→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

Linking Solid Earth and Cryosphere in Antarctica

Jörg Ebbing

Linking Solid Earth and Cryosphere in Antarctica

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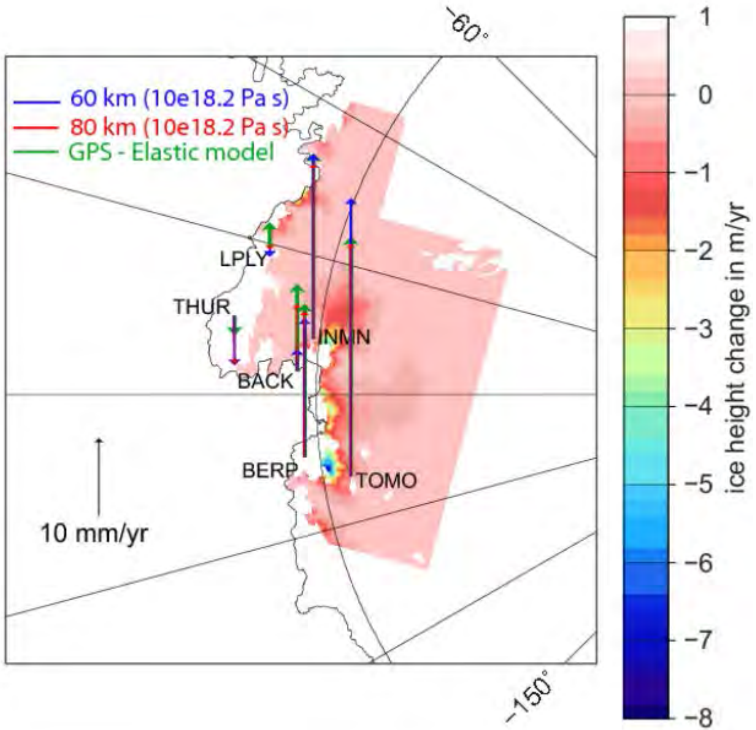
Ice dynamics with GOCE and GRACE

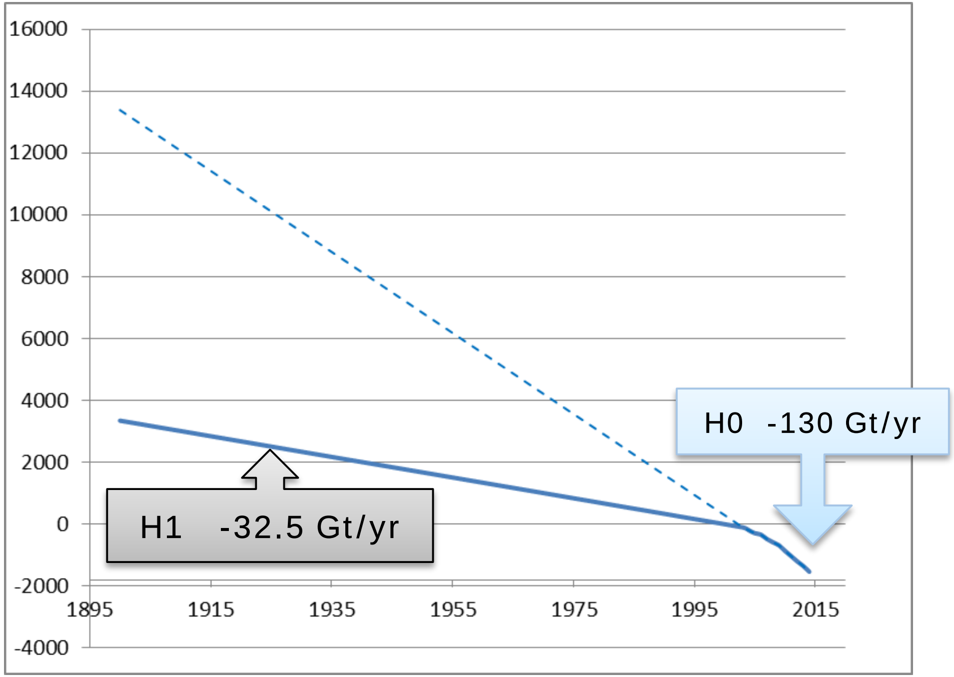
The recent ice history in West Antarctica

Only low upper mantle viscosity can explain the extremely large uplift rates in the Amundsen Sea Sector

This means present-day signal has a 'memory' of only a few hundred years



The recent ice history in West Antarctica



We use an history model for the last 12 years derived from repeat altimetry (by Ben Smith)

+ from 1900 up to 2002 we assume 1/4 of the present day melting rate - H1

Our assumption is based on ice history based on Mouginot, J., E. Rignot, and B. Scheuchl (2014) *GRL*

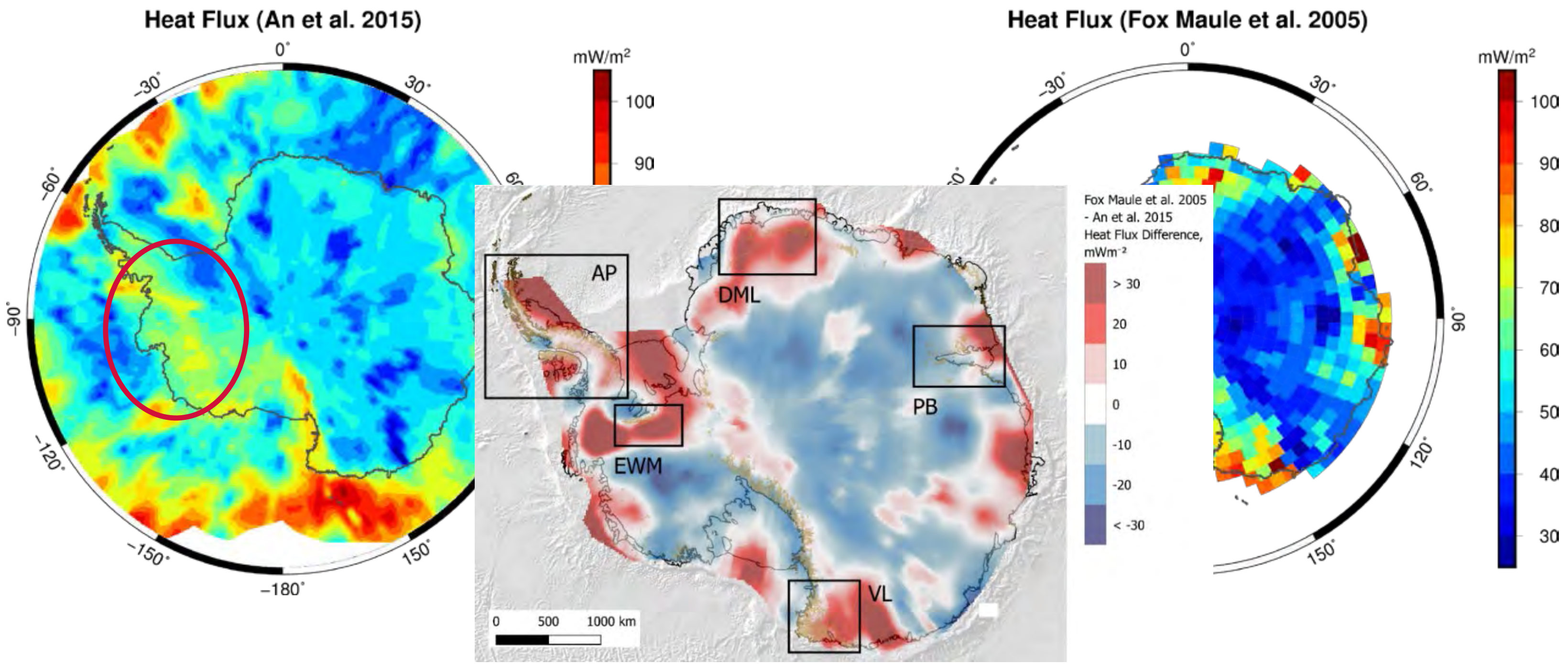
Ice-sheet dynamics

Bell, 2008

In West Antarctica (**b**), subglacial water results from basal melt in the interior and in the ice-stream tributaries. Beneath the ice streams, water is stored in subglacial lakes that periodically drain downstream into the surrounding ocean. Regions of **elevated geothermal heat** can produce increased subglacial water.

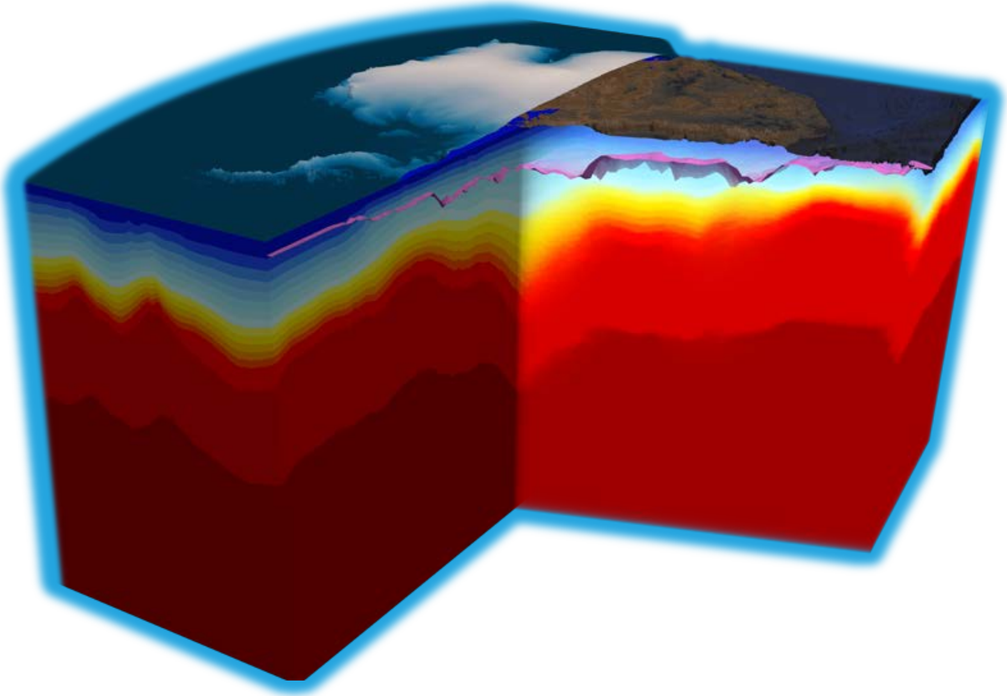
- Important are temperature conditions at bottom and surface of ice sheet
- Elevated geothermal heat reason for rapid acceleration?

Elevated geothermal heat?



