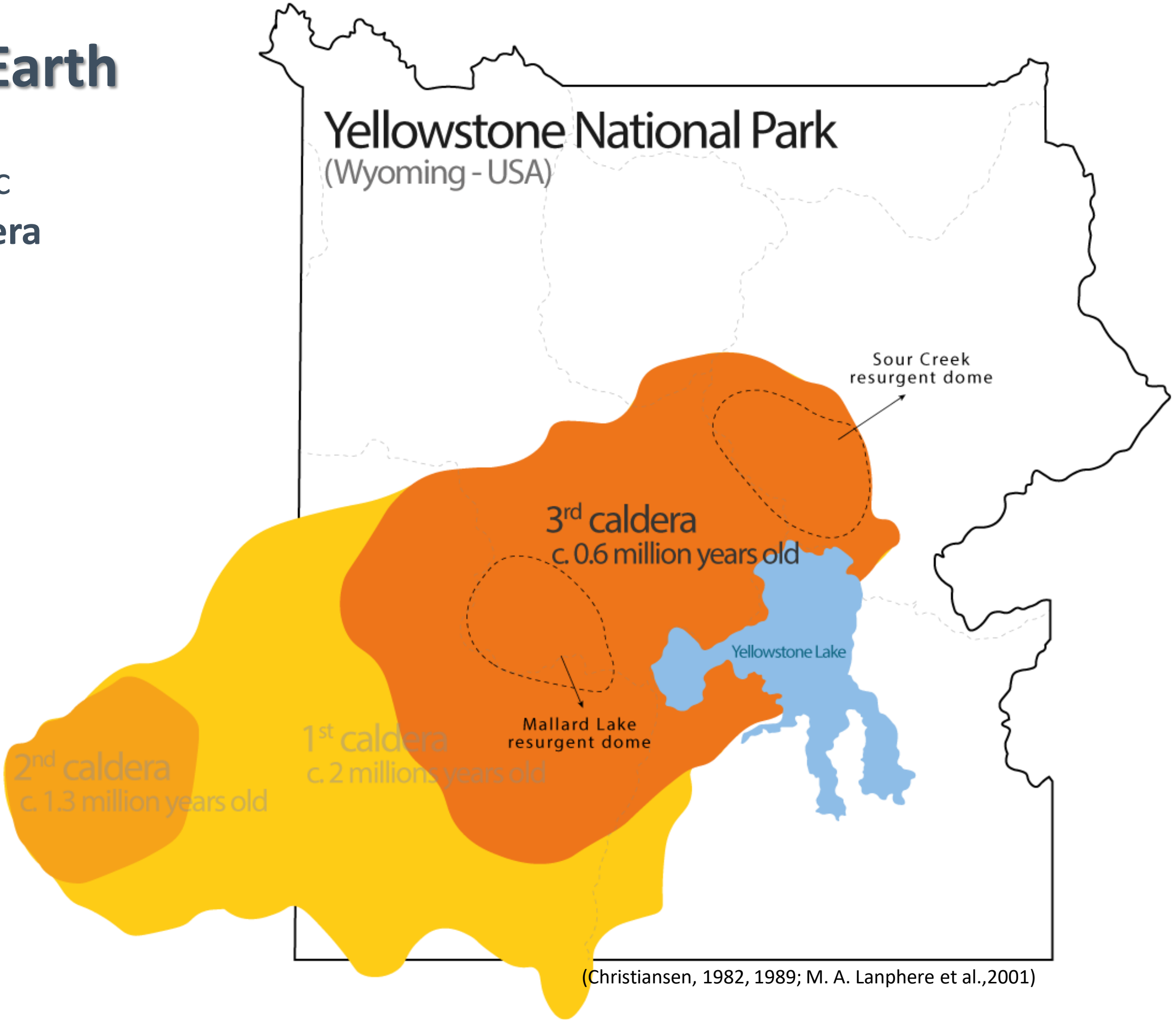
The Yellowstone Volcanic Field is one of the largest centers of silicic magmatism on Earth

The **Yellowstone hotspot** is responsible for a series of volcanic eruptions over millions of years, creating the **Yellowstone Caldera** and other volcanic features





(Christiansen, 1982, 1989; M. A. Lanphere et al.,2001)

Yellowstone draws significant scientific attention due to its massive eruption potential and active geothermal system

Yellowstone: cosa accadrebbe se eruttasse il temuto supervulcano?

Spesso si sente dire che Yellowstone stia per eruttare. Ma è davvero così?

Yellowstone è un vulcano attivo situato principalmente in Wyoming, negli USA, sotto l'omonimo parco nazionale. A differenza dei classici vulcani, non è visibile una struttura "a cono" che svetta nel cielo come una montagna: Yellowstone infatti è una "grande caldera", proprio come i l'area dei Campi Flegrei in Campania.

