GOCE AND FUTURE GRAVITY MISSIONS FOR GEOTHERMAL ENERGY EXPLOITATION

Alberto Pastorutti(1), Carla Braitenberg (1), Tommaso Pivetta(1), Patrizia Mariani(1)

(1) Dept. of Mathematics and Geosciences, University of Trieste, via Edoardo Weiss 1, 34128 Trieste (Italy), Email: berg@units.it

ABSTRACT

Geothermal energy is a valuable renewable energy source the exploitation of which contributes to the worldwide reduction of consumption of fossil fuels oil and gas. The exploitation of geothermal energy is facilitated where the thermal gradient is higher than average leading to increased surface heat flow. Apart from the hydrologic circulation properties which depend on rock fractures and are important due to the heat transportation from the hotter layers to the surface, essential properties that increase the thermal gradient are crustal thinning and radiogenic heat producing rocks. Crustal thickness and rock composition form the link to the exploration with the satellite derived gravity field, because both induce subsurface mass changes that generate observable gravity anomalies. The recognition of gravity as a useful investigation tool for geothermal energy lead to a cooperation with ESA and the International Renewable Energy Agency (IRENA) that included the GOCE derived gravity field in the online geothermal energy investigation tool of the IRENA database. The relation between the gravity field products as the free air gravity anomaly, the Bouguer and isostatic anomalies and the heat flow values is though not straightforward and has not a unique relationship. It is complicated by the fact that it depends on the geodynamical context, on the geologic context and the age of the crustal rocks. Globally the geological context and geodynamical history of an area is known close to everywhere, so that a specific known relationship between gravity and geothermal potential can be applied. In this study we show the results of a systematic analysis of the problem, including some simulations of the key factors. The study relies on the data of GOCE and the resolution and accuracy of this satellite. We also give conclusions on the improved exploration power of a gravity mission with higher spatial resolution and reduced data error, as could be achieved in principle by flying an atom interferometer sensor on board a satellite.

1. INTRODUCTION

The direct measurement of the thermal state of the Earth crust is a time consuming and costly task, technologically limited to the first kilometres of depth. The distribution of samples is far from uniform: it depends on logistical constraints and, often, on economical interest in exploitation of the subsurface. In addition, the availability of public data is scarce and there is an ongoing effort to uniform the published datasets to a common standard.

For such reasons, most of the knowledge on the thermal structure of the subsurface relies on models constrained with indirect predictions alongside the direct measurements. These insights come from the results of petrological investigations on igneous petrogenesis, metamorphism and mantle xenoliths, from the rheology information derived from seismological tomographies, and from other physical observables that have been found to be in relationship with temperature [1,2]

Still, the spatial sampling of these methods is inhomogeneous. On the contrary, gravity models derived from satellite measurements provide a global coverage with uniform sampling.

We enquired the suitability of the latest release of the global gravity model from the European Space Agency's Gravity field and steady-state Ocean Circulation Explorer mission (GOCE, see [3,4]) as a geothermal tool, in predicting the surface heat flow over continental crust.

While no simple relationship between the gravity field (or its defined anomalies) and the surface heat flow is observed, it should be noted that most of the high-degree content of the gravity disturbance is due to undulations in the Moho depth.

For such, satellite gravimetry is an invaluable tool to obtain the crustal thickness, via an inversion process.

The continental crust plays a key role in the total heat flow across the Earth surface due to the radiogenic heat production that occurs in its volume. [5]

It is enriched in radioactive elements due to the magmatic differentiation processes involved in its formation and accretion; mainly uranium, thorium and potassium, which are all incompatible elements with respect to mantle mineral phases. [1]

We tested the link between the factors controlling heat flow and gravity by forward modelling a set of synthetic sections, defined by the distribution of density, radiogenic heat production and thermal conductivity.

From the results of the synthetic tests, we devised a workflow to apply the model to the available data. We obtained the crustal geometry trough a gravity inversion process and used it to estimate the crustal contribution to the surface heat flow, assuming a standard model of

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its composition.
This enabled us to separate the deeper, sub-continental heat flow components, which are superimposed to the crustal and near-surface phenomena.
This was tested on a 900 by 800 km sector encompassing a wide assortment of thermal conditions in a geodinamically active area, encompassing most of the Alps and surrounding basins, the upper Rhine graben and part of the Bohemian basin.
These preliminary results show how a global gravity model at the scale and accuracy of the one derived from the GOCE data can be physically linked to thermal characteristics, providing an adequate constrain for heat flow predictions.
With such data, the gaps between sparse heat flow measurements can be reliably filled while being bounded to geological conditions, instead of directly resorting to interpolation.
The results also suggest that there is room for improvement by refining the crustal modelling, both in terms of gravity inversion and thermal parameterization, and that the procedure here devised should be scalable even to higher spatial resolutions, an aspect that we consider should be addressed in planning future gravity missions.

