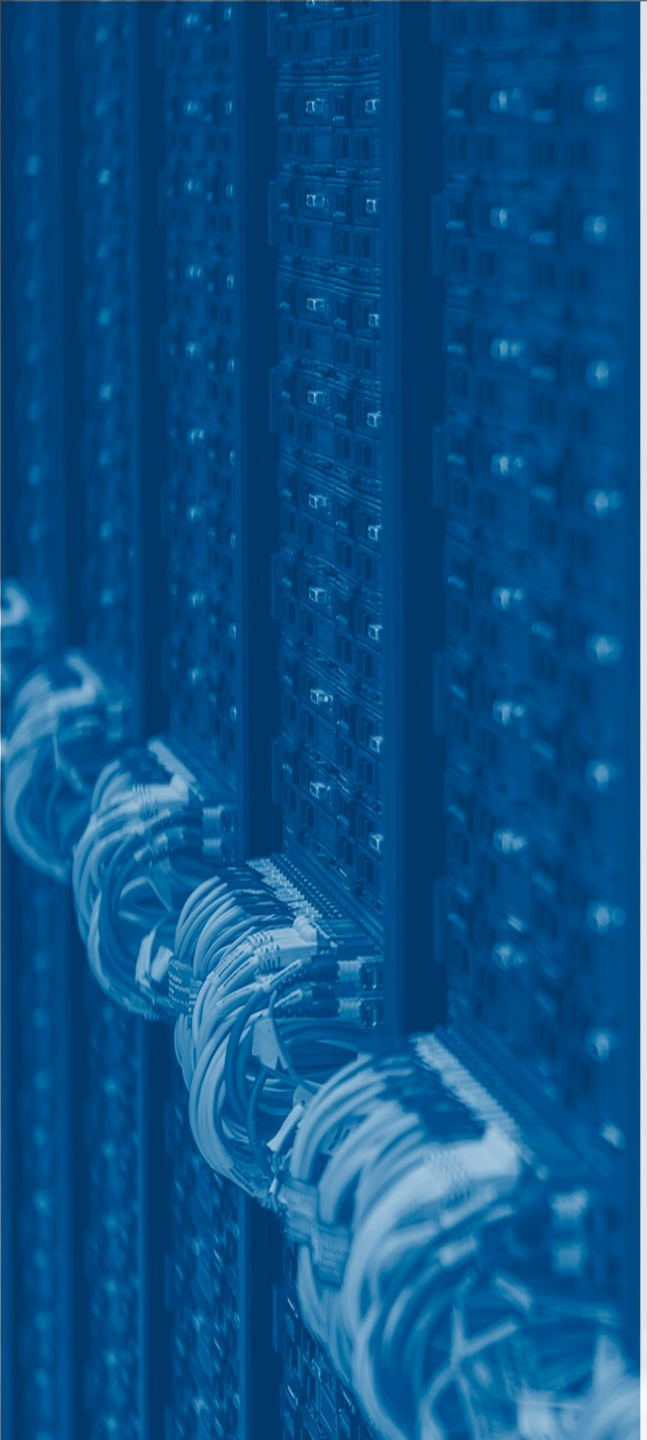

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

HPC electromagnetic modeling for geotermal reservoir charaterization: Tenerife case study

Octavio Castillo-Reyes[1], *Juanjo Ledo*[2], *Perla Viña-Varas*[2], *Pilar Queralt*[2]

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Barcelona Supercomputing Center (BSC)

[2] Institut Geomodels, Departament de Dinàmica de la Terra i de l'Oceà
University of Barcelona (UB)

HPC, Deep Learning, and Numerics in Geophysics
MATHROCKS WORKSHOP 2021

Motivation

- Electromagnetic (EM) methods, both active and passive, help mapping the subsurface:
  - Electrical conductivity/resistivity as a **diagnostic physical property**
  - They are **sensitive to fluids**
  - Among the most **cost-effective** geophysical data
  - Effective both for **soil characterization and monitoring**

- Numerical simulations have become **inexpensive**:
  - Allow **validating our models** by direct comparison between data and synthetics

Oil & gas

Geothermal

Mineral exploration

Volcanology

Geophysical EM modeling tool

- **PETGEM**
  - Main driver is mostly written in Python
  - High-order edge finite element method (**accurate**)
  - Unstructured and adapted tetrahedral meshes (**flexible**)
  - HPC support (**feasible runtime**)
  - Open source under GPLv3 license (**free**)
  - https://petgem.bsc.es

- Curl-curl formulation of the Maxwell's equations in frequency domain (EM fields are time-harmonic)

$$\nabla \times \mathbf{E} = i\omega\mu\mathbf{H} + \mathbf{K},$$
$$\nabla \times \mathbf{H} = \mathbf{J} + (\sigma + i\omega\epsilon)\mathbf{E}$$

$\mathbf{J}, \mathbf{K}$ = electric and magnetic sources
i = imaginary unit
ω = angular frequency
μ = free-space magnetic permeability
ϵ = constant model permittivity
σ = variable electric conductivity tensor

Active-source EM
Controlled source electromagnetic method (CSEM)

$$\nabla \times \nabla \times \mathbf{E} - i\omega\mu\sigma\mathbf{E} = i\omega\mu\mathbf{J}$$

Passive-source EM
Magnetotelluric method (MT)

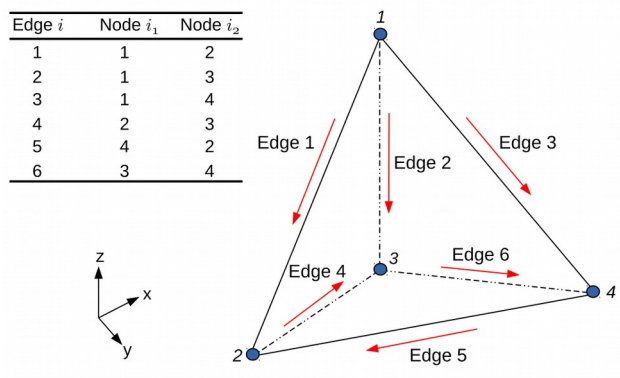
$$\nabla \times \nabla \times \mathbf{E} - i\omega\mu\sigma\mathbf{E} = 0$$

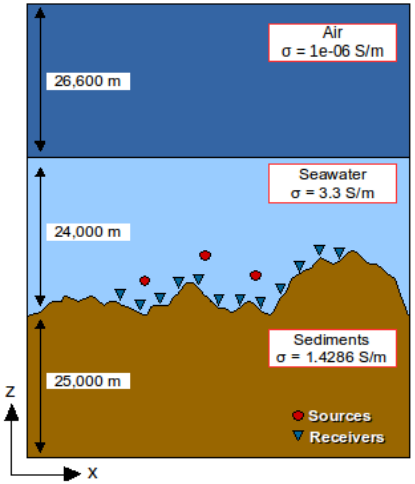
Geophysical EM modeling tool

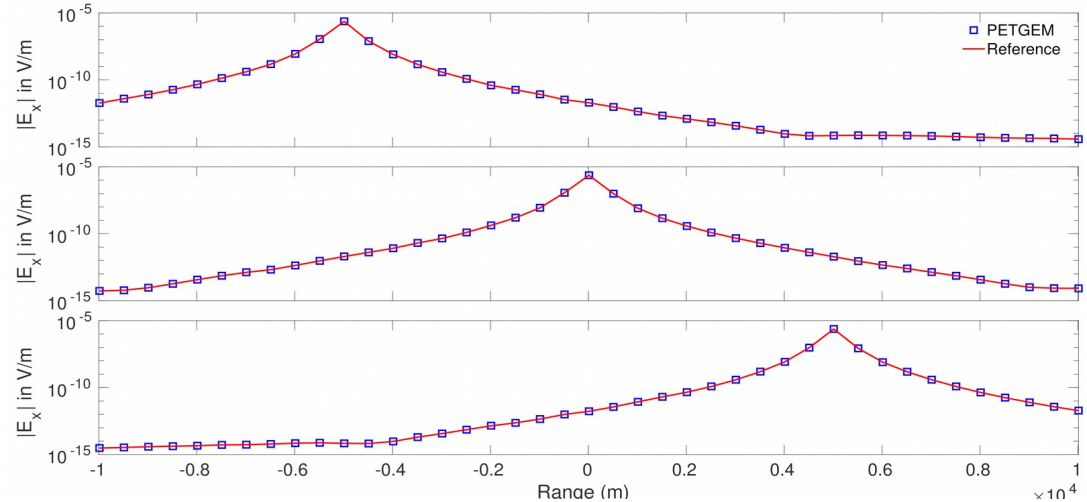
2018

Castillo-Reyes, O., de la Puente, J., Cela, J. M. (2018). **PETGEM: A parallel code for 3D CSEM forward modeling using edge finite elements**. Computers & Geosciences, vol 119: 123-136. ISSN 0098-3004. Elsevier.