Difference between
geothermal flux models

Antarctica without the ice and in depth

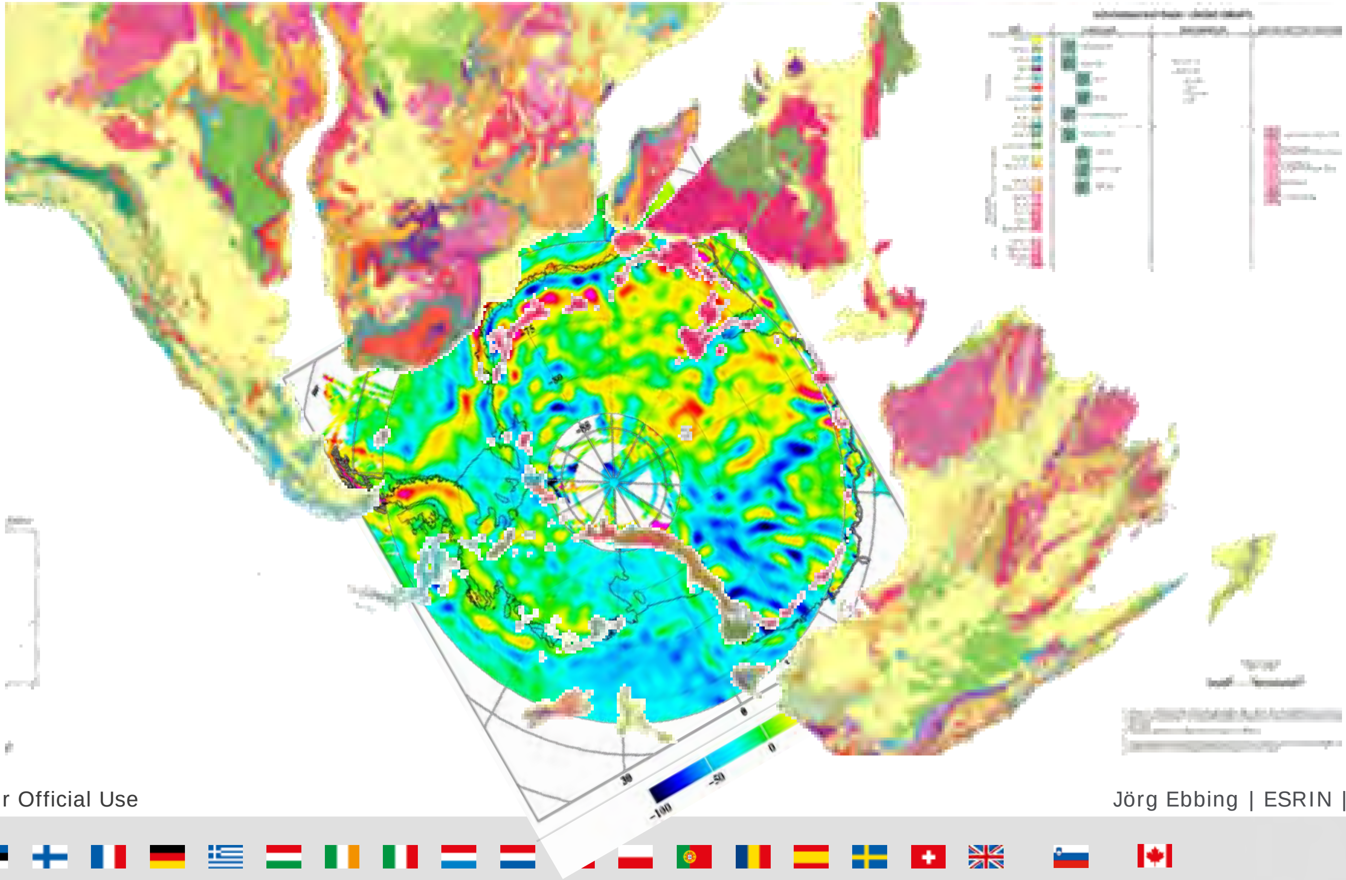


How is the structure of the Antarctic continent?

How hot is Antarctica?

How does the Solid Earth affect the Cryosphere?

Antarctica gravity after GOCE ...



Crustal thickness of Antarctica

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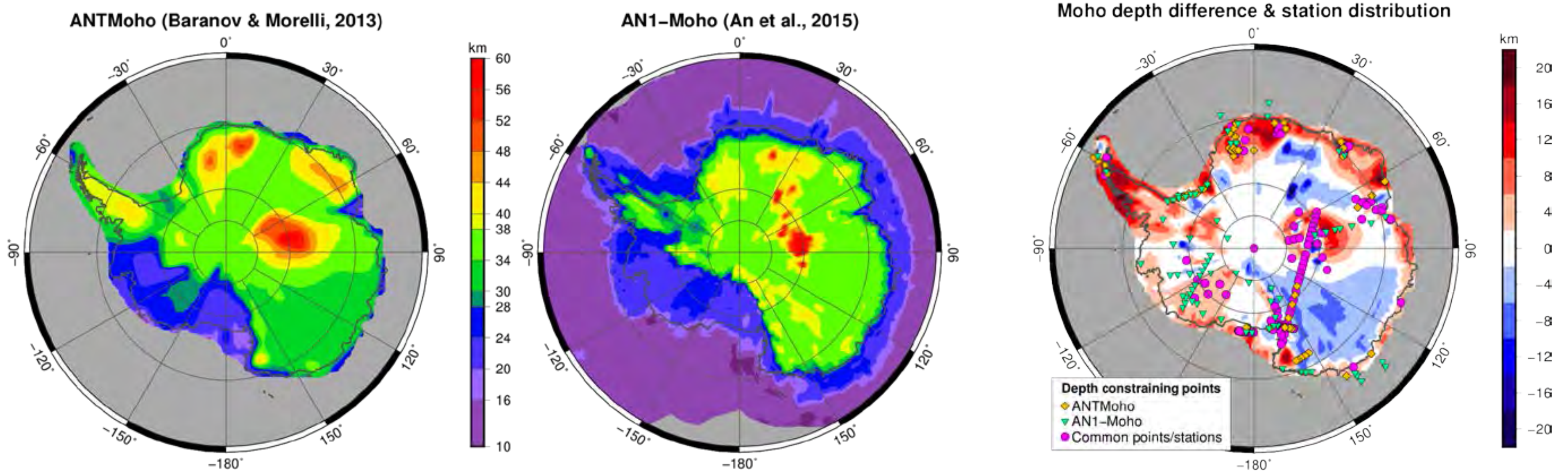
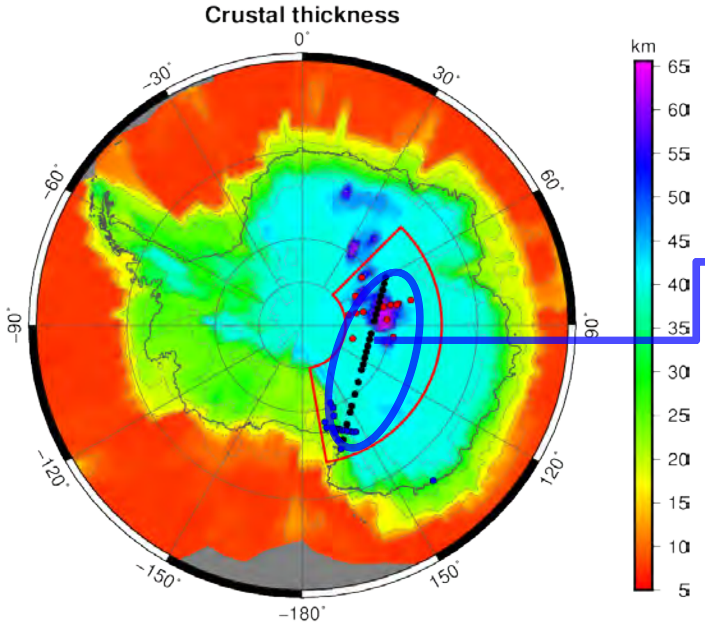
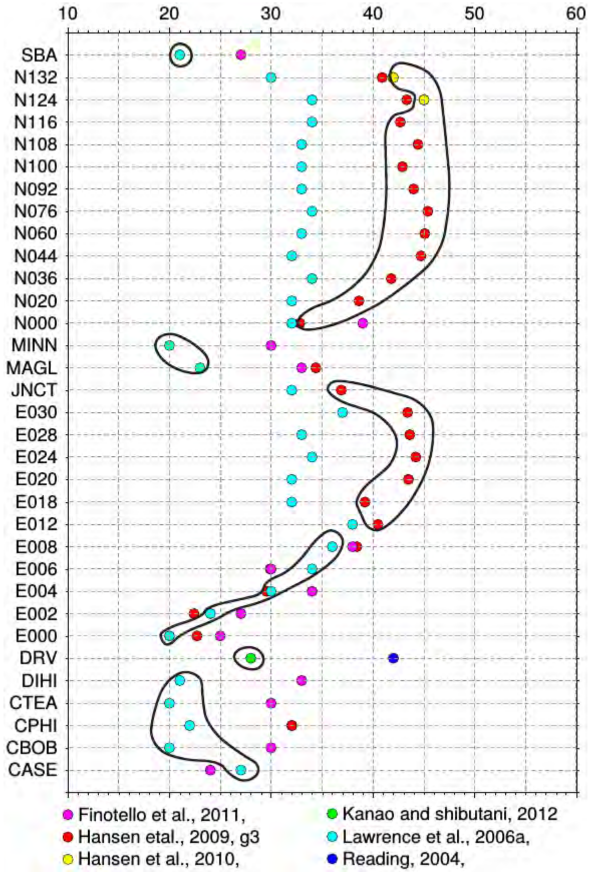


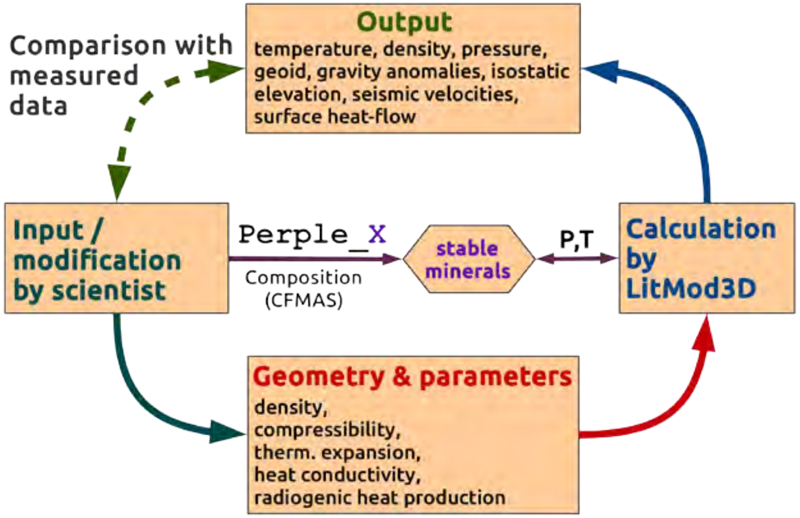
Accuracy of seismic estimates





Up to 10km discrepancy in Moho depth.
→ Shallow (~30km) or deep (~40km) Moho?

Lithospheric modelling: methodology



LitMod3D = LIThospheric MODelling in a 3D geometry:

combined geophysical-petrological forward modelling of the lithosphere and the sublithospheric mantle in finite difference.

- heat equation
- isostasy
- seismic body wave velocities
- rock properties as functions of temperature, pressure and composition

Perple_X: thermodynamic modelling of stable mineral phases for mantle compositions in the CFMAS system (CaO, FeO, MgO, Al_2O_3, SiO_2)

LitMod3D: J. Fullea et al., ‘LitMod3D: An Interactive 3-D Software to Model the Thermal, Compositional, Density, Rheological and Seismological Structure of the Lithosphere and Sublithospheric Upper Mantle’, Geochemistry, Geophysics, Geosystems 10, no. 8 (2009).
Perple_X: J. A. D. Connolly, ‘Computation of Phase Equilibria by Linear Programming: A Tool for Geodynamic Modeling and Its Application to Subduction Zone Decarbonation’, Earth and Planetary Science Letters 236, no. 1 (2005): 524–541.

