Parameter Sensitivity in Satellite-Gravity-Constrained Geothermal Modelling

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EGU 2017, Wien 23-28 April

X3.106
EGU2017-16678

INTRODUCTION

The heat flow measured at the solid Earth surface is a complex superposition of multiple contributing factors (*components*) spanning through the spatial scales. Bodies at different depths and their associated heat transfer mechanisms involve different timescales to reach equilibrium and a varying extension of the footprint of their contribution at the surface.

Fig. 1

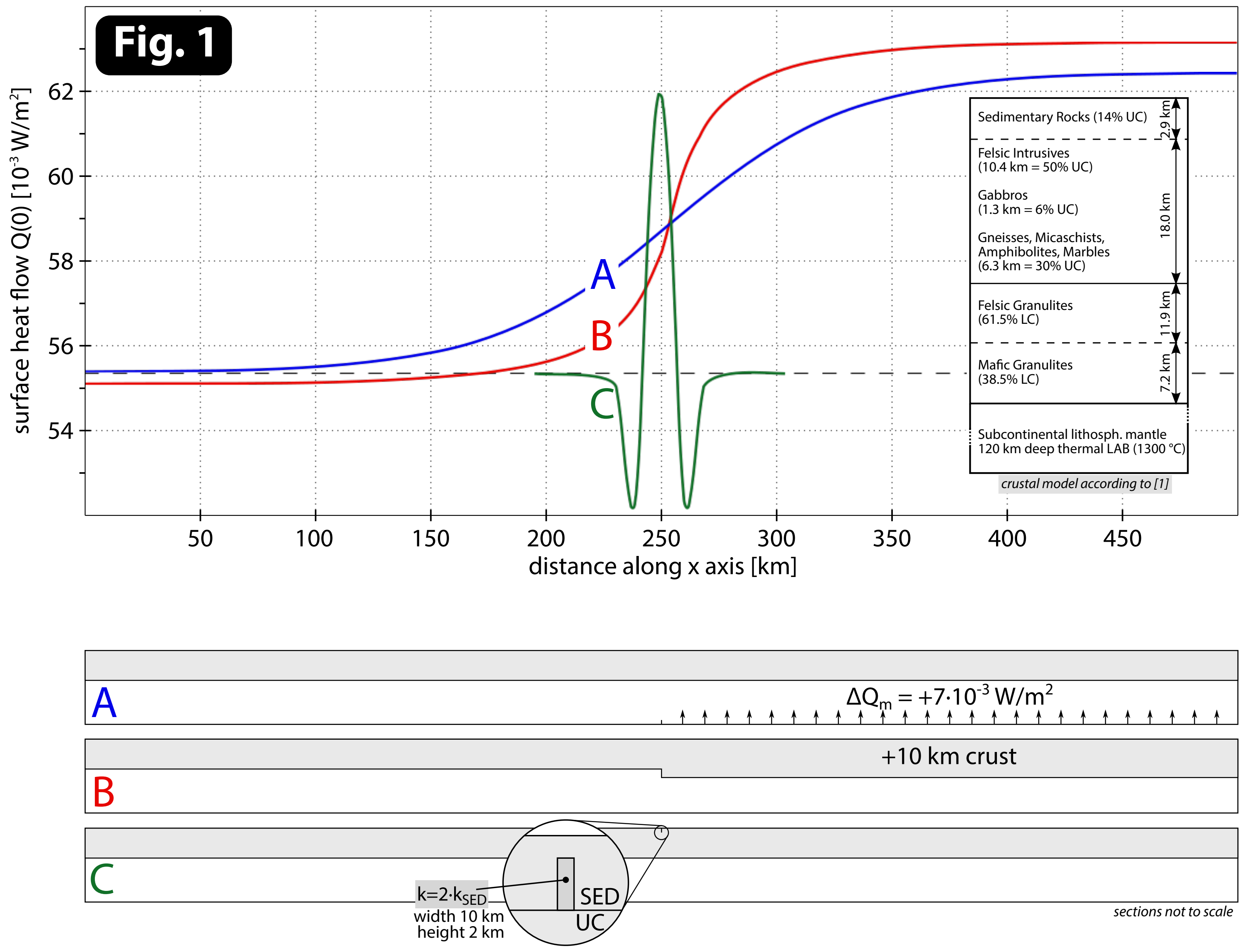

Fig. 1 Surface heat flow resulting from three different models departing from a reference lithosphere (dashed line, see column).
A an increase in heat flow from the mantle; **B** crustal thickening (from 40 to 50 km, layers uniformly scaled); **C** a localised near-surface condition resulting in increased heat transfer from the basement through the sedimentary layer.
Surface heat flow for the reference lithosphere column: 55.4 mW/m^2, composed of 16.3 mW/m^2 due to conduction from the mantle and 39.1 mW/m^2 due to heat production in the crust.
All the three models result in around 7 mW/m^2 of increase, with a largely different footprint.

Maps of surface heat flow are commonly obtained by interpolation of non-homogeneously sampled measurements. In areas where samples are sparse and/or biased towards high fluxes (e.g. due to geothermal energy wells), **local anomalies risk being smeared over distances far larger than their actual footprint**.

Estimating one of the heat flow components from proxy observables (such as gravity) allows for a better constrained extrapolation of the available measurements at distance.