Edge i	Node i_1	Node i_2
1	1	2
2	1	3
3	1	4
4	2	3
5	4	2
6	3	4



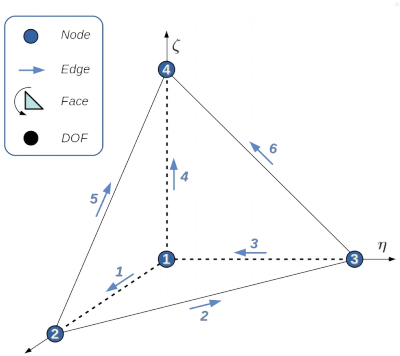


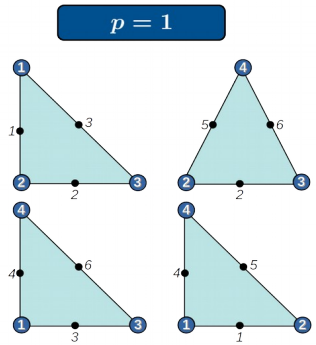


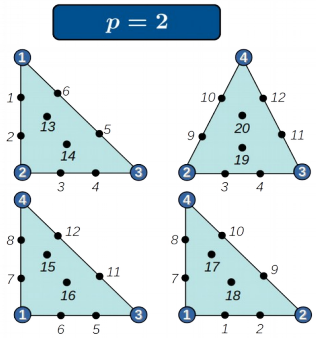
Geophysical EM modeling tool

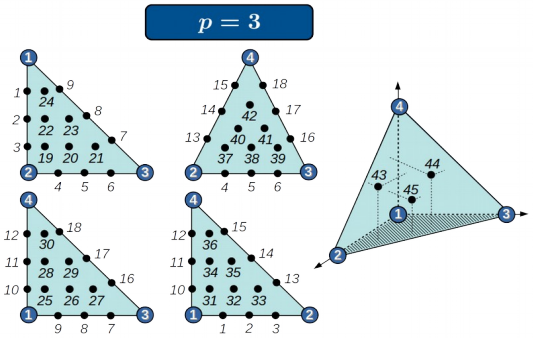
2018 2019

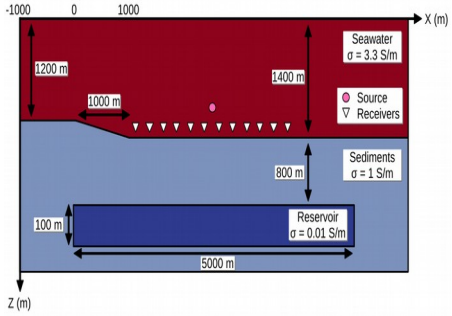
Castillo-Reyes, O., de la Puente, J., García-Castillo, L. E., Cela, J. M. (2019). **Parallel 3D marine controlled-source electromagnetic modeling using high-order tetrahedral Nédélec elements**. Geophysical Journal International, ggz285, vol 219: 39-65. ISSN 0956-540X.

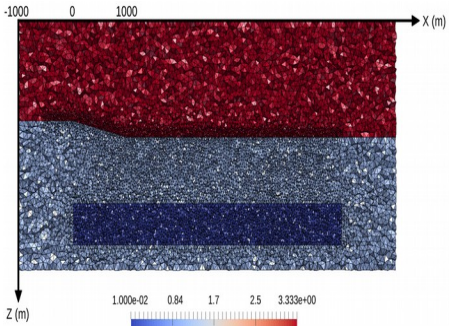


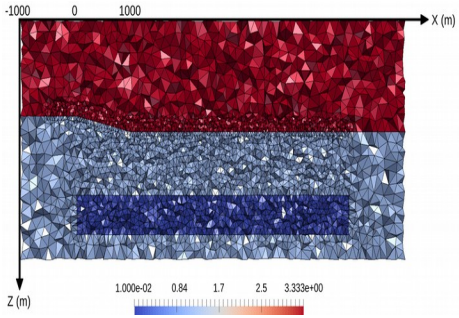


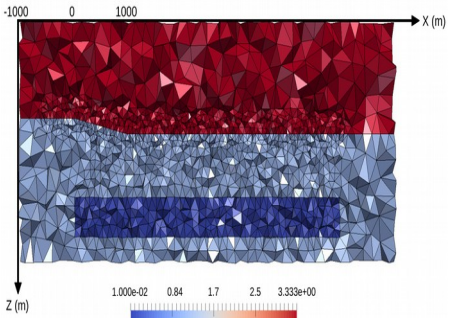












Geophysical EM modeling tool

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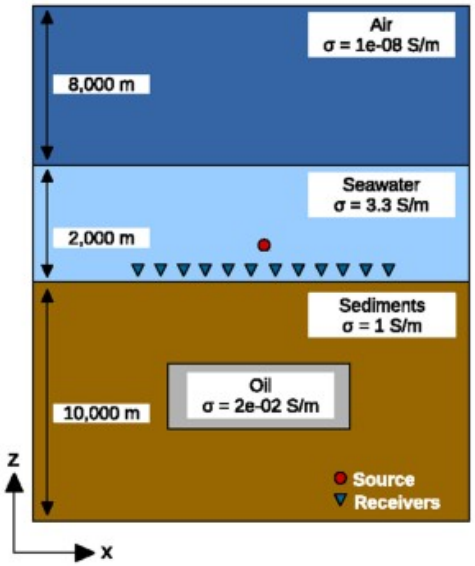
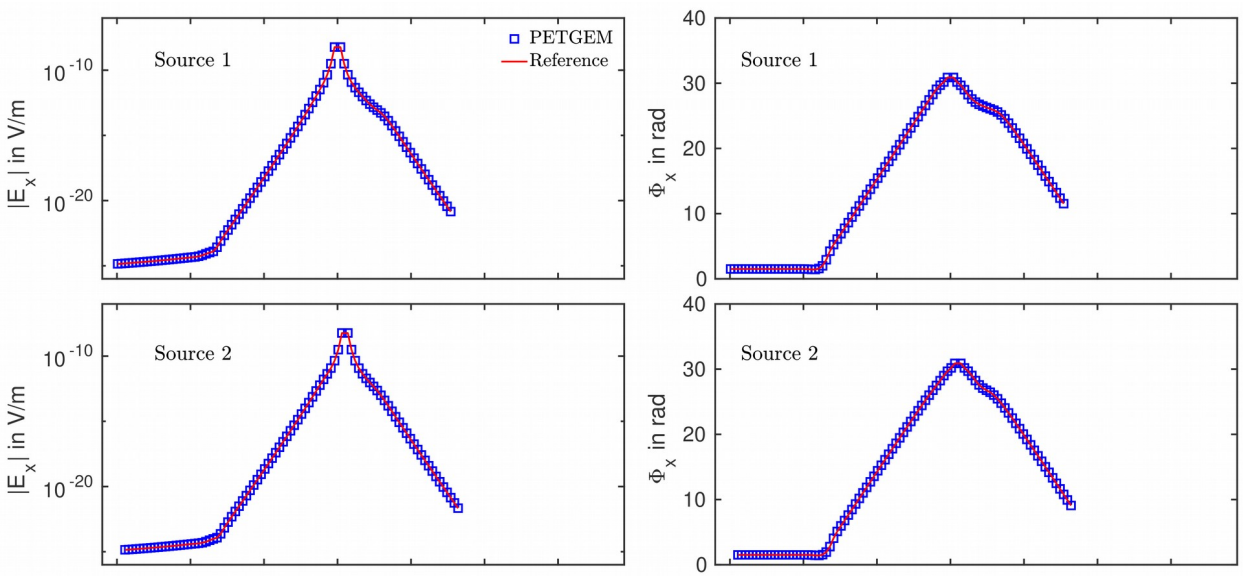
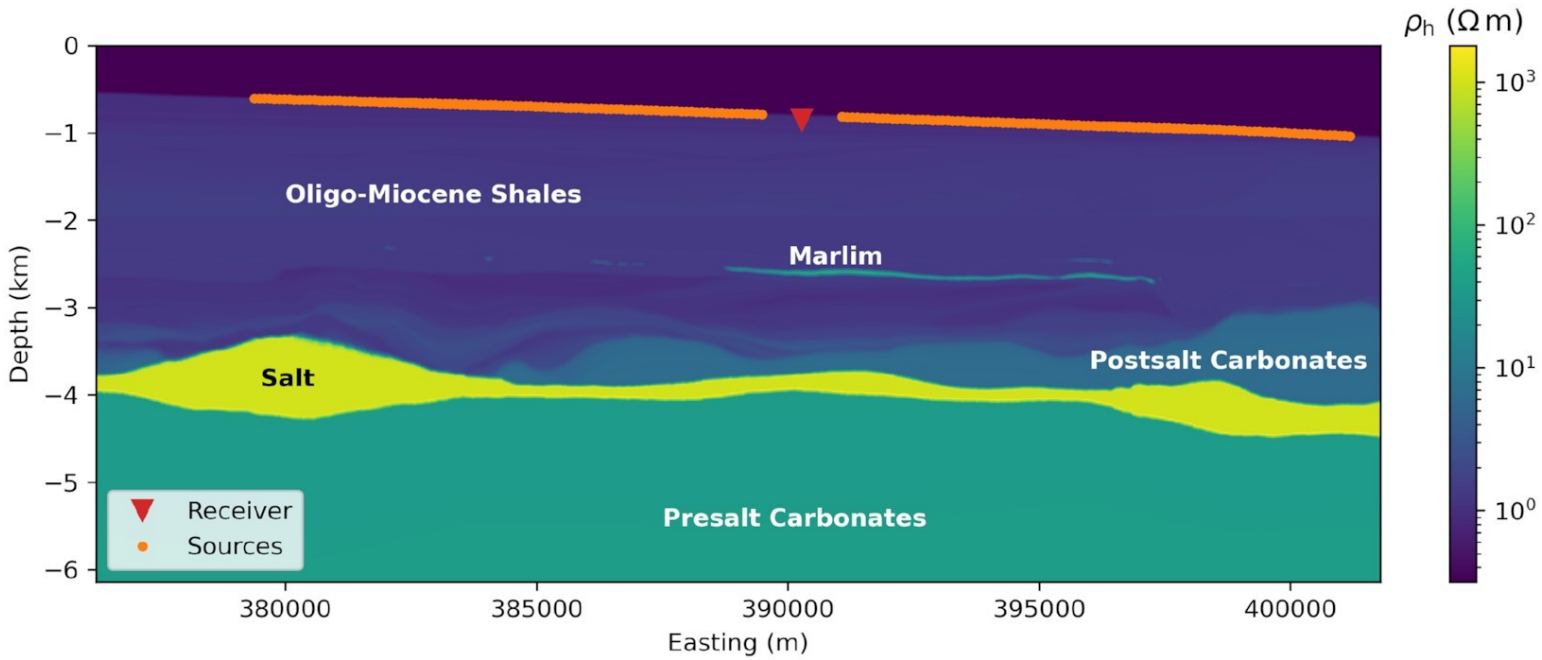