Lithospheric modelling: methodology

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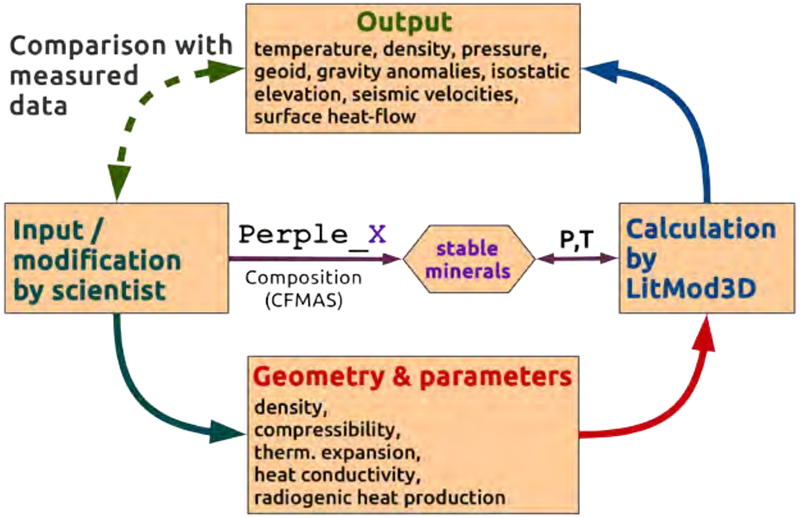

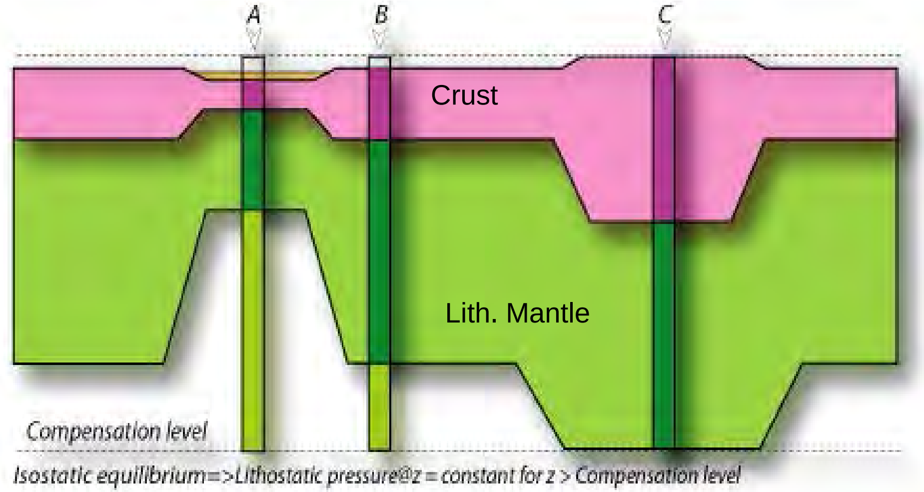

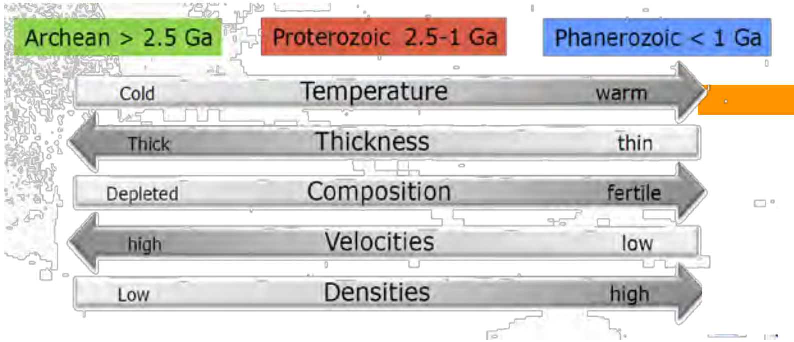

Sensitivity to Moho depth estimates

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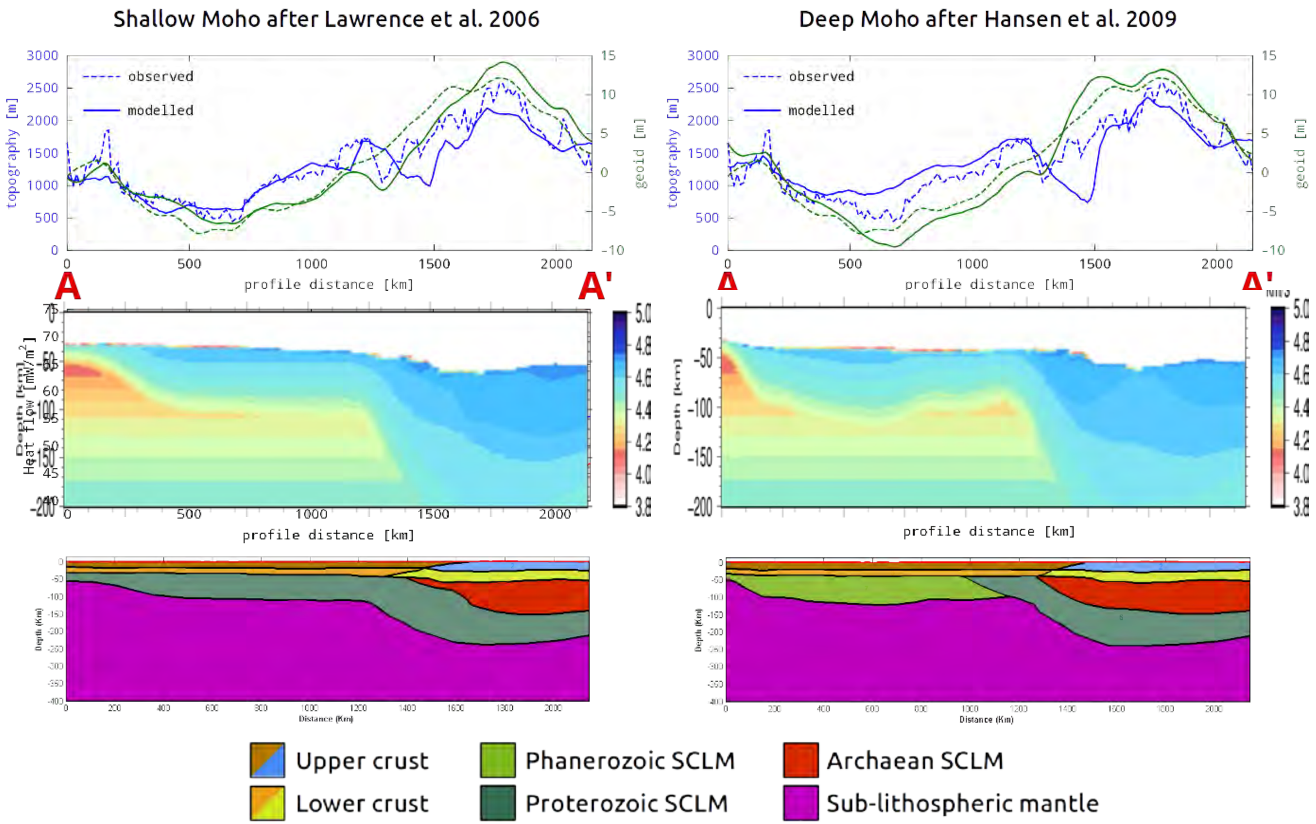
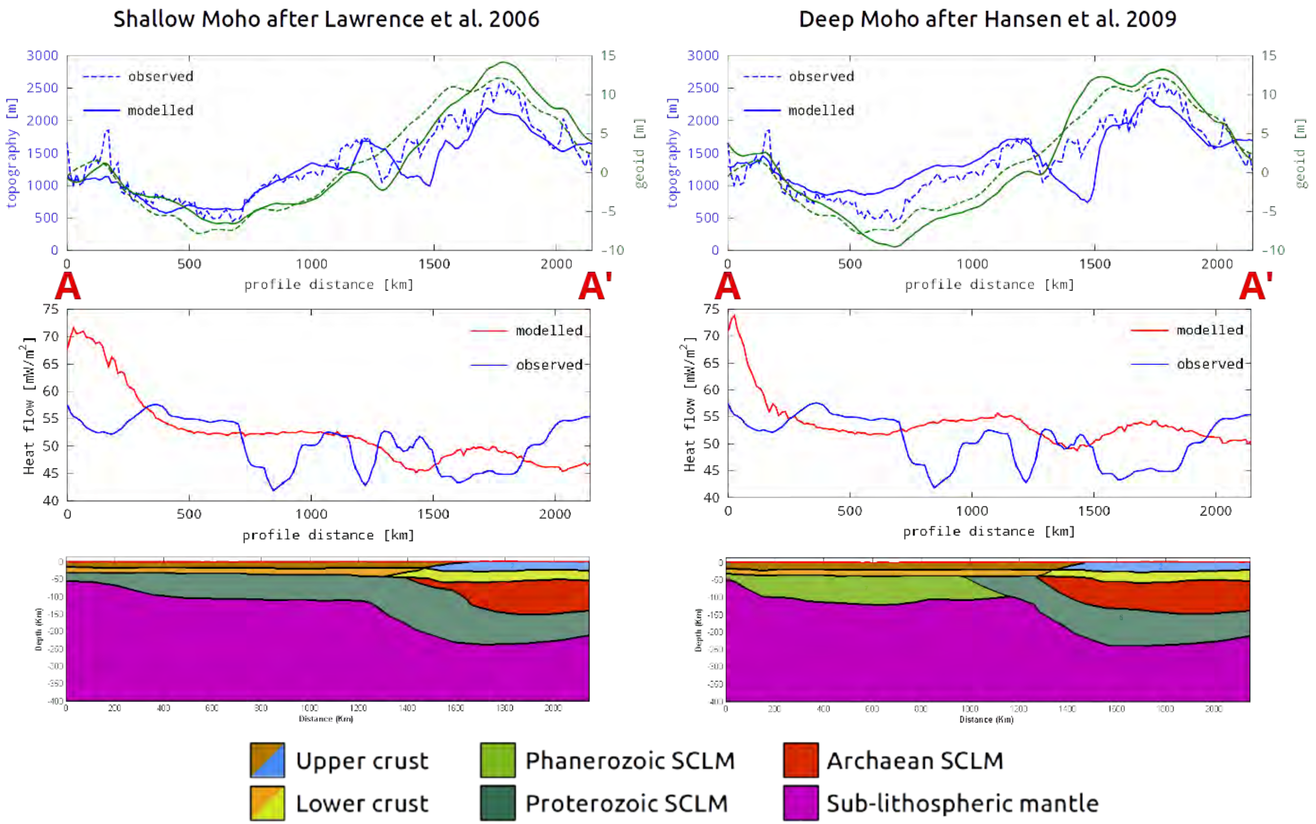