The significant density contrast at a lithologically-defined crust-mantle boundary is a dominant part of the signal in the highest degrees of the Bouguer anomaly obtained from satellite-derived Global Gravity Models.

A reliable link between the crustal structure obtainable from gravity data and radiogenic heat production in the crust is a useful constraint, both in obtaining the long-wavelength conductive contribution from the mantle (backstripping) and in the upward continuation of temperature estimates.

METHOD

The framework we are using involves a crustal heat production forward-modelled estimate, scaled with a CMB depth, which in turn is obtained through an iterative Parker-Oldenburg inversion [3] of the Bouguer anomaly.

We devised it to **assess the performance of a GOCE-derived GGM for thermal estimates [4]**, at a scale comparable to the half minimum resolved wavelength (at the surface) resolved by satellite-only gravity models (e.g. 70 km for N=280).

Forward model details
We are using a 2D finite-difference solver, for steady-state heat diffusion in a conservative, implicit form, given a model of thermal conductivity and heat production.
The **dependence of thermal conductivity on temperature** is taken account of via an iterative procedure, using a constant temperature gradient from the surface to the LAB as a starting model.

DISCUSSION

1. Relationship between CMB depth and cumulative crustal heat production

- there is a high variance in rock composition and in their radiogenic heat production (RHP) [5]
- the real distribution of heat production with depth significantly deviates from any simple stratigraphic model: the occurrence of high RHP rocks at the base of crust is not uncommon [6].
- the nature of the relationship in itself: it can be positive and stronger in collisional margins, when part of the thickening is due to the thrusted crustal sequences; to weaker or inverse in areas of thick crust.