Geophysical EM modeling tool

2018 2019 2021 (a)

Werthmüller, D., Rochlitz, R., Castillo-Reyes, O., & Heagy, L. (2021). **Towards an open-source landscape for 3-D CSEM modelling**. Geophysical Journal International, 227(1), 644-659.



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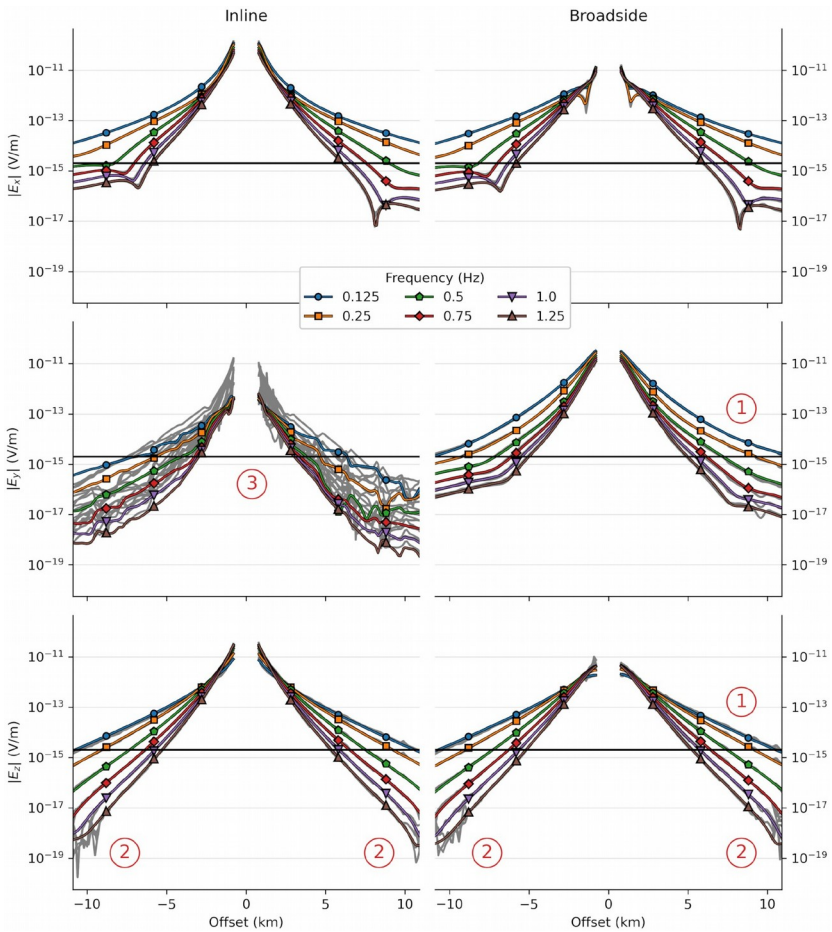
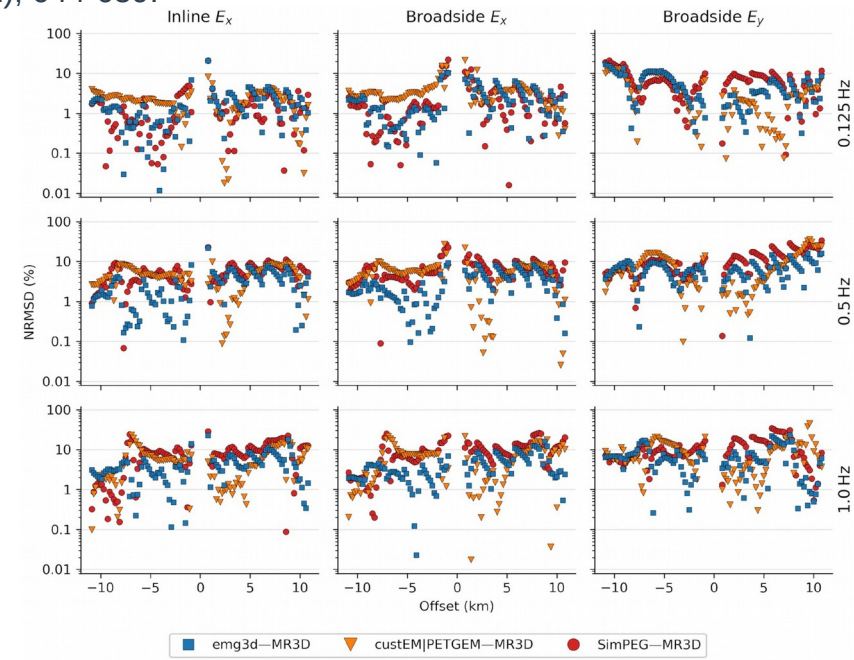


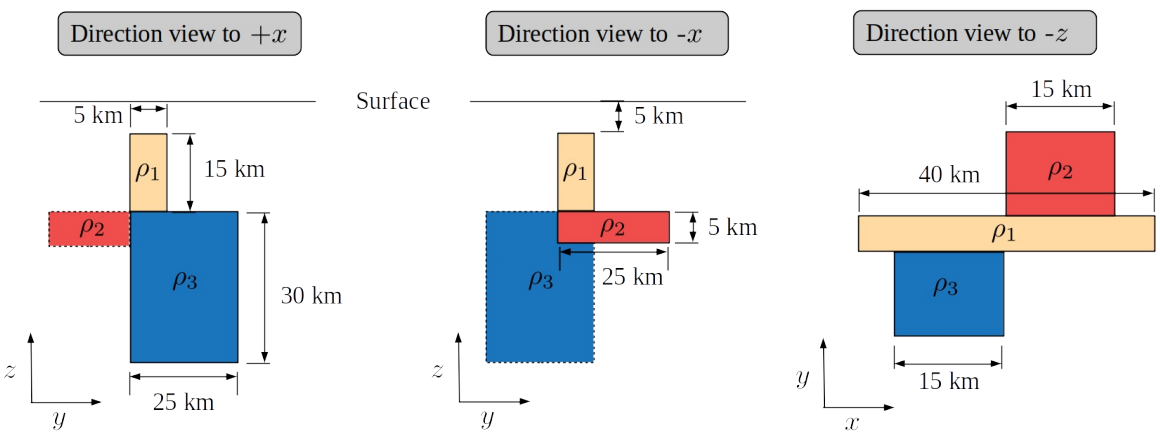


Code	#Procs	Runtime (s)	Memory (GiB)	#dof
custEM	64	872	230.1	1918106
emg3d	1	1246	0.5	5998992
PETGEM	96	524	175.4	1918106
SimPEG	4	422	12.8	720146

Geophysical EM modeling tool

2018 2019 2021 (b)

Castillo-Reyes, O., Modesto, D., Queralt, P., Marcuello, A., Ledo, J., Amor-Martin, A., de la Puente, J., García-Castillo, L.E. (2021). **3D magnetotelluric modeling using high-order tetrahedral Nédélec elements on massively parallel computing platforms**. Submitted to Computers & Geosciences.