Sensitivity to Moho depth estimates



Sensitivity to Moho depth estimates

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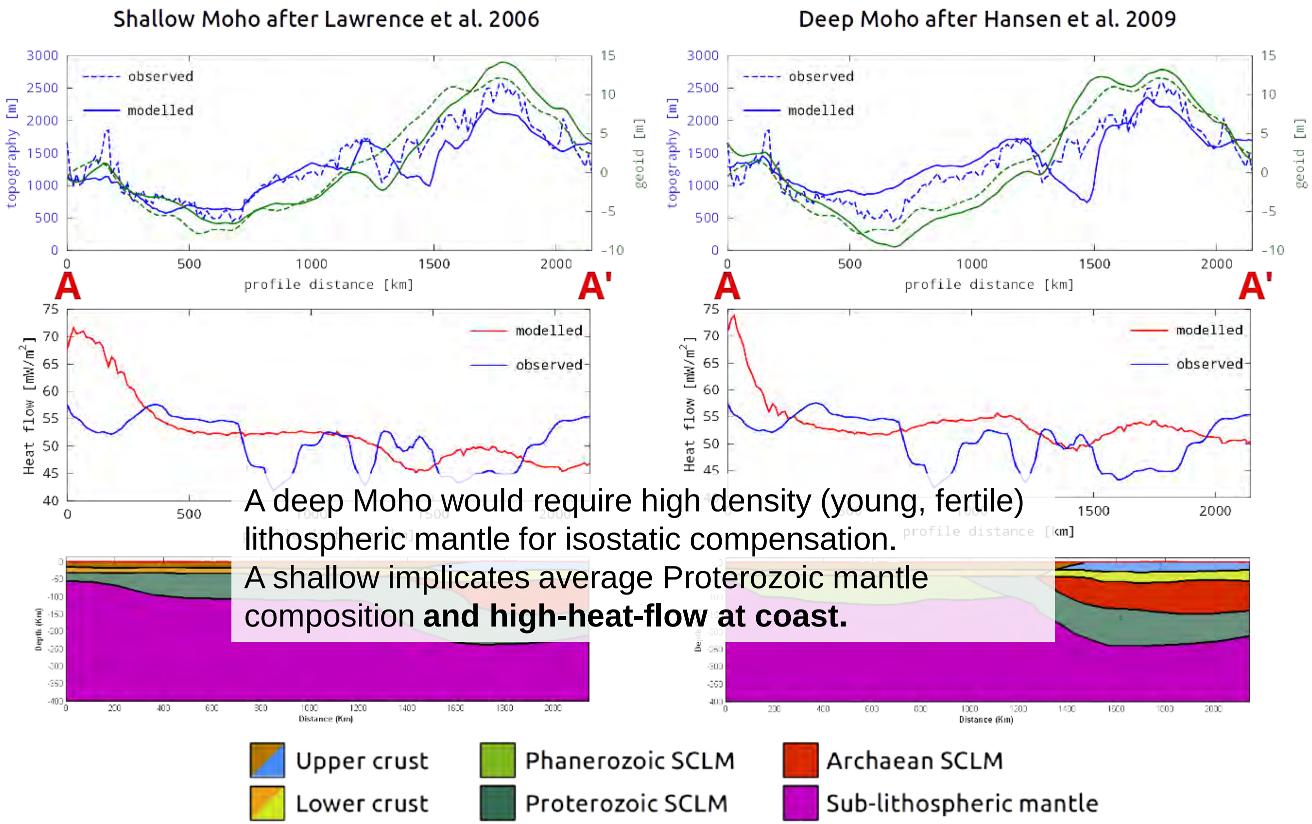
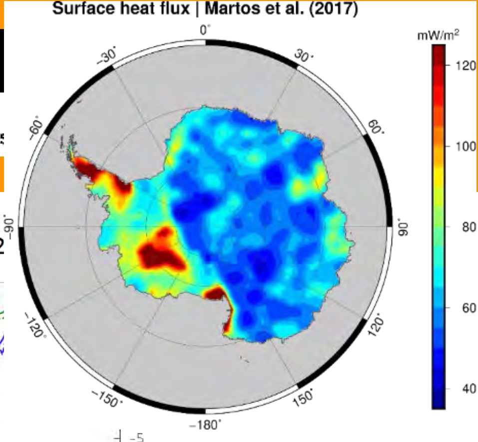
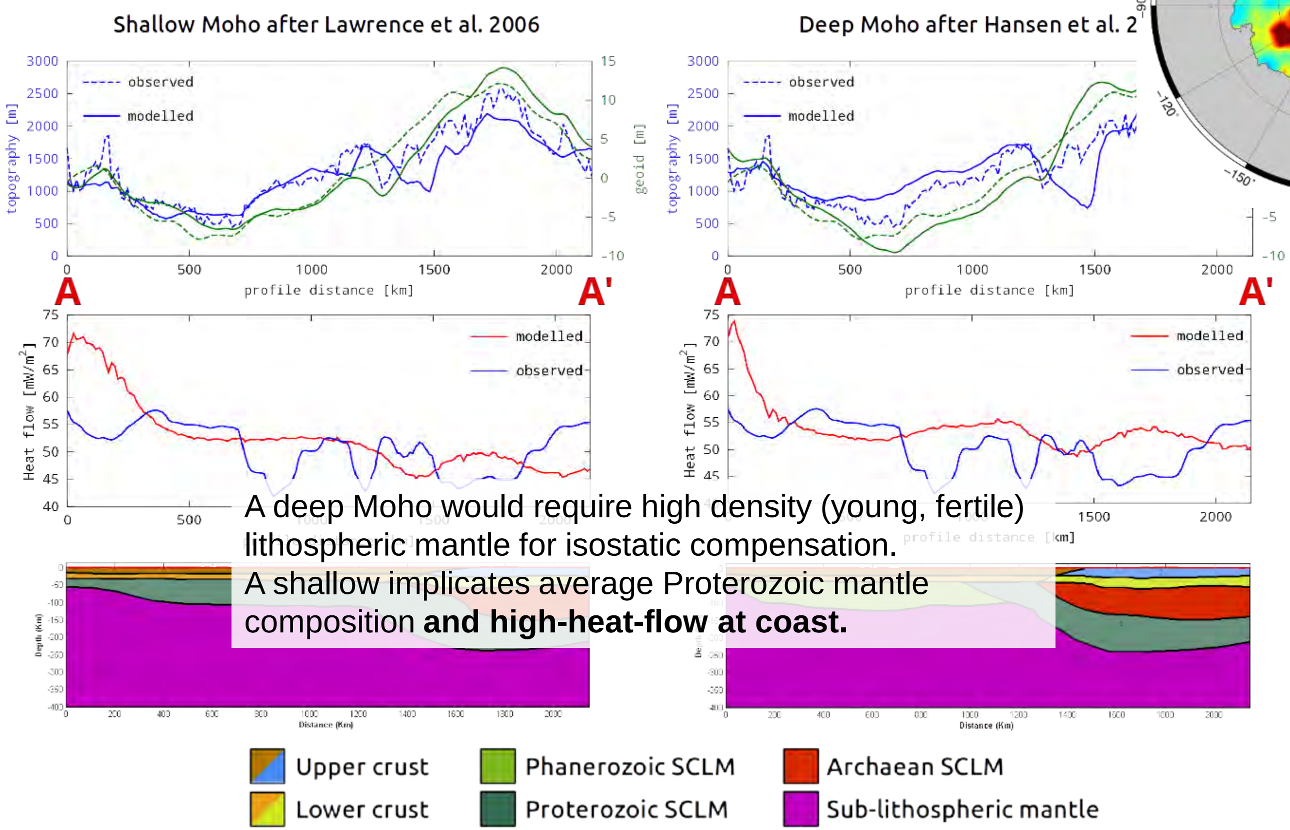


A deep Moho would require high density (young, fertile) lithospheric mantle for isostatic compensation.
A shallow implicates average Proterozoic mantle composition **and high-heat-flow at coast.**

Sensitivity to Moho depth estimates





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Validation against the gravity field

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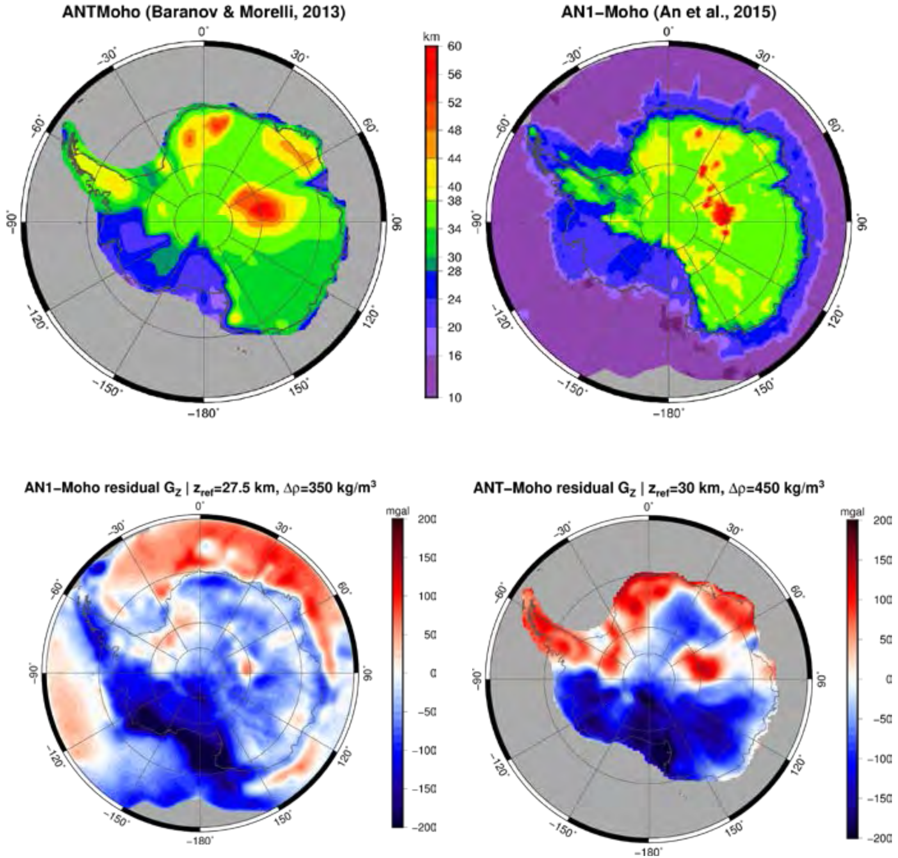

Both seismic based crustal thickness models do not fit the gravity field

- Models wrong?
- Contributions from crust or sub-crustal part?

Extension to full 3D lithospheric model over Antarctica using GOCE gravity gradients

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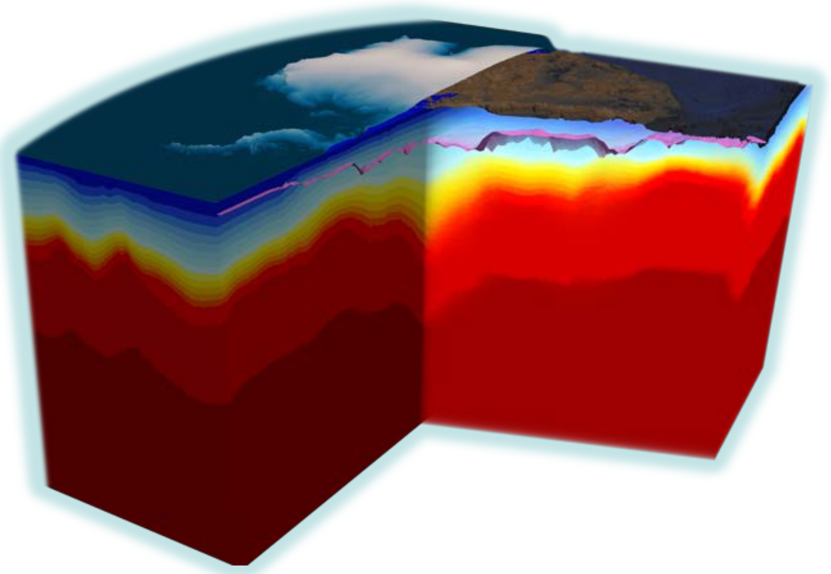

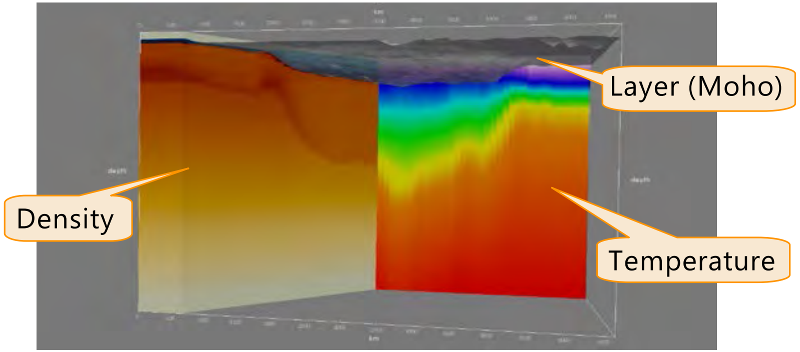

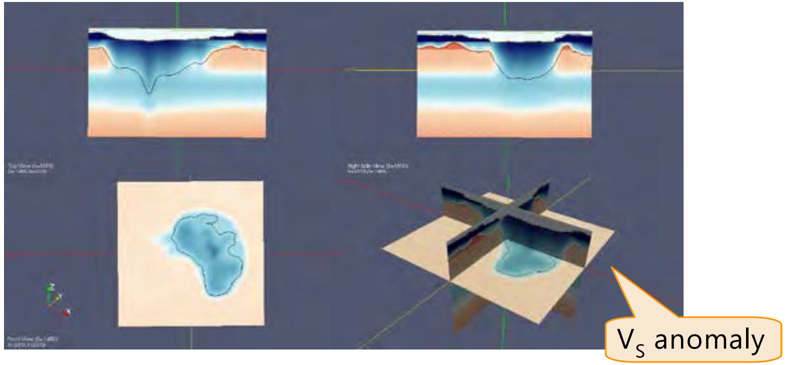

Lithospheric modelling: set-up

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Model dimensions:

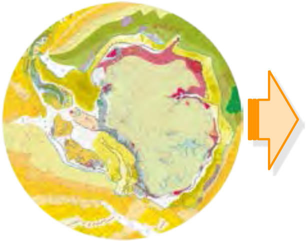
6620 km × 6620 km × 400 km | 50 km × 50 km × 2 km cell size.