Fig. 2

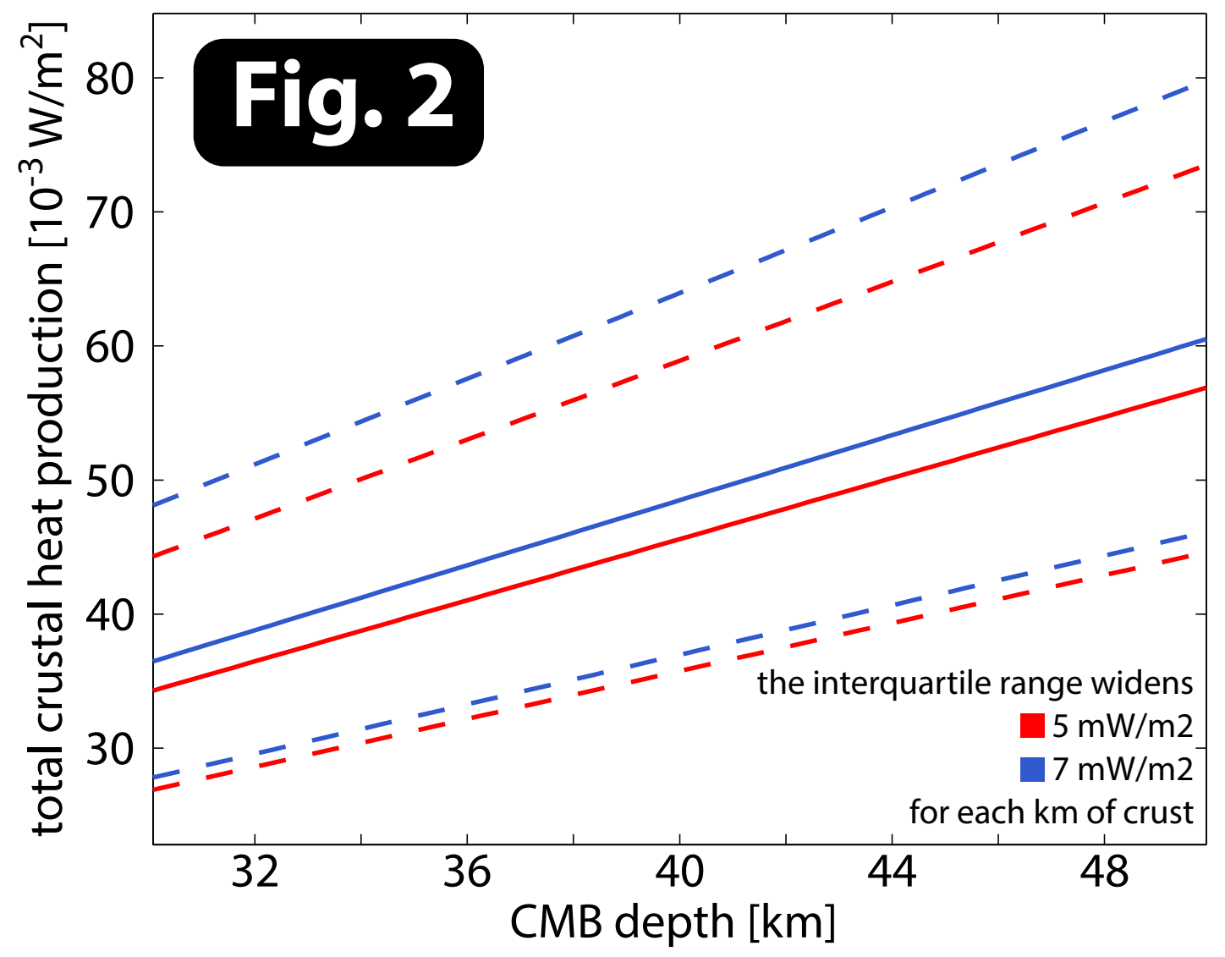

Fig. 2 What is the uncertainty in the estimate, before including tectonic and/or petrologic information?
A linear scaling relationship between crustal thickness and bulk heat production constitutes a simple reference, while reality is known to significantly deviate from it. By assigning a probability density function to each variable in our reference lithosphere and running a Monte Carlo uncertainty propagation, we get a first order estimate of how also the uncertainty is scaled. **Dashed lines**: 1st and 3rd quartile of the results. The lower crust RHP in the **blue model** has twice the variance than the other one.

2 . A-priori thermal parameters

Surface heat flow sensitivity to lithospheric thermal conductivity below a CMB undulation.

