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Development of OSI Forward Modelling Capacity for Non-Seismic Geophysical Techniques

a) Rizzello, D., b) Koivisto, E.A.L., b) Gaya Pique, L., c) Armadillo, E.

a) Tellus-Explora sas, Genoa, Italy
b) On-Site Inspection Division, CTBTO Preparatory Commission, Vienna International Center, Austria
c) Applied Geophysics Laboratory, DISTAV, University of Genoa, Genoa, Italy

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INTRODUCTION

- On-site inspections (OSI) use geophysical methods to detect Underground Nuclear Explosion (UNE) observables.
- We present 3D MAG (magnetic field mapping), GRV (gravity field mapping), ERT (electrical resistivity tomography), FDEM (frequency-domain electromagnetics) and TDEM (time-domain electromagnetics) simulations of the observables, done by means of ad-hoc developed Python functions.
- By varying the observable parameters, we built a portfolio of 870 geophysical anomalies, crucial for:
  - Survey design
  - Interpretation of the collected data
  - Training for inspectors
  - Update of equipment list

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GENERAL WORKFLOW

Physical/geometrical parametrization of UNE observables by literature review

Identification of realistic UNE scenarios including different observables

Development of Python code for 3D multi-geophysical forward simulations

Forward 3D multi-geophysical simulations of the scenarios

Assessment of geophysical methods effectiveness/limits and development of anomalies portfolio

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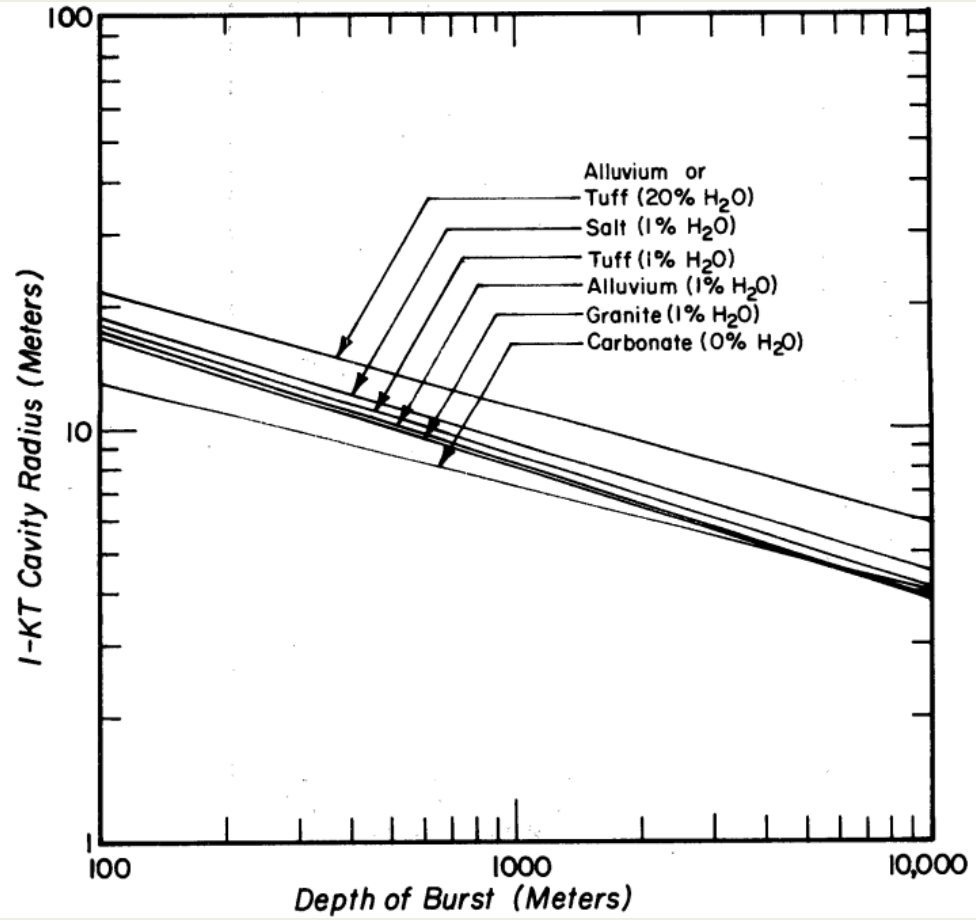
PHYSICAL/GEOMETRICAL PARAMETRIZATION OF UNE OBSERVABLES

- Underground Nuclear Explosion **cavity radius (Rc)** vs depth of burial (**DOB**):
  - Rc was retrieved from the multi-lithology Castagnola and Carnahan (1971) diagram, by hypothesizing an UNE 1 kt - yield in alluvium as reference, and different DOBs
  - Other geological environment could be however considered (tuff, salt, etc.)



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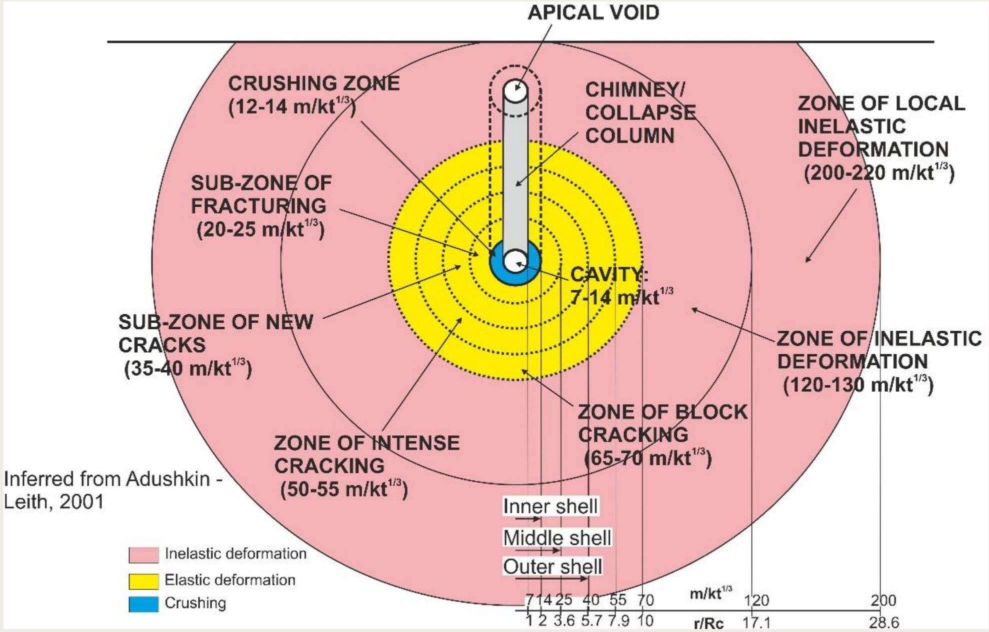
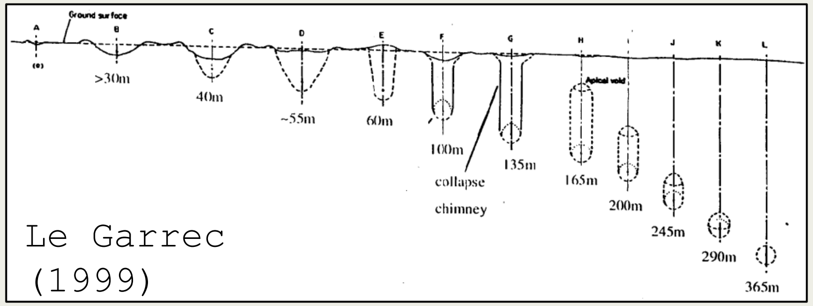
PHYSICAL/GEOMETRICAL PARAMETRIZATION OF UNE OBSERVABLES