July 23, 2024
a hydrothermal explosion occurred at **Biscuit Basin** serving as a stark reminder of the volcanic-geothermal hazards in the park

Studying the **thermal state** of the Crust beneath the Yellowstone National Park is crucial as it provides insights into the dynamics of one of the world's most active volcanic systems

GOAL AND APPROACH

Investigate the **thermo-rheological state of Yellowstone crust**, focusing on the interactions between **thermal dynamics** and **crustal mechanics**, which are essential for evaluating volcanic activity, geothermal potential, and the region's long-term stability

MODELLING WORKFLOW

Curie Surface Mapping & Geometry set-up

- From Aeromagnetic data to Curie surface at depth
- Integration of geological and geophysical information for constructing model geometry

⬇

3D Conductive Thermal Modelling

Given the large scale of the study area, a conductive approximation is appropriate, as it accurately represents the dominant heat transfer process over vast regions

Thermal Parameters Optimization Process

Iterative Approach aimed at minimize the residuals between MODELLED and MEASURED data

⬇

Rheological Model

- Comprehensive modelling of brittle-ductile transition
- Correlation with earthquake distribution (seismicity cut-off)

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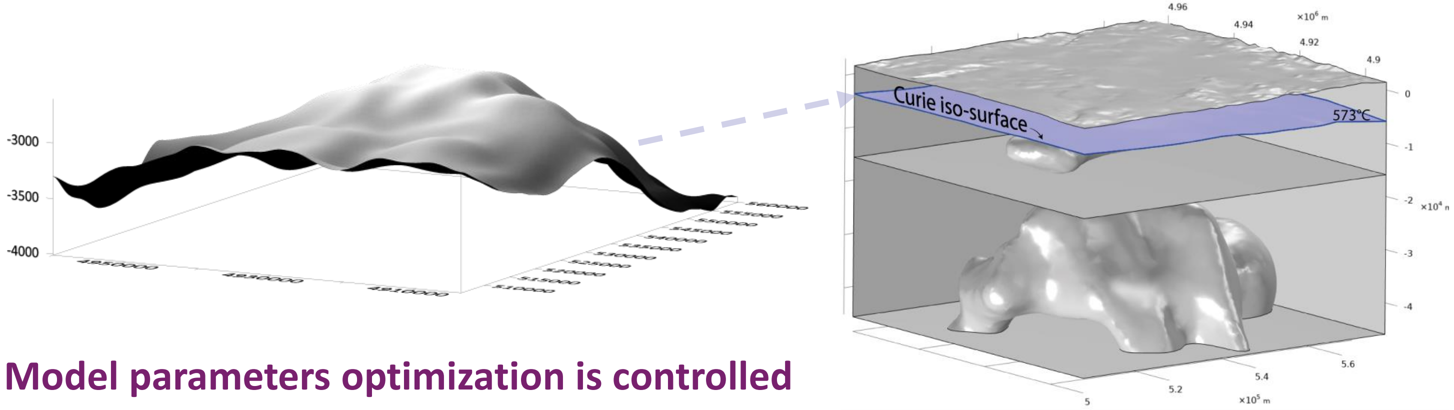
The Curie iso-surface* was obtained using a high-resolution aeromagnetic dataset, with techniques based on spectral analysis of magnetic anomalies

The **Curie surface** is the depth in the crust where temperatures reach the Curie point, causing magnetic minerals to lose their magnetization

The depth of the Curie surface is important in geophysics because it **gives insight into the thermal structure of the Earth's crust** and helps identify areas with potential geothermal resources



Model parameters optimization is controlled by the Curie isotherm at 573°C

*The Curie isosurface mapping originates from Dr. *Brahmi Mouna* PhD thesis (2017)

