eXperimental jOint inveRsioN (XORN) project: first results of a 3D joint gravity and magnetic inversion

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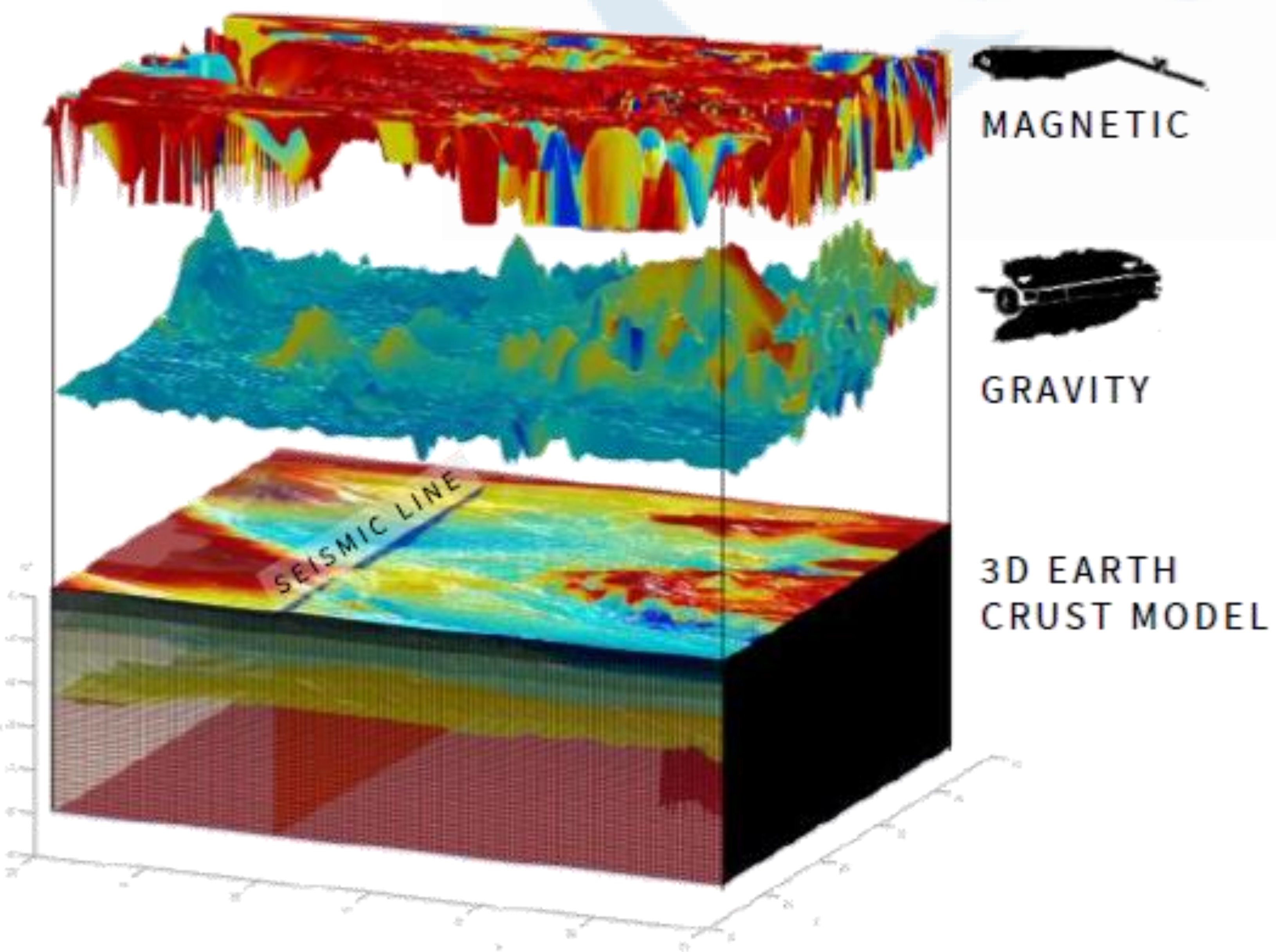
INTRODUCTION

The Earth crust represents less than 1% of the volume of our planet but is exceptionally important as it preserves the signs of the geological events that shaped our planet and it is the place where the natural resources we need for living can be accessed.

Potential fields methods, exploiting gravity and magnetic fields, are among the most important tools to recover fundamental information on its structure.



The **challenge** to be faced nowadays is represented by the **development of ad-hoc techniques to fully exploit the different geophysical data at both global and regional scales** in order to recover information on the Earth's crust.

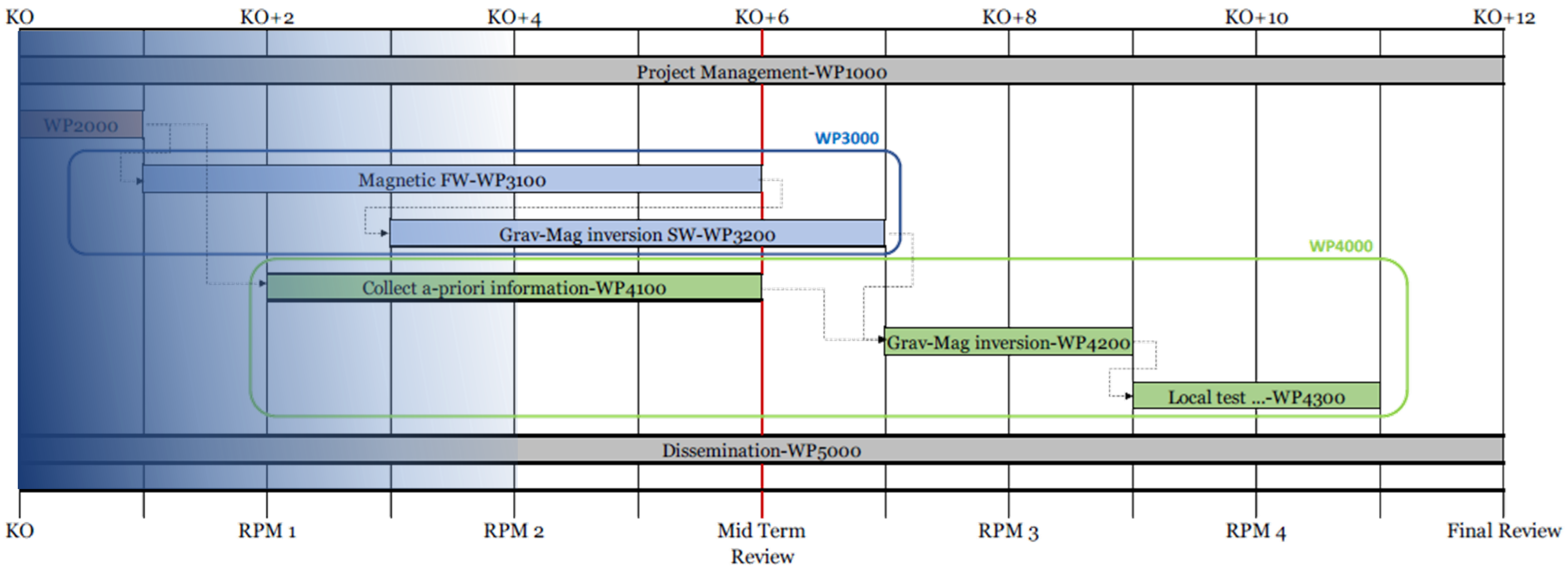
XORN PROJECT

The project, fundend by the European Space Agency through the EO4society program, has started in January 2022