- **Alteration shell radii**:
  - inferred from Adushkin and Leith (2001) (providing shell radii normalized to $\mathrm{yield}^{1/3}$)
- **Chimney height/radius:**
  - from Le Garrec (1999)





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PHYSICAL/GEOMETRICAL PARAMETRIZATION OF UNE OBSERVABLES

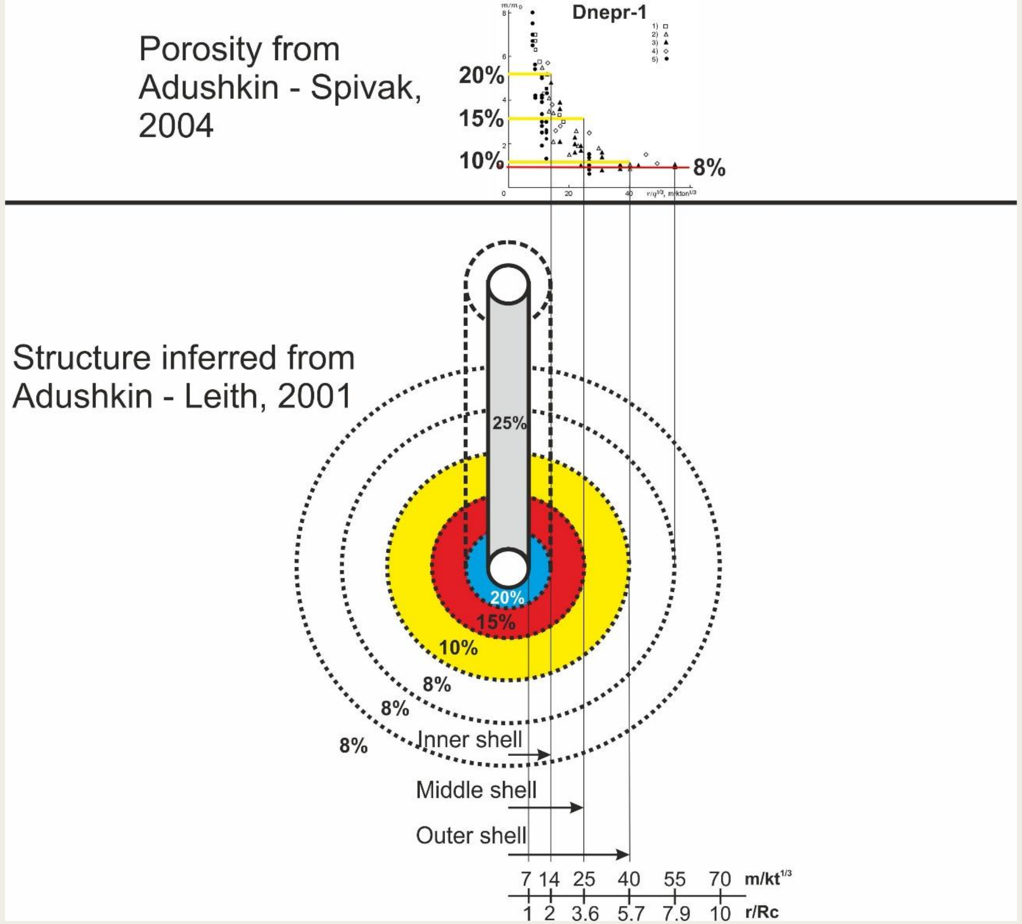
- **Shell porosities:**
  - Adushkin and Spivak (2004) real case
- We identified three shells (porosity> background) and accordingly computed:
  - **density** (Gassmann's equation)

$$\rho_{bulk} = (1 - F)\rho_{ma} + F(S_w\rho_w + S_g\rho_g)$$

  - **electrical resistivity** (Archie's law)

$$R_{\boldsymbol{bulk}} = a\phi^{-m} s_w^{-n} R_w$$

- **Magnetic susceptibility:**
  - From Maris (2019) (no relationship with porosity)



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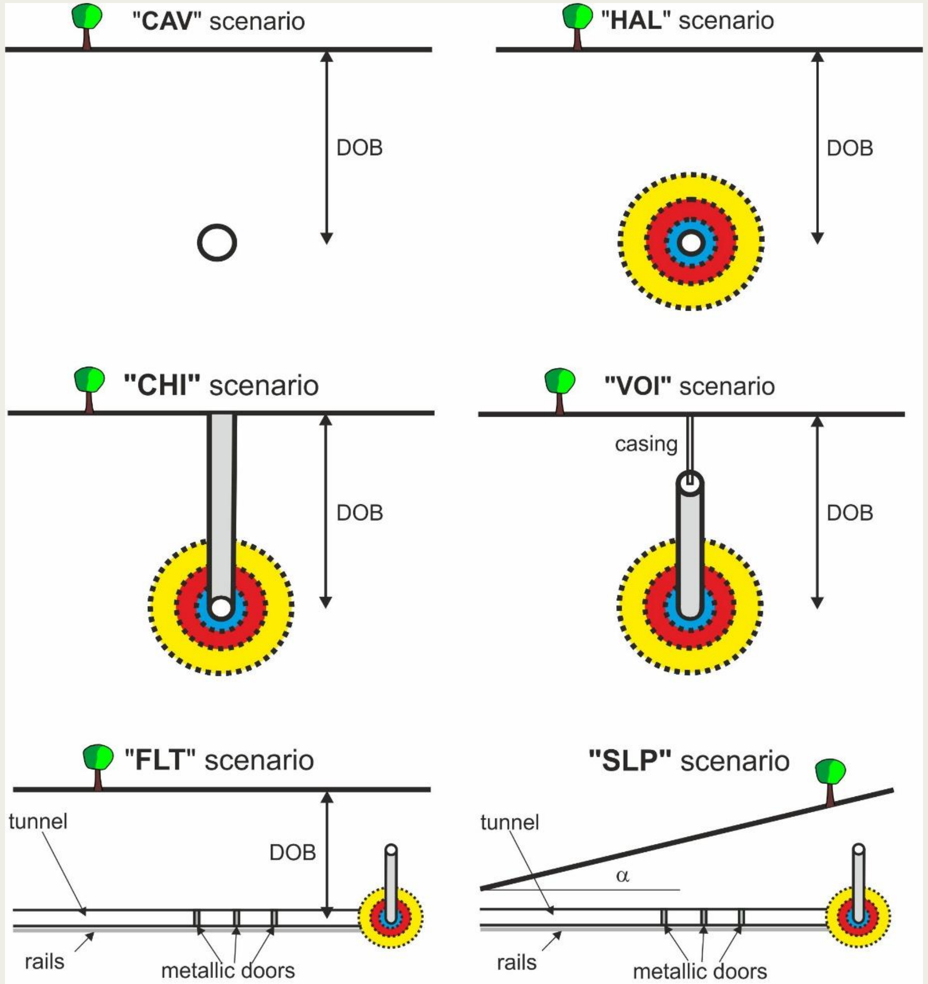
CONSIDERED SCENARIOS