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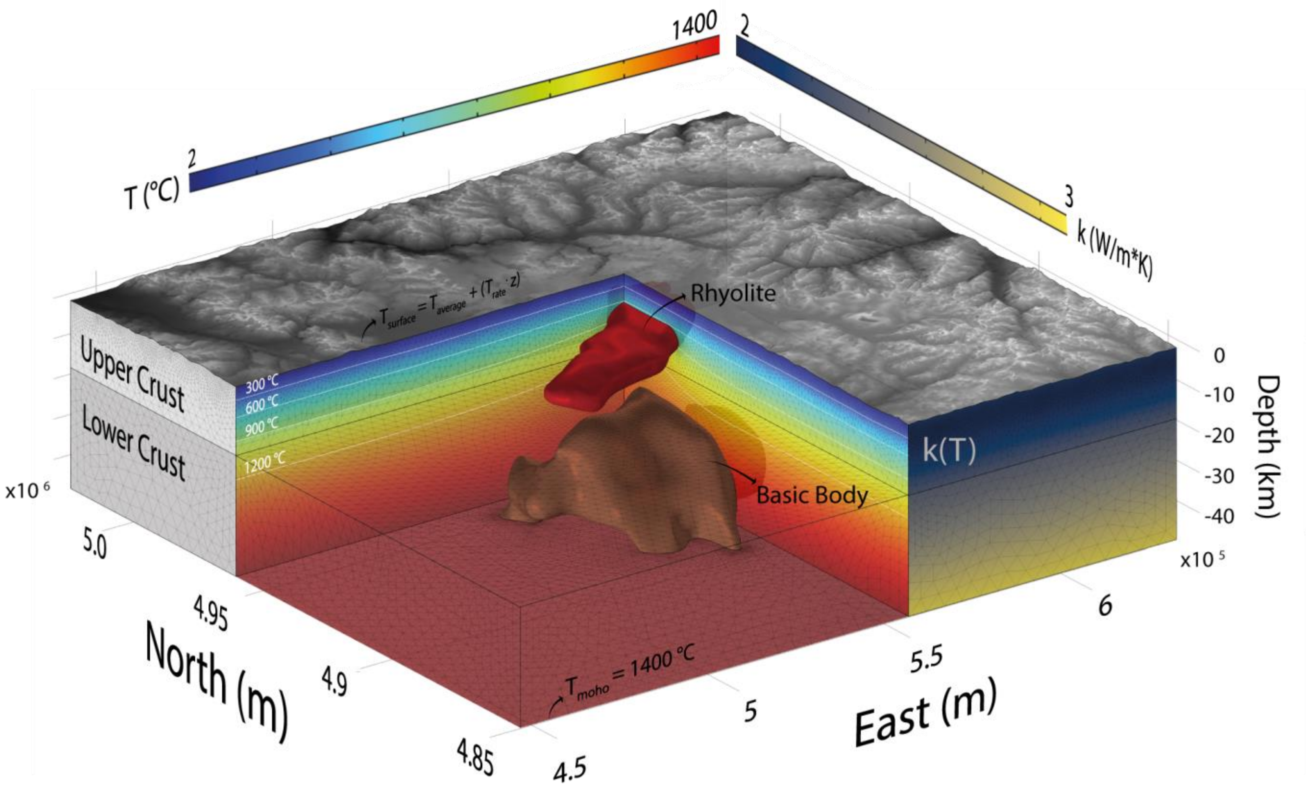
From literature conceptual model to 3D THERMAL MODEL of the Yellowstone magmatic system



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PARAMETER OPTIMIZATION

$$LS(\mathbf{p}) = \sum_{i=1}^{N} w_i \cdot \left(y_{\text{modelled},i}(\mathbf{p}) - y_{\text{measured},i}\right)^2$$

Method: **COORDINATE SEARCH**

Once calculated the **Least Square Objective Function (LS)**, representing the difference between simulated model values and experimental data, the associated **RMSE** is given by:

$$\textbf{Root Mean Square Error (RMSE)} = \sqrt{\frac{LS \times 2}{N}}$$

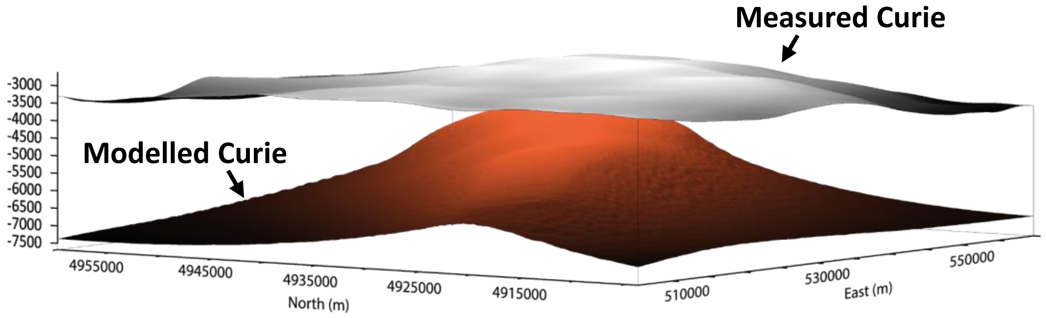
Where $N=9200$ is the **number of experimental data points** from the calculated Curie Surface. The smaller the **RMSE**, the better the model's predictive accuracy.