Objectives

- Develop an integrated approach, to perform **3D joint inversion of gravity and magnetic** fields data, **constrained by seismic** and geological a-priori information
- Study the crust in the Mediterranean Sea area

XORN https://xorn-project.eu/

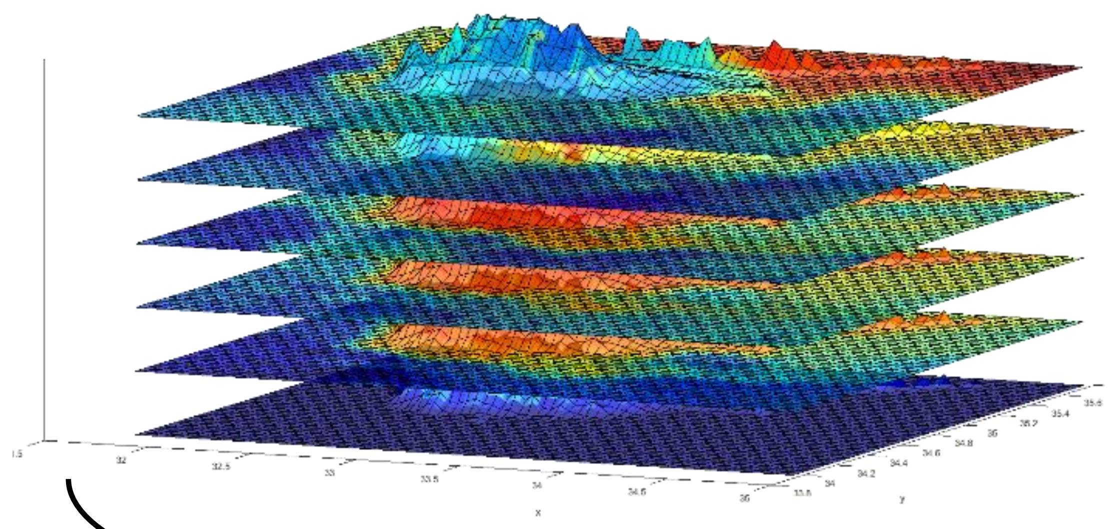


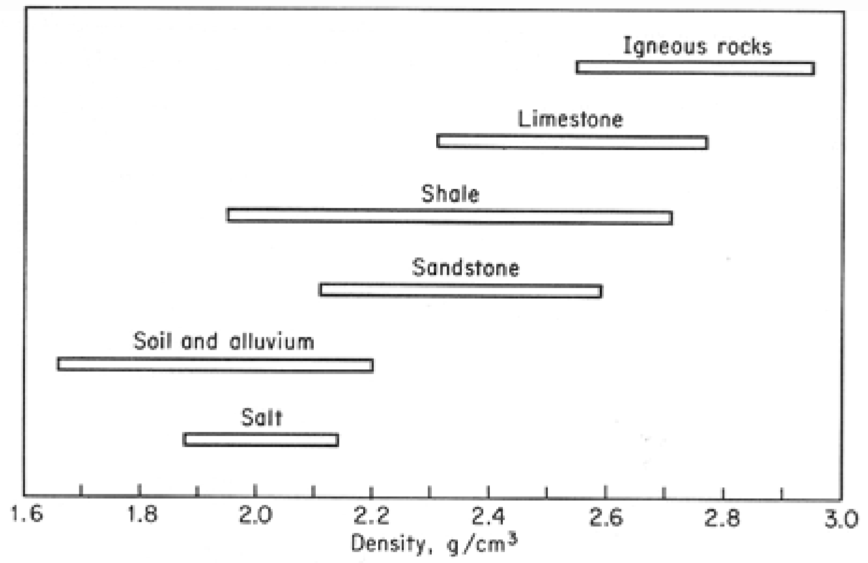
Partners

GReD and **Laboratoire Magma et Volcans, Université Clermont Auvergne** (Dr.Erwan Thèbault)

METHOD

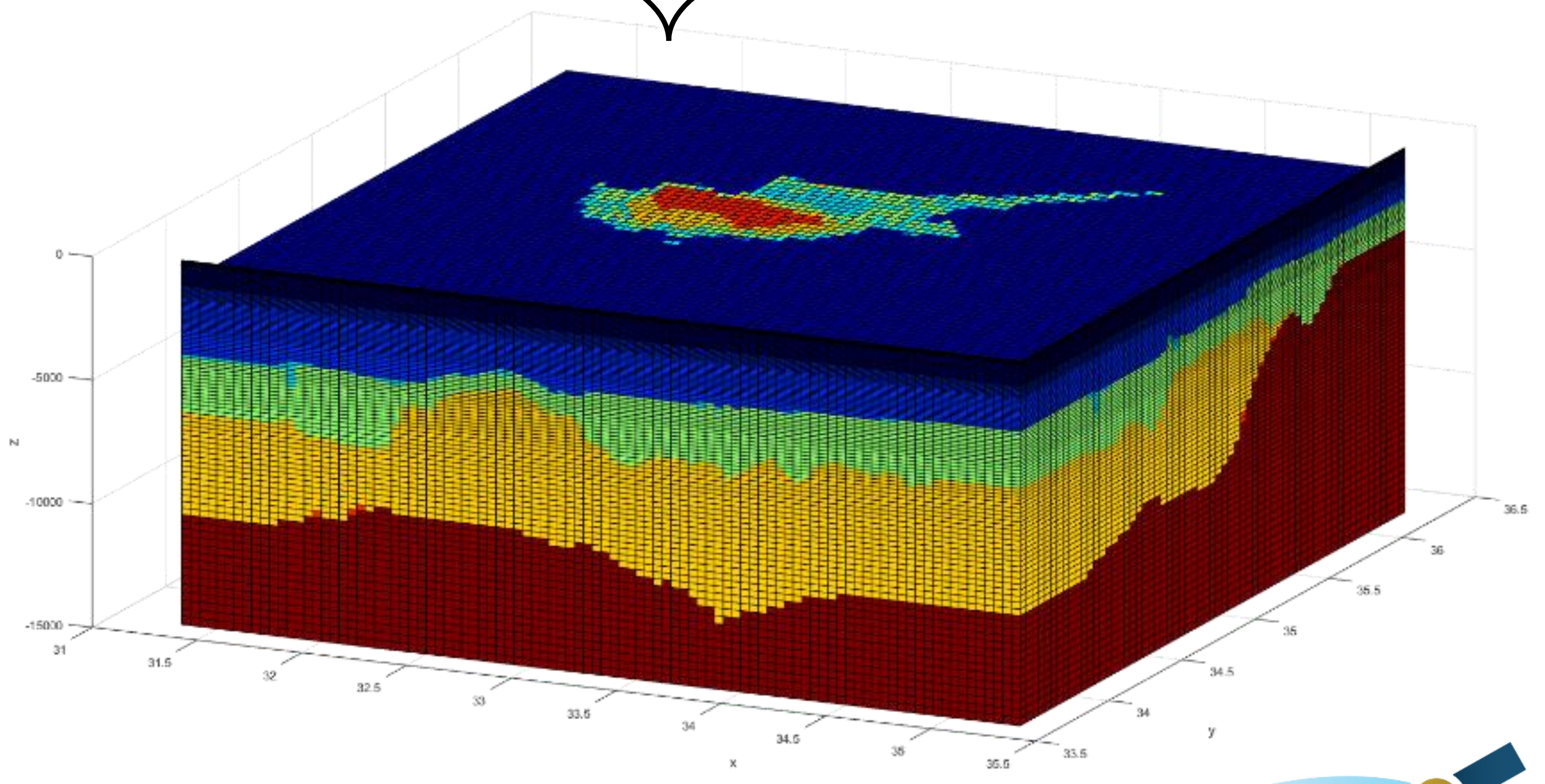
A Bayesian approach is used to solve the gravity and magnetic inversion problem in order to estimate geometries, density distribution and susceptibility distribution in the studied volume. The volume is divided into voxels, each one *i* described by 3 random variables:





- ρ_i mass **density** (continuous variable);
- χ_i magnetic **susceptibility** (continuous variable);
- L_i **label** (categorical variable characterizing the geological material)

Unknown parameters ➡ $$\boldsymbol{x} = [\rho_1, \rho_2, \dots, \rho_n, \chi_1, \chi_2, \dots, \chi_n, L_1, L_2, \dots, L_n]^T = \begin{bmatrix} \boldsymbol{\rho} \\ \boldsymbol{\chi} \\ \boldsymbol{L} \end{bmatrix}$$



Each voxel is described by a right rectangular prism used to compute its contribution to the total gravity and magnetic signals.

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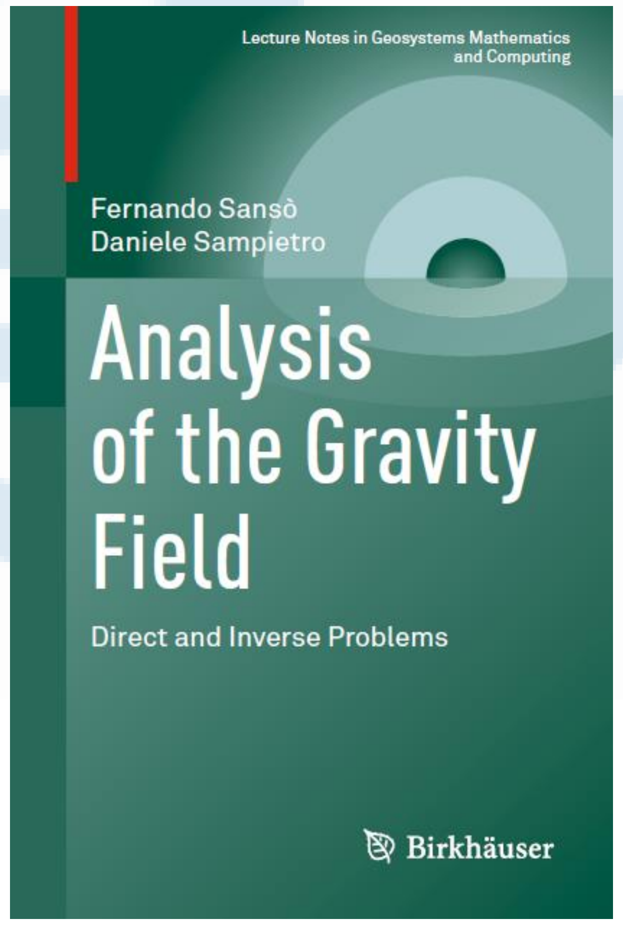
METHOD

Following the Bayesian formalism, the proposed method aims at retrieving the posterior probability, namely the probability of a certain hypothesis (i.e. the a-priori geological model) given the observed evidence (i.e. the gravity and magnetic observations):



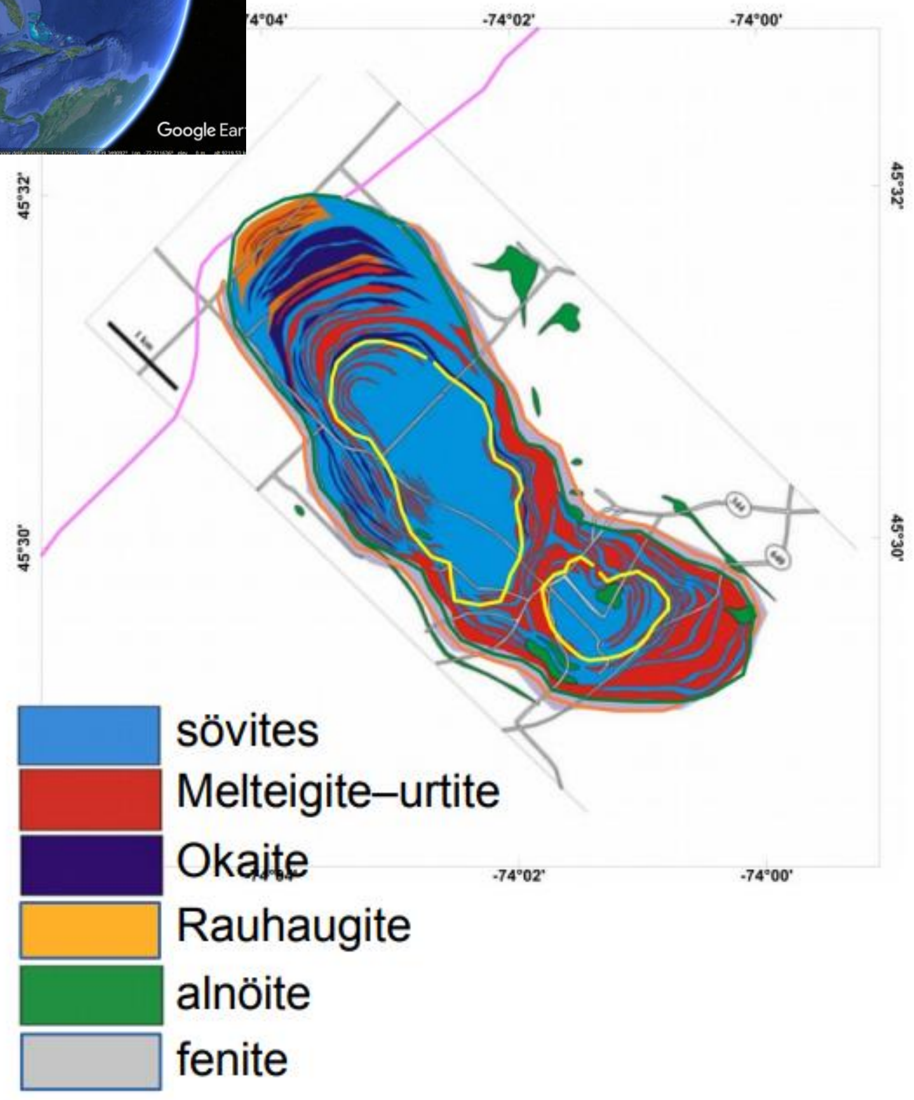
$$P(\rho,\chi,L|y_g,y_m) = \mathcal{L}(y_g,y_m|\rho,\chi,L)P(\rho,\chi,L)$$