- After an extensive bibliographic review, we identified five main UNE scenarios:
  - Cavity ("**CAV"**)
  - Cavity + alteration shells ("**HAL"**)
  - HAL + collapse chimney ("**CHI"**)
  - HAL + collapse chimney + apical void + casing ("**VOI"**)
  - Horizontal emplacement:
  - horizontal topography ("**FLT"**)
  - or sloping topography ("**SLP"**)



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IMPLEMENTED CODE

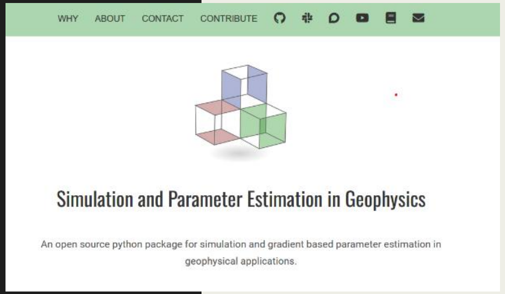
- The need for 3D geophysical simulations was evident
- We therefore developed Python codes for each scenario, by using the open-source SimPEG libraries for geophysical simulations
- Codes designed for the geophysical instruments available at CTBTO and relevant input/output data file format:
  - ABEM Terrameter LS2 (ERT)
  - Iris Promis (FDEM)
  - Abem WalkTEM (TDEM)
- Output files ready for inversion
- Developed code released to CTBTO

cav_grav_fwd.py | voi_grav_fwd.py | VOI_grav_script.py | hor_grav_fwd.py | VOI_script_NEW.py | S

```
################################################################################
#                              Import modules
################################################################################
from discretize import TreeMesh
from SimPEG.utils import plot2Ddata, model_builder
from SimPEG import maps
from SimPEG.potential_fields import gravity
import numpy as np
import matplotlib as mpl
import matplotlib.pyplot as plt
try:
    from pymatsolver import Pardiso as Solver
except ImportError:
    from SimPEG import SolverLU as Solver
import time
from winsound import Beep

################################################################################
#                              Function beginning
################################################################################
def cav_grav_fwd(dom_width,
                 dh,
                 topo_width,
                 dt,
                 surv_width,
                 dm,
                 surv_h,
                 profile_or,
                 profile_coord,
                 background_density,
                 cavity_density,
                 cavity_radius,
                 cavity_depth,
                 file_out_name,
                 par_file,
                 topo_file):

    save_file = True
```



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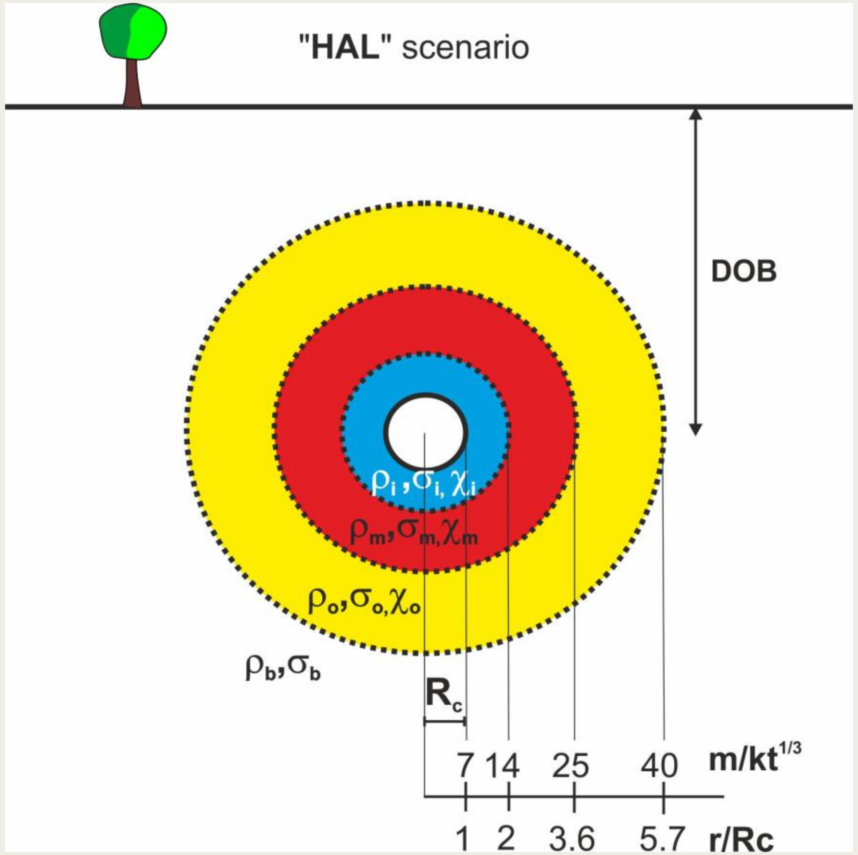
“HAL" MODELS

- Considered variable parameters:
  - DOB (Depth Of Burial)
  - R_c (cavity radius)
  - ρ_i, ρ_m, ρ_o, ρ_b (shell/back. density contrasts, dry/saturated)
  - χ_i, χ_m, χ_o (shell magnetic susceptibility contrasts)
  - I (magnetic inclination)
  - σ_i, σ_m, σ_o, σ_b(shell/back. el.conductivity, dry/saturated)

	min	max
DOB	100 (m)	500 (m)
R_c	13 (m)	45 (m)
ρ_i (e.g.)	-0.58 (g/cm3)	-0.16 (g/cm3)
χ_i (e.g.)	-5.1*10-3 (S.I.)	-3.7*10-3 (S.I.)
I	-90°	90°
σ_i (e.g.)	8e-4 (S/m)	5e-3 (S/m)