Parameter	Symbol	Law	Upper Crust		Lower Crust	Rhyolite	Basic Body
			scenario 1 $k_{ii} = k_{jj}$	**scenario 2** k_{zz}			
Thermal conductivity **(scenario 1)**	$k_{ii} = k_{jj} = k_{zz}$ [W/(m^3 K)]	$k(T) = \left[k_M + \left(\frac{T_{ref} \cdot T_M}{T_M - T_{ref}}\right) \cdot (k_{ii,jj,zz} - k_M) \cdot \left(\frac{1}{T} - \frac{1}{T_M}\right)\right]$ k_M = 1.8[W/(m^3 K)]; T_{ref} = 293[K]; T_M = 1473[K] [Sekiguchi, 1984]	2.1*	2.1*	4	2.4	1.6
Thermal conductivity **(scenario 2)**	$k_{ii} = k_{jj} \neq k_{zz}$ [W/(m^3 K)]		2.2*	1.2*	4	2.4	1.6
Heat capacity	c_p [J/(kg·K)]	/	900		1000	840	950
Density	ρ [kg m^{-3}]	/	2500		2800	2500	2900
Radiogenic Heat production	HP_{rad} [μW m^{-3}]	$A(z) = A_0 \cdot e^{-z/D_a}$ [Lachenruch, 1970]	4.0*	4.5*			
		D_a [m]	17.4*	19.4*			
Additional Heat production **(scenario 1)**	HP [μW m^{-3}]	/	8.0*	/			
Magmatic Heat production	HP [μW m−3]	/				1.45*	19.0*

*optimized parameters

- Over **1200 iterations** were conducted, stabilizing RMSE within a temperature range of 165°C
- This indicates that the process achieved a consistent **objective function plateau**
- However, the lateral sides of the surface remain significantly divergent from the expected Curie surface profile, which exhibits a more uniform regional behavior

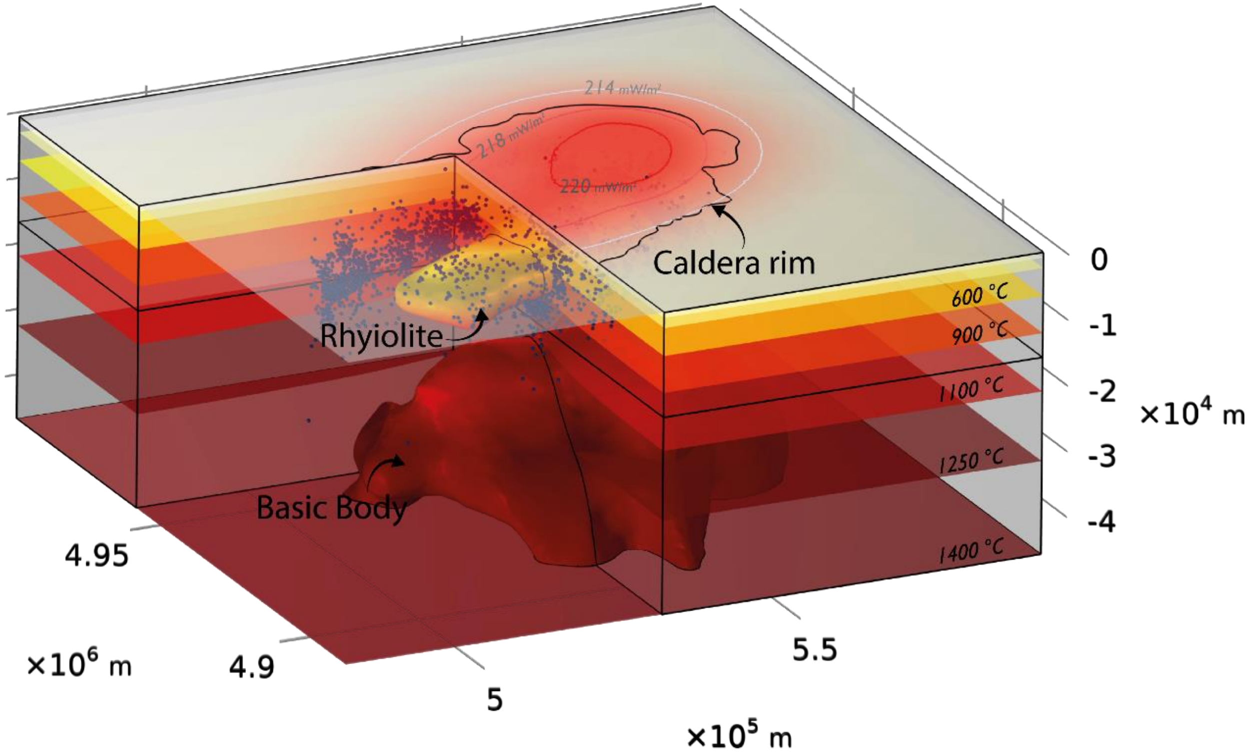
This discrepancy suggests that adjustments to the modelling approach may be needed to achieve closer alignment with the measured Curie surface