2. METHOD

All the modelling involved in these tests is based on assuming a steady state, one-dimensional, heat conduction from the base of the lithosphere to the surface. Heat generation is considered confined in the crust only, an approximation justified by the 50-fold difference against sub-continental lithospheric mantle content in U, Th, K [1,6].
The measured heat flow at the surface is considered as the result of the superposition of three sources: a deep flow resulting from mantle dynamics, chiefly convection up to the lithosphere-asthenosphere boundary (LAB); a crustal contribution from radiogenic decay of the elements thereby concentrated by the crystallization of partial melts; and a near-surface effect of superficial inhomogeneities, recent sedimentation and fluid circulation.
These conditions imply that the heat flow at the surface, as defined by Fourier's equation, can be expressed as in the following solution:

$$Q_0 = k_0 \frac{dT}{dz}\bigg|_{z=0} = -\int_0^{z_c} A(z)dz + Q_m + Q_{ns} \quad (1)$$

Where Q_m is the flow from the mantle, through the base of the crust, Q_{ns} the flow from superficial redistribution and inhomogeneities and the integral of the radiogenic heat production distribution *A(z)* in respect to depth is Q_c, or the crustal contribution to the heat flow. It should be noted how these three distinct components all have corresponding sources of signal in observed gravity.

2.1. Synthetic model

We started from a standard model of continental crust, slightly modified from the section of [7] to model the depth wise distribution of radiogenic heat production, using the compilation of values provided by [1].
The heat production in the upper crust is modelled as exponentially decaying with depth, after correcting the reference parameters (which are given for a boxcar-shaped distribution) to result in an equivalent cumulative production.

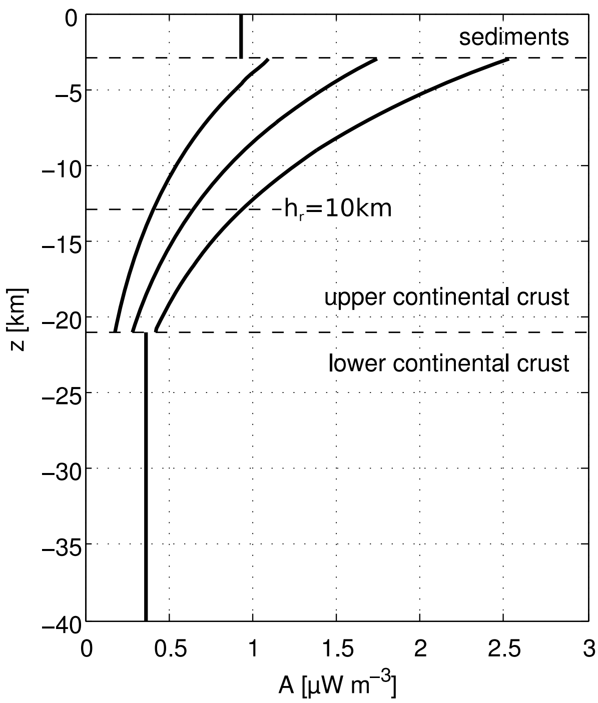

Figure 1. *The depth wise distribution of radiogenic heat production adopted as standard crustal column, both in the synthetic model and the application on data. Modified from the column by [7], with values by [1]. Three different curves are shown for the upper crust, to take into account the large variability in its composition.*

A set of synthetic sections, representative of different combinations of crustal and lithospheric thickness, was defined and the geometry of the standard column was scaled to fit the one of each discretized step of the section. The integral of the depth wise distribution of the heat production is evaluated to obtain the crustal heat flow contribution Q_c.
The LAB depth, thermally defined as the depth of the 1280 °C isotherm [2,6], is converted in Q_m using the equivalent conductivity of the series of layers from there to the surface.
The thermal conductivity, which shows a dependence with temperature and depth, was modelled according to the following relationship by [9]:

$$k(T, z) = k_0(1 + cz)(1 + bT) \quad (2)$$

Where the *c* parameter accounts for the depth dependence and *b* for the one against temperature.
This required the implementation of an iterative process to calculate the *T(z)* curve (geotherm), starting with the one resulting from a standard constant gradient (25 °C/km).