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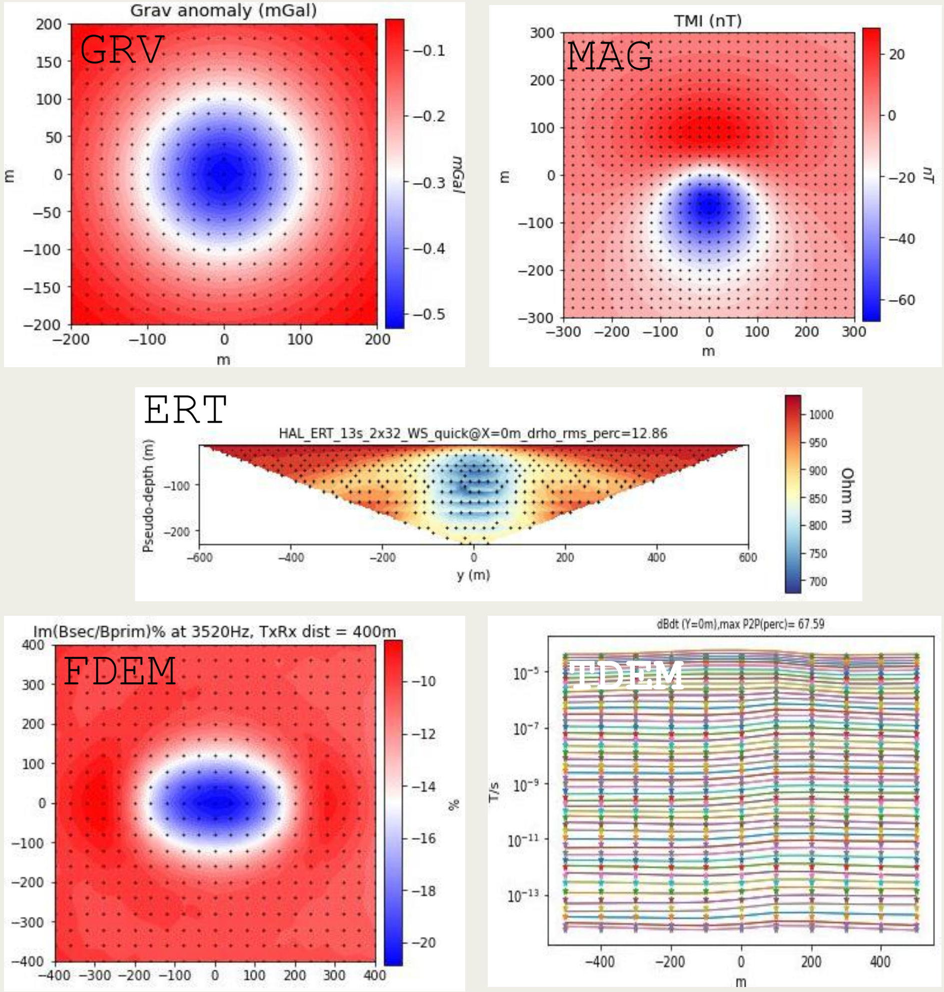
“HAL" MODEL RESULTS

- GRV: not suitable (very low anomalies)
- MAG: useful with shallow alt. zone and high χ contrasts
- **ERT**: generally useful; better with shorter arrays
- FDEM: very difficult for dry rocks; perceivable with high-freq and long Tx-Rx separation in sat.rocks
- TDEM: difficult; small loops preferable

	Suitable	Part. suitable	Not suitable	Anomaly range
GRV			x	0.08-0.47 mGal (P2P)
MAG		x		1.6-96 nT (P2P)
ERT	x			1.8-12.9 (dρ_RMS%)
FDEM		x		0.002-8.3 (P2P%)
TDEM		x		11.5-68 (P2P%)

Anomaly maps and profiles (best cases)
(color scales normalized to min/max values)



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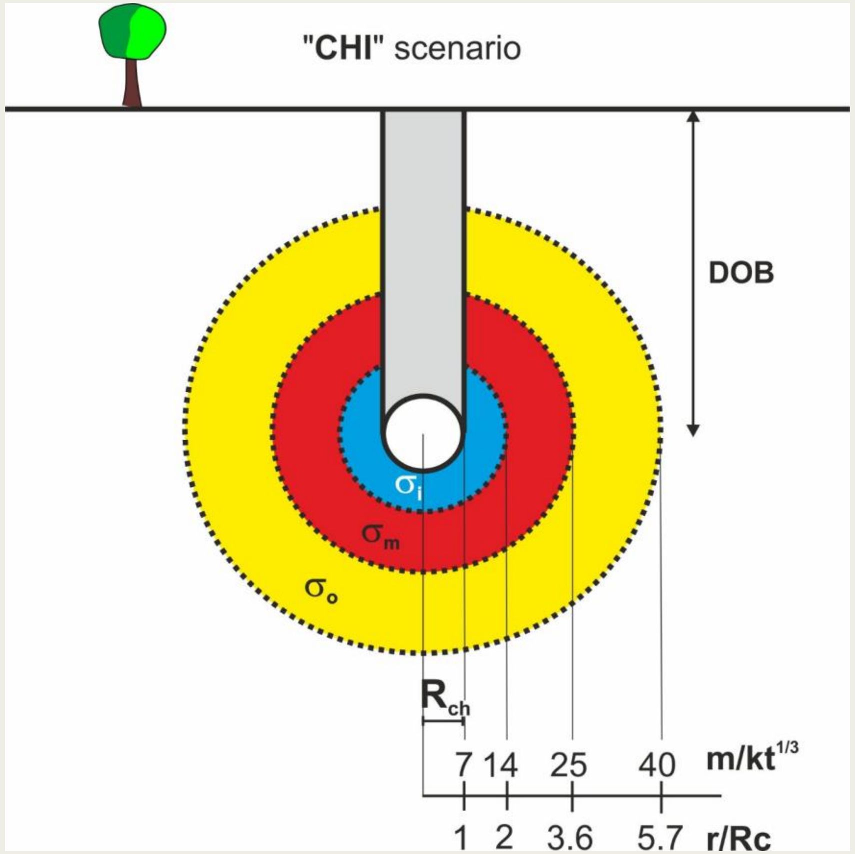
“CHI" MODELS

- Considered variable parameters:
  - DOB (Depth Of Burial)
  - R_{ch} (chimney radius)
  - $\sigma_i, \sigma_m, \sigma_o, \sigma_b$ (shell and background el.conductivity, dry/saturated)
  - I (magnetic inclination)

	min	max
DOB	100 (m)	500 (m)
R_c	11 (m)	45 (m)
σ_i (e.g.)	8e-4 (S/m)	5e-3 (S/m)
I	-90°	90°