Fig. 3

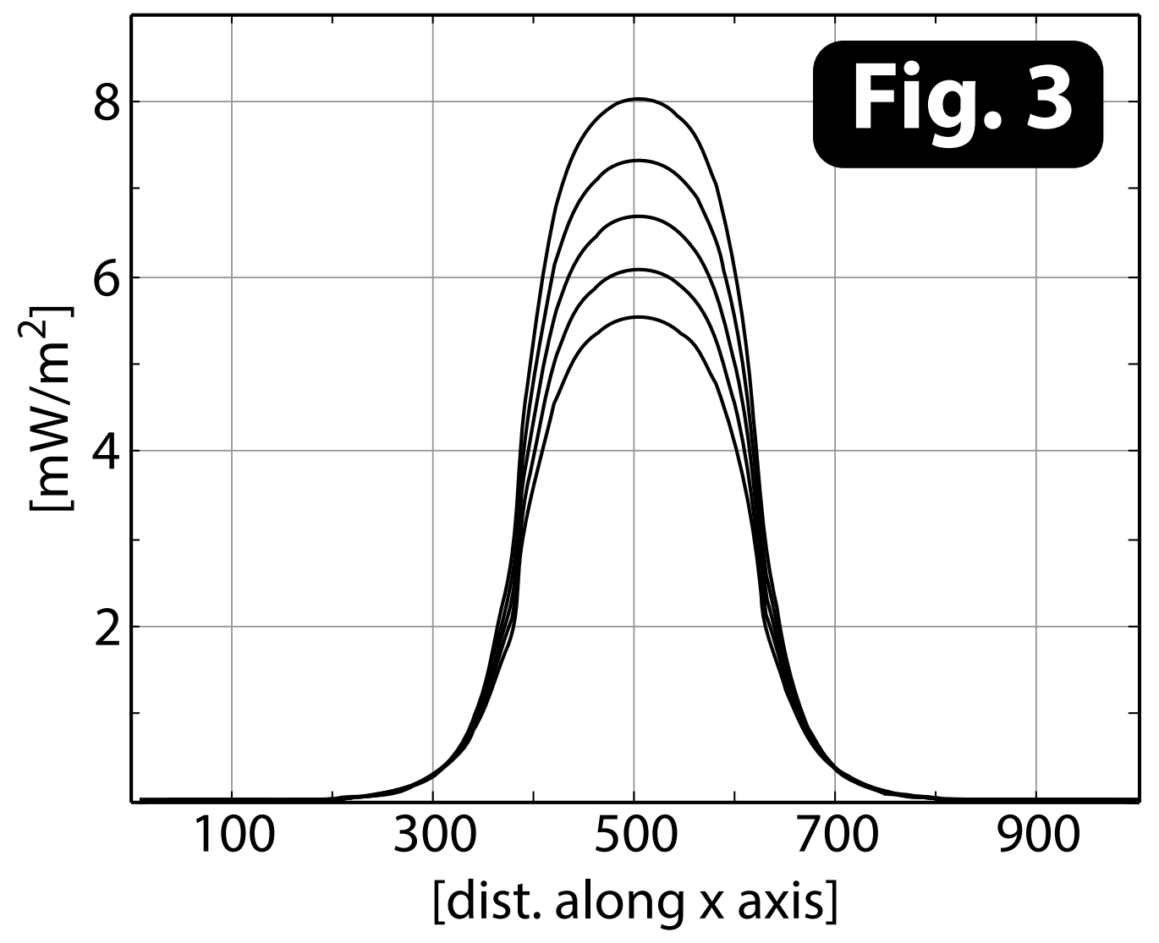

Fig. 3 The effect of varying the sub-crustal lithospheric mantle conductivity (from 2 to 6 W/m·K, at surface conditions), underlying a 300 km wide 10 km crustal thickening. It is expressed as an anomaly against the constant reference lithosphere of fig. 1.

3. Validation of method

Synthetic model: heat flow for constant bottom lithosphere depth and 10 km crustal thickening. Standard parameters for thermal conductivity, heat production and density of crust and mantle.