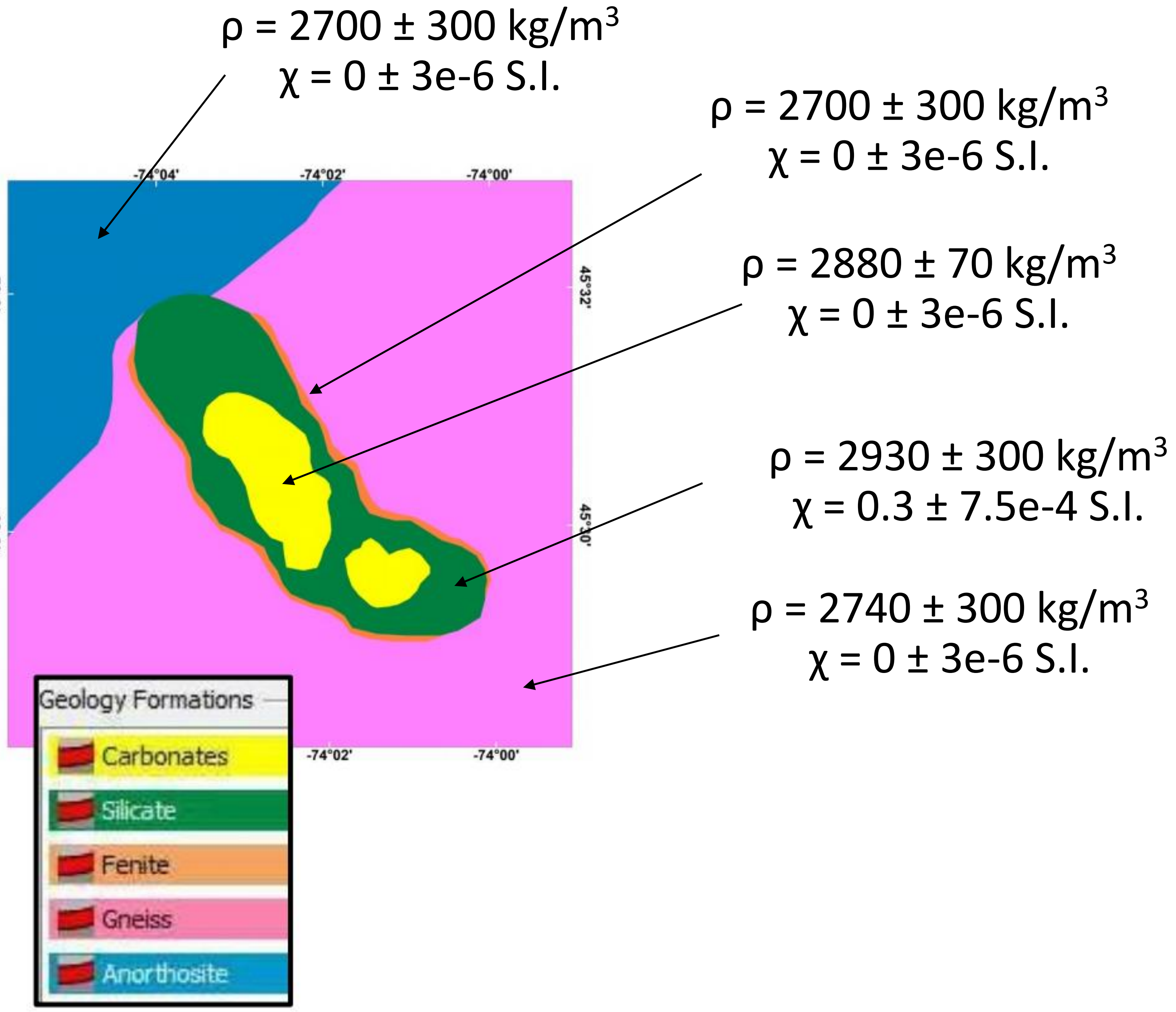
$$P(\rho,\chi,L|y)=\frac{1}{A}\exp\left\{\underbrace{\underbrace{-\frac{1}{2}(y_g-F_g\rho)^T C_{gg}^{-1}(y_g-F_g\rho)}_{\textit{Gravity residual}}\ \underbrace{-\frac{1}{2}(y_m-F_m\chi)^T C_{mm}^{-1}(y_m-F_m\chi)}_{\textit{Magnetic residual}}}_{\text{LIKELIHOOD}}\ \underbrace{\underbrace{-\frac{\eta}{2}\sum_{i=1}^{n}\frac{\left(\rho-\mu_\rho(L_i)\right)^2}{\sigma_\rho^2(L_i)}}_{\textit{“distance” from the average densities}}\ \underbrace{-\frac{\eta}{2}\sum_{i=1}^{n}\frac{\left(\chi-\mu_\chi(L_i)\right)^2}{\sigma_\chi^2(L_i)}}_{\textit{“distance” from the average susceptibility}}\ \underbrace{-\frac{\gamma}{2}\sum_{i=1}^{n}s_i^2(L_i)}_{\textit{“distance” from the initial geometries}}\ \underbrace{-\frac{\lambda}{2}\sum_{i=1}^{n}\sum_{j\in\Delta_i}q^2(L_i,L_j)}_{\textit{Neighbors clustering}}}_{\text{PRIOR}}\right\}$$

The inversion solution corresponds to the 3D geological model that better interprets the gravity and magnetic datasets coherently with the prior geological information and it is found by maximizing the posterior probability (MAP) by means of a simulating annealing with a Gibbs sampler.