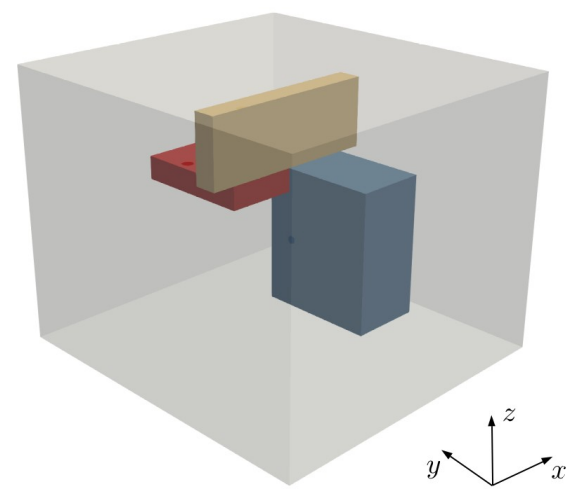
$\rho_{\text{air}} = 10^9\,\Omega\,\text{m}$

$\rho_{\text{earth}} = 100\,\Omega\,\text{m}$

$\rho_1 = 10\,\Omega\,\text{m}$

$\rho_2 = 1\,\Omega\,\text{m}$

$\rho_3 = 10\,000\,\Omega\,\text{m}$



Geophysical EM modeling tool

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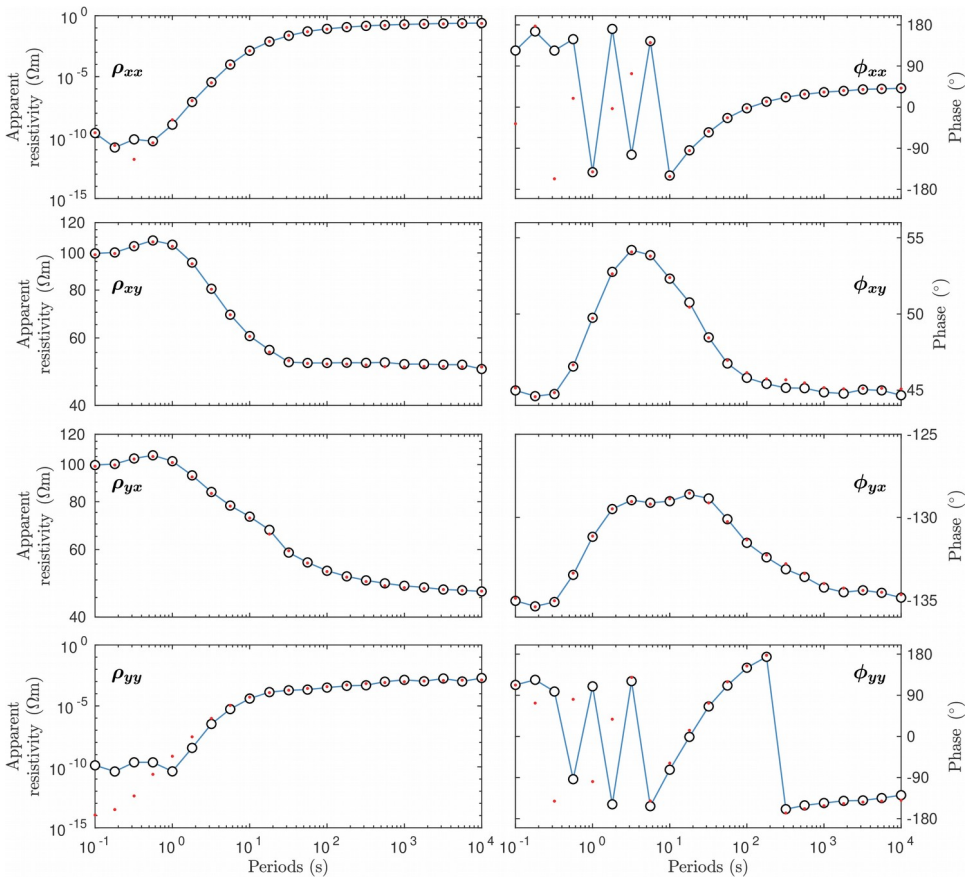
- Unstructured mesh adapted for **second-order** polynomials (2,774, 334 dofs)
- ≈14 min of run-time using 240 CPUs and the MUMPS parallel solver
- **Excellent run-times**
  - Reference: ≈57 hrs
  - PETGEM: ≈4.9 hrs
- **Positive** impact of **adapted meshes** for each period



Geophysical EM modeling tool

2018 2019 2021 (b)

- Extensively validated on realistic models:
  - Active-source and passive-source
  - Experience in this work-flow is crucial to **exploring useful underground resources**
  - What is next?
  - Transfer expertise from oil & gas to other **scenarios/applications**
    - **Geothermal energy**

GEO-URBAN

GEOTHERMICA

PIXIL

Interreg POCTEFA

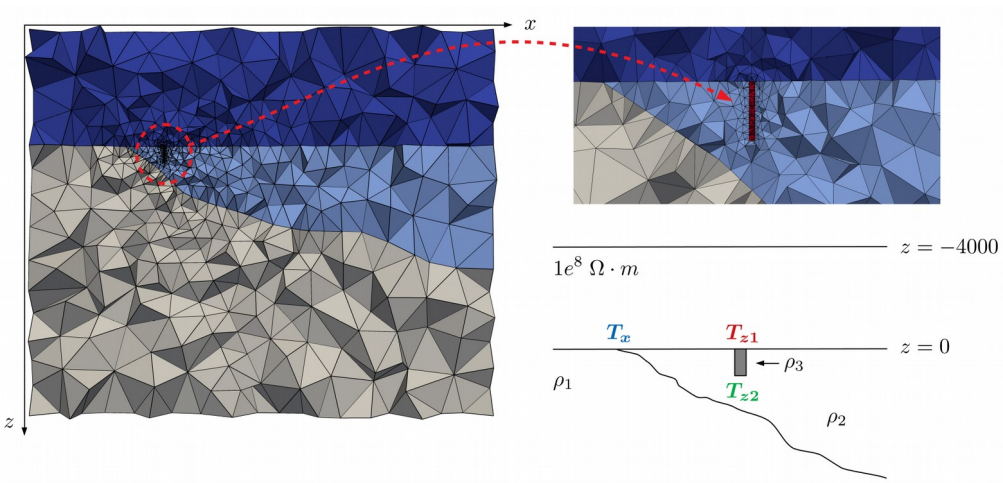
UNIÓN EUROPEA
UNION EUROPÉENNE

Geophysical EM modeling tool

2018 2019 2021 (c)

Castillo-Reyes, O., Queralt, P., Marcuello, A., & Ledo, J. (2021). **Land CSEM simulations and experimental test using metallic casing in a geothermal exploration context: Vallès Basin (NE Spain) case study**. IEEE Transactions on Geoscience and Remote Sensing.