Vertically layered crust:

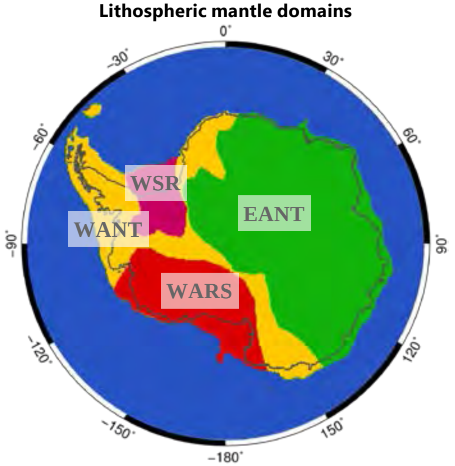
Type	Bulk density [kg/m³]	Therm. Expans. [K⁻¹]	Compressibility [GPa⁻¹]	Heat prod. [μW/m³]	Therm. cond. [W/mK]
Upper crust	2670	1.0 e-6	1 e-10	1.0	2.35
Middle crust	2750	1.0 e-6	1 e-10	0.4	2.25
Lower crust	2800	1.0 e-6	8 e-11	0.4	2.0
Oceanic crust	2950	0	0	0.1	3.0

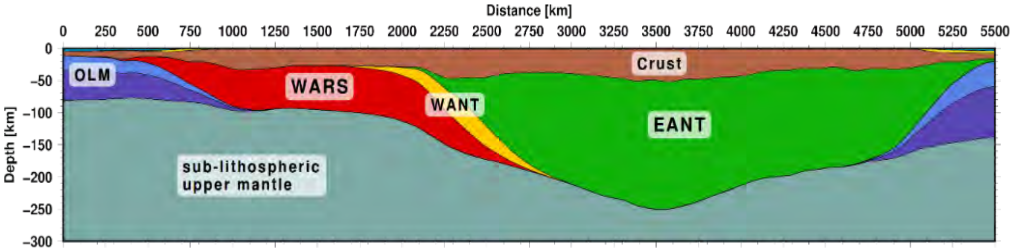
Lithospheric mantle domains:

- East Antarctica: Proterozoic composition,
- West Antarctica: Phanerozoic composition,
- Rift systems: primitive upper mantle composition,
- Oceanic: vertical harzburgite / lherzolithe layering.



Grikurov & Leychenkov (2012)





Lithospheric modelling: data

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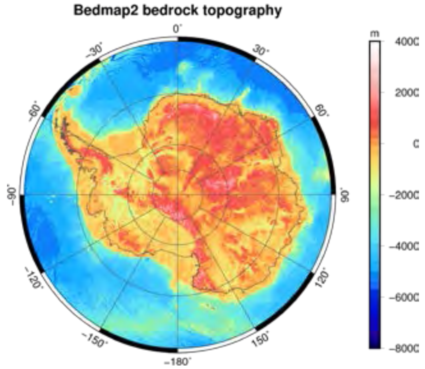
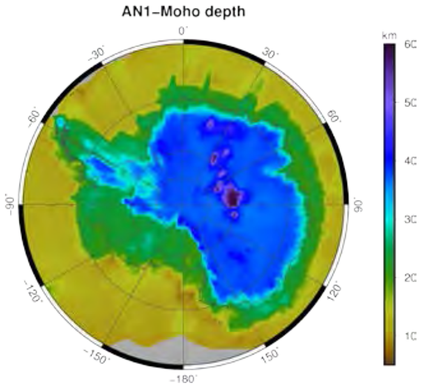
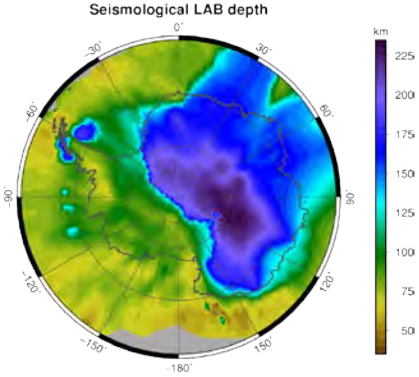
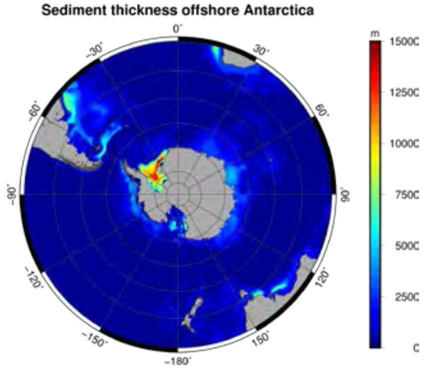
Initial geometry of main lithospheric layers from:

- BEDMAP2 dataset: ice thickness, bedrock topography,
- multiple sources for offshore sediments,
- seismological models.

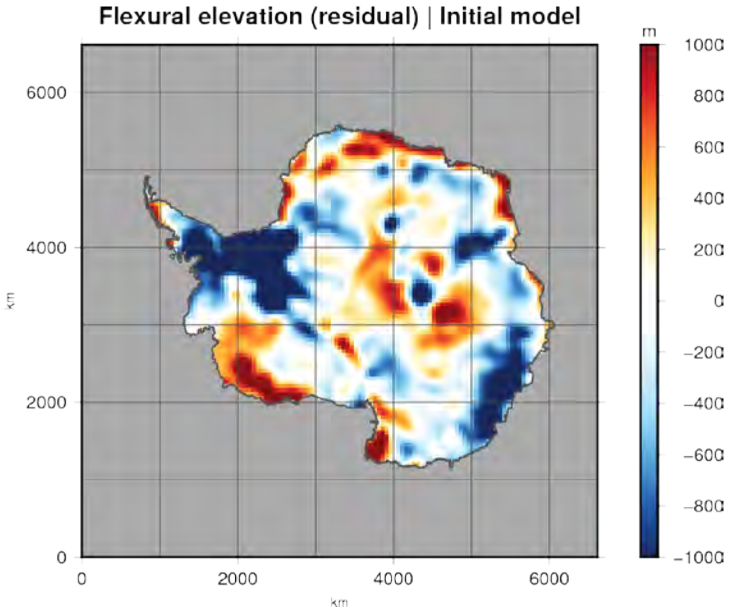








Lithospheric modelling: results



High misfit from initial model geometry

Model 1:

- homogeneous crust, rough mantle domains

Model 2:

- refined crustal domains, Archaean lith. mantle blocks to improve gradient fit, shifted Moho & LAB to fit isostasy.

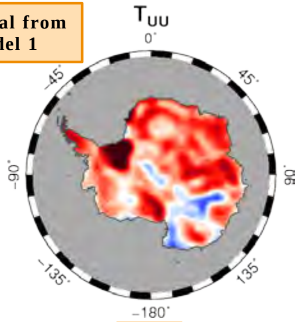
Model 3:

- based on Model 2, released isostatic equilibrium, shifted Moho & LAB to fit gravity gradients.

Lithospheric modelling: results

Models 2 & 3

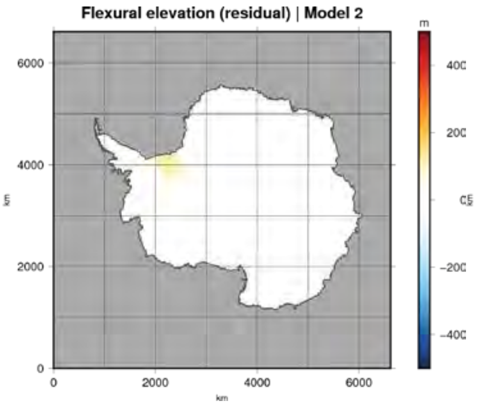
Residual from Model 1

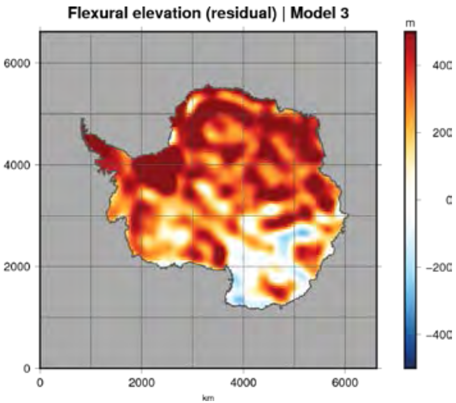


Regions of crustal / lithospheric mantle blocks

Model 2
(fitted to elevation)

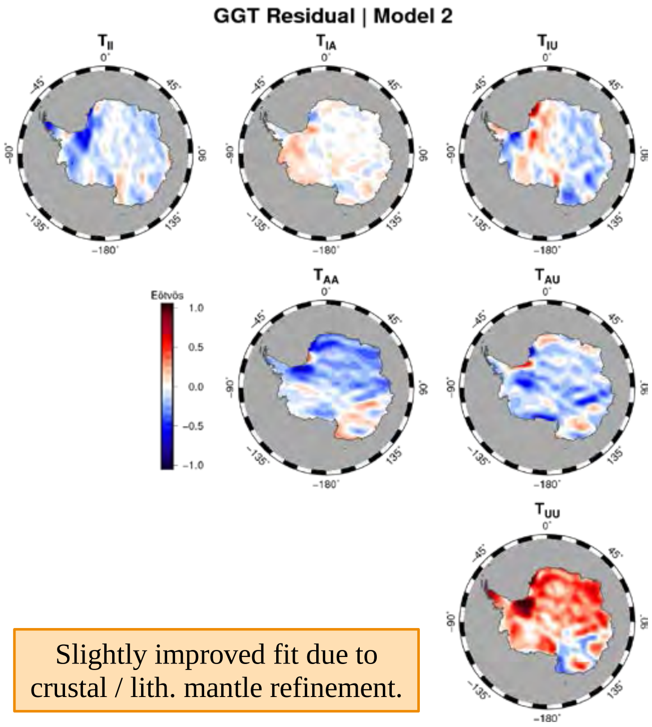
Model 3
(fitted to gradients)

