Integrating gravity and surface elevation with magnetic data: mapping the Curie temperature beneath the British Isles and surrounding areas

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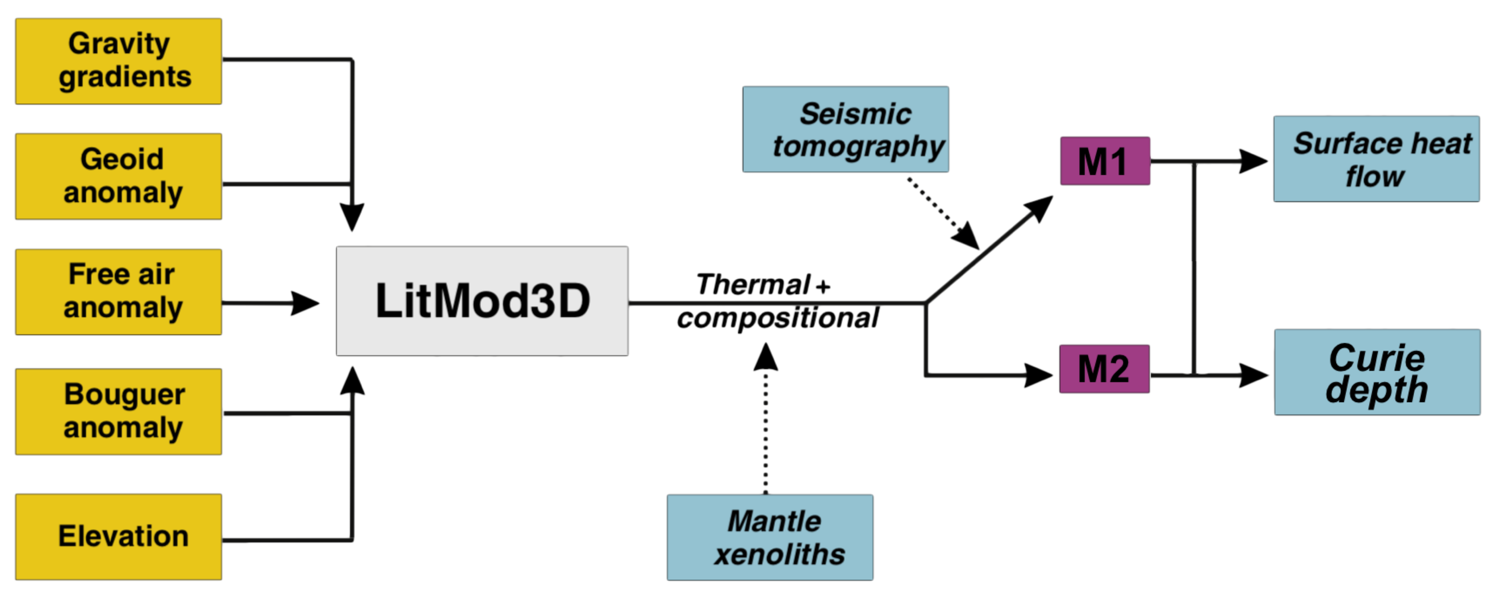
Abstract

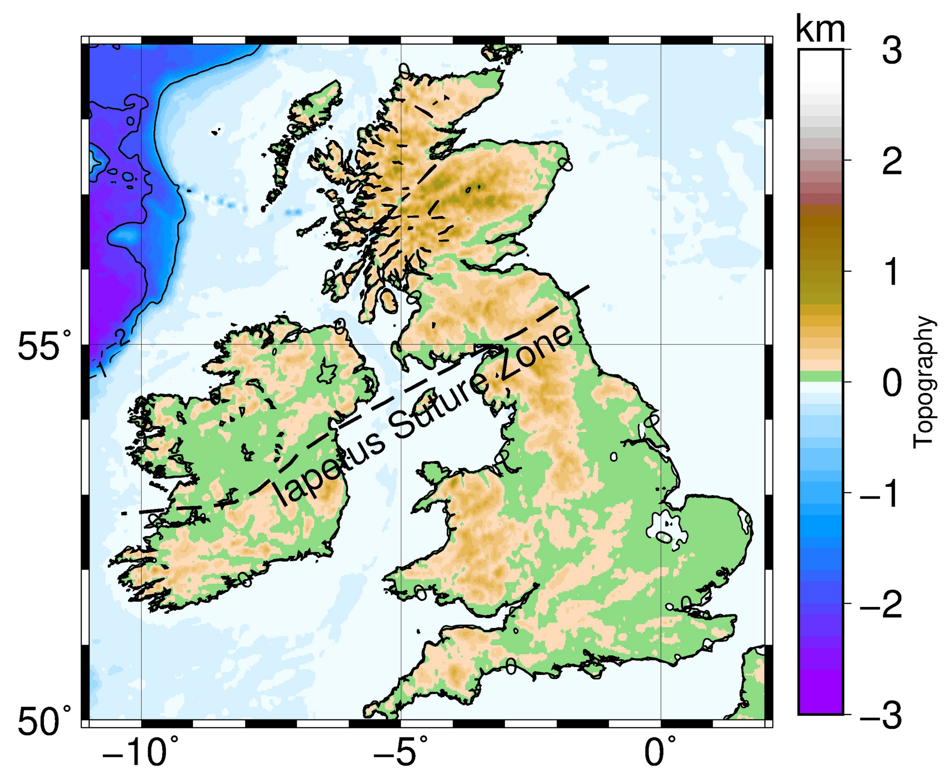
We study the lithospheric structure of the British Isles using a methodology that allows for forward modelling of the Curie temperature depth based on seismic, elevation and gravity observations within an integrated geophysical-petrological approach (LitMod3D). We compute 3D thermal models and self-consistently determine the density in the mantle based on temperature, pressure and bulk composition. Finally, we derive Curie temperature depth maps and forward calculate magnetic anomalies at the airborne level using a spherical magnetic modelling software (*magnetic tesseroids*) to estimate the geothermal magnetic signal. Our results show lateral lithospheric variations across the model domain, with Great Britain being characterized in general by thicker and colder lithosphere, especially in the south-east, and the thinnest and warmest lithosphere being located beneath west Scotland, Northern Ireland and in the north-west oceanic area. Our estimated Curie temperature depth map resembles the values obtained using other techniques (spectral method and surface heat flow inversion) in some areas, but discrepancies are notable in general. We determine that the effect of typical lateral temperature variations (i.e., Curie isotherm depth) accounts for 5-15%, on average, and up to 70% locally of the crustal magnetic signal at the airborne level (5 km altitude). Our lithospheric models are in general agreement with published tomography models as well as other geophysical studies.

Framework

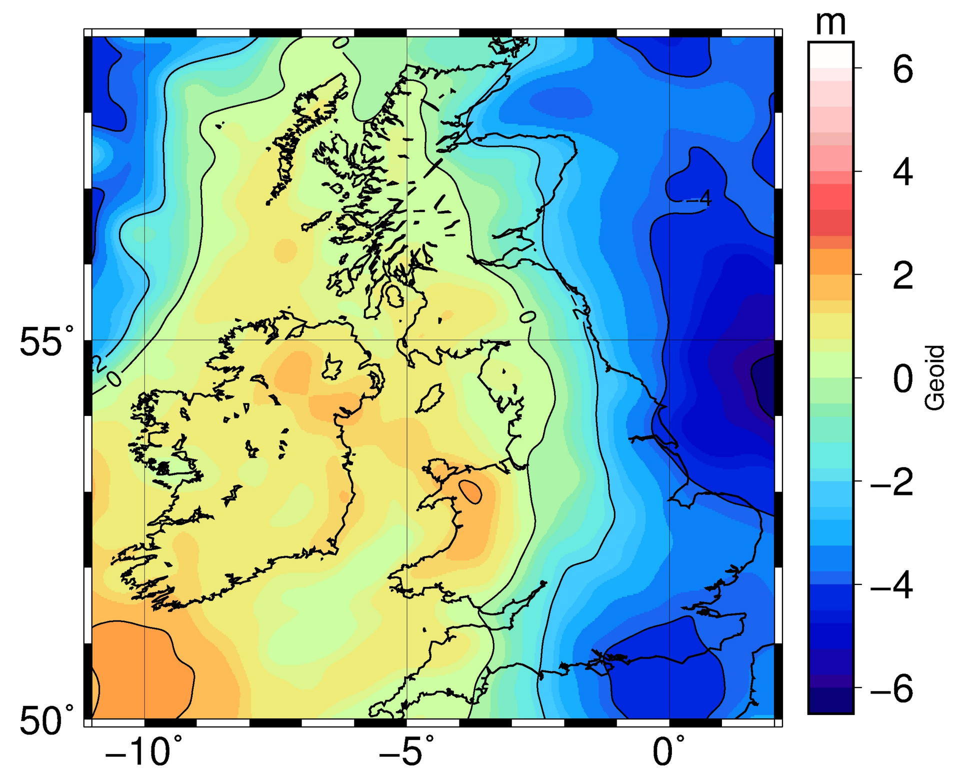


modified after *Fullea et al., 2014*

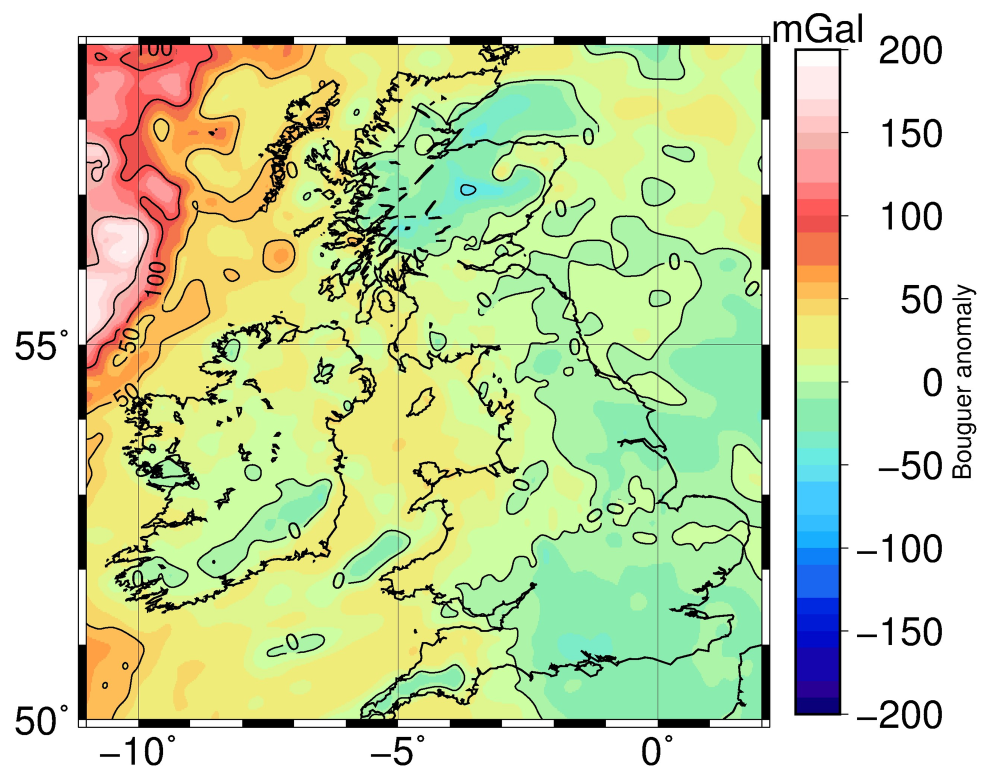
Geophysical observables



Elevation ETOPO 2v2 (National Geophysical Data Center, 2006)

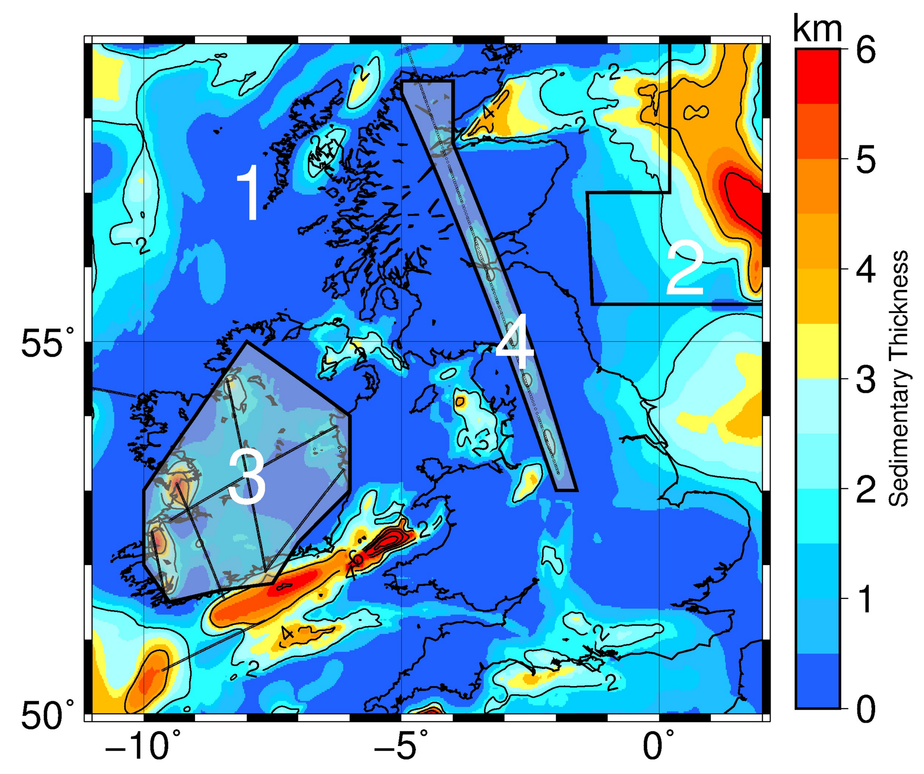


Geoid XGM2016
(*Pail et al. 2018*) Long wavelengths (>4000 km, degrees 2-9) are removed

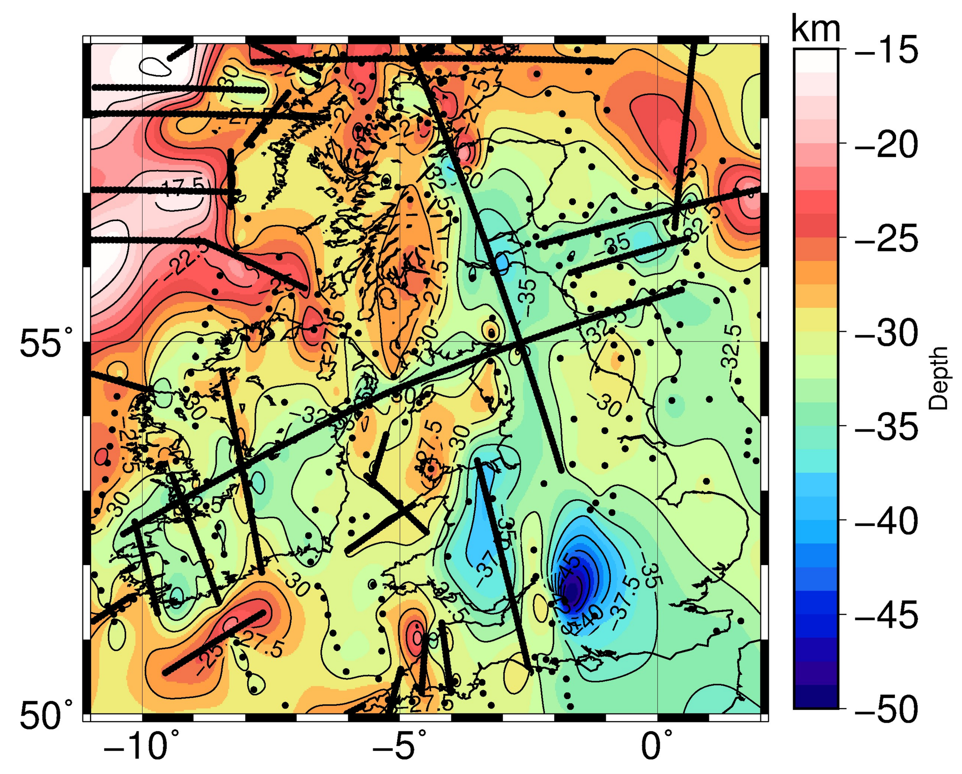


Bouguer anomaly map
Computed from XGM2016 corrected by FA2BOUG (*Fullea et al., 2008*) with added onshore data from Great Britain Land Gravity Survey and the Dublin Institute for Advanced Studies and the Geological Survey of Northern Ireland

Crustal model: seismic constraints



Combined model of sedimentary thickness
(1) *Oakey and Stark (1995)*
(2) *Whittaker et al. (2013)*
(3) *Landes et al. (2005)*
(4) *Barton (1992)*

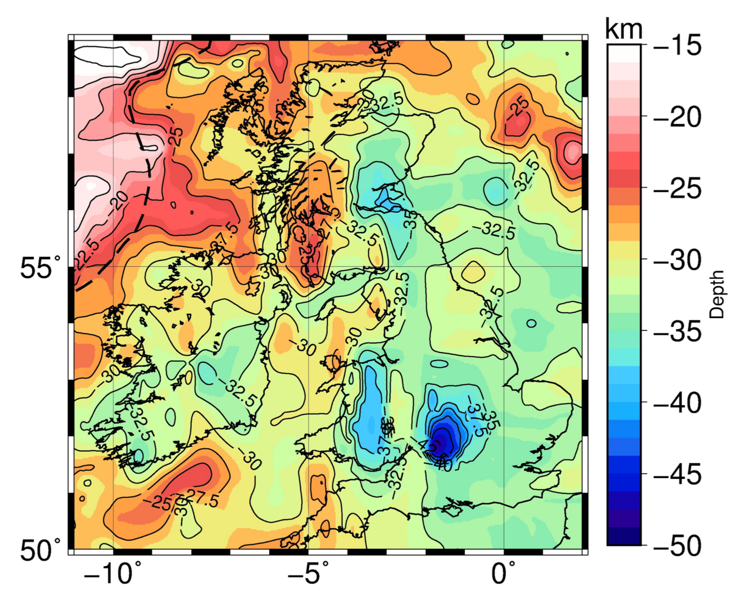


Moho model derived from reflection, wide angle refraction and broad band and short period receiver function seismic data
(*Kelly et al., 2007; Davis et al., 2012; Licciardi et al., 2014*)

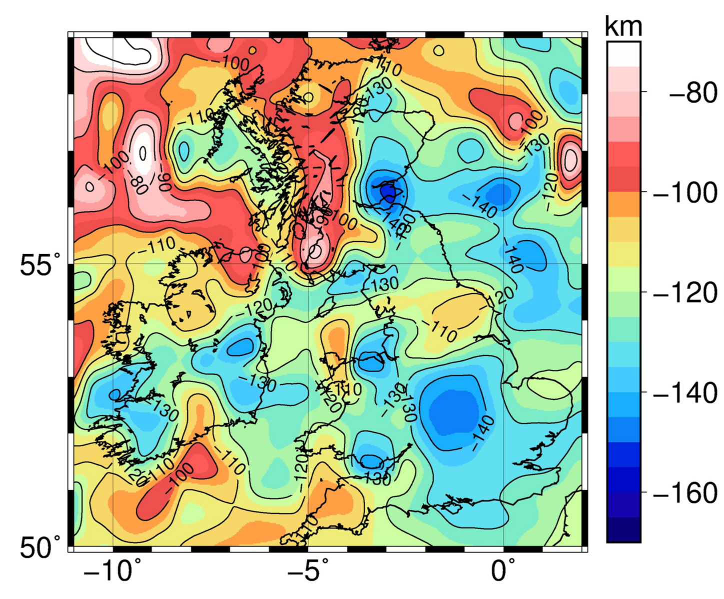
Type	Density [kg/m³]	Therm. Cond [W/m K]	Heat production rate [W/m³]
Model M1 based on seismic data			
Sediments	2650	2.5	$2 \cdot 10^{-6}$
Continental crust	2700 +10 per each km	2.5	$1 \cdot 10^{-6}$
Deep crust	3250	2.1	$0.1 \cdot 10^{-6}$
Oceanic crust	2850	2.1	$0.1 \cdot 10^{-6}$
Mantle	*	**	$0.1 \cdot 10^{-7}$
Model M2 based on gravity data			
Sediments	2650	2.5	$2 \cdot 10^{-6}$
Continental crust	2830	2.5	$1 \cdot 10^{-6}$
Oceanic crust	2920	2.1	$0.1 \cdot 10^{-6}$
Mantle	*	**	$0.1 \cdot 10^{-7}$

Lithospheric model

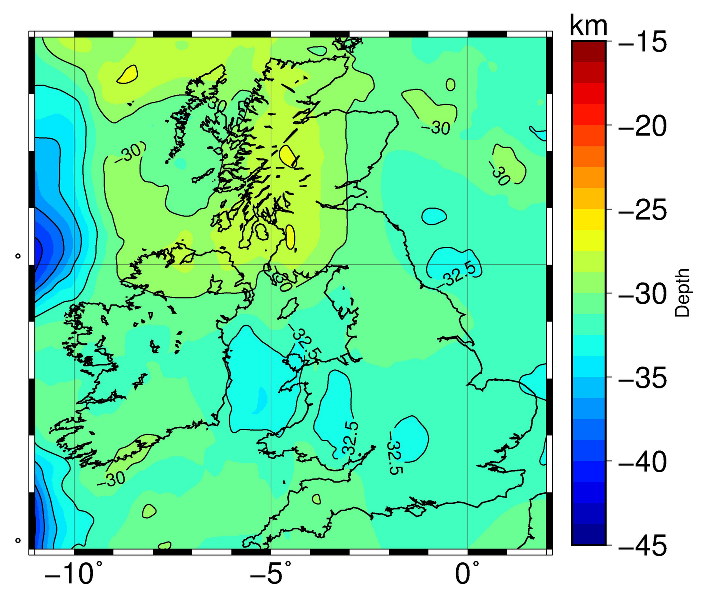
Model M1 with Moho based on seismic data



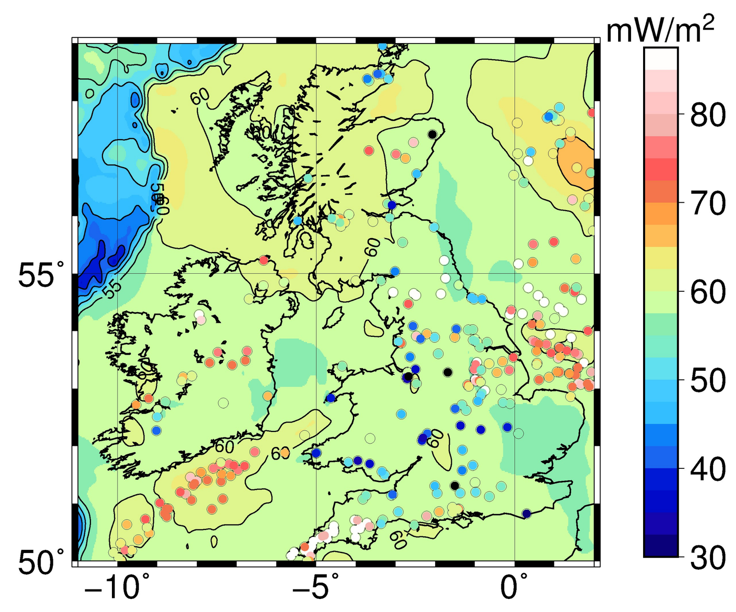
Model's Moho



Model's Lithosphere-asthenosphere boundary



Estimated Curie Depth

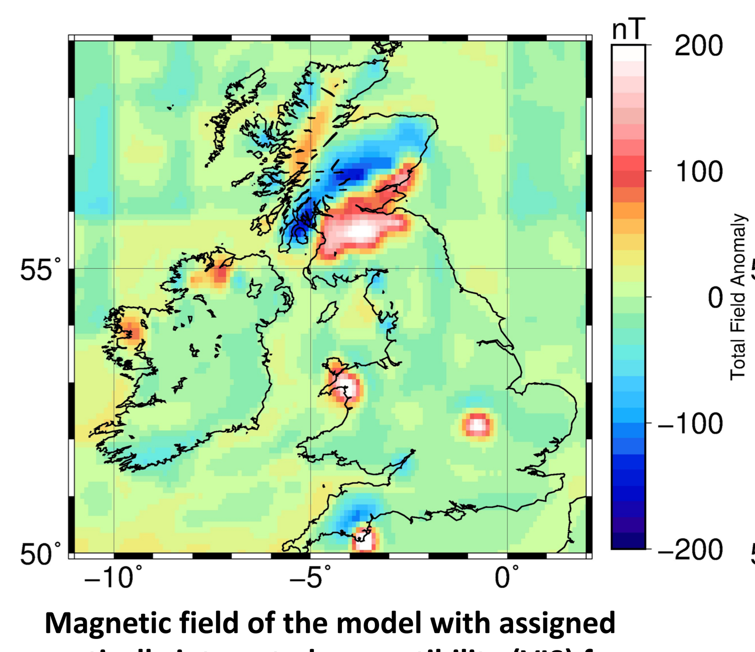


Estimated surface heat flow. Dots indicate heat flow measurements from the global database

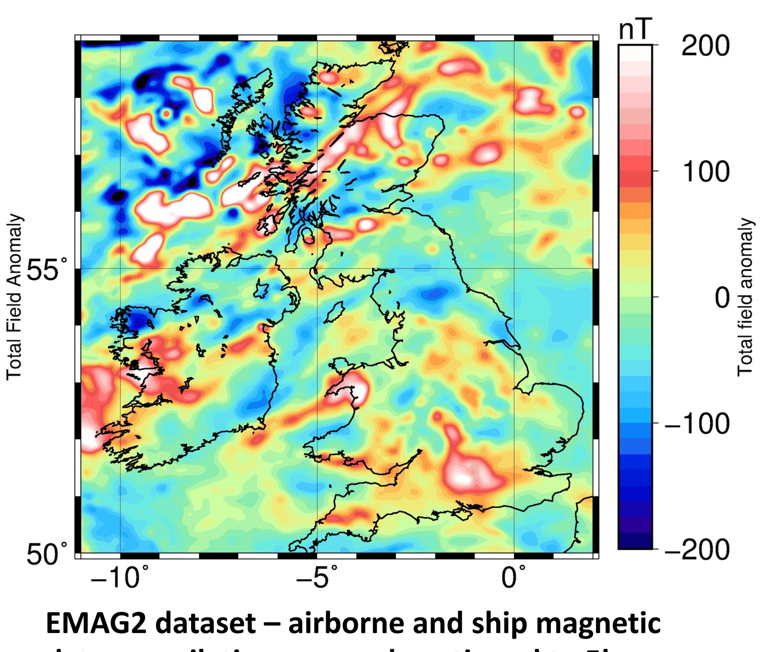
The lithosphere changes considerably across our modeling domain. There is a clear boundary roughly N-S trending dividing, to the west, an area