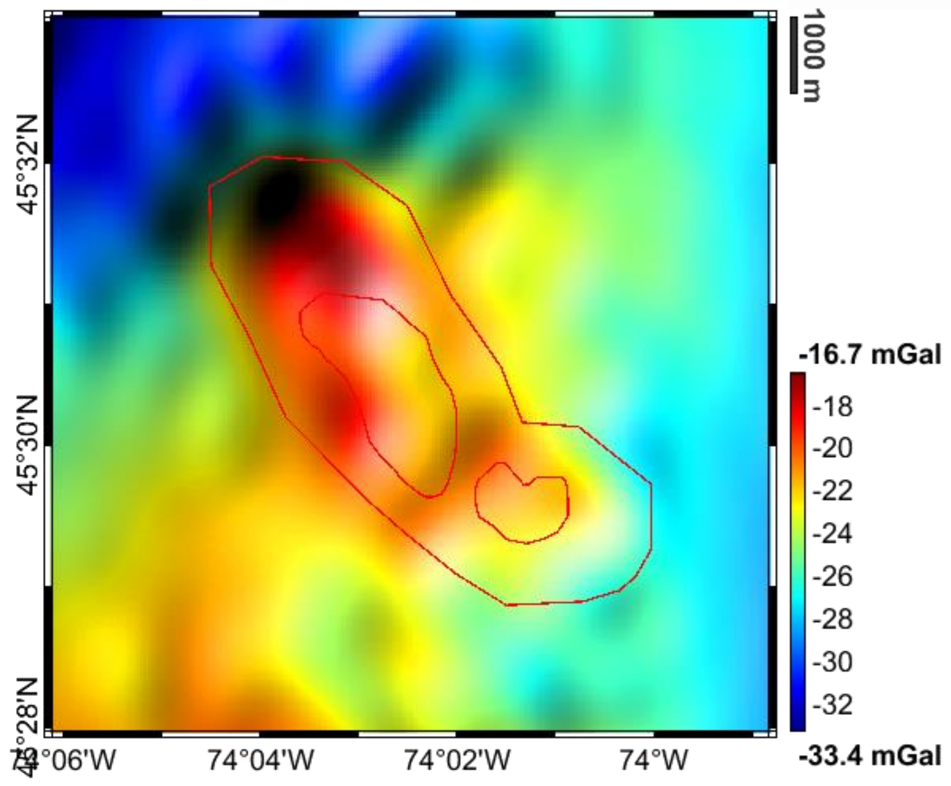
EXAMPLE: THE OKA CARBONATITE COMPLEX

The Oka complex is a composite pluton in Quebec, Canada. It is characterized by a peculiar ring structure and, in the past, it has been exploited for mining operations for Niobium and other rare earths.

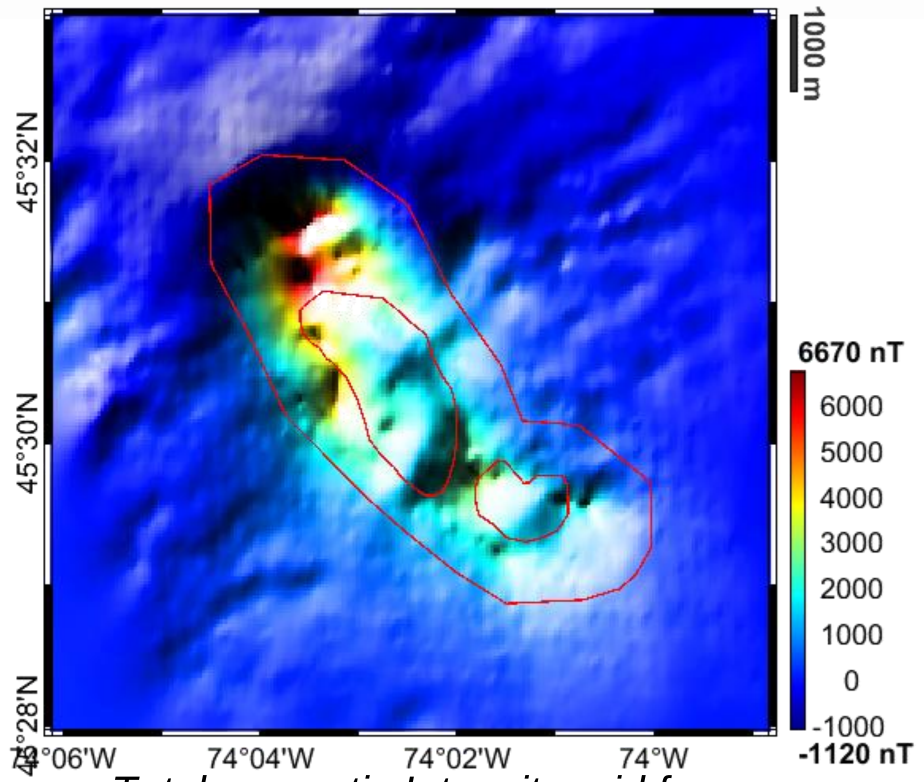




From: The Oka Carbonatite Complex, Quebec: deep structure from joint 3D gravity and magnetic data inversion. Sander Geophysics.



Bouguer anomalies from ground stations (computed by GReD).



Total magnetic Intensity grid from Natural Resources Canada

- $\Delta x = \Delta y = 100$ m
- Δz = variable from 50 to 500 m
- Maximum depth 10 km
- N. volumetric elements: 100 x 100 x 61 ~= 1.8e^6 unknowns
- Inducing magnetic field from CHAOS-7.8