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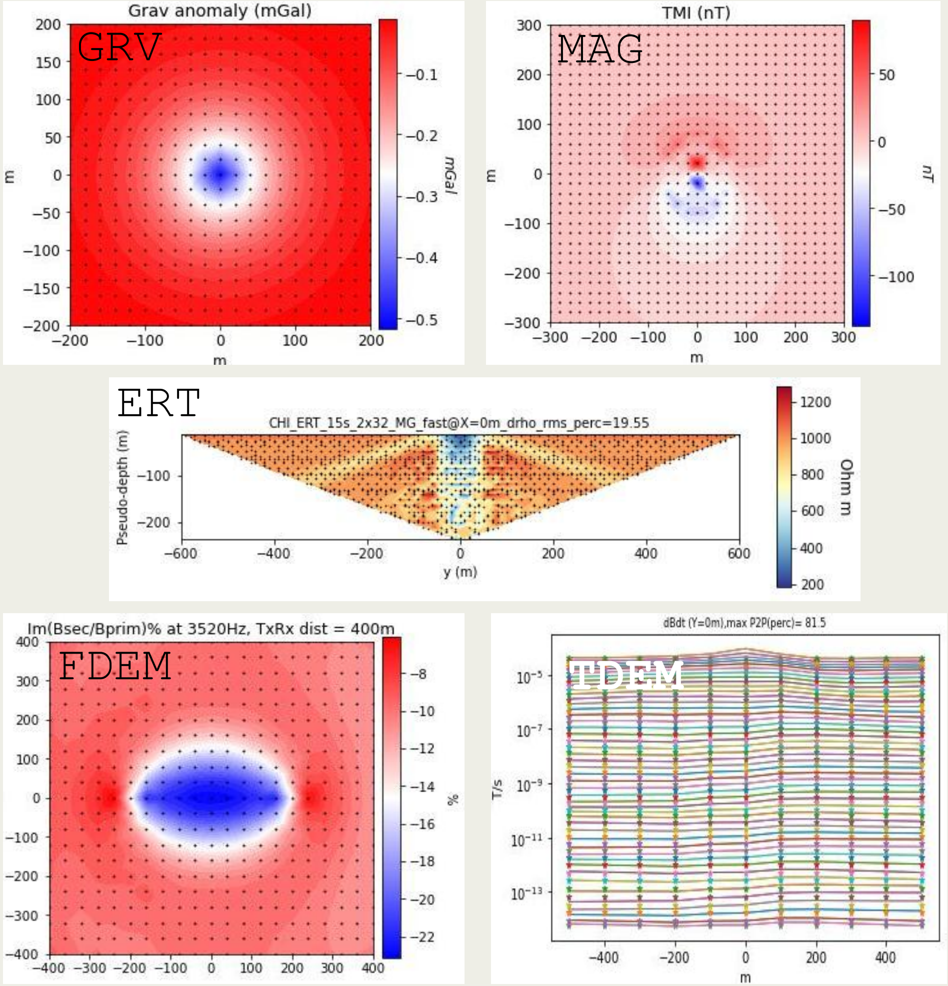
“CHI" MODEL RESULTS

- GRV: not useful (perhaps the chimney only)
- **MAG**: useful (alt. halo signature also retrievable)
- ERT: useful to detect the chimney; short arrays
- FDEM: useful with high-freq, long Tx-Rx separation and saturated conditions
- TDEM: detectable for big R_{ch}; better small loops and saturated rocks

	Suitable	Part. suitable	Not suitable	Anomaly range
GRV			x	0.1-0.6 mGal (P2P)
MAG	x			30-227 nT (P2P)
ERT		x		4.5-19.5 (dρ_RMS %)
FDEM		x		0.02-8.6 (P2P%)
TDEM		x		11.5-81.5 (P2P%)

Anomaly maps and profiles (best cases)
(color scales normalized to min/max values)



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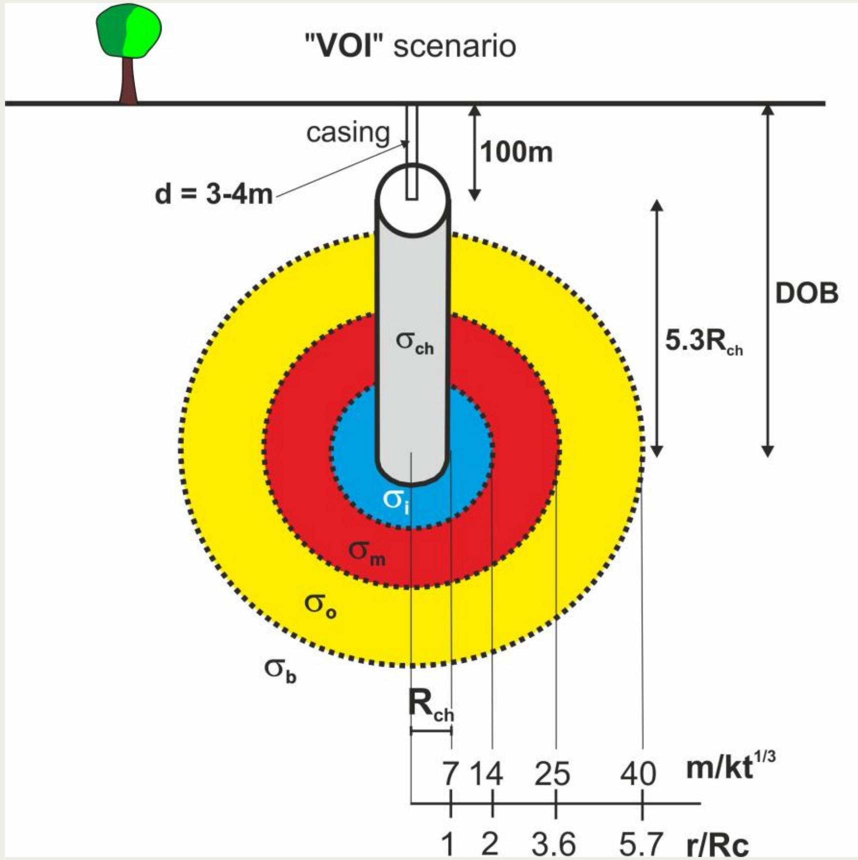
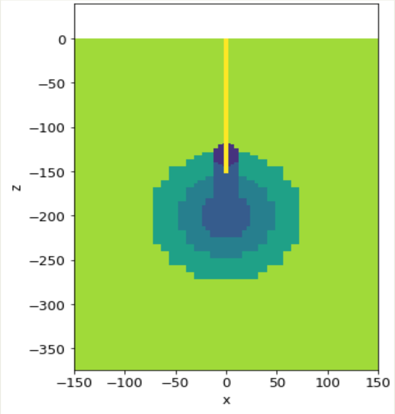
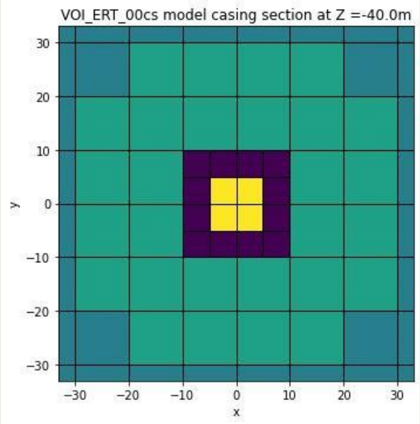
“VOI" MODELS