$$\nabla \cdot (-k\nabla T) = HS_{rhyolite} + HS_{basicbody} + A_{radiogenic}$$

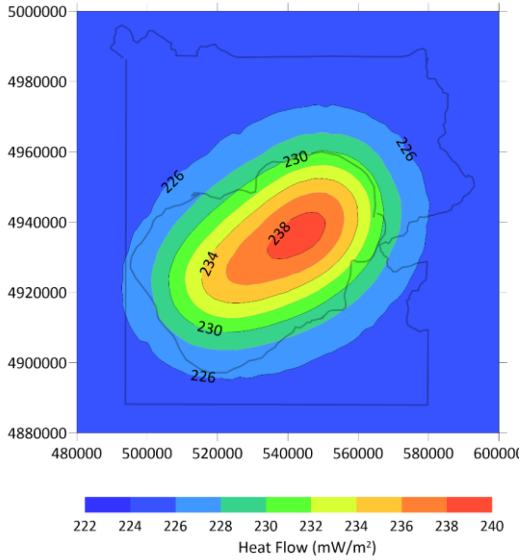
Additional «generic» Heat Source

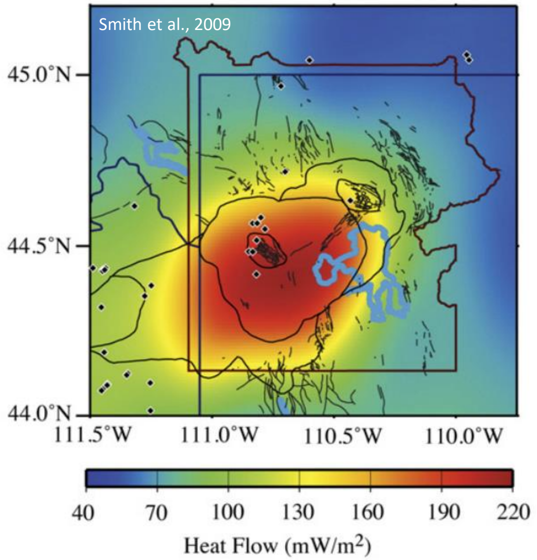
$$\nabla \cdot (-k\nabla T) = HS_{rhyolite} + HS_{basicbody} + HS_{generic} + A_{radiogenic}$$



MODEL VALIDATION

Surfac Heat Flux anomaly (SHF)





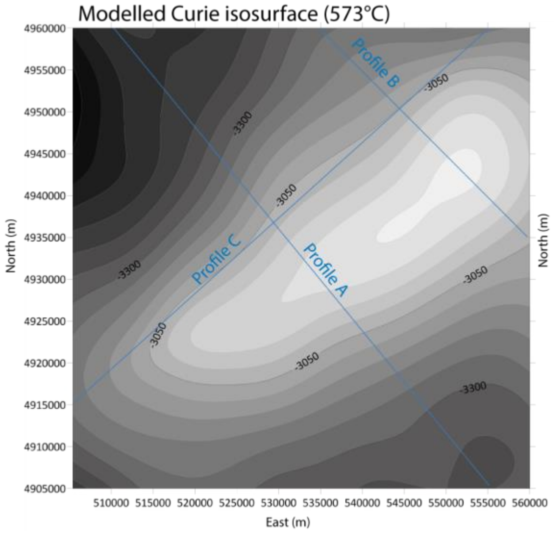
Average Heat Flow:

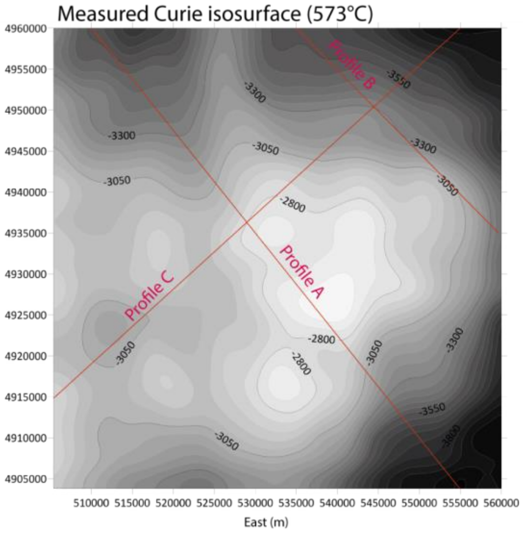
100 (outside caldera) -220 (inside caldera) mW/m²