The resulting effect on the gravity was forward modelled with a prism-based algorithm [8] and expressed as an anomaly against a reference model (which is kept constant along the section).
The sensitivity of the result to the a-priori choice of parameters which make up the standard crustal column is simultaneously varied along the y-axis of a contour map of the predicted heat flow, the x-axis of which corresponds to the distance along the section.

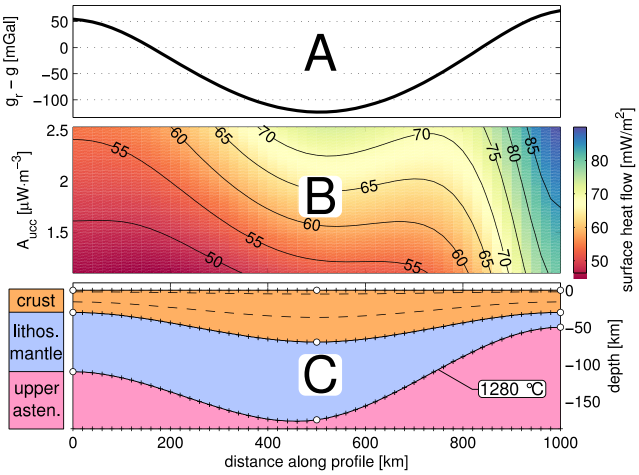

Figure 2. *An example output of the synthetic models, showing **A)** the resulting gravity anomaly **B)** a contour map of the resulting surface heat flow, where the parameter under test varies along the y-axis **C)** the synthetic section used as input.*

2.2. Application to data

We used the crustal thickness resulting obtained from inverse modelling on the gravity data to estimate the crustal component of the heat flow, using the same forward modelling adopted for the synthetic sections.
This enabled us to remove it from the measured surface heat flow, where available, obtaining the deep component Q_m, which was then interpolated on the whole study area using a kriging algorithm.

The heat flow data comes from the database maintained by the International Heat Flow Commission [13], a raster map of which is available in the IRENA global atlas [10]. Since heat flow measurements are affected by a bias towards very high fluxes [5], often localized in wells for geothermal energy exploitation, we pre-processed the data by removing the near surface effect using a combination of simple geostatistics and a wavelength based criteria: we calculated the median heat flow for each cell of a 20 by 20 km grid and then convolved the resulting array with a Gaussian kernel, sized for a 320 km-1 low pass cut off.

We calculated a global Bouguer field (now publicly available in [10]) from the go_cons_gcf_2_tim_r5 global gravity model solution derived from ESA's GOCE [4], using the GrafLab software [11]. The Bouguer anomaly was obtained as the difference between the gravity disturbance 8 km above the GRS80 ellipsoid and the topography effect, evaluated using the Earth2012 topography model [12], limited to N=280, coherently with the highest degree of the gravity model. We used a reduction density of 2670 kg m^{-3} for land topography and 1030 kg m^{-3} for oceans.
The obtained anomaly was projected and re-gridded on the same cell array of the smoothed surface heat flow. The 20 km cell size results in an oversampling of about 3.5 times the minimum resolved half wavelength of the global gravity model.

The gravity inversion was implemented with the routine available in the Lithoflex software [17] in a two-step, spectrally separated setup: firstly the undulation of the crust-mantle interface was inverted and low pass filtered, then the residual between the Bouguer anomaly and the field resulting from the inversion result was used as input for a second inversion pass. In this second step we set a shallower initial depth to invert the undulation of an upper-lower crust interface, assuming it as sharp density contrast of +200 kg/m^3.
This assumption, while unlikely to correspond to the actual crustal structure, provides a scaling parameter between the thickness of the less dense, felsic, more differentiated and radioactive shallow rocks and the less radioactive mafic rocks which make up the lower continental crust.

3. RESULTS AND DISCUSSION

3.1. Output of the synthetic sections

We selected three different sections and their associated outputs. In **Fig. 3** the effect of crustal thickness is shown: a negative correlation between gravity anomaly and surface heat flow, reflecting the increased heat production and mass deficit of a thickened crust. A 20 km change in the depth of the CMI results in a change of about 10 mW/m^2 in the flow. Compositional variations have an effect of smaller but comparable magnitude.
In **Fig.4** a variation in the LAB depth is added. On the section’s leftmost side a coupling between lithospheric and crustal thickness is shown, while the two are de-coupled on the right side. In the middle, a thinning condition where the crustal heat production is almost irrelevant compared with the large flow due to asthenosphere-to-surface conduction. The opposite situation is observed at the sides.