- Vallés Basin (NE, Spain) relevant region because several **geothermal anomalies** are present there
- Modeling in the presence of **metallic borehole**



Case label	ρ_1 (Basement)	ρ_2 (Sediments)	ρ_3 (Casing)
$T_x\beta\beta\beta$	β	β	β
$T_{z1}\beta\beta\beta$	β	β	β
$T_{z1}\beta\beta\gamma$	β	β	γ
$T_{z1}\beta\beta\delta$	β	β	δ
$T_{z2}\beta\beta\gamma$	β	β	γ
$T_{z2}\beta\beta\delta$	β	β	δ
$T_x\alpha\beta\gamma$	α	β	γ
$T_{z1}\alpha\beta\delta$	α	β	δ
$T_{z2}\alpha\beta\gamma$	α	β	γ
$T_x\alpha\beta\delta$	α	β	δ
$T_{z1}\alpha\beta\gamma$	α	β	γ
$T_{z2}\alpha\beta\delta$	α	β	δ

$\alpha = 1000$ $\beta = 20$ $\gamma = 0.005$ $\delta = 0.001$

Geophysical EM modeling tool

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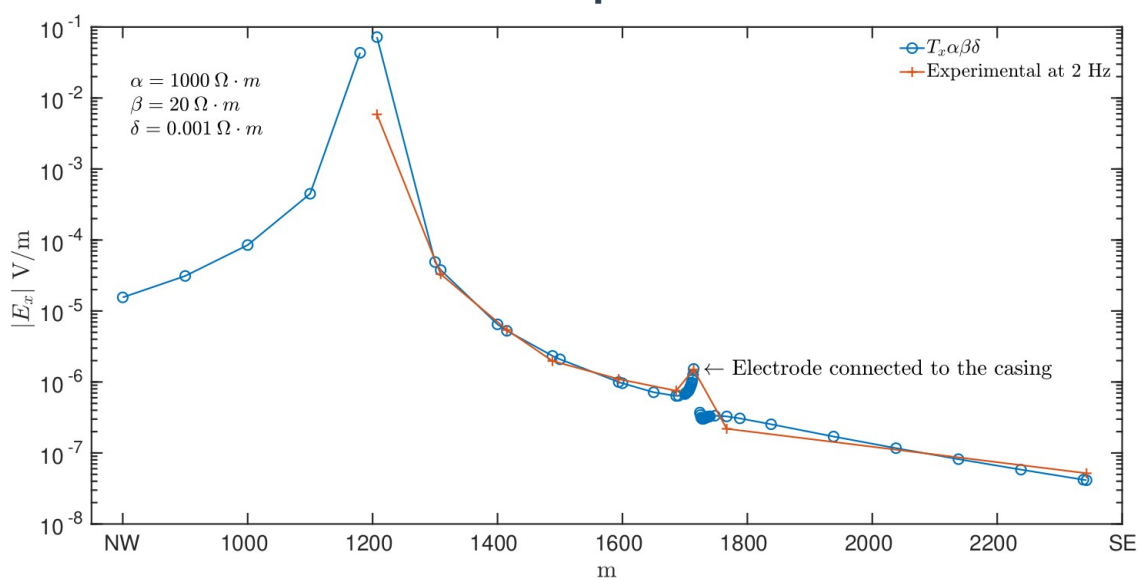
Castillo-Reyes, O., Queralt, P., Marcuello, A., & Ledo, J. (2021). **Land CSEM simulations and experimental test using metallic casing in a geothermal exploration context: Vallès Basin (NE Spain) case study**. IEEE Transactions on Geoscience and Remote Sensing.

- Comparison between experimental data in-situ of the Vallés Basin profile compared with synthetics obtained with **PETGEM**

Amplitude



Geophysical EM modeling tool

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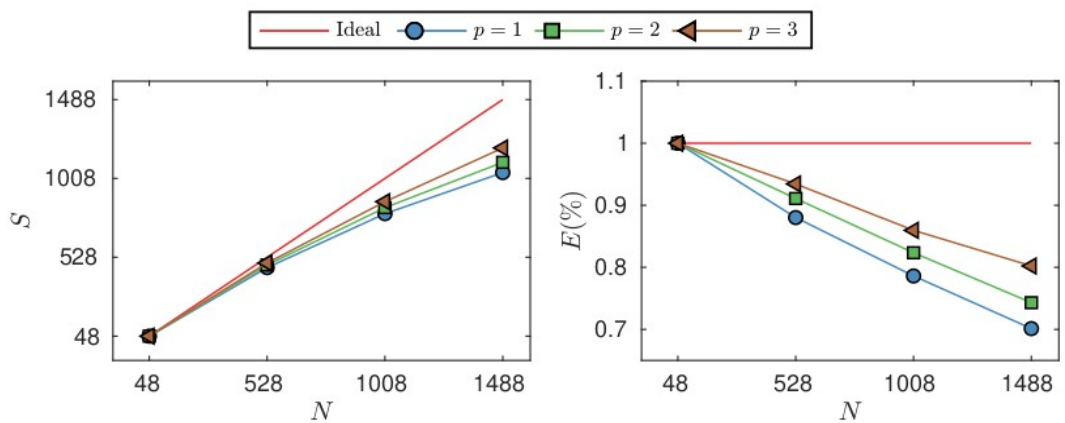
- **Excellent** and **competitive** run-times (**solver** is the main **discriminator)**
- Although **higher-order** polynomials increase the run-time, they offer **better parallel efficiency** ratios
- Computational efficiency depends of the **solver-type** and the **input model**

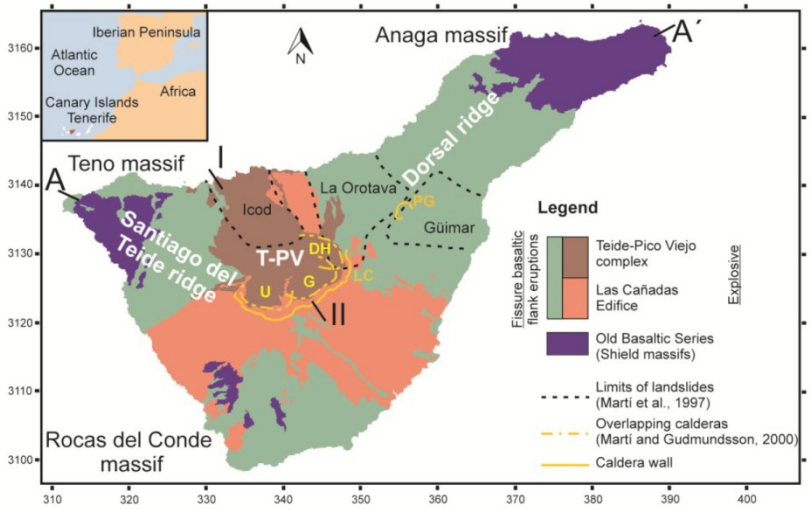


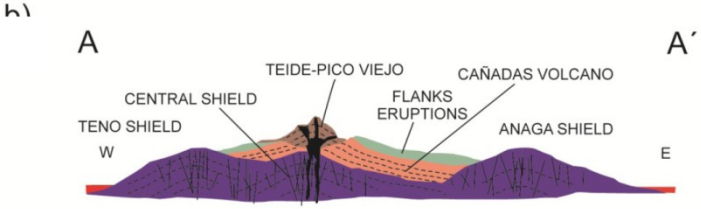
CPU	48	528	1008	1488
$p = 1$ with 1 249 109 dof				
Run-time	98.71	10.19	5.97	4.54
S	—	9.68	16.53	21.74
E (%)	—	.8806	.7861	.7013
$p = 2$ with 6 697 994 dof				
Run-time	392.18	39.14	22.67	17.02
S	—	10.01	17.29	23.04
E (%)	—	91.09	82.35	74.31
$p = 3$ with 19 454 679 dof				
Run-time	985.28	95.85	54.58	39.62
S	—	10.27	18.05	24.86
E (%)	—	93.44	85.96	80.22

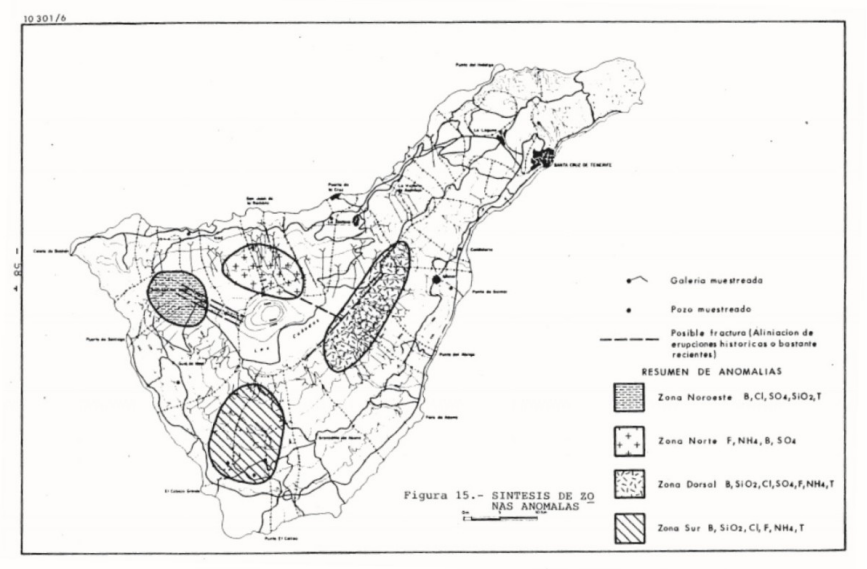
Tenerife island

- **Complex geological history**: alternation in both **constructive** and **destructive** episodes