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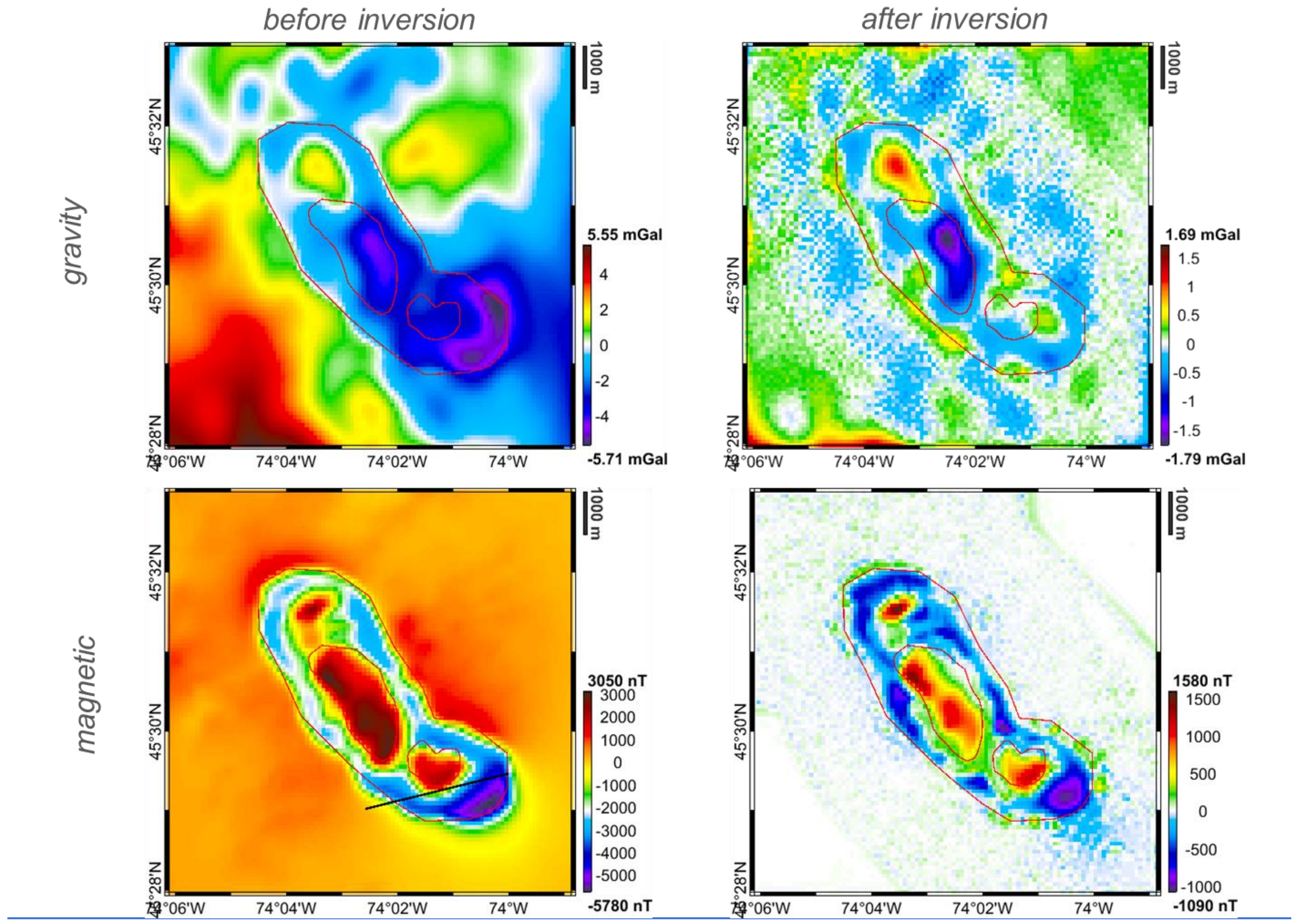
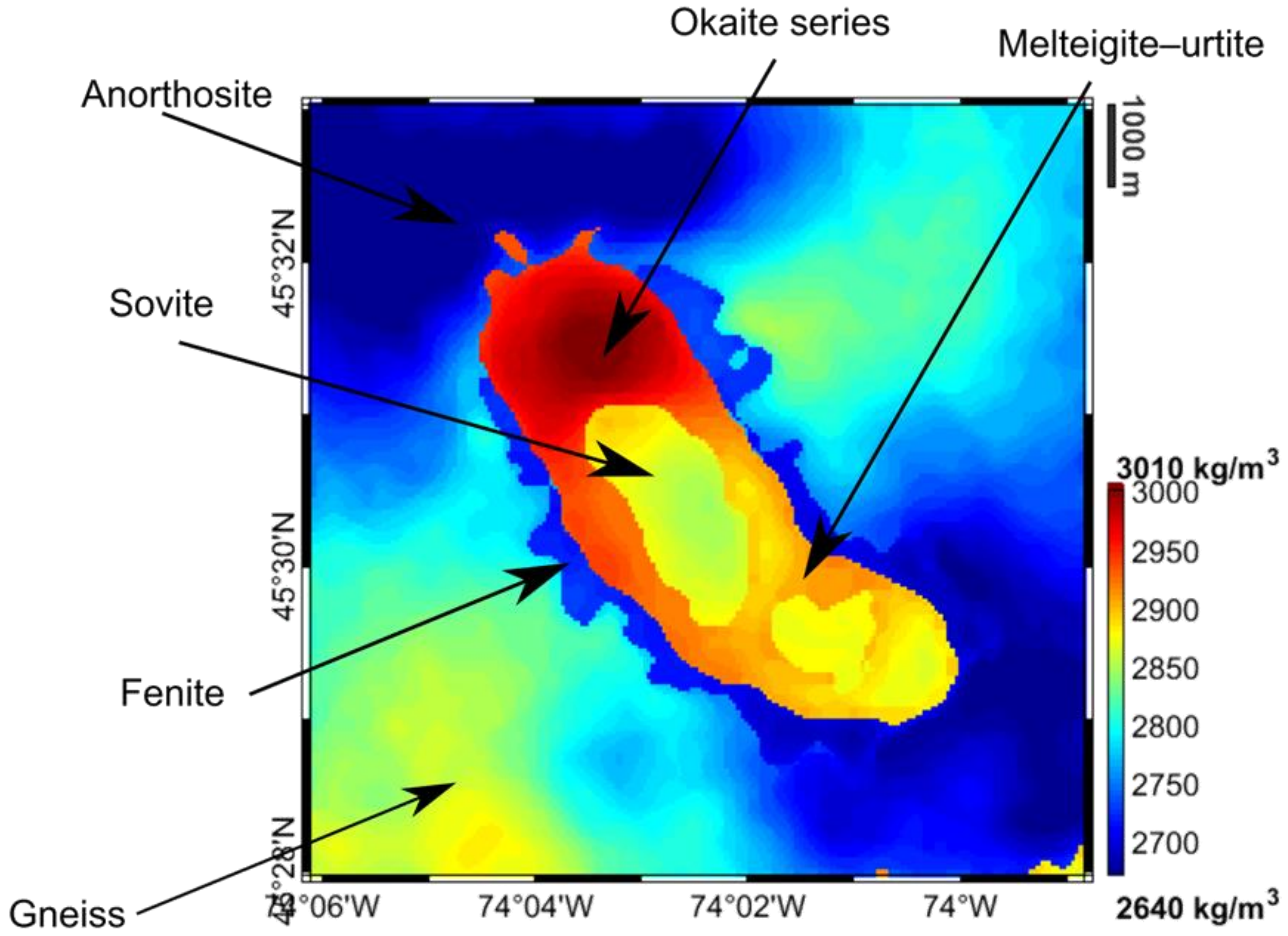
EXAMPLE: THE OKA CARBONATITE COMPLEX

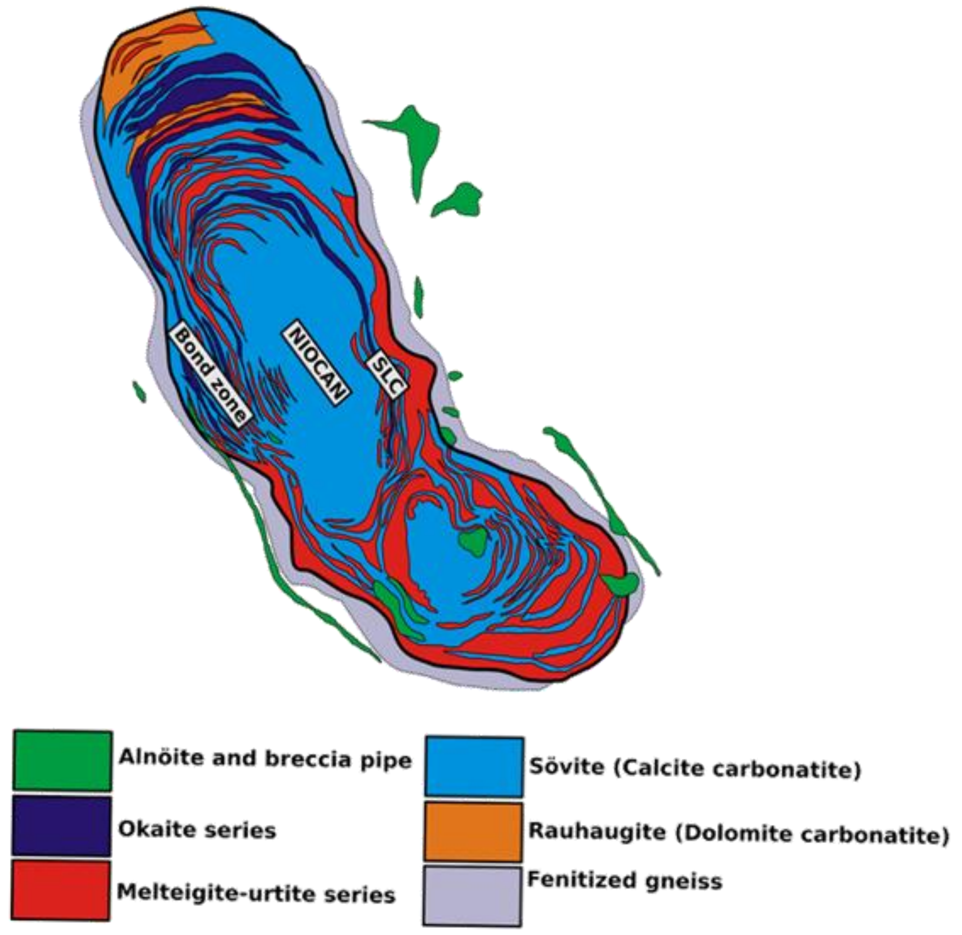
The Bayesian joint inversion ha been successfully applied to the Oka complex case study. The results show that the algorithm is able to adjust in a realistic manner the geological model in order to maximize the coherence with the gravity and magnetic observations