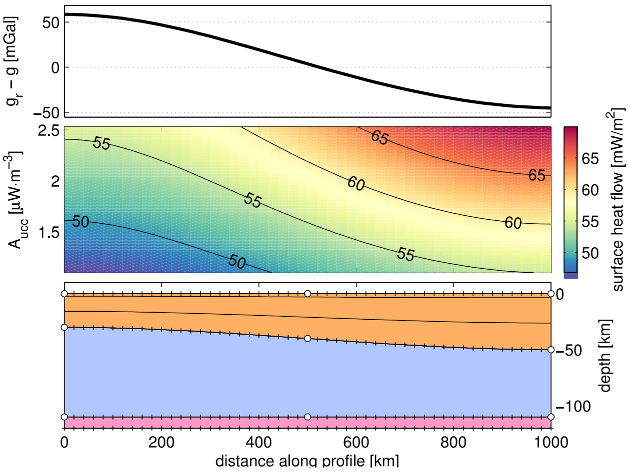

Figure 3. *Flat lithosphere, varying crustal thickness. Parameter under test: A_{ucc}, heat generation of the upper continental crust.*

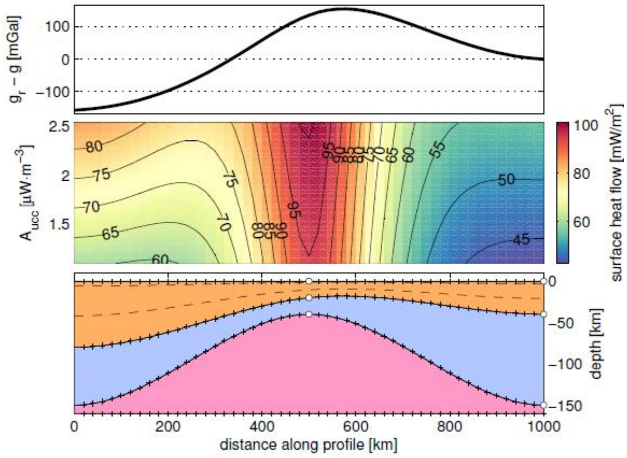

Figure 4. *Varying the LAB depth: coupled (**left**) and uncoupled (**right**) with the crustal thickness. Parameter under test: A_{ucc}, as in Fig. 3.*

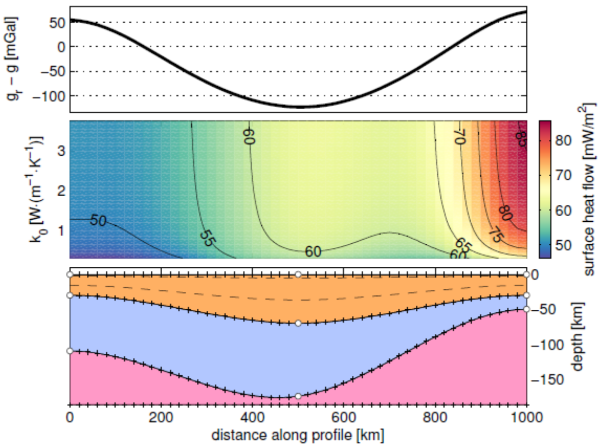

Figure 5. *Combined effect of lithospheric and crustal thickness. Parameter under test: k_0, thermal conductivity of the uppermost layer.*

Fig. 5 shows the combined effect of lithospheric and crustal thickness moving across two extreme situations with the same crustal thickness: a cold lithosphere (left) and a hot one (right), the latter an approximation of a syn-rifting condition. The large difference in magnitude between crustal and lithospheric signal is highlighted: we have chosen a contrast of only +50 kg/m^3 between sub-continental lithospheric mantle and the underlying asthenosphere, the former being the less dense. This can be a source of ambiguity, and calls for an integration with other data sources. The surface conductivity, an highly variable parameter, is hardly disrupting the pattern, having a significant effect only when the lithosphere is extremely thin. Anyway, it should be noted how cap rocks with low conductivity can hinder the reaching of equilibrium. The situation of basins, characterized by constant influx of cold sediments, has a similar effect. In those cases, the steady state approximation would surely be inadequate.