- Target of **geothermal exploration** studies since the 80s



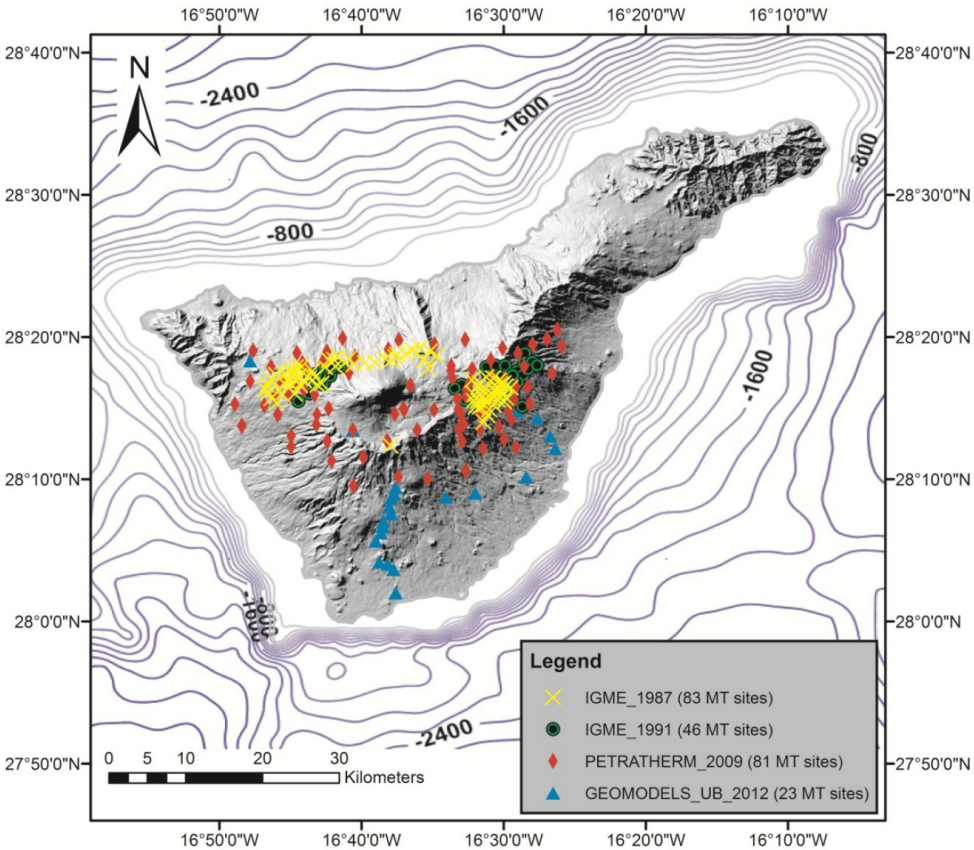




Water anomalies reported by the Geological and Mining Institute of Spain (IGME 1983-1993)

Tenerife island

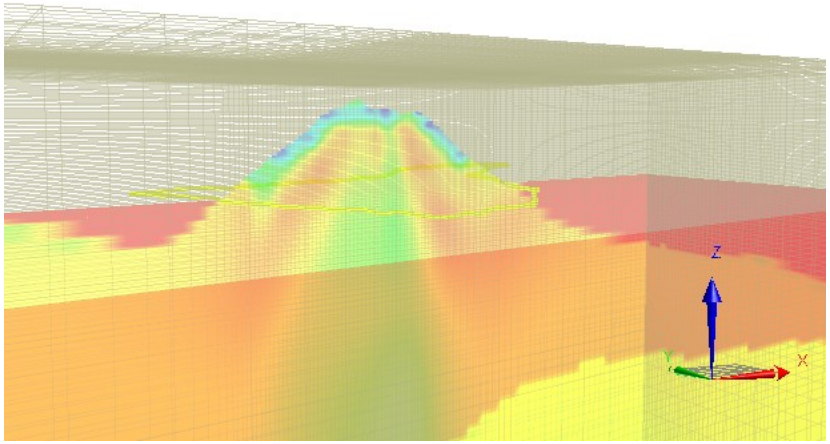
- **233 MT** sites in total
- **129 digitalized** from old MT surveys
- **3D** data dimensionality
- **Data distorted** by:
  - Steep topography
  - Surrounding ocean
- **Challenging** from a **numerical modeling** perspective

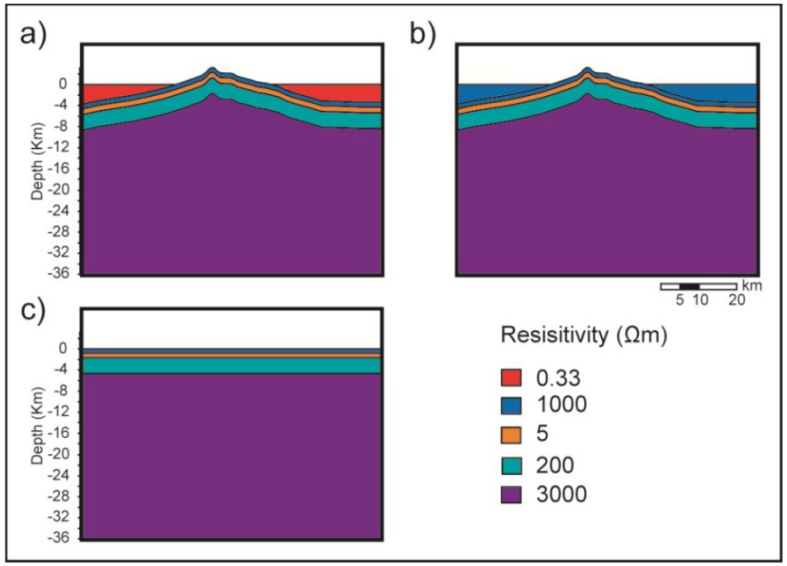


Tenerife island

- Steep topography and the surrounding ocean: **effect on the MT data**

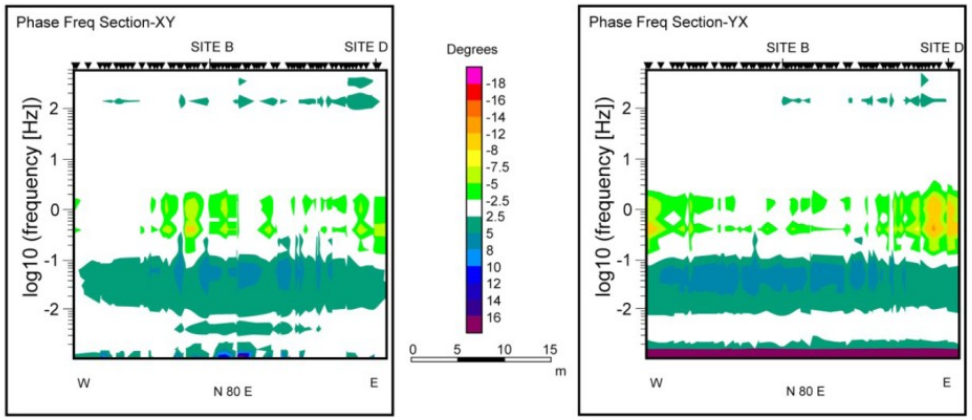
- Three different conceptual models:
  - (a) **Ocean model**: including topography and ocean
  - (b) **Land model:** including topography but not the conductive surrounding model
  - (c) **1D model**: no topography, neither ocean



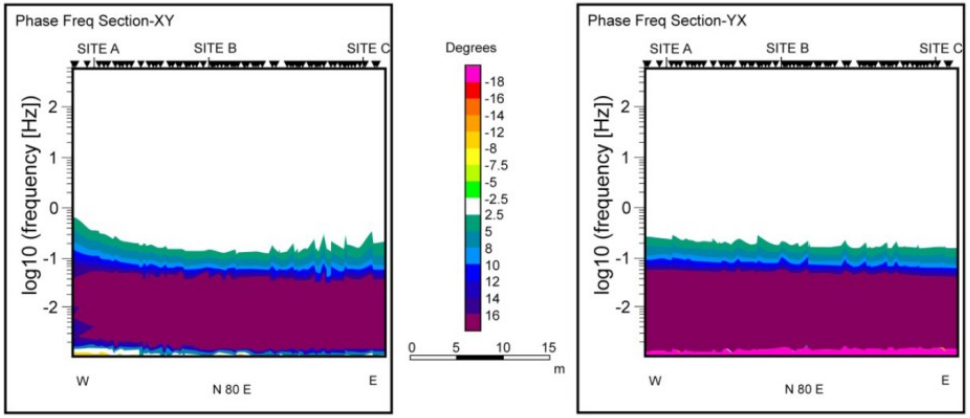


Tenerife island

- Steep topography and the surrounding ocean: **effect on the MT data**
- **MT data strongly distorted** by the presence of the steep topography and the surrounding ocean at **frequencies lower** than **0.1 Hz**



Pseudosection plots of phase difference between land and 1D model.