Fig. 4

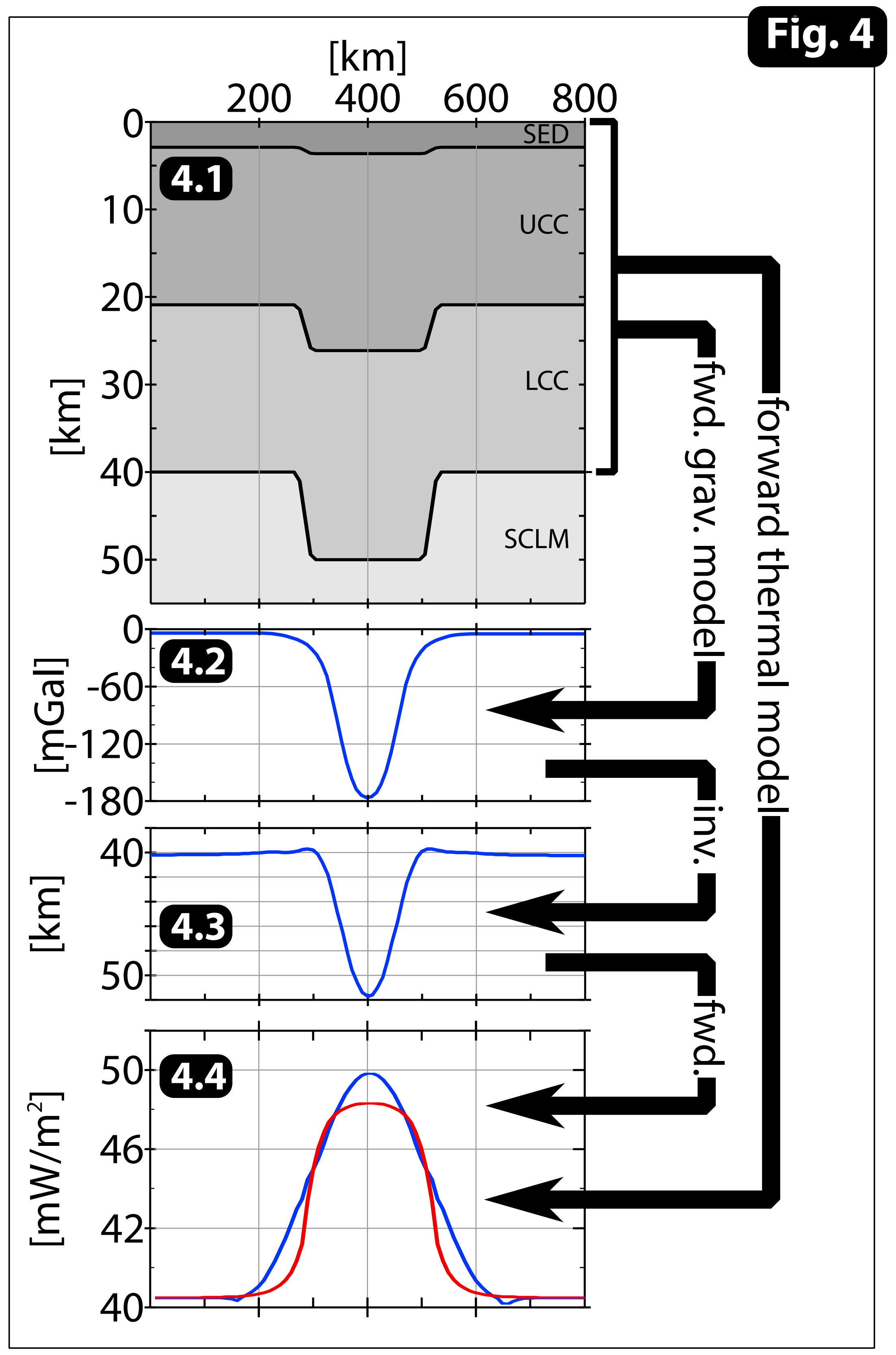

Fig. 4 Flux diagram of heat flow recovery:
4.1 Synthetic crustal model
4.2 Forward gravity field (anomaly against crust-mantle reference model)
4.3 Gravity inversion of crustal thickness
4.4 Comparison between synthetic (**red**) and estimated (**blue**) heat flow

Good agreement of synthetic and estimated heat flow can be verified.

Pitfalls:
- inhomogeneity of crustal density and of heat production;
- effect of LAB depth variations (thermal lithosphere thickness)
- sedimentary cover
- heat transfer in hydrothermal complexes (*generally* local)

CONCLUSIONS

1. Link between gravity and surface heat flow: crustal thickening produces increased radiogenic heat flow and negative Bouguer gravity.

2. Gravity inversion can recover crustal thickness, therefore parameter-dependent heat flow values.

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This work is supported by a
University of Trieste PhD Fellowship,
through resources of
Region Friuli Venezia Giulia
European Social Fund
Operational Program 2014/2020
"FSE-EUS/4 scholarship"