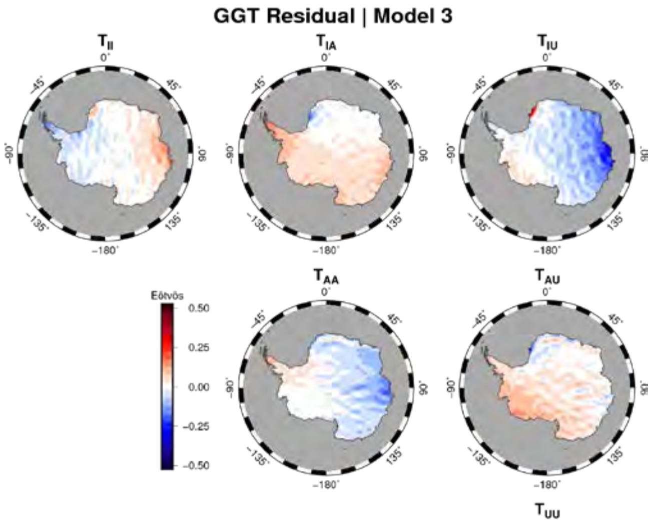


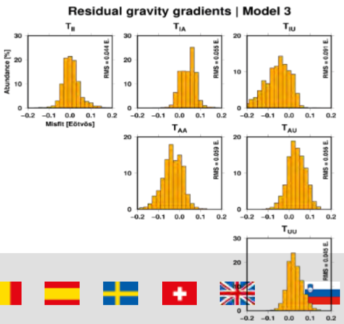


Lithospheric modelling: results

Gravity gradients

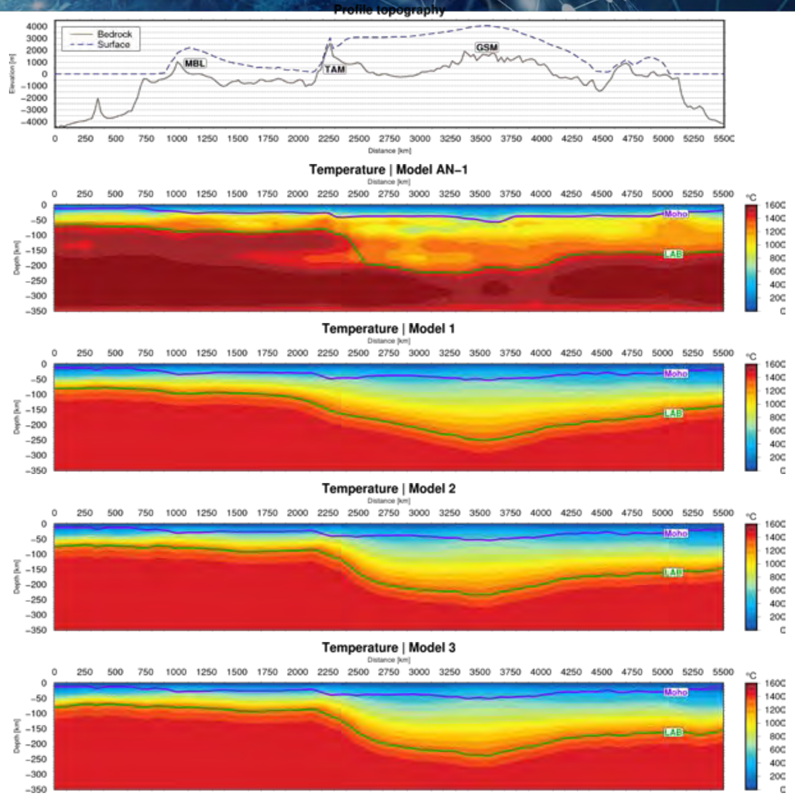


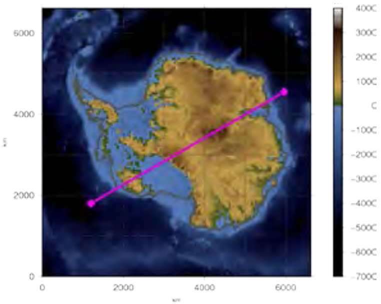


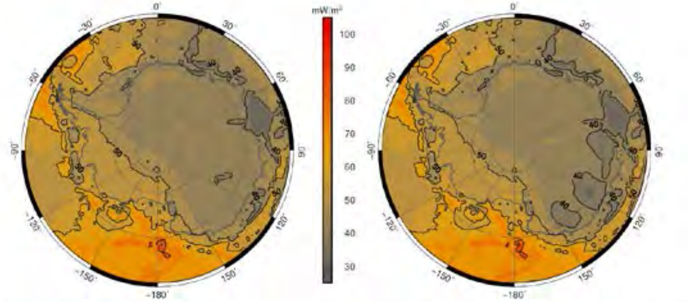


Slightly improved fit due to crustal / lith. mantle refinement.

Lithospheric modelling: Temperature





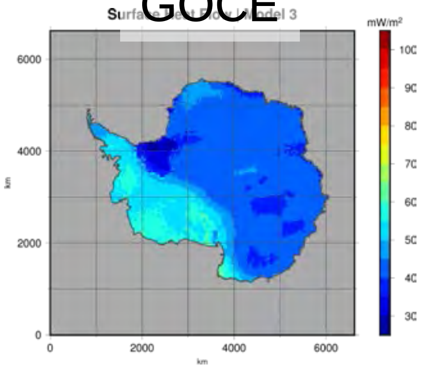


Surface heat flow w/o Archaean mantle

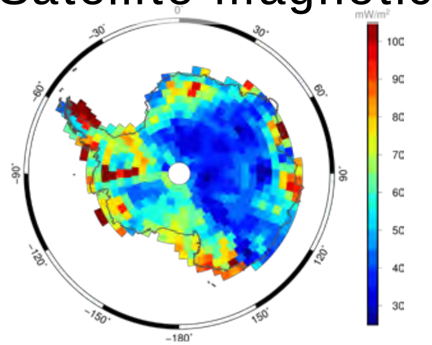
Surface heat flow with Archaean mantle

Comparison of heat flow models

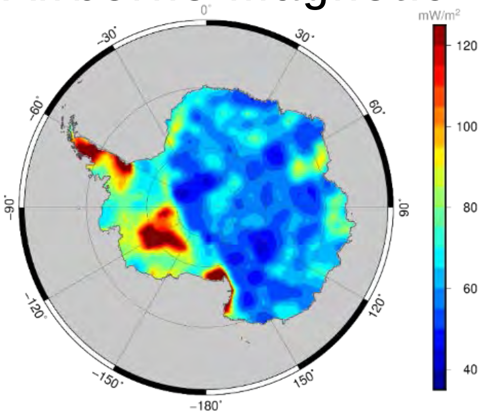
GOCE

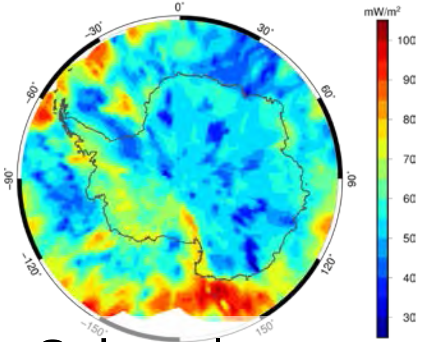


Satellite magnetic

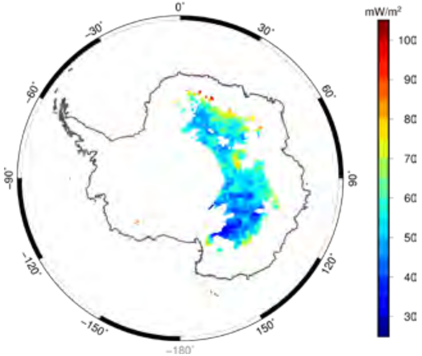


Airborne magnetic





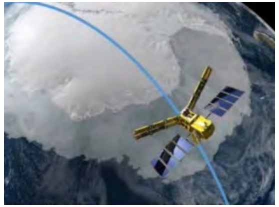
Seismology



Ice temperature

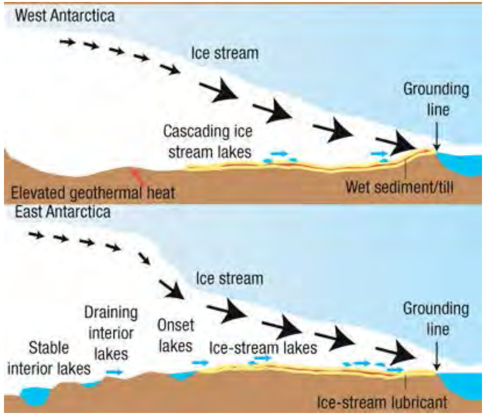
How to reconcile heat-flow models?

Analysis of uncertainties in Solid Earth models
and feedback to Ice temperatures



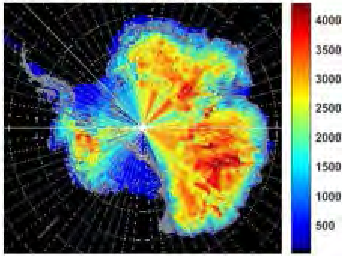
Aims

0. Joint analysis with seismological models
1. Curie depth estimates based on (0) and combination with aeromagnetic data and crustal heat-production
2. Reconciliation of Solid Earth models and ice temperature profiles
3. Implications for ice-sheet modelling



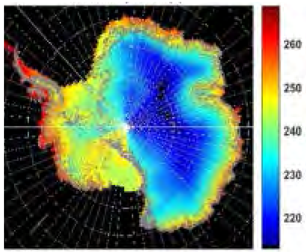
Temperature Profile from Glaciological models

Ice Thickness



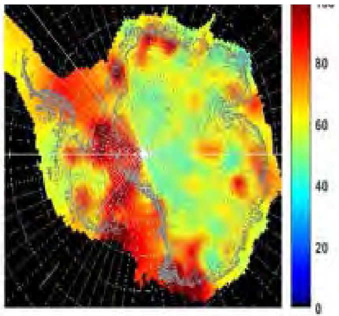
From Bedmap2

Surface Temperature



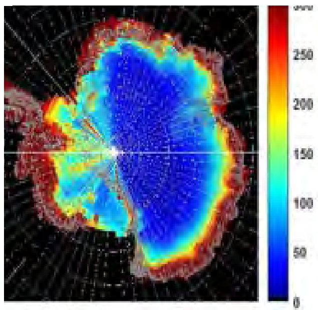
From CROCUS

Geothermal Flux



From Fox Maule

Accumulation

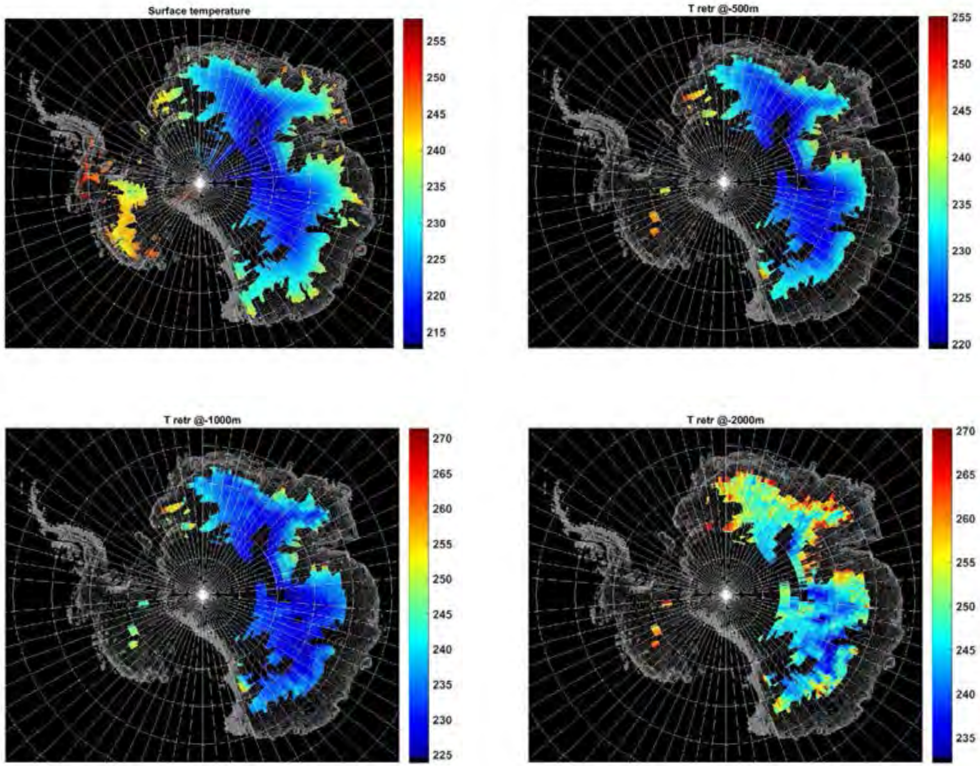


From D'Agosta

$$T(z) = T_s - \frac{G\sqrt{\pi}}{2k_c\sqrt{\frac{M}{2k_d H}}}\left(\mathrm{erf}\left(z\sqrt{\frac{M}{2k_d H}}\right) - \mathrm{erf}\left(H\sqrt{\frac{M}{2k_d H}}\right)\right)$$