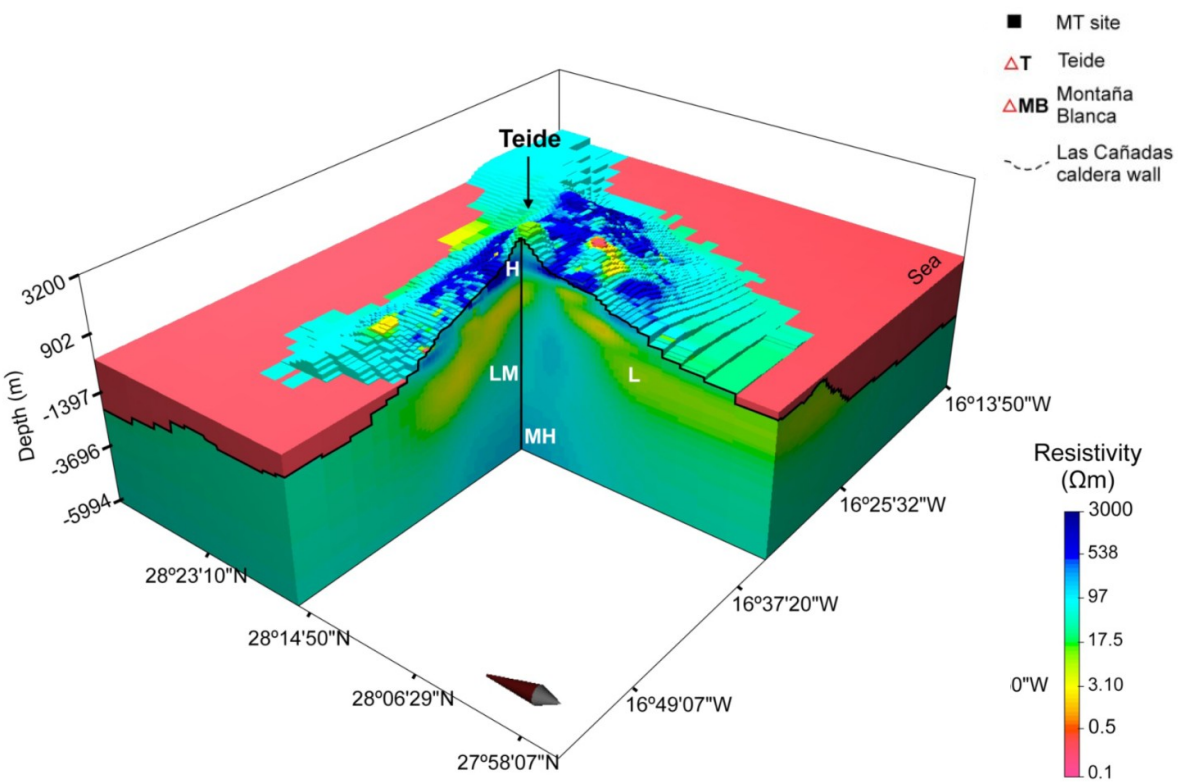


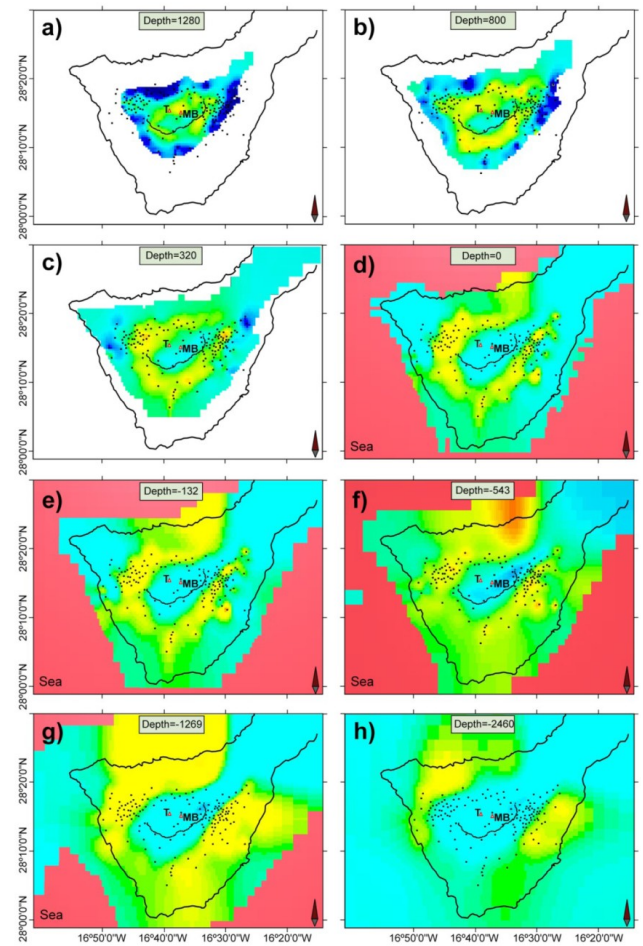
Pseudosection plots of phase difference between land and sea model.

Tenerife island: 3D resistivity model

- Most striking feature: **Low resistivity layer** (L) located in the central part of the island

- Low resistivity layer (L) **characterized by**:
  - Resistivity values **lower** than 10 Ohm.m
  - **Ring-shape open** in the central part of the island, in
  - agreement with the location of the Las Cañadas Caldera

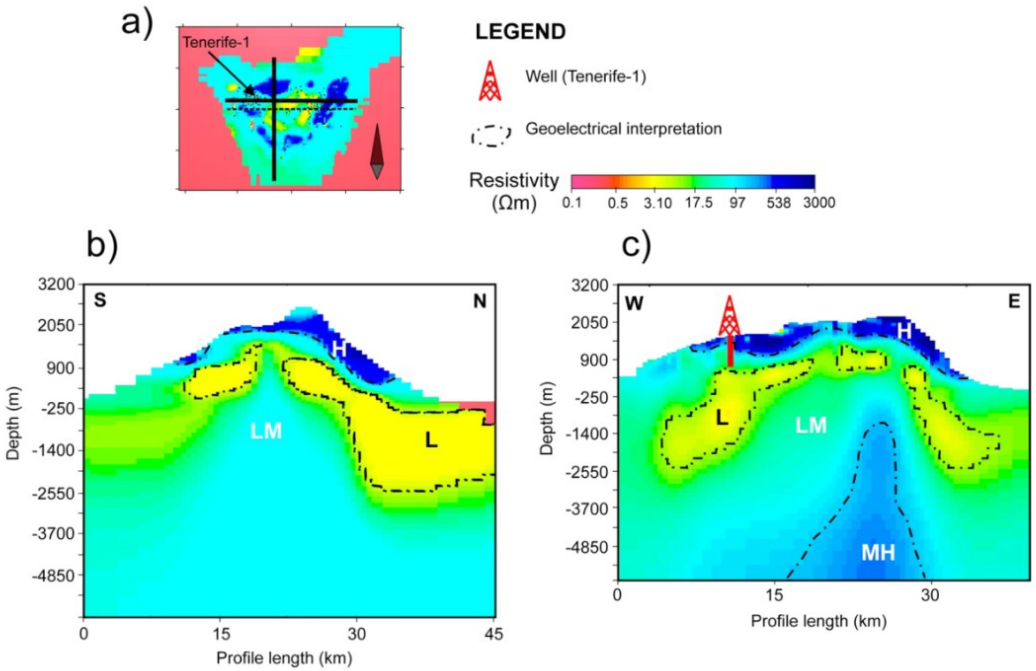


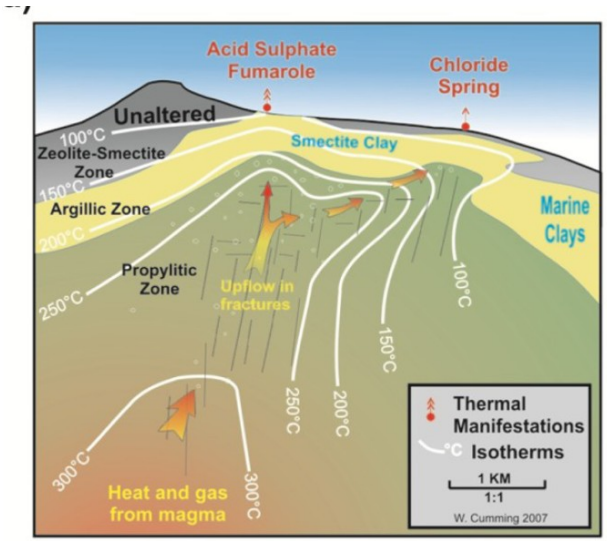


Tenerife island: geothermal system

- Resistivity distribution, from shallow to depth:
  - H: **High** resistivities, 1000 Ohm.m
  - L: **Low** resistivity layer, <10 Ohm.m
  - LM: **Low-medium** resistivities, 20-100 Ohm.
  - MH: **Medium-high** resistivities, 100-500 Ohm