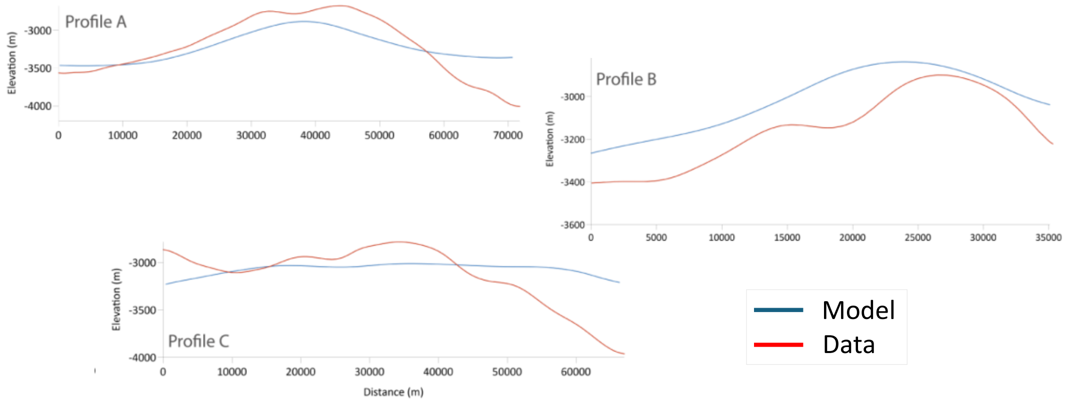
Localized Heat Flow (e.g. Geyser Basins):

Up to 500 mW/m², with extreme cases reaching 2,000 mW/m²

Curie iso-surface (~573°C)