Ts = Surface Temperature G = Geothermal Heat Flux, M = Accumulation ; H = ice thickness ; kc = ice conductivity, kd = ice diffusivity

Ice temperature from CryoSMOS study

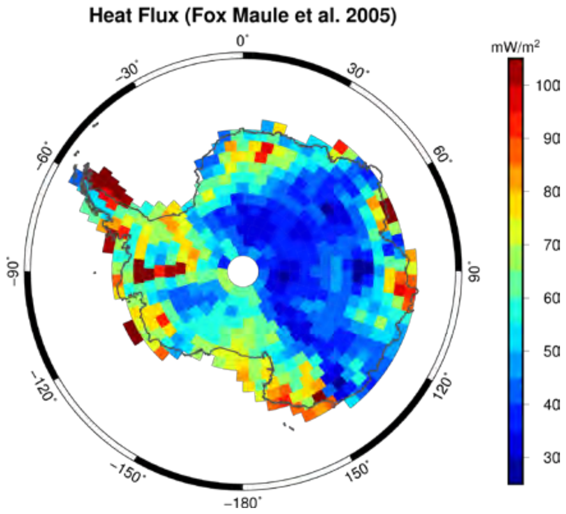


Products available at: https://www.catds.fr/Products/Available-products-from-CEC-SM/CryoSMOS-project

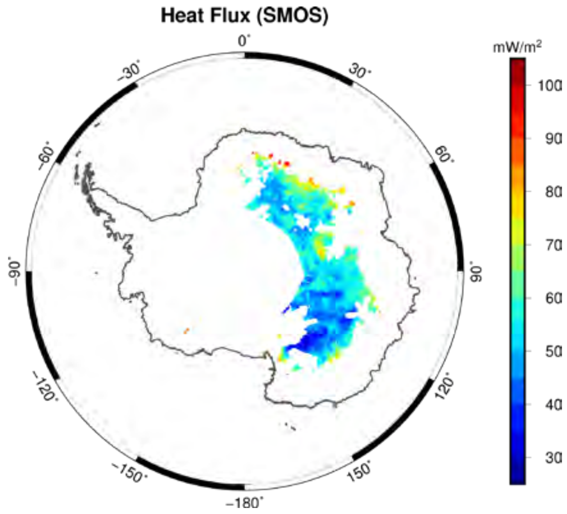
Giovanni Macelloni

Geothermal heatflow from CryoSMOS

Input

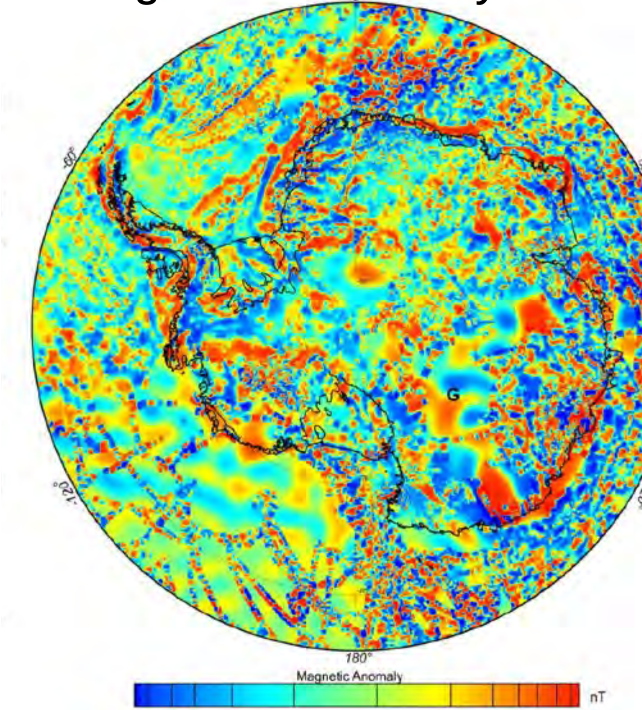


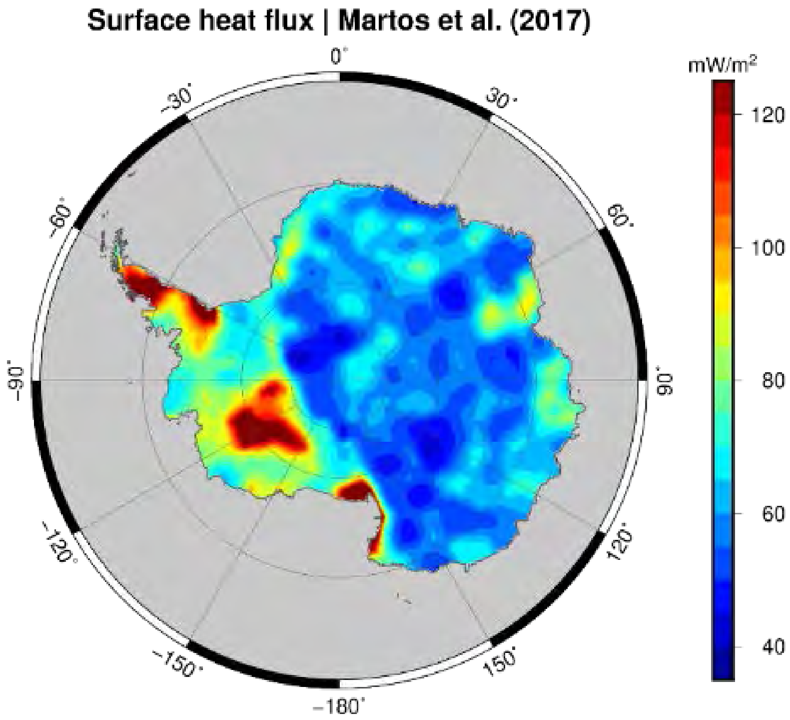
Output



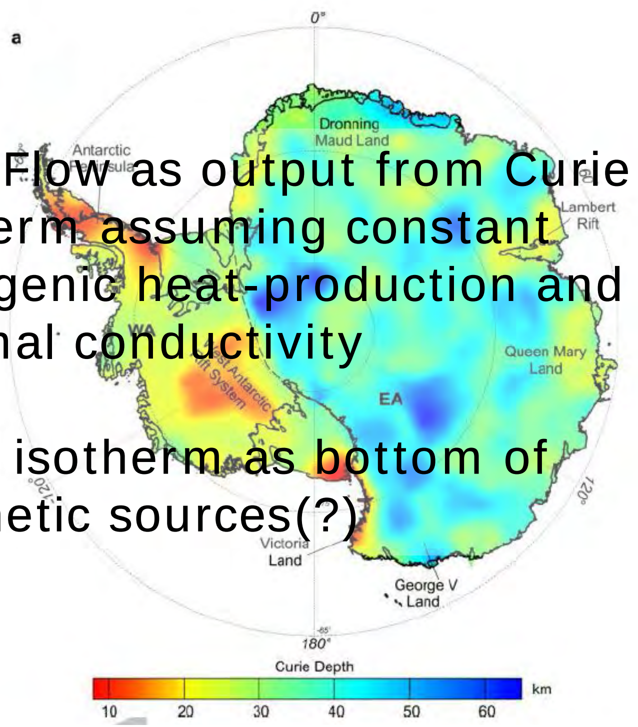
Magnetic heat-flow estimates based on centroid method

Magnetic anomaly



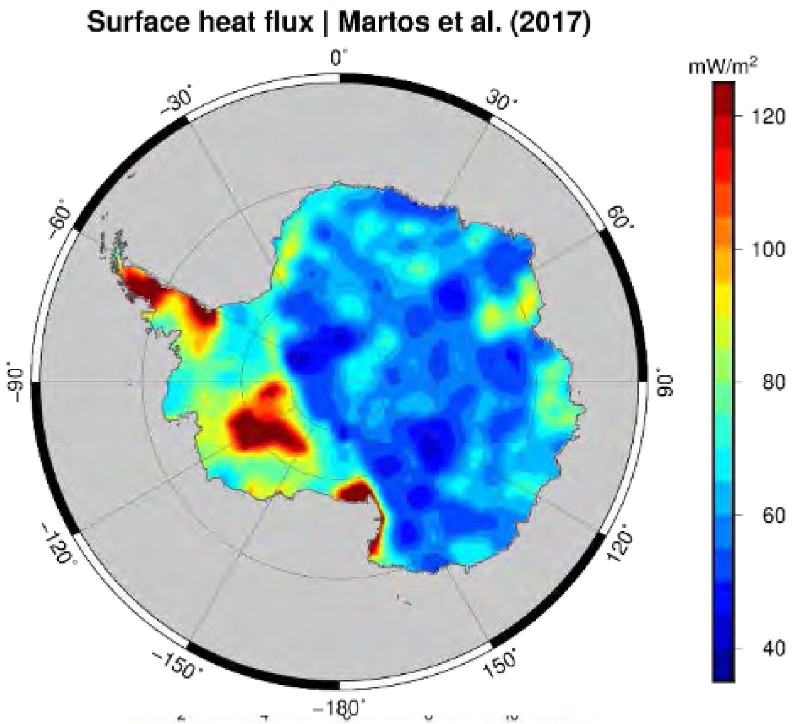


Magnetic heat-flow estimates based on centroid method



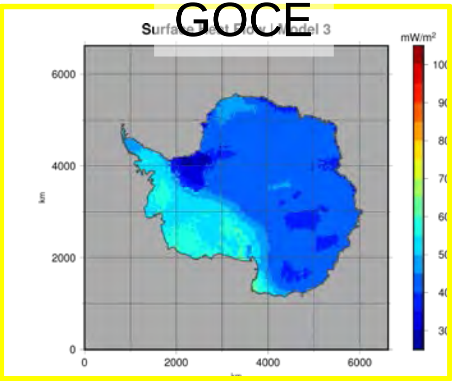
Heat-Flow as output from Curie isotherm assuming constant radiogenic heat-production and thermal conductivity

Curie isotherm as bottom of magnetic sources(?)