Geoelectrical distribution of a **high-temperature geothermal system**



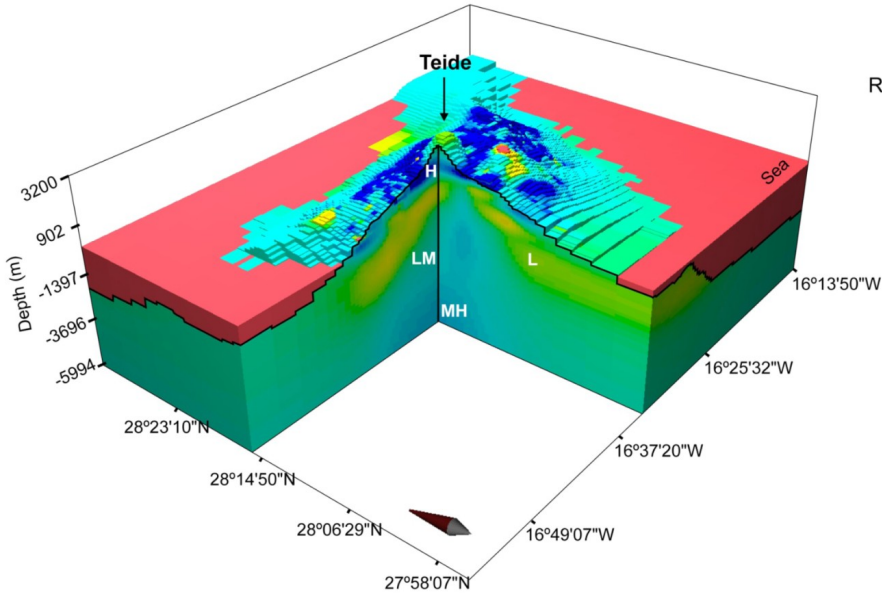


Tenerife island: MT/CSEM modeling

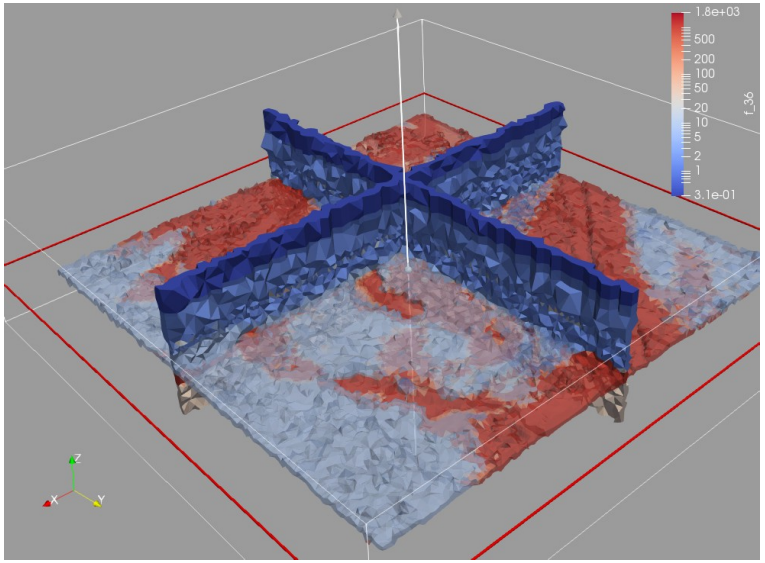
- PETGEM computations to analize MT/CSEM responses:
  - **Experimental data** to build the computational domain
  - Finite difference grid to finite element grid (**adapted mesh**)
  - Compare **synthetic** EM responses against **experimental** responses

- **Improve** our **knowledge** about the Tenerife model:
  - Previous MT results allow us to **verify, control, and restrict** the CSEM responses
  - Confirm the role of **electromagnetic geophysical**

Tenerife model



PETGEM



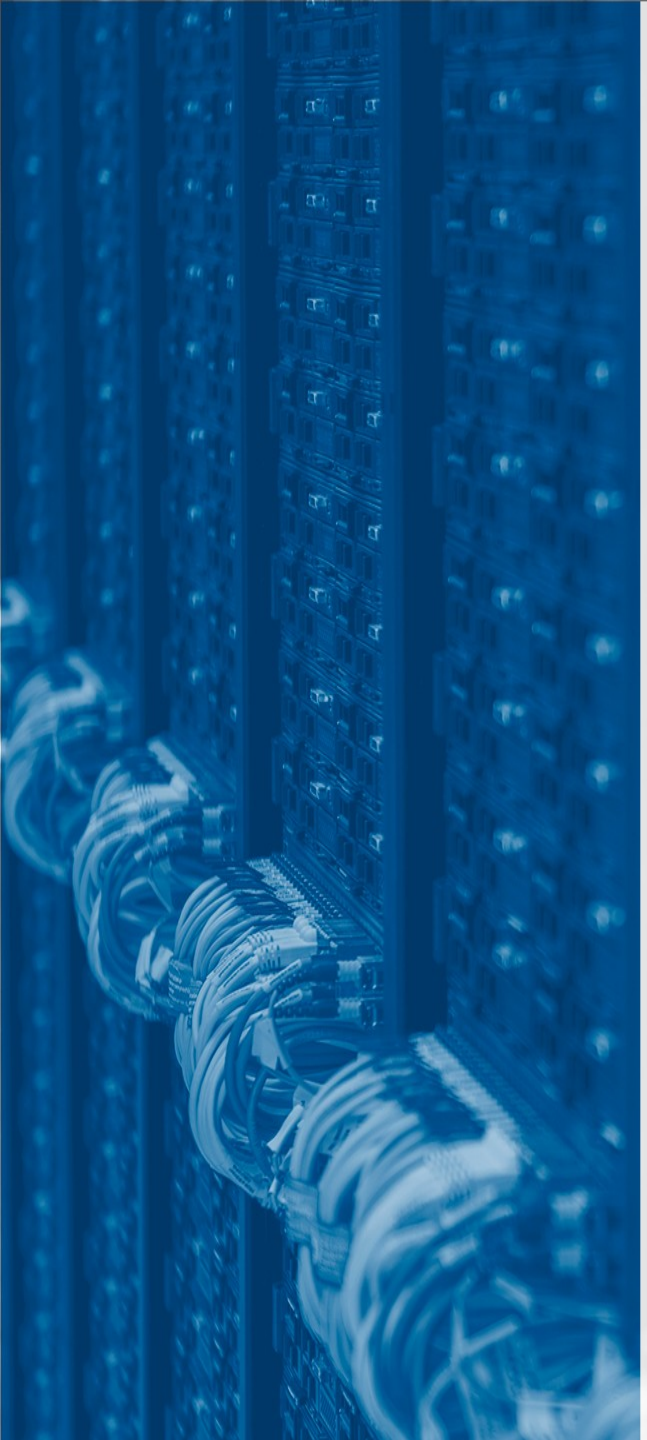
Conclusions

- **A triple helix approach** based on high-order basis, *hp*-adapted meshes, and HPC can be **extremely competitive** for the solution of realistic and complex 3-D MT/CSEM models
  - Full 3-D analysis of EM fields
  - Run-time, accuracy, speed-up and parallel efficiency

- **Know-how** is fundamental for **future** modeling tasks and **developments** (e.g. EM inversion routines)
  - **Suitable workflow** for many and diverse applications (oil & gas, geothermal energy)
  - Transfer expertise to **non-conventional scenarios**
  - Critical role in solving the next generation of geoscience problems: complex, multidisciplinary, and **require collaboration**

Conclusions

- PETGEM uses in **conventional/non-conventional** energy surveys:
  - **Prior** to drilling;
    - Study sensitivity to different reservoir configurations
    - Plan data acquisition strategies
    - If data is available: obtain conductivity maps (i.e. find fluids)
  - **After** drilling:
    - Monitor fluid leaks



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Thank you!

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