- Considered variable parameters:
  - DOB (Depth Of Burial)
  - R_{ch}(chimney radius)
  - $\sigma_i, \sigma_m, \sigma_o, \sigma_b$ (shell/background el.conductivity, dry/saturated)
  - I (magnetic inclination)
  - d (casing diameter)
  - Presence/absence of casing

	min	max
DOB	150 (m)	500 (m)
R_{ch}	13 (m)	45 (m)
σ_i (e.g.)	8e-4 (S/m)	5e-3 (S/m)
I	-90°	90°
d	3 m	4 m







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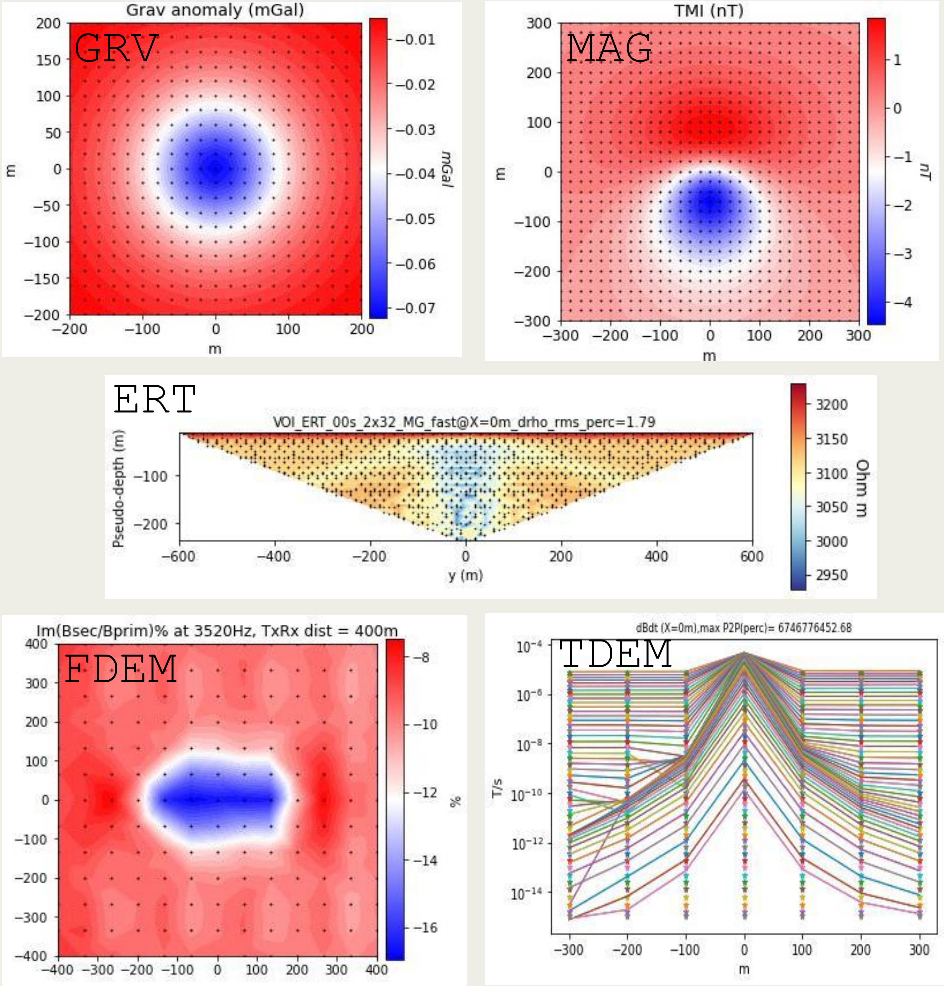
“VOI" MODEL RESULTS

- GRV: generally not useful (only the chimney identified)
- MAG: high with casing or shallow alteration zone
- **ERT**: suitable; small arrays preferable
- FDEM: suitable with casing if one coil lies over it (unlikely)
- TDEM: without casing suitable with shallow alt. zone; casing dominates the response; small loops preferable

	Suitable	Part. suitable	Not suitable	Anomaly range
GRV		x		0.05-2 mGal (P2P)
MAG		x		4-417 nT (P2P, no cas.)
ERT	x			1.7-8.7 (dρ_RMS%)
FDEM		x		0.01-4.7 (P2P%)
TDEM		x		9.1-38.7 (P2P%)

Anomaly maps and profiles (best cases)
(color scales normalized to min/max values)