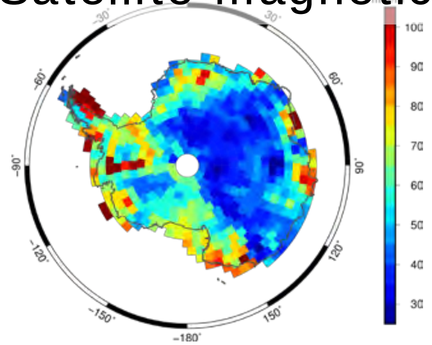


Comparison of heat flow models

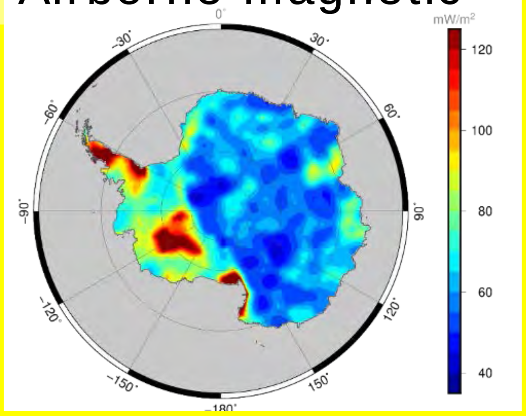
GOCE

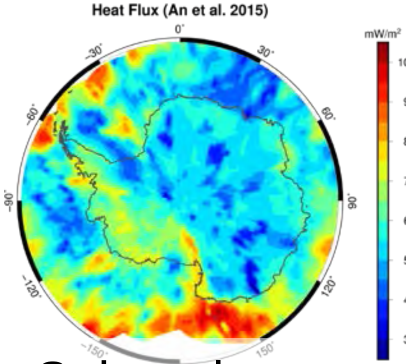


Satellite magnetic

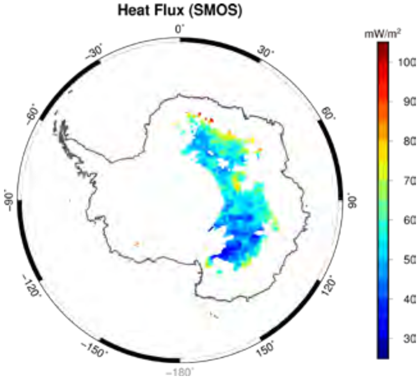


Airborne magnetic





Seismology



Ice temperature

Model validation by Bayesian inversion

Put all model parameters (**Moho, LAB, Curie depth**) at all grid cells in a vector $\boldsymbol{m}$

Put all observed data in a vector $\boldsymbol{d}$

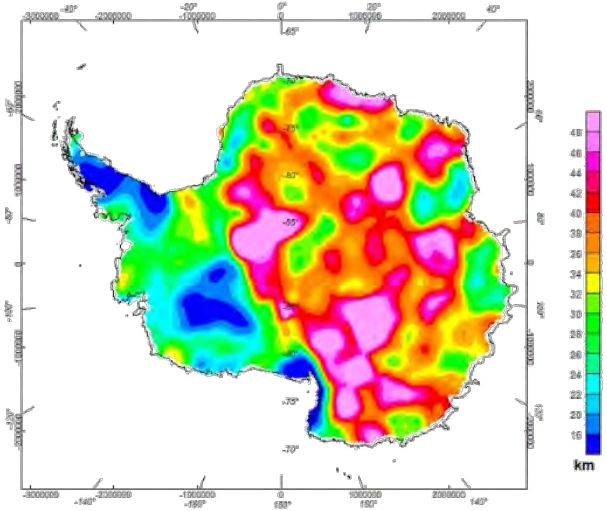
Each model is assigned a **prior probability** $P(\boldsymbol{m})$

Each model is assigned a **likelihood** based on how good it fits the data $P(\boldsymbol{d}|\boldsymbol{m})$

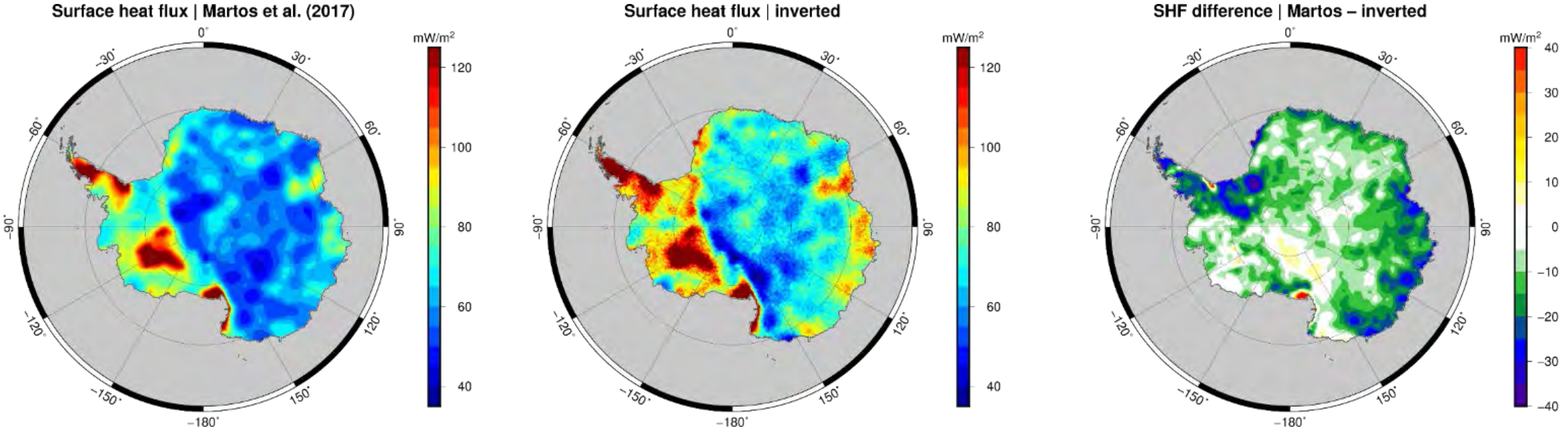
Bayes theorem gives posterior probability:

$$\boxed{P(\boldsymbol{m}|\boldsymbol{d}) = \frac{P(\boldsymbol{d}|\boldsymbol{m})P(\boldsymbol{m})}{P(\boldsymbol{d})} \propto P(\boldsymbol{d}|\boldsymbol{m})P(\boldsymbol{m})}$$

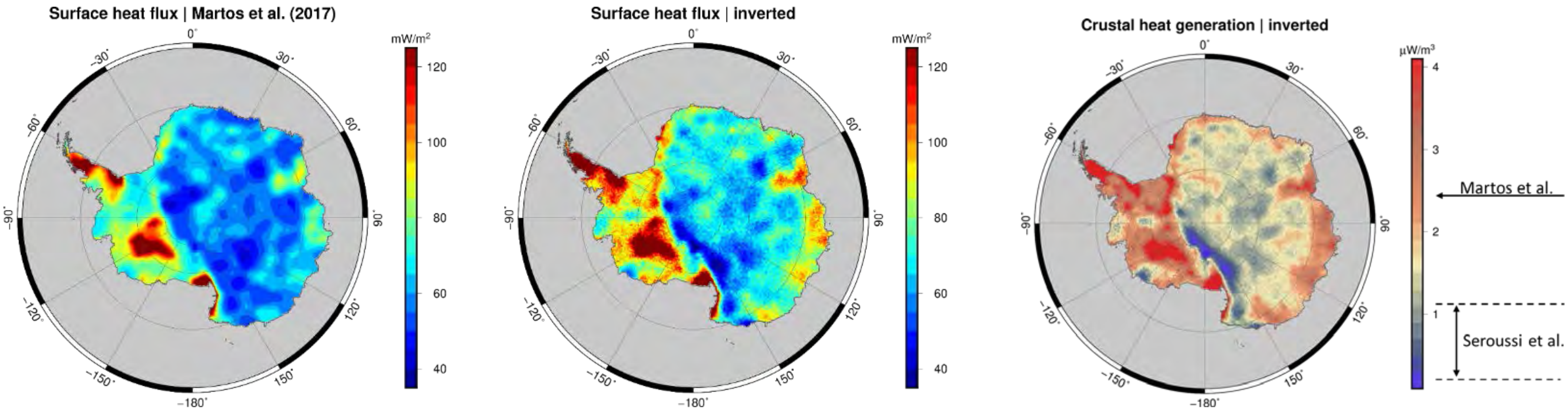
Curie isotherm



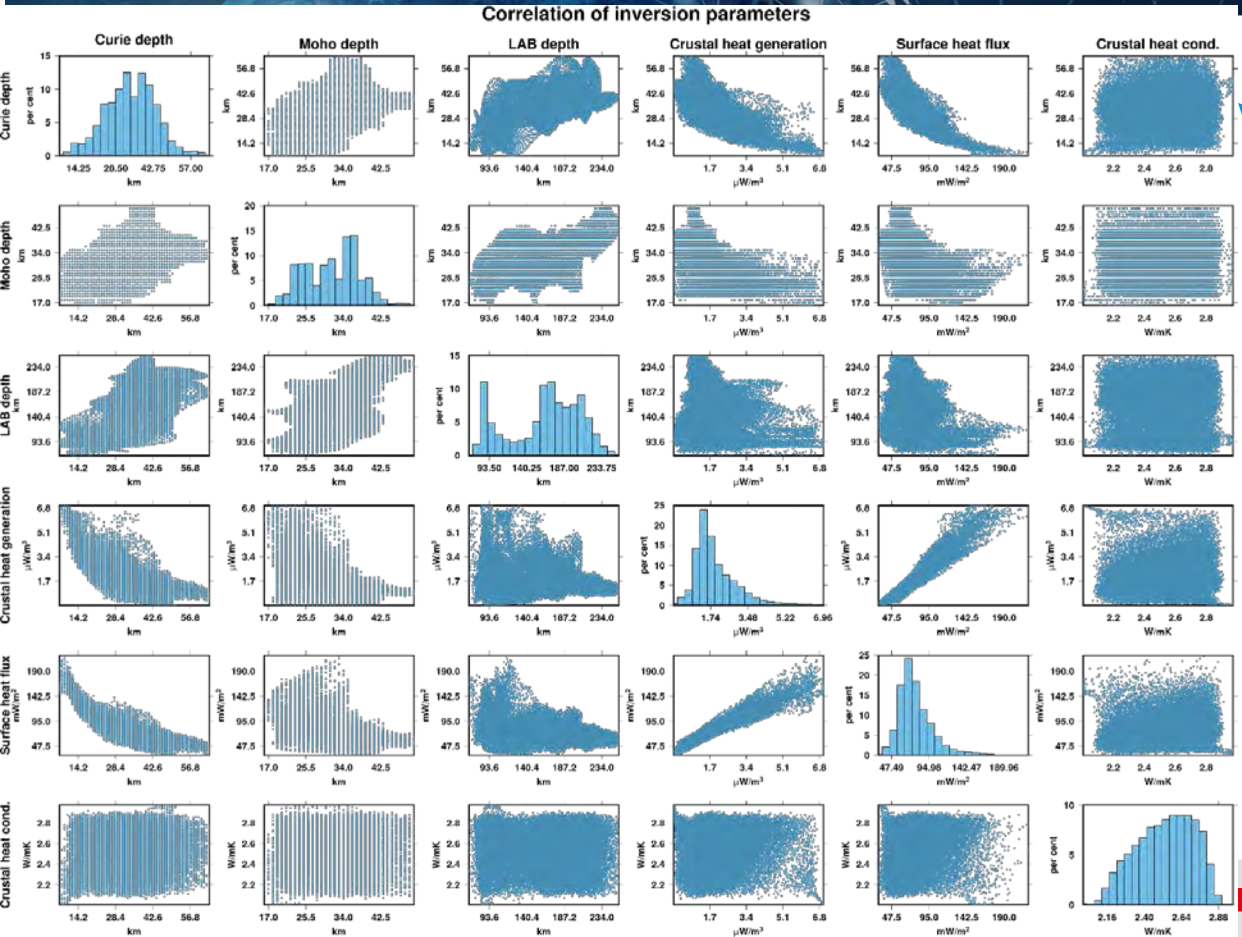
Inversion results



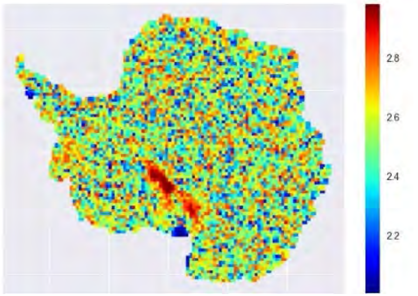
Inversion results



Correlation between variables from input and output



Results seem reasonable
But: some random correlations between parameters



Too strong influence by magnetic heat-flow estimates?

Conclusions

Solid Earth structure of Antarctica is despite recent efforts still not well known

Satellite data can help to fill gaps in data coverage

- GOCE is useful for lithospheric modelling
- Provides background heat-flow

Better estimates of geothermal heat-flow are needed to understand Solid Earth-Cryosphere coupling

- Possibilities by Probabilistic inversion to detangle differences between geophysical methods in estimating heat-flow