Antarctica crustal model by means of the Bayesian gravity inversion

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The gravity inversion problem

Objective

Find the density distribution that fits the observed gravity signal (possibly physically meaningful)

The gravity inversion is **an ill-posed problem** suffering of:

- **Non-uniqueness** of the solution: various densities distributions produce the same gravity response
- **Instability** : extremely different density distributions can generate small differences in terms of gravity

To solve the problem it has to be **regularized** by adding independent information

Classical solutions 1/2

- **Parker-Oldenburg algorithm**

Published in the early '70s it is based on FFT and to solve the non-uniqueness of the solution it requires to fix geometries or the densities.

PROs

- it is fast, being based on FFT
- density model can have sharp edges between different layers

CONs

- modify one layer at the time (in depth or density)
- to guarantee convergence it requires manipulation on data (similar to low pass filtering)

Classical solutions 2/2

- **Li-Oldenburg algorithm**

Published in 1996 it is a 3D algorithm where the non-uniqueness of the solution is solved by means of a Tikhonov regularization

PROs

- it is an algorithm which can be used to solve full 3D inversion problems

CONs

- it leads to smooths solutions, avoiding sharp discontinuities between layers
- it requires a weighting functions that has to be empirically determined

In the following years this algorithm has been improved by many contributors both in terms of the density estimation and of the criteria to optimally choose the weighting function

Bayesian solution 1/2

- **CLASSICAL SOLUTIONS:** the logic behind the gravity inversion problem was to find a geological explanation to the solution of a mathematical/physical problem

- **NOW: we reversed the problem!**

Given a geological model we developed an inversion algorithm to adjust this model in order to fit the gravity data and, at the same time, to be compliant with all the a-priori available geological constraints

Examples of a-priori geological constraint

- Each layer can have an uncetainty defined by two grids representing the upper and lower range of admissible variability
- for densities, the uncertainty can be expressed in terms of standard deviation assigned to the initial density model

Bayesian solution 2/2

Following a Bayesian formalism the gravity inversion problem can be expressed as follow

$$P(x|y) \propto L(x|y)P(x)$$

Probability of the posterior model

Degree of fit with observations

Probability of the prior model

The objective function can be considered made by four contributions

$$P(\rho,L|y)=\frac{1}{A}exp\left\{\underbrace{-\frac{1}{2}(y-F\rho)^T C_{vv}^{-1}(y-F\rho)}_{\text{Gravity residual}}\underbrace{-\frac{\eta}{2}\sum_{i=1}^{n}\frac{\left(\rho-\mu_\rho(L_i)\right)^2}{\sigma_\rho^2(L_i)}}_{\text{“distance” from the initial density model}}\underbrace{-\frac{\gamma}{2}\sum_{i=1}^{n}s_i^2(L_i)}_{\text{Neighbors clustering}}\underbrace{-\frac{\lambda}{2}\sum_{i=1}^{n}\sum_{j\in\Delta_i}q^2\left(L_i,L_j\right)}_{\text{“distance” from the initial geometries}}\right\}$$

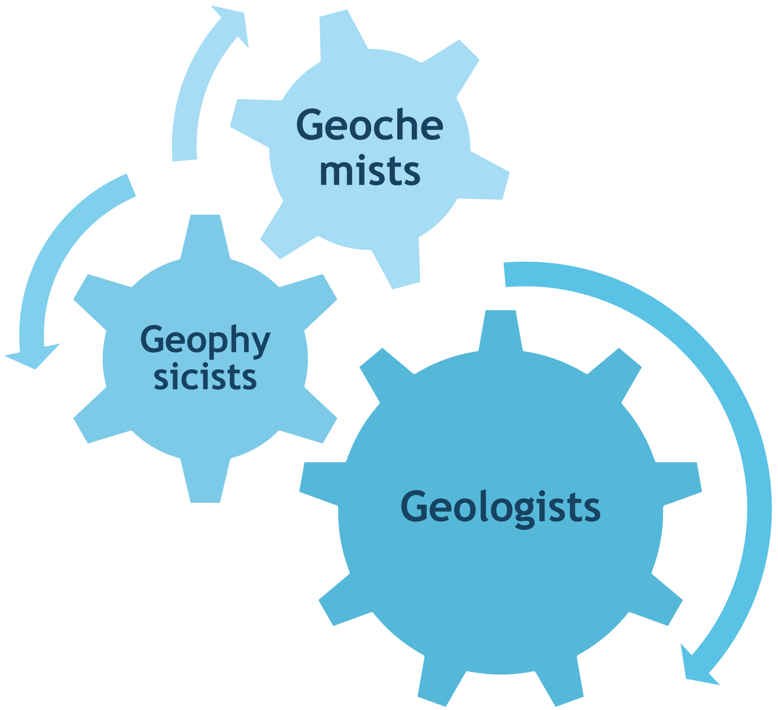
The global minimum is found with a Simulation Annealing by means of a Gibbs sampler(1)

1. Marchetti, P., Sampietro, D., Capponi, M., Rossi, L., Reguzzoni, M., Porzio, F., & Sansò, F. (2019). Lithological constrained gravity inversion. A Bayesian approach. In 81st EAGE Conference and Exhibition 2019 (pp. 1-5). EAGE Publishing BV.

How to use the Bayesian inversion

The **cooperation is fundamental** to setup the problem

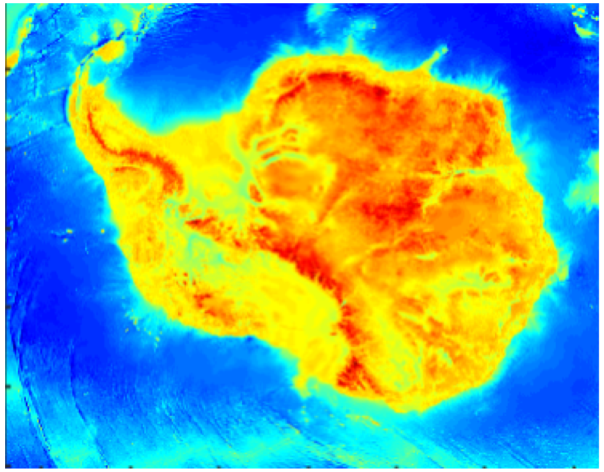
- Geologists, geophysicists and geochemists etc. **working together** can build the initial model satisfying as much as possible the physics of the system



- the collaboration is essential also in the analysis of the results in order to properly interpret the final model and, if necessary, to introduce more restricted constraints to the solution, according to geological/petrological/ geochemical/geophysical relations

The Antarctica

- In a challenging environment, like the Antarctica, the indirect investigation represents a valuable solution to improve our knowledge and, after dedicated missions, satellite gravity data became an important source of information(2)



- The challenge today is the capability to invert such gravity data on large areas with the aim to obtain a 3D density model of the Earth crust

We applied the Bayesian inversion to infer a model of mass density distribution

Without a specific background from the geological, geophysical/chemical point of view of this continent we started collecting data from literature with the aim to present the potentiality of the Bayesian inversion software

2. Pappa, F., Ebbing, J., Ferraccioli, F., & van der Wal, W. (2019). Modeling satellite gravity gradient data to derive density, temperature, and viscosity structure of the Antarctic lithosphere. *Journal of Geophysical Research: Solid Earth*

The Antarctica initial model 1/4

Studied Area:

- φ (-61, -90) deg
- λ (0, 360) deg
- max depth 60 km

Model Resolution [3] **:**

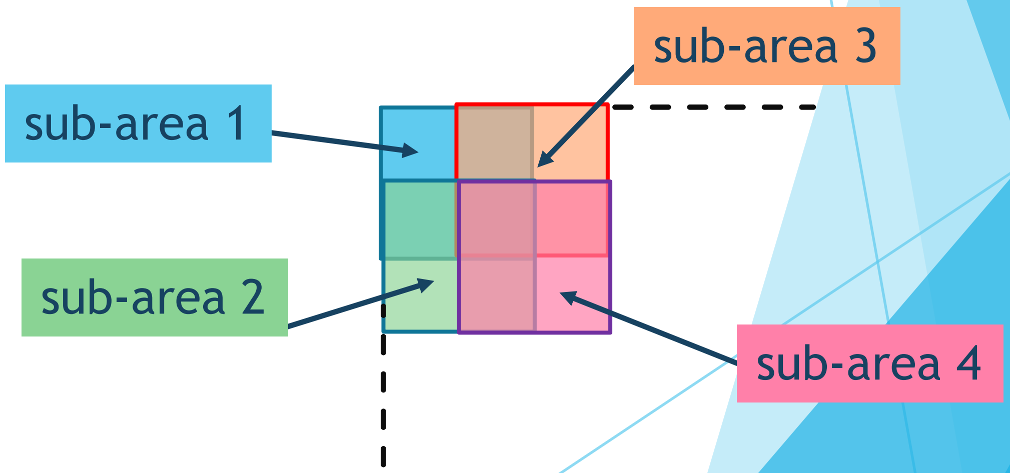
- Δx = 17 km; Δy = 20 km;
- Δz increasing with depth from 100 m at 0 level to 900 m
- max depth = 60 km

Total number of unknowns: 910 x 655 x 131 x 2 = 1.5·10^8

(nx = 910, ny = 655, nz = 131, label, ρ = 2)

Total computational time required on HPC: 15 hours

In order to perform the inversion the model has been divided into 35 sub-areas, partially overlapped



3. Sampietro, D., & Capponi, M. (2019). Practical Tips for 3D Regional Gravity Inversion. Geosciences, 9(8), 351.

The Antarctica initial model 2/4

To create the initial model in terms of layers and densities we interpolated the following data on our grid:

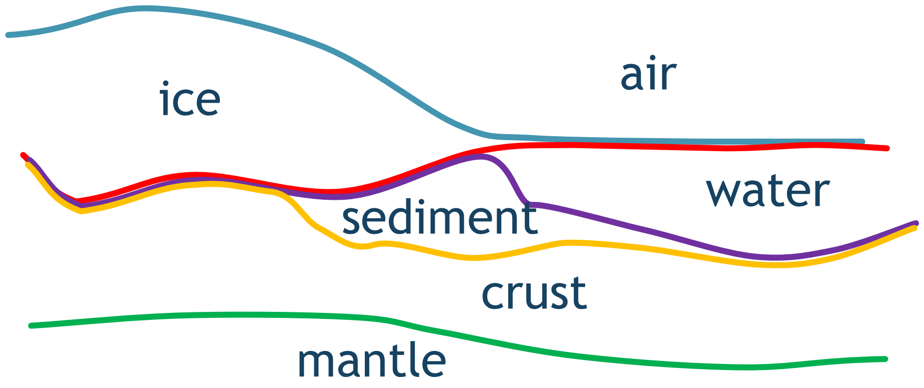
for ice, topography and bathymetry

- Etopo1 (https://www.ngdc.noaa.gov/mgg/global/)
- Bedmap2 (https://www.bas.ac.uk/project/bedmap-2/#about)

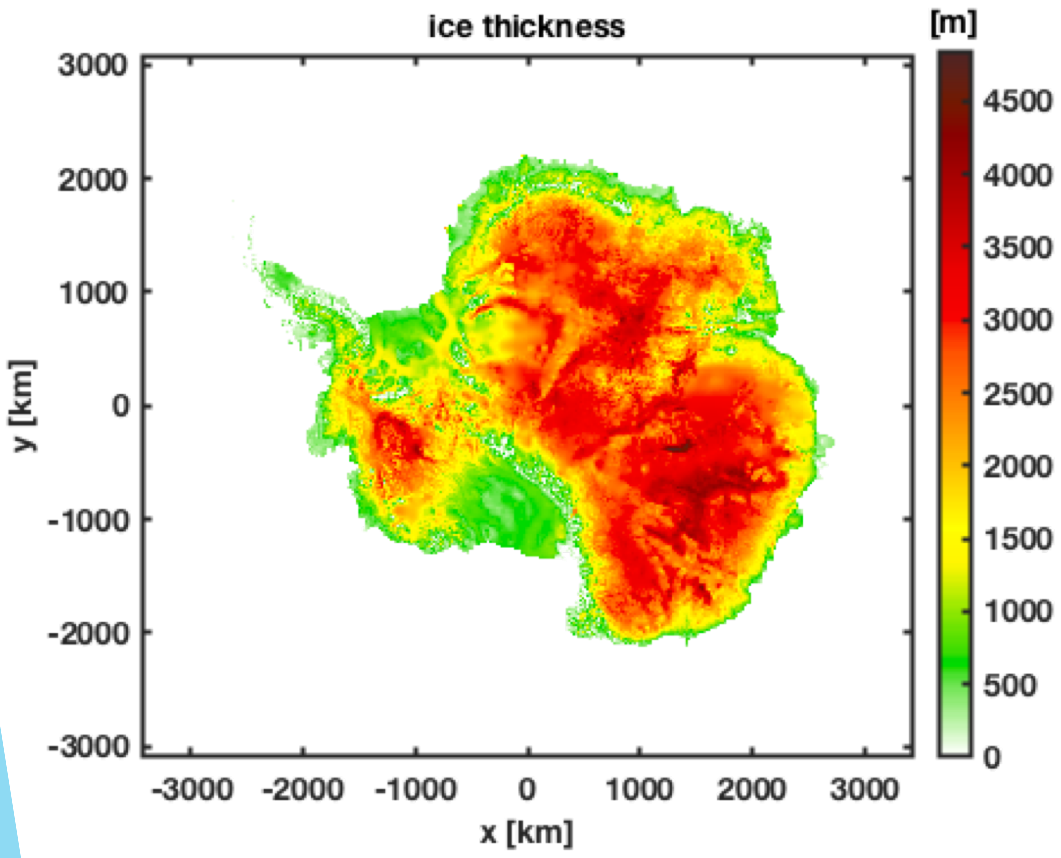
for sediments, crust and Moho

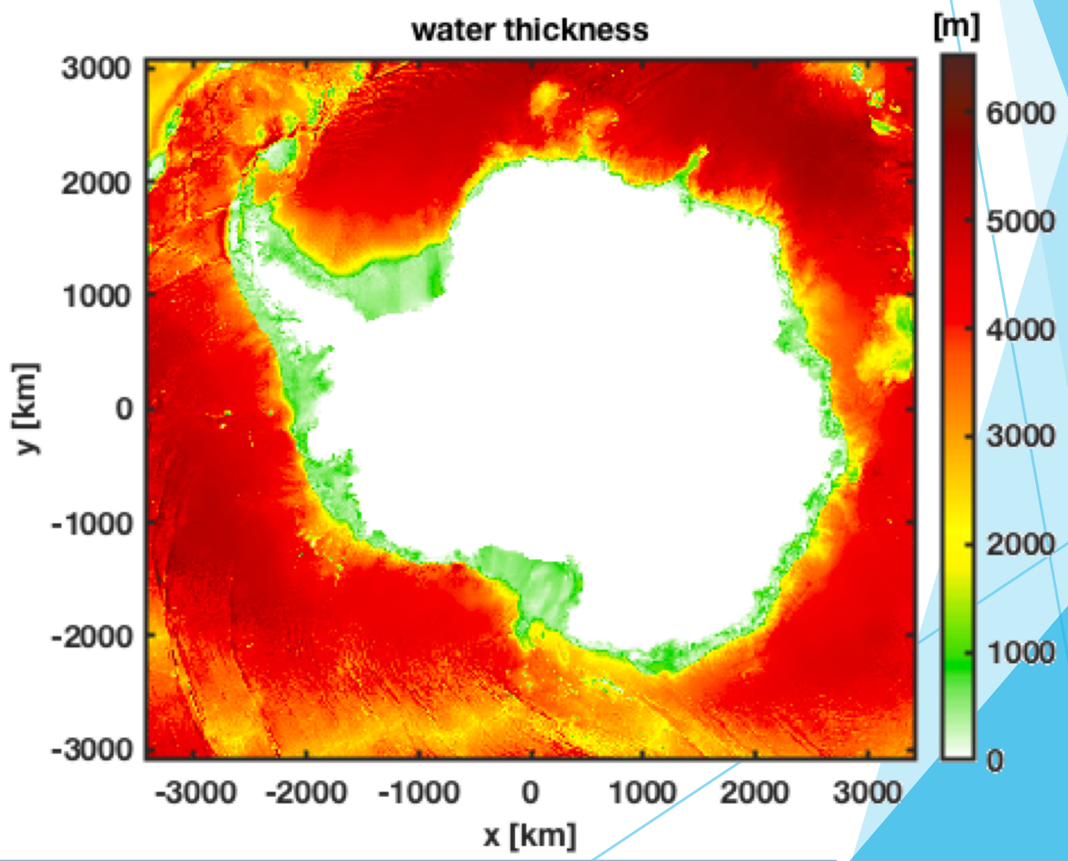
- Crust1.0 (https://igppweb.ucsd.edu/~gabi/crust1.html)