3.2. Testing on real data

The steps of the workflow outlined in section 2.2 are represented in **Fig. 6** and **Fig. 7**. The predicted Q_c is in strong accordance with the Bouguer anomaly, with its maximum flow values focused on the gravity minimums, as expected. The adopted period-based separation gives more weight in scaling the heat production to the anomalies with the higher frequency content, which we assumed are due to shallow sources (e.g. emplacement of granitic plutons, stacking of upper crust due to thrusts and décollements). The different sources of heat flow are evident by looking at the difference between Q_c and Q_0: the areas interested by extensional dynamics, chiefly the upper (southernmost) Rhine graben –which are linked to lithospheric thinning [14]– show little to no crustal heat production, while the total heat flow is particularly high, even when filtered for local spikes. At the same, the Molasse foredeep (lying North of the Alps) shows a combination of the two sources. The southern alpine sector exhibits a low heat flow, associated with reduced Q_m due to the thickened lithosphere, with local higher spots. The Bohemian massif (NE part of the map) is the most uniform, while it should be noted that local very high flow sample points where filtered out. These results show a satisfying coherency with the geological evidence. Still, care must be taken in regions where near-surface phenomena, that here we considered and filtered as strictly local, occur at a large scale. It is the case of the aforementioned Molasse foredeep, where widespread basement faulting and aquifers have a large part in the geothermal play [15]; and in the cold Po basin, where the fast sedimentation in the Plio-Quaternary causes a far-from-equilibrium thermal blanketing [16].

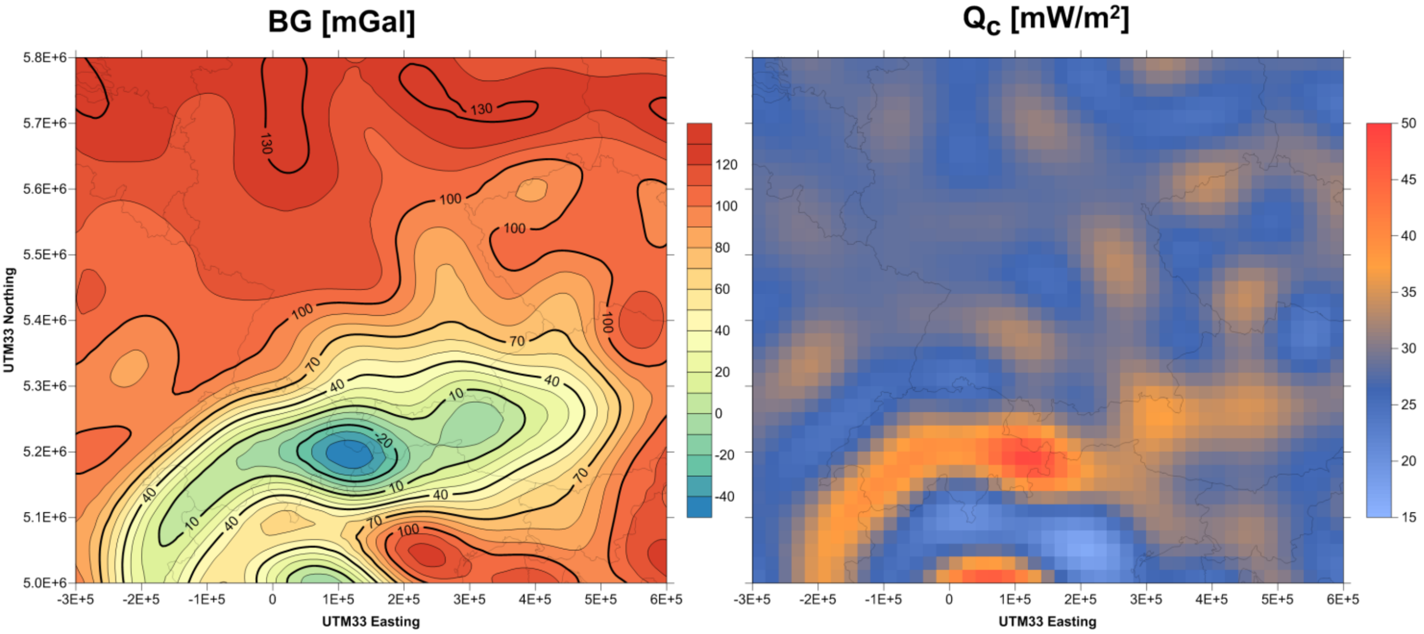

Figure 6. Left: *contoured Bouger anomaly (8 km above GRS80).* ***Right***: *crustal heat flow component, calculated from forward modeling of the gravity inversion results.*

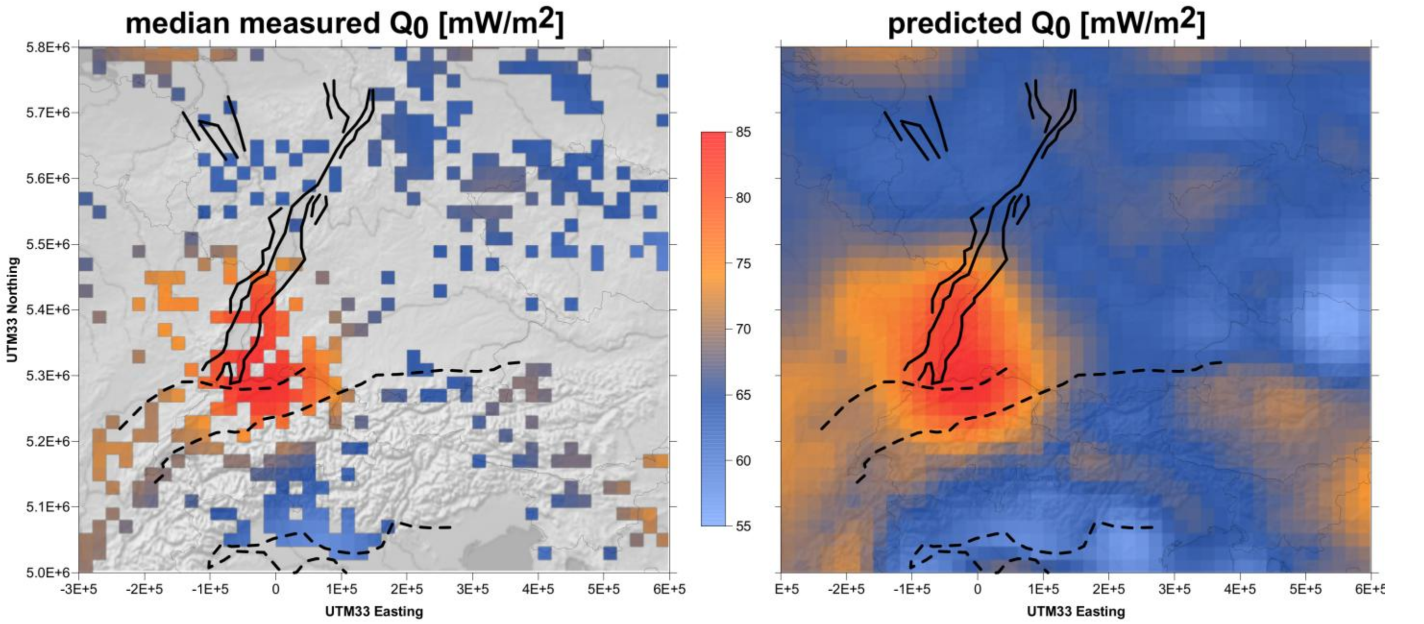

Figure 7. Left: *median measured surface heat flow from [13], on a 20x20 km grid, after filtering (as described in).* ***Right***: *heat flow data filled in the prediction method, using the gravity inversion as constraint for the crustal component of the heat flow. Hillshade: SRTM. Tectonic lineaments from [14] — normal faults, - - - thrusts.*

4. CONCLUSIONS

These results have shown how even a comparatively simple set of starting assumption can help in defining the non-trivial physical link between gravity field and surface heat flow.

All other parameters constant, the local gravity minimum associated with a crustal thickening exhibits increased heat flow, while the high flow associated with a thin thermal lithosphere can be still masked by the stronger crustal signal.

While these kind of observations hold for a constant composition, we note how different geodynamical settings result in different petrogenetical processes, so an integrated approach for parameter selection must be adopted for more precise, reliable predictions.

The method devised to test this model on real data provided a first, encouraging insight on the potential of adopting a geological constraint, derived from a global gravity model of adequate resolution, to fill the gaps between sparse heat flow measurements.

5. ACKNOWLEDGEMENTS

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