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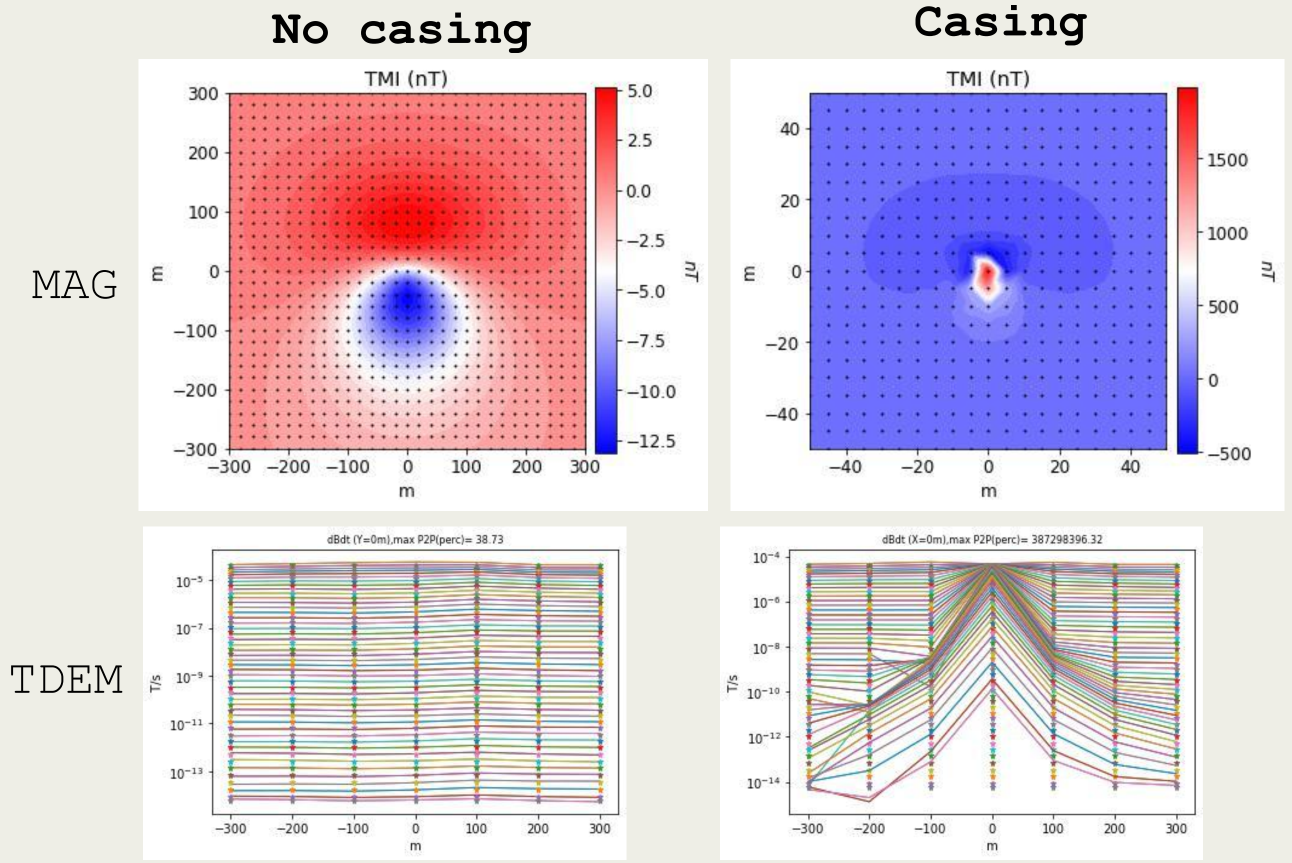
“VOI" MODEL RESULTS –INFLUENCE OF CASING

- Examples of MAG and TDEM anomalies: high increase of the geophysical anomaly with metallic casing



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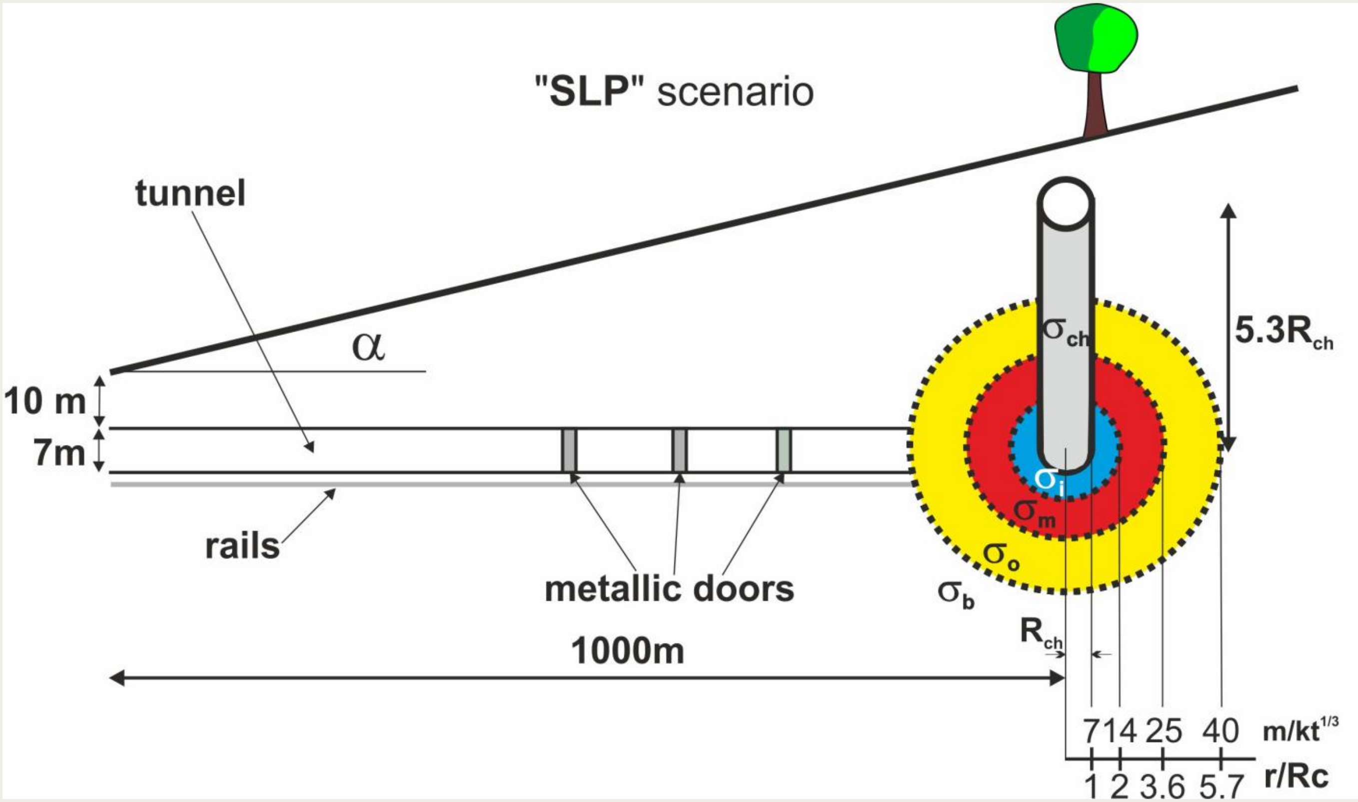
“SLP" MODELS

- Considered variable parameters:
  - α (slope)
  - $\sigma_i, \sigma_m, \sigma_o, \sigma_b$ (shell and background el.conductivity, dry/saturated)
  - I (magnetic inclination)