STD	a-priori	a-posteriori
gravity [mGal]	2.2	0.28
magnetic [nT]	1130	211



Density distribution at 1 km depth from joint gravity magnetic inversion



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EXAMPLE: THE MEDITERRANEAN SEA AREA

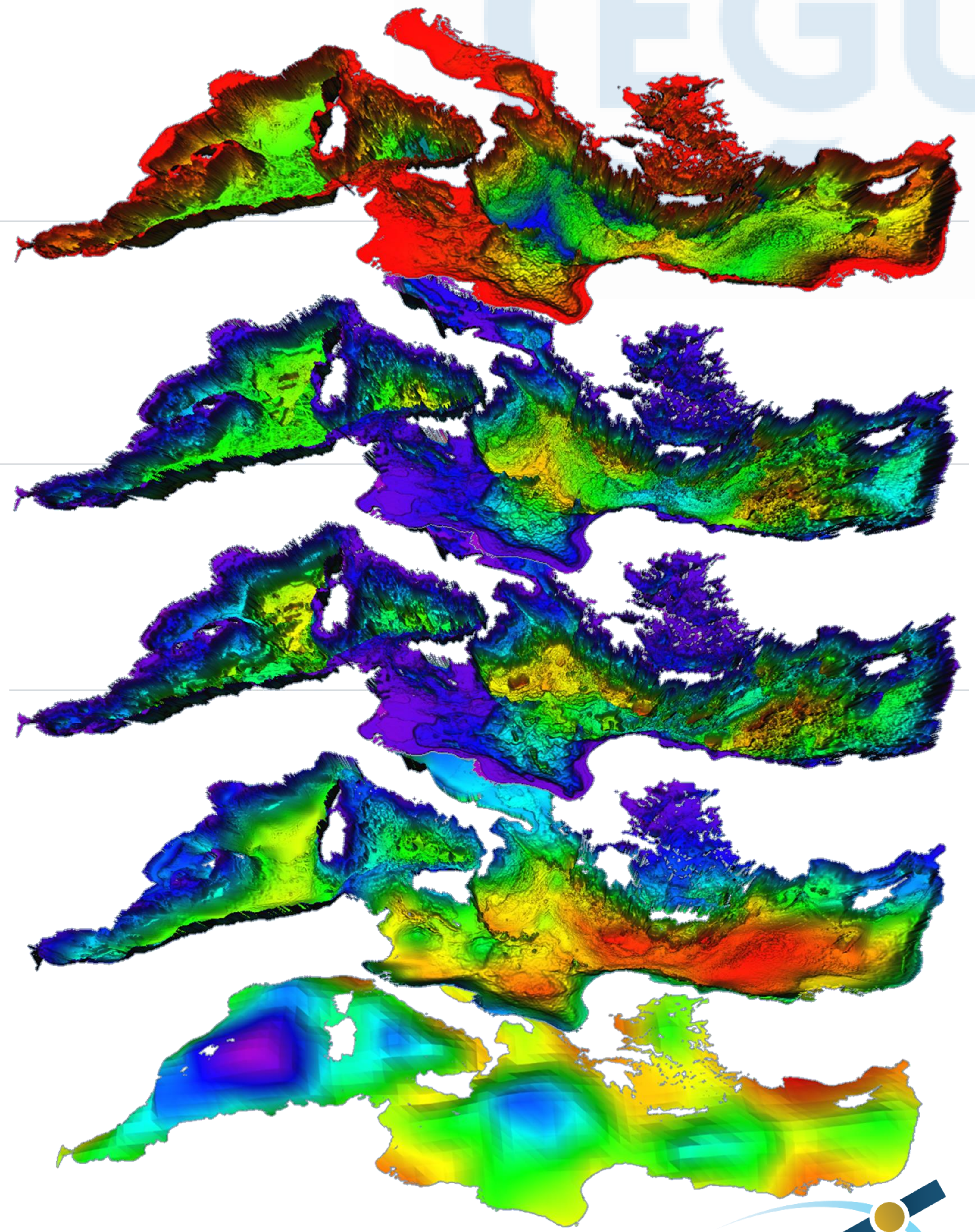
For the Mediterranean test case we started collecting data and models to build the a-priori geological model in terms of layers and density and susceptibility distribution.

We have built a model, till a maximum depth of 50 km, made by the following layers:

- Bathymetry
- Plio-Quat. sediments bottom
- Messinian sediments bottom
- Basement
- Moho

LAYER	AVERAGE DENSITY $[kg/m^3]$	DENSITY GRADIENT $[kg/m^3/km]$	SUSCEPTIBILITY $[10^{-6} SI]$
Water	1030	0	-13
Plio-Quaternary	2220	0	10000
Messinian	2170	0	-30
Pre-Messinian	2400	6	1500
Crust	2890*	6	36796*
Upper Mantle	3321*	0	0

*Crust and Upper mantle models lateral density and susceptibility distributions have been taken from Fullea et al. (2021) and Hunt et al. (1995).



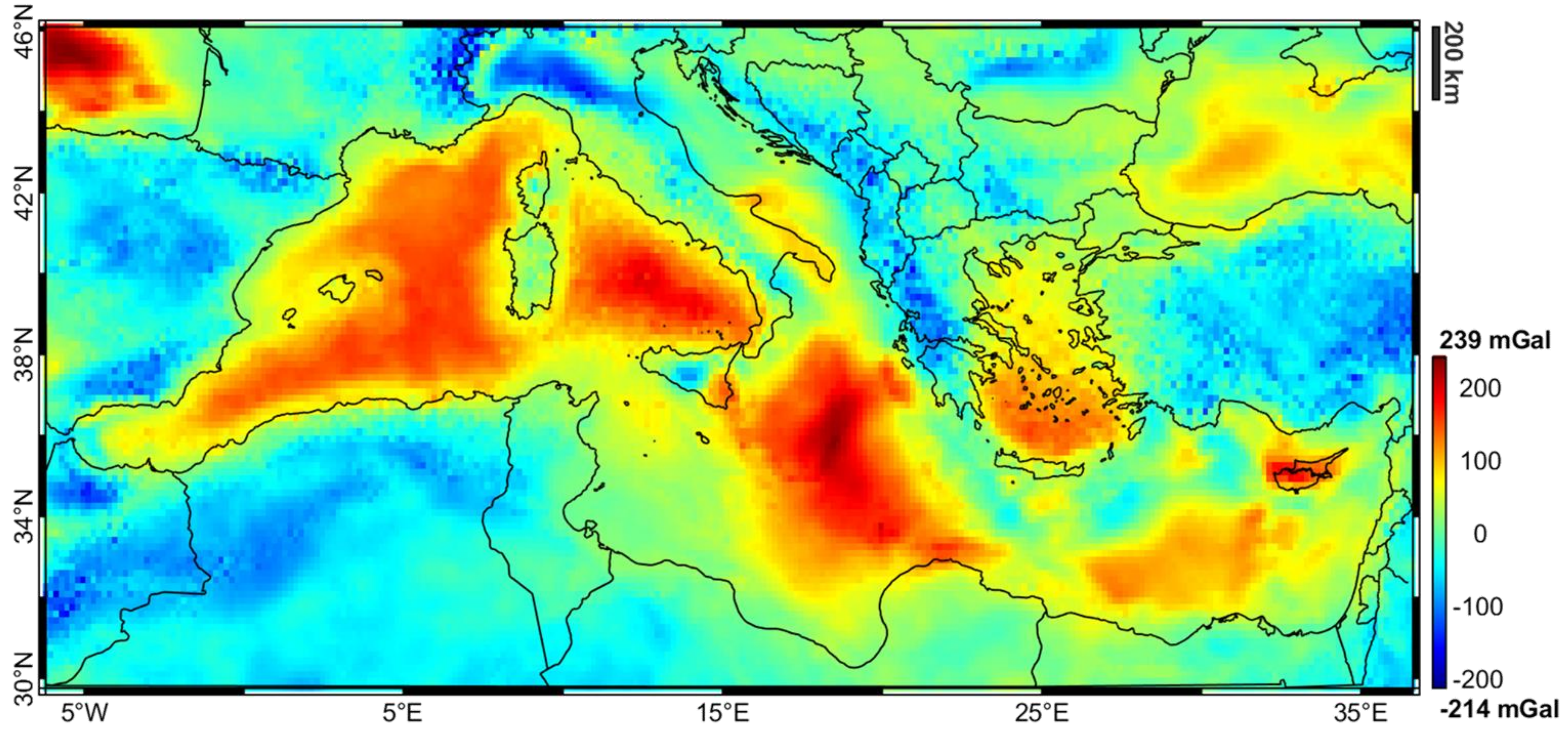
EXAMPLE: THE MEDITERRANEAN SEA AREA

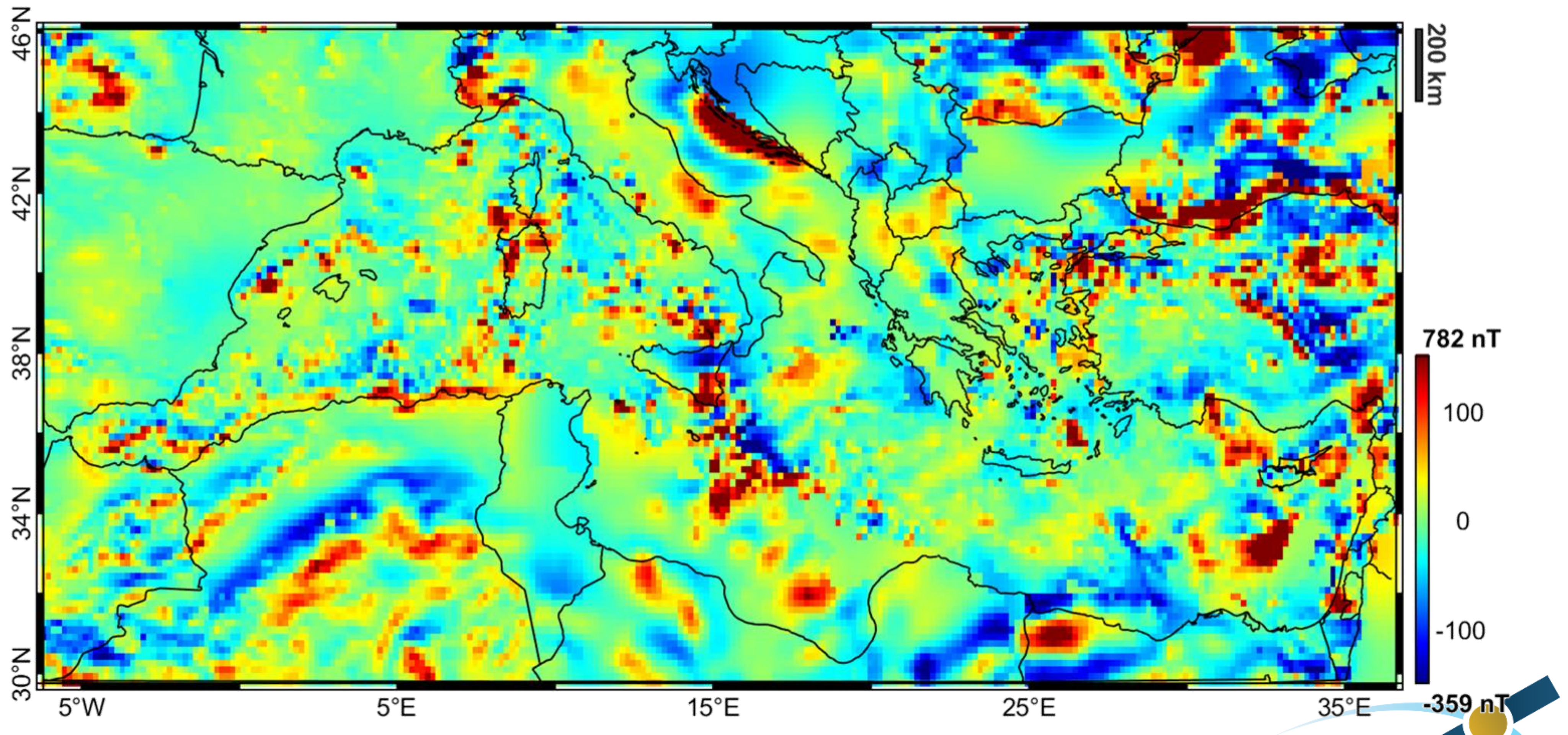
As gravity observation we selected the synthesis of gravity anomalies from **XGM2019e** up to degree and order 5540 corresponding to a spatial resolution of about 1.6 km.

To evaluate the accuracy we used a set of shipborne data and we retrieved an error std of ~ 3 mGal with correlation length of ~ 5 km.

As magnetic observation we selected the **WDMAM-2** global model (spatial resolution of about 1.6 km).

To evaluate the accuracy we used independent data and we retrieved an error std of ~23 nT with correlation length of ~ 20 km.





CONCLUSIONS

- In the current work we presented a procedure to perform joint gravity and magnetic inversion; the algorithm is able to retrieve at the same time the 3D density, magnetic susceptibility distributions and the geometry of the main geological units
- The proposed method has been successfully applied on a 3D (local) inversion in Canada
- We are working now to improve the software by modelling the Curie isotherm and by allowing the introduction of remanent magnetization
- We will develop all the algorithms to estimate also uncertainties of the results in terms of density/susceptibility distribution and geometries
- We will improve the a-priori geological model of the Mediterranean Sea area by refining the density model in the mantle and properly accounting for the effect of deep mantle up to the LAB
- We will perform the joint gravity and magnetic inversion in Mediterranean Sea to study the crust.

XORN

Thank you for the attention

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