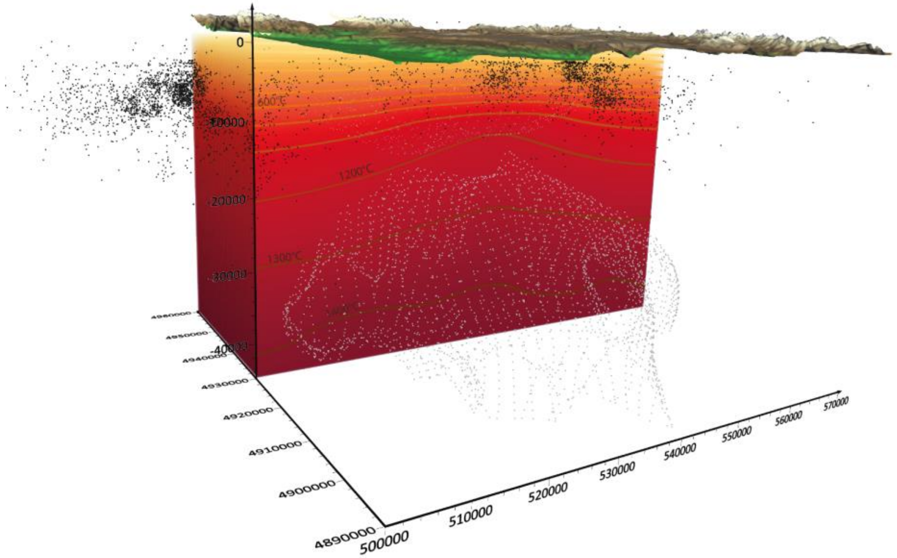


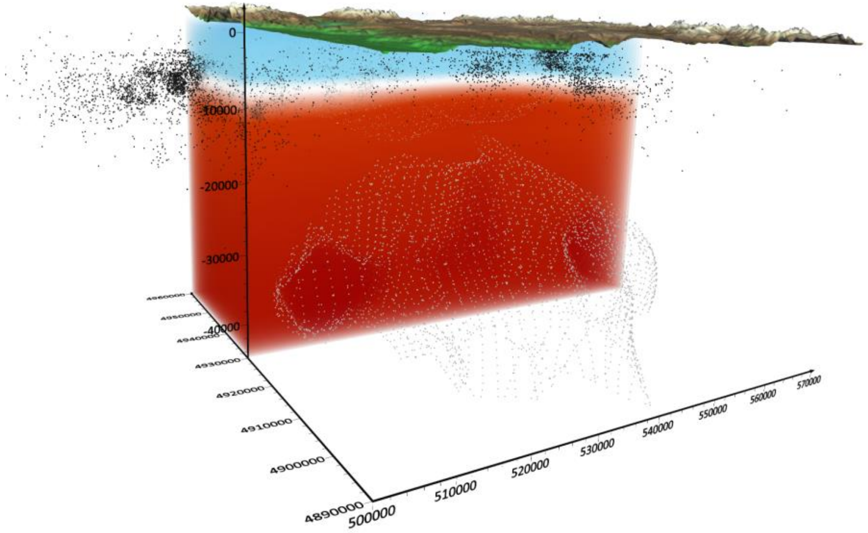




FROM THERMAL TO RHEOLOGICAL MODELLING

RHEOLOGY VALIDATION THROUGH SEISMIC EVENTS DISTRIBUTION



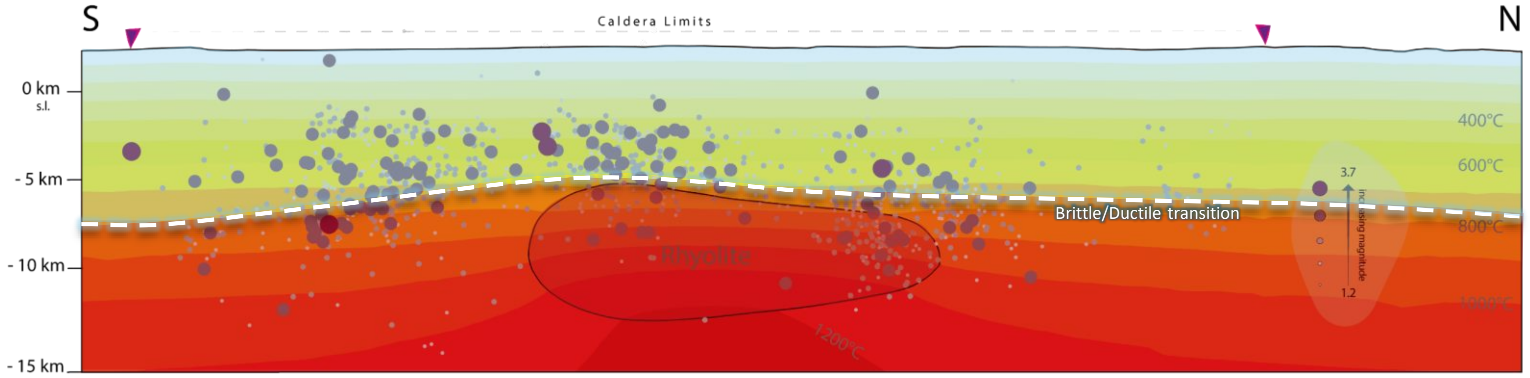


Brittle behaviour is expressed by the linear friction failure law proposed by Sibson (1974):

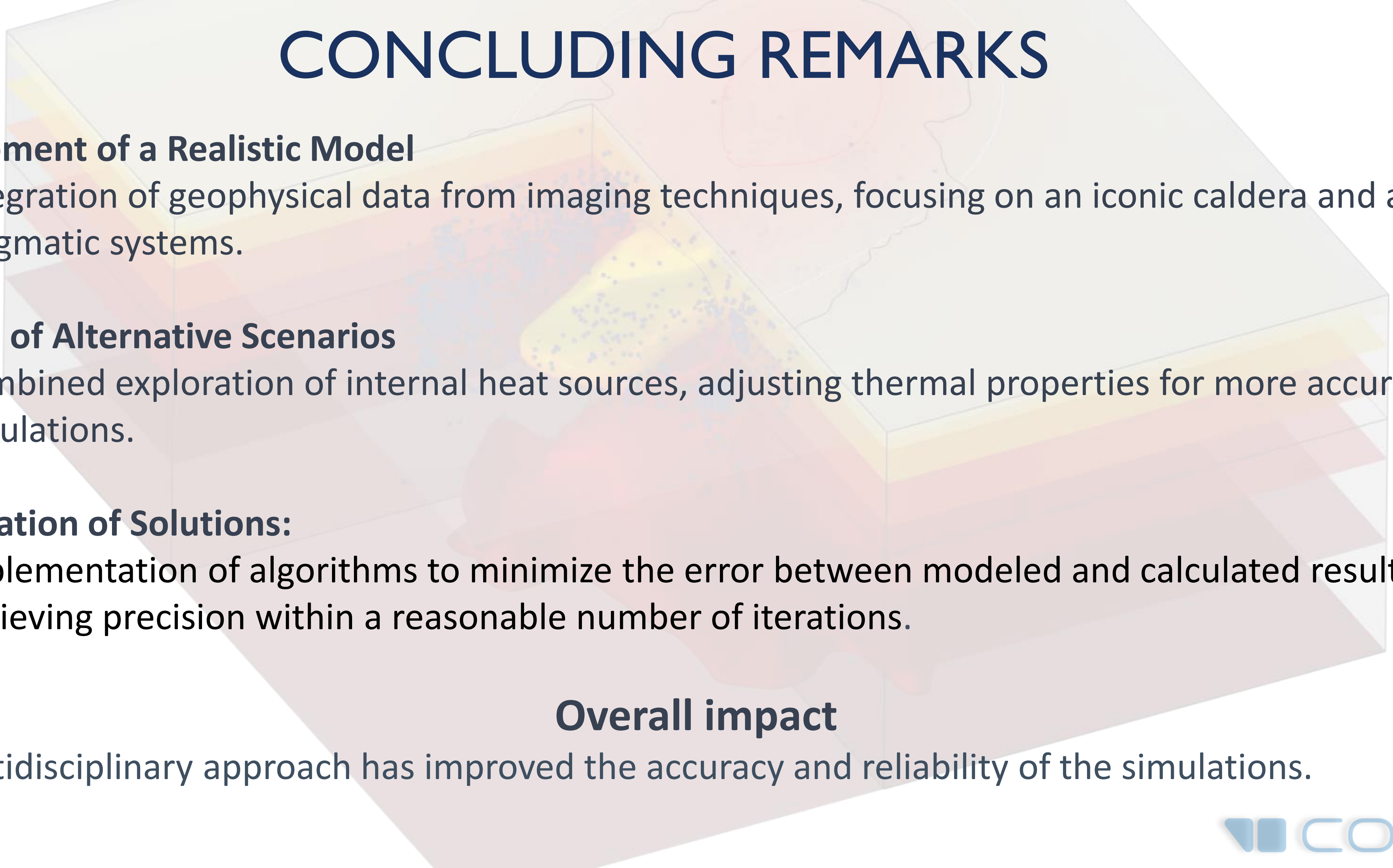
$$(\boldsymbol{\sigma_1 - \sigma_3})_{\boldsymbol{Brittle}} = \beta \cdot \rho \cdot g \cdot (1 - \lambda)$$