Our initial model is made by 5 layers (ice, water, sediments, crust and Moho)



The Antarctica initial model 3/4





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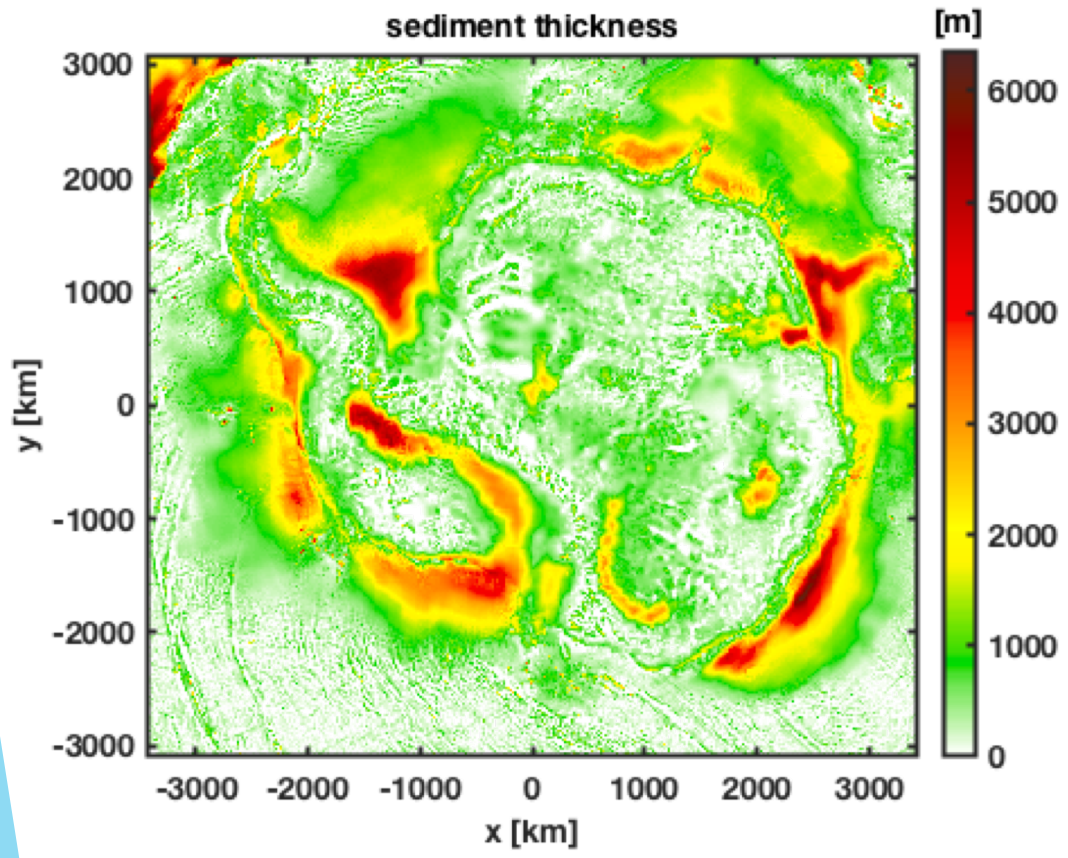
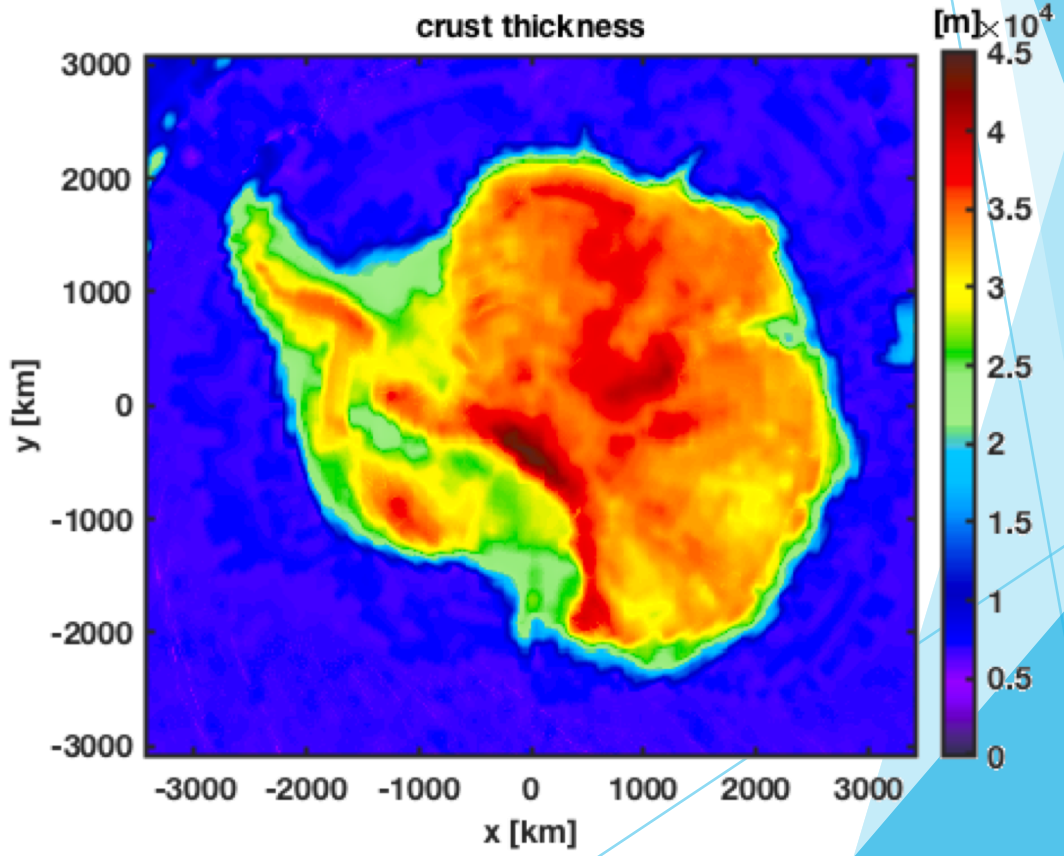
The Antarctica initial model 4/4