	min	max
α	10°	30°
σ_i (e.g.)	8e-4 (S/m)	5e-3 (S/m)
I	-90°	90°



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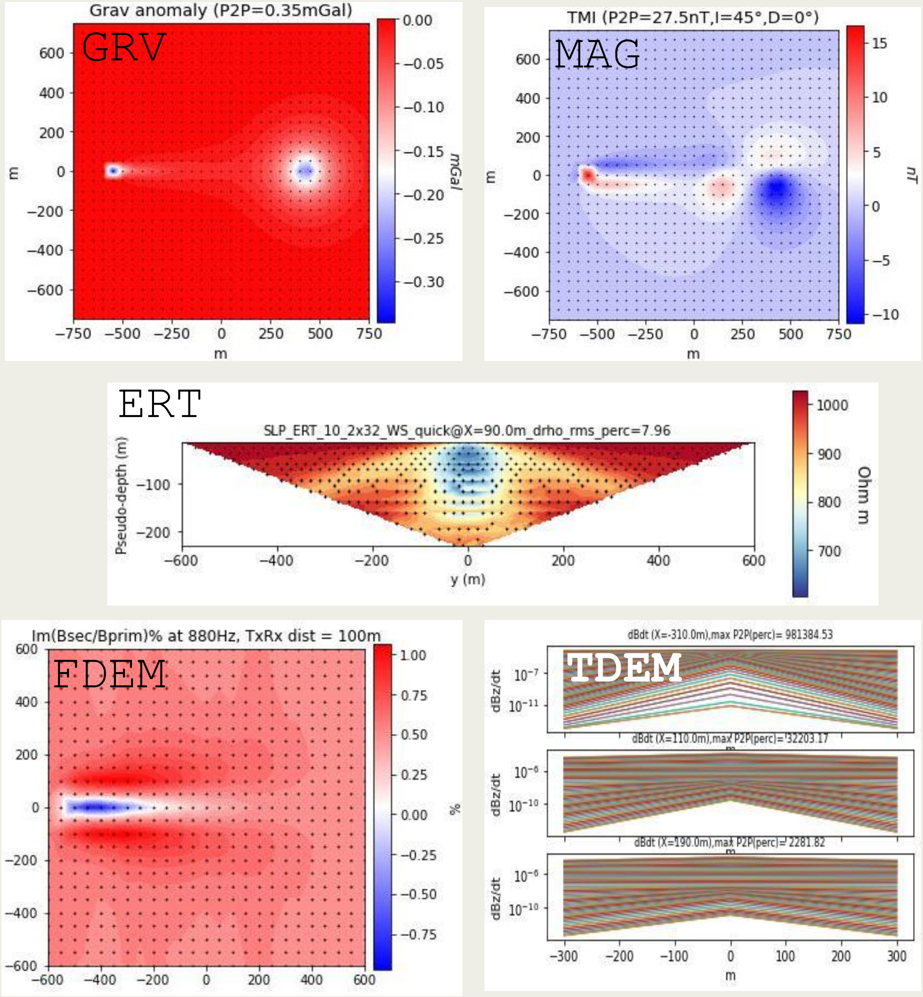
“SLP" MODEL RESULTS

- GRV: not suitable (low anomaly)
- **MAG**: tunnel always retrievable up to 20° for mid-mag.latitudes
- ERT: part.suitable up to 15° (doors not retrievable)
- FDEM: better medium-large separation, dry
- **TDEM**: useful in all cases; small/big loops equivalent

	Suitable	Part. suitable	Not suitable	Anomaly range
GRV			x	0.1-0.35 mGal (P2P)
MAG	x			12-27 nT (P2P)
ERT		x		0.6-6.7 (dρ_RMS%)
FDEM		x		2.3-60 (P2P %)
TDEM	x			34-44000 (P2P%)

Anomaly maps and profiles (best cases)
(color scales normalized to min/max values)



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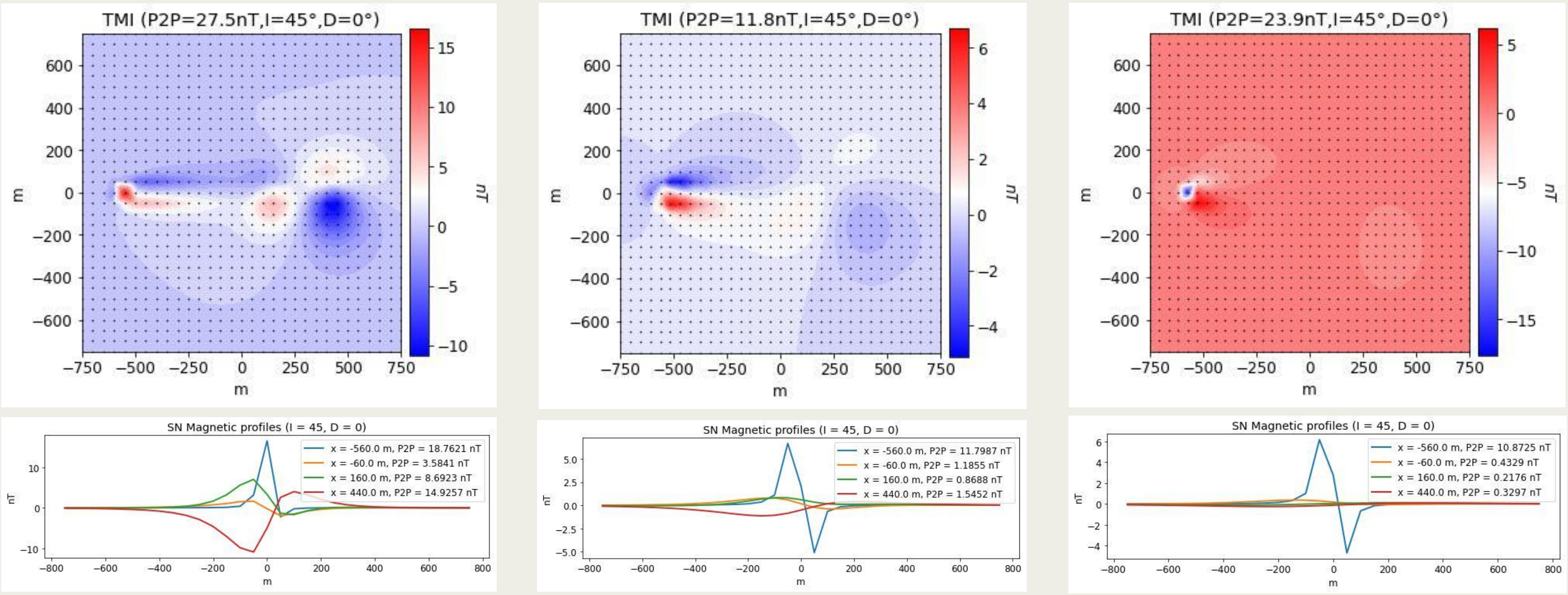
“SLP" MODEL RESULTS – INFLUENCE OF THE SLOPE (MAG CASE)

- MAG anomaly vs slope:
  - Overall significant up to 20° slope
  - Always high at the tunnel entrance

10° 20° 30°



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CONCLUSIONS

- A comprehensive geophysical simulation study of synthetic Underground Nuclear Explosion scenarios has been carried out
- The computations have been done by means of ad-hoc developed Python codes, which can also be used on-site
- We built a portfolio of 870 geophysical anomalies, stemming from 358 UNE models and multiple acquisition settings
- The portfolio is essential for:
  - OSI geophysical method choice/survey design and on-site acquisition strategies
  - Interpretation of the collected data
  - Surrogate inspectors training
  - CTBTO equipment list development

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THANK YOU !