At sufficiently high temperatures, the creep strength strongly depends on temperature, and **ductile behaviour** can be empirically described by a **power law creep** (Kirby, 1983):

$$(\boldsymbol{\sigma_1 - \sigma_3})_{\boldsymbol{Ductile}} = \left(\frac{\dot{\varepsilon}}{A}\right)^{1/n} e^{\left(Q/nRT\right)}$$



CONCLUDING REMARKS



1. Development of a Realistic Model

- ✓ Integration of geophysical data from imaging techniques, focusing on an iconic caldera and associated magmatic systems.

2. Analysis of Alternative Scenarios

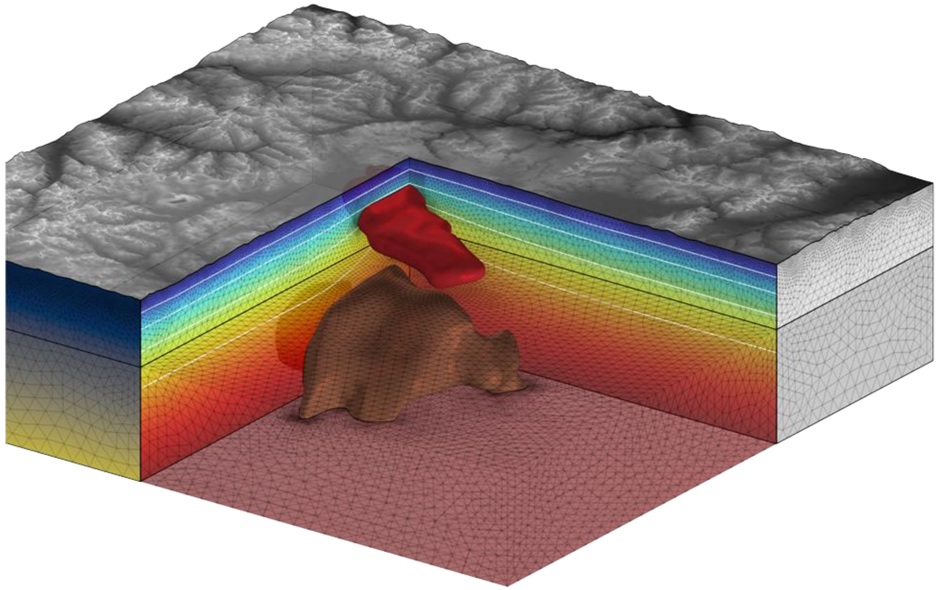
- ✓ Combined exploration of internal heat sources, adjusting thermal properties for more accurate simulations.

3. Optimization of Solutions:

- ✓ Implementation of algorithms to minimize the error between modeled and calculated results, achieving precision within a reasonable number of iterations.

Overall impact

A multidisciplinary approach has improved the accuracy and reliability of the simulations.



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Thanks for your attention!

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