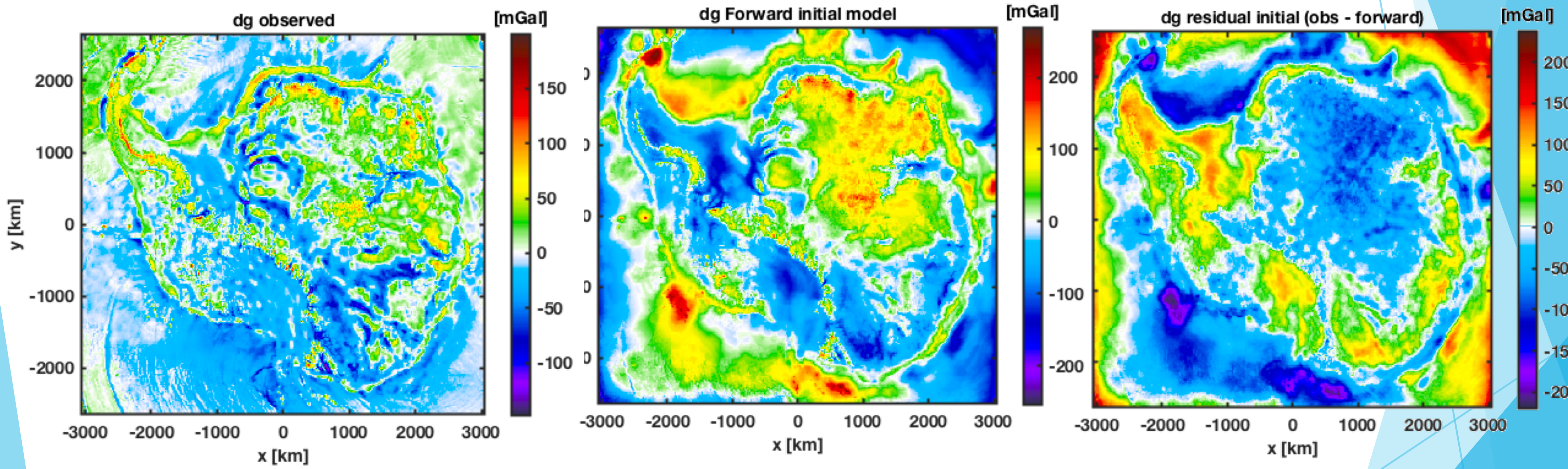




The Antarctica gravity observations

As gravity observations we synthetised gravity disturbances from XGM2019e[4] - degree 4590.

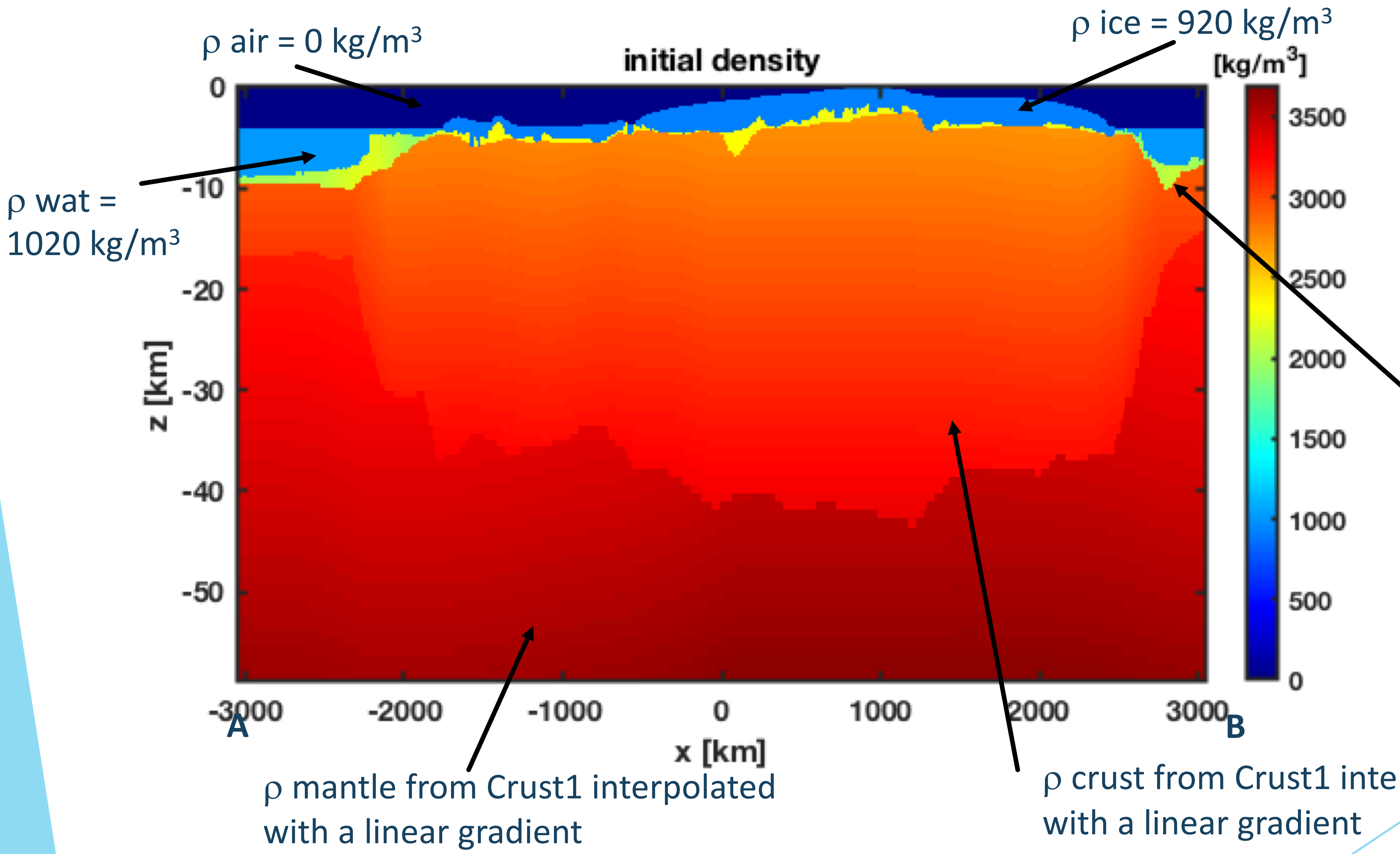
The Bayesian inversion software anyway can use as gravity observations also second radial derivatives (Tzz) and it allows to perform single (dg or Tzz) or joint inversion (dg + Tzz).

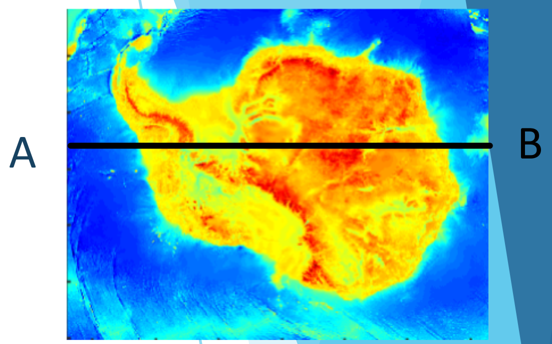


As shown in the third figure, the gravity signal generated from our initial model is quite different from the observed one with a std of about **64 mGal**

4. Zingerle, P., Pail, R., & Gruber, T. (2018). High-resolution combined global gravity field modelling-Next generation XGM Models. In International Symposium Gravity, Geoid and Height Systems 2.

The Antarctica initial densities - example

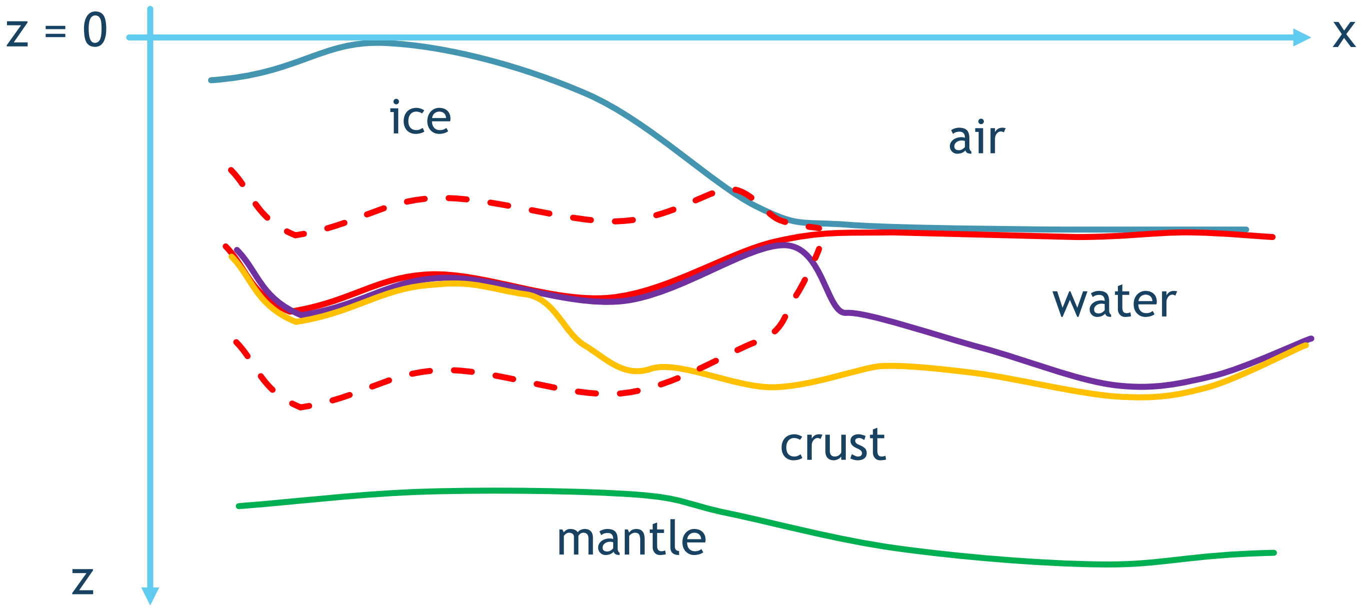




First inversion test

In these difficult times, with the ongoing COVID-19 emergency, we were able to perform two preliminary tests

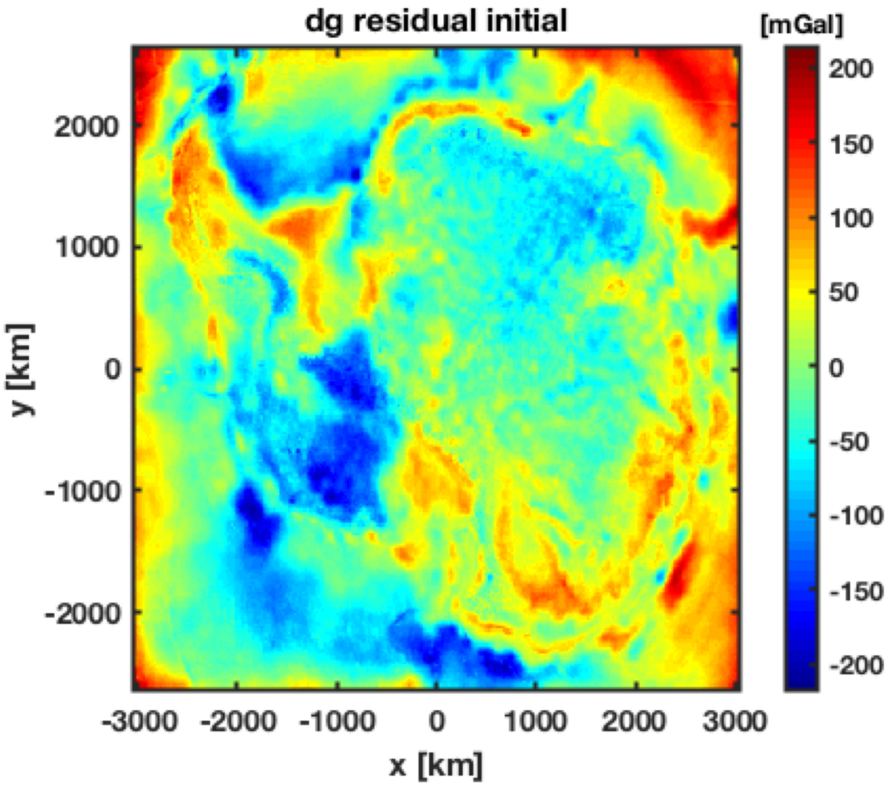
- In a **first test** we created an initial model from available literature, setting realistic uncertainties for both layers and densities **BUT** introducing an unrealistic uncertainty for the bedrock layer.

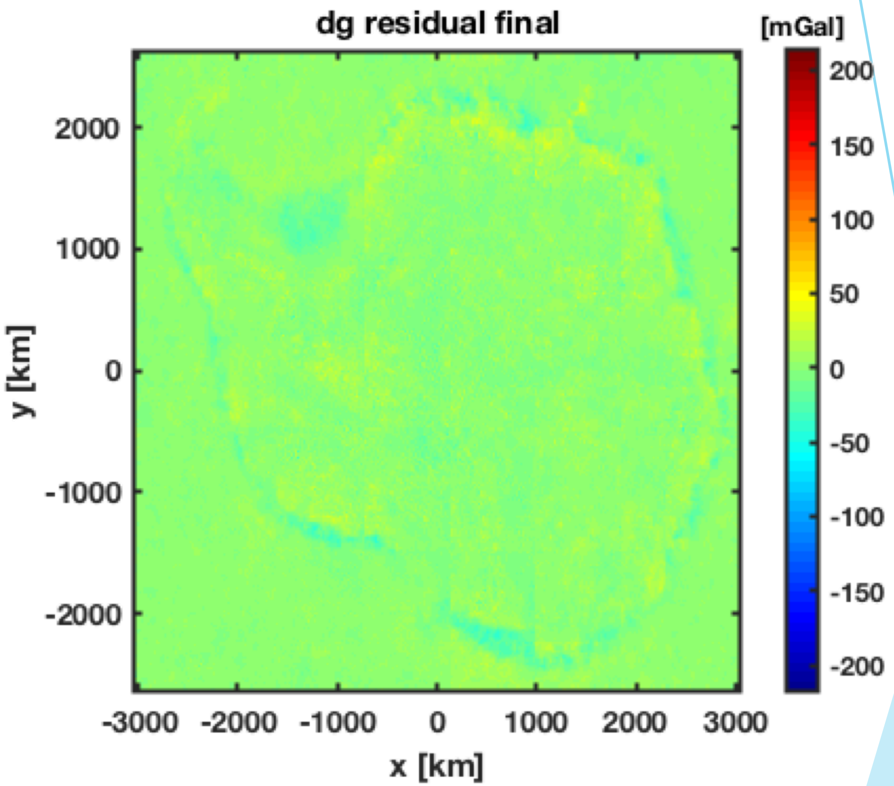


- We supposed that the topography everywhere below ice was known with a constant accuracy of $\pm$ **1000 m**

First inversion test results 1/3

- gravity residuals before and after the inversion





MIN	-218.3 mGal
MAX	213.3 mGal
STD	63.2 mGal

MIN	-45.2 mGal
MAX	38.8 mGal
STD	6.0 mGal

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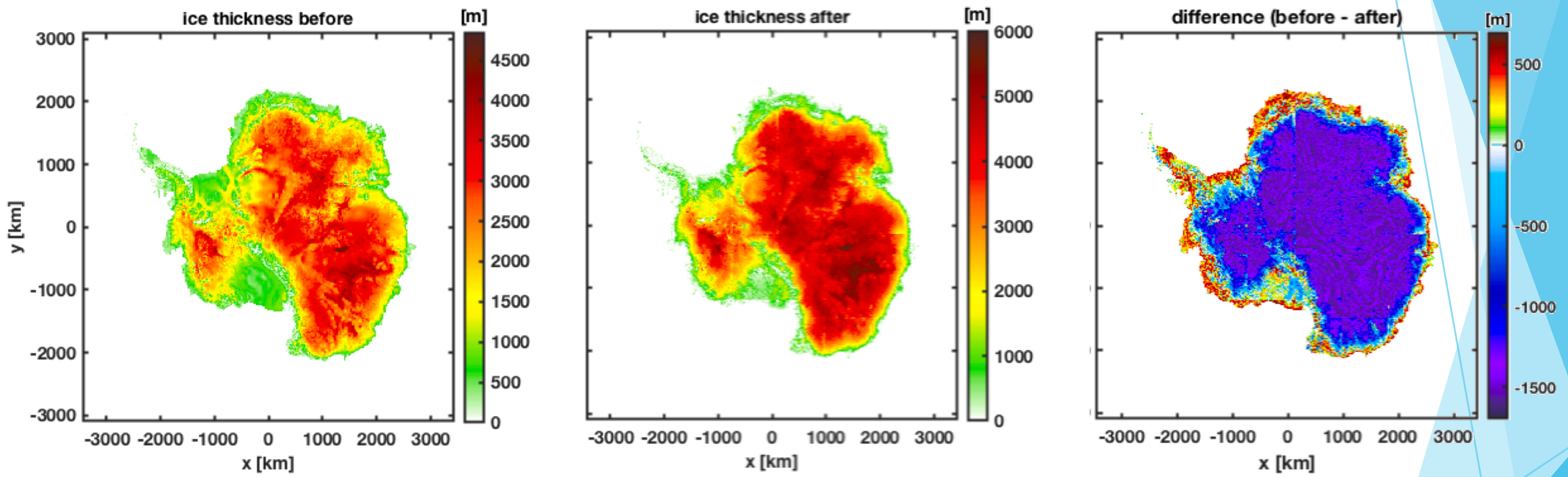
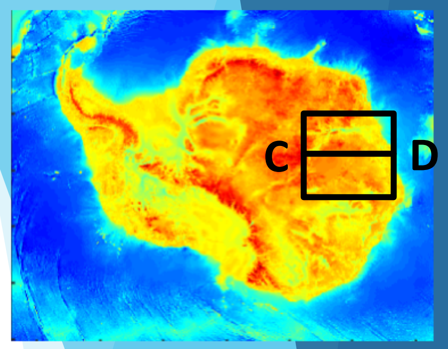
First inversion test results 2/3

- Ice thickness before and after the inversion

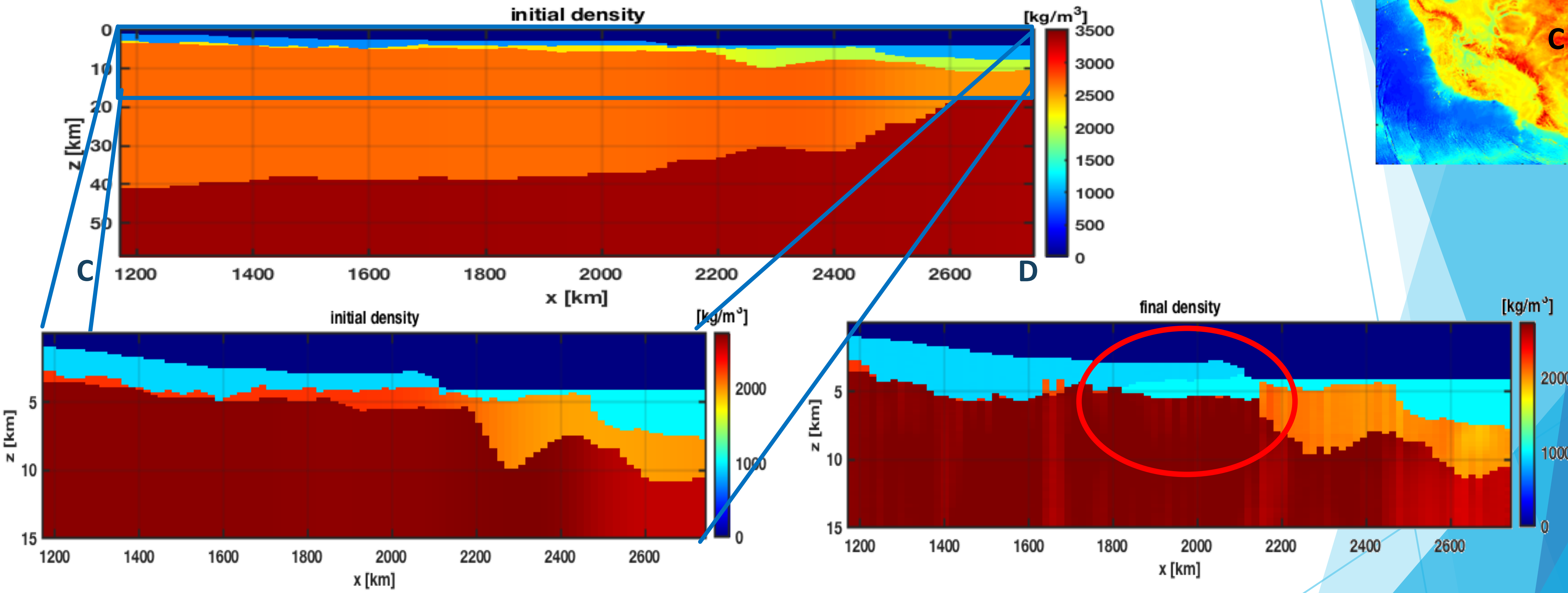


- The last figure shows that the algorithm increases almost everywhere the ice thickness (except for the border of the continent) according to the user-defined settings
- **BUT WE KNOW THIS IS NOT REALISTIC! So we have to modify the geological constrains making them more restricted**

First inversion test results 3/3



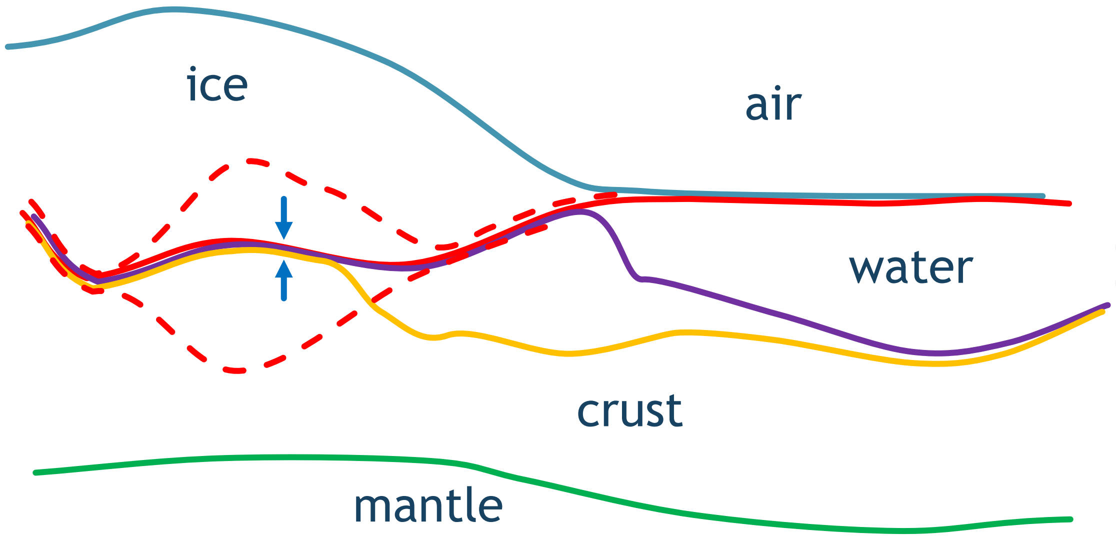
- Zoom on a section of sub-area 28 before and after the inversion

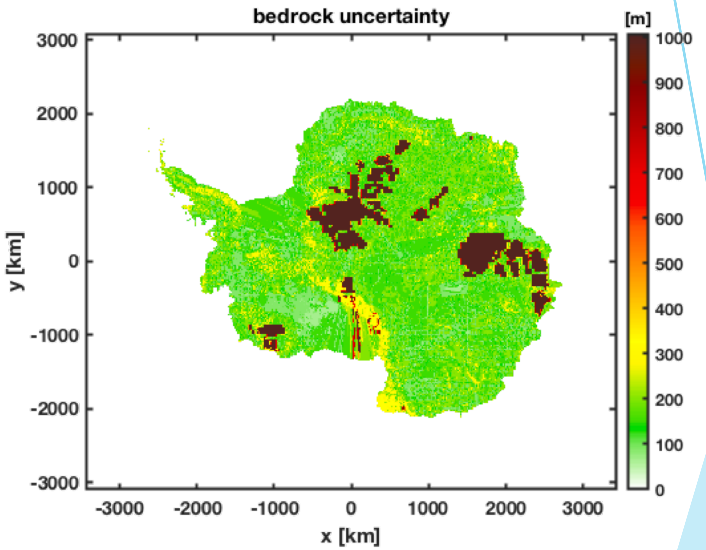


- These figures show how **the algorithm change densities and moves the layers BUT** in this test, **it generated a not physical situation** (it segmented the sediment layer introducing water between the ice and the crust – in red circle)

Second inversion test

- So in the **second test** we introduced a much more realistic uncertainty for bedrock layer based on literature [5], supposing that the topography below ice is known with an accuracy of $\pm$ **200 m with peaks of 1000 m ONLY in certain regions**



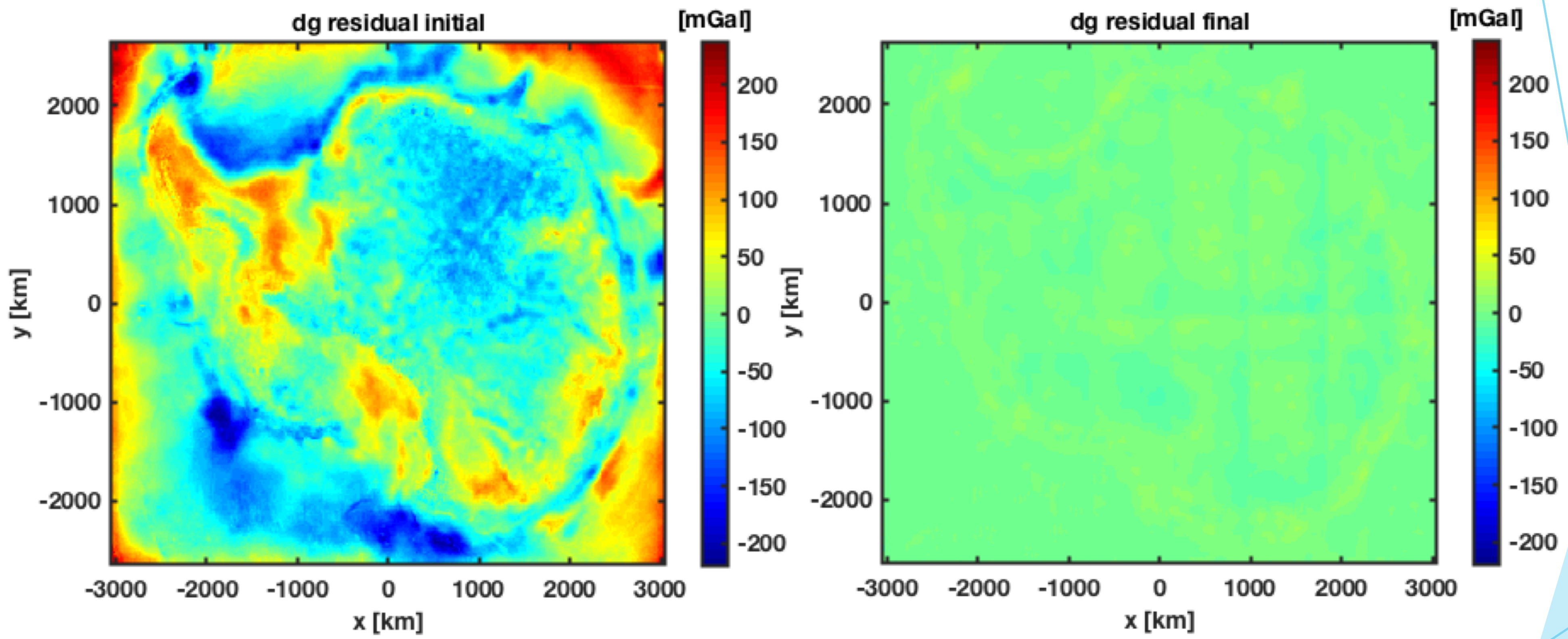


- And we introduced **a new constrain to impose the contact** between bedrock and ice (to avoid "water intrusions")

5. Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., ... & Catania, G. (2013). Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere*, *7*(1), 375-393.

Second inversion test results 1/3

- gravity residuals before and after the inversion

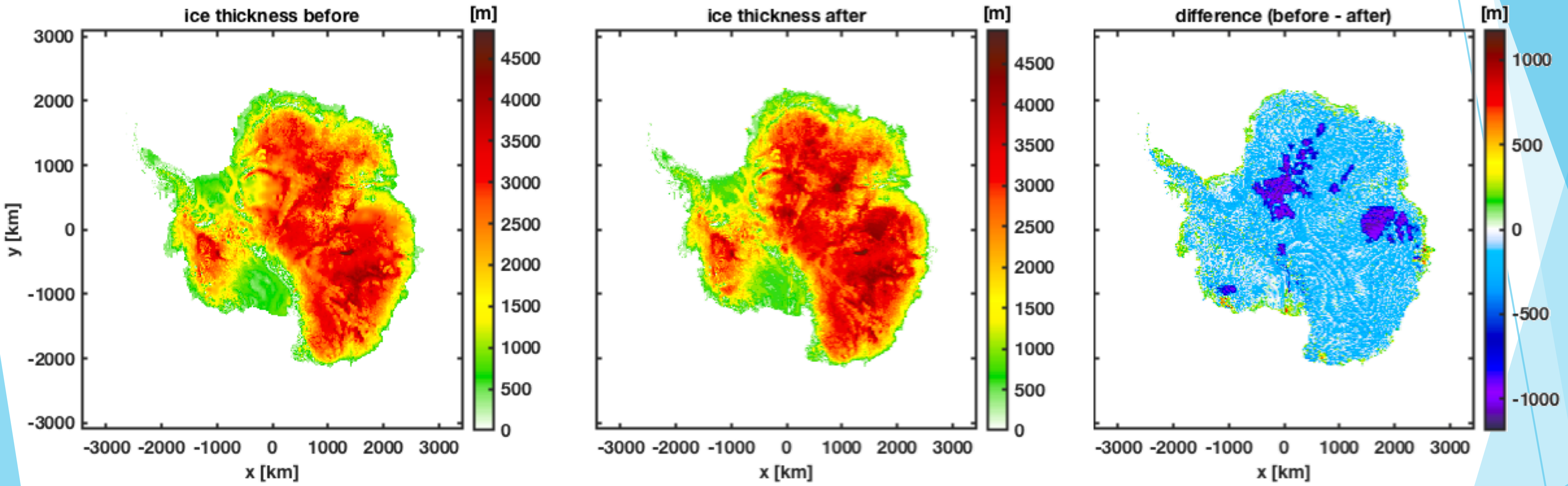


MIN	-220.4 mGal
MAX	236.8 mGal
STD	64.2 mGal

MIN	-47.0 mGal
MAX	44.0 mGal
STD	5.9 mGal

Second inversion test results 2/3

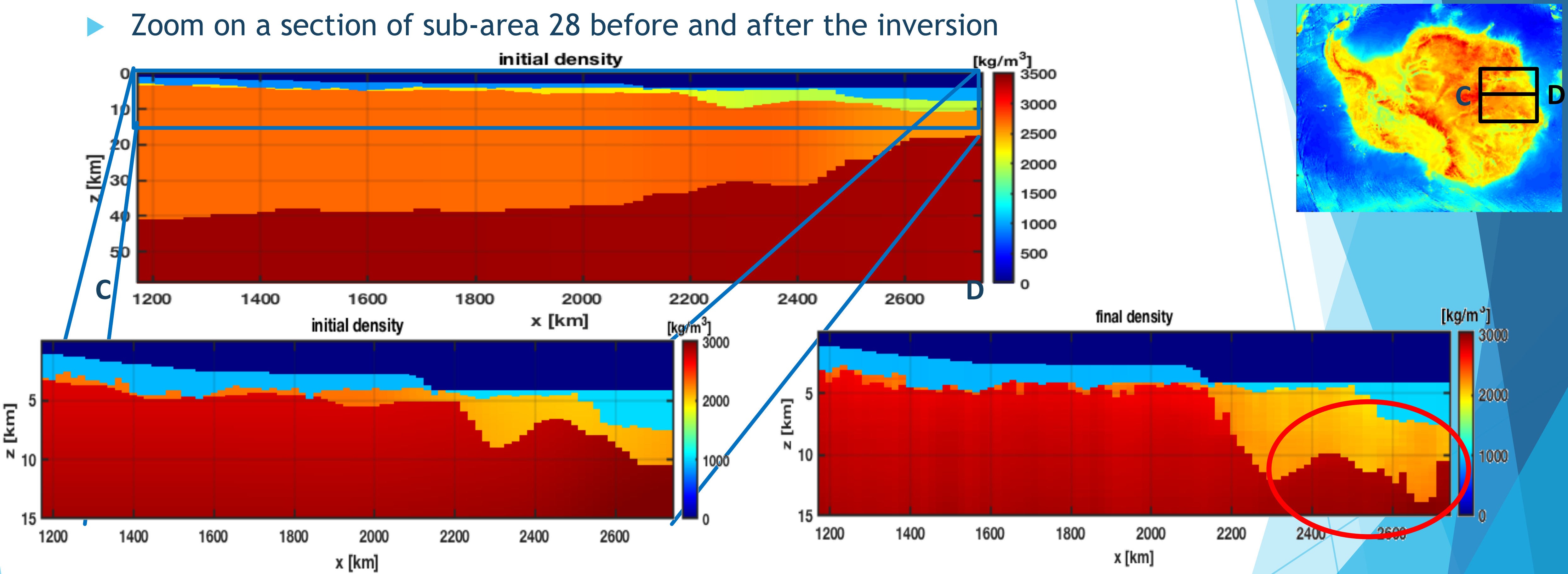
- Ice thickness before and after the inversion



- The last figure shows that the algorithm increased the ice thickness, where it is admissible by the constraints
- These figures demonstrate that the algorithm **respects the user-defined settings** and adjust the initial model in such a way to fit the gravity signal

Second inversion test results 3/3

- Zoom on a section of sub-area 28 before and after the inversion



- These figures show that in the second inversion the contact constrain has been satisfied
- It can be noticed that in this solution the crust (in red circle) presents an “unrealistic” roughness that can be properly calibrated by the user in the initial setting (but we haven’t done it yet!)

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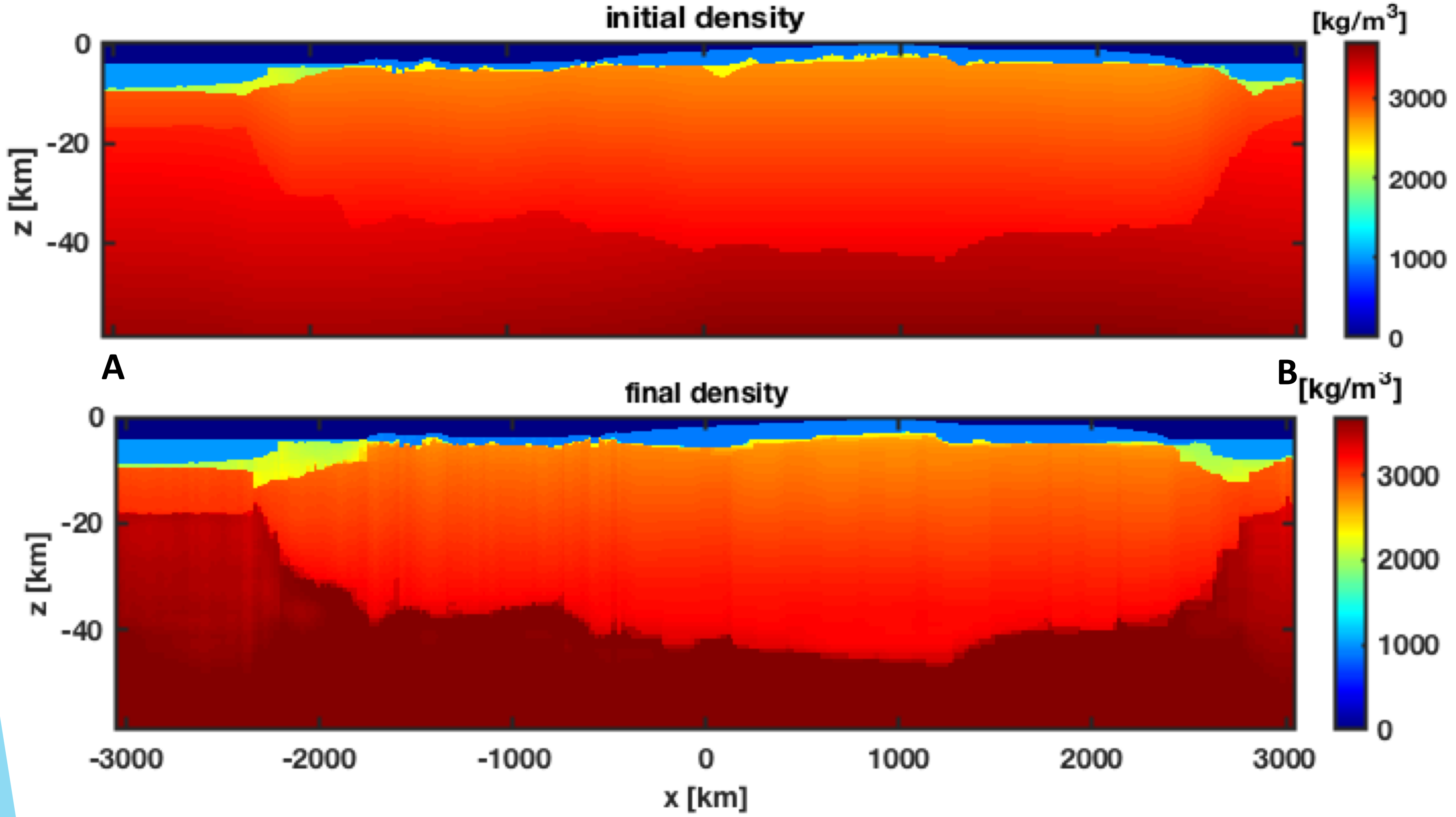
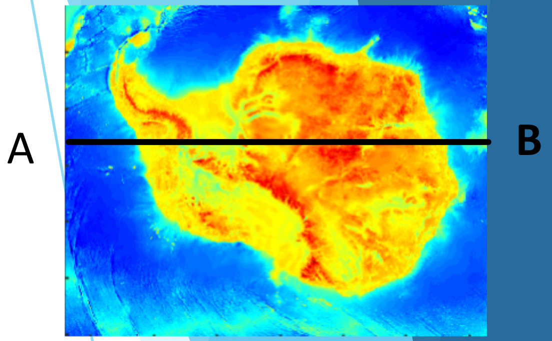
Second inversion test results: full section





- From this sections emerge that the algorithm increases the sediments and reduces the mantle density below the ocean … BUT this is just a preliminary result!

Conclusions

- The Bayesian algorithm we proposed introduces a probabilistic approach in the gravity inversion problem; differently from the classical solutions we reversed the problem: so given a geological model we developed an algorithm to adjust this model in order to fit the gravity data
- The Bayesian inversion algorithm applied to the Antarctica continent shows that it improve the fit of the gravity data adjusting the initial model according to the user constraints
- The preliminary tests here presented demonstrate that the definitions of the initial model and of the constraints are very important because they guide the inversion solution
- It **is FUNDAMENTAL the cooperation between different experts:** geologists, geophysicists, geochemists etc. working together can merge their knowledge improving the quality of the gravity inversion results and rejecting the solutions not admissible from the physical point of view
- We hope to continue investigating the Antarctica continent…**so if you can help us in building a much more realistic initial model please contact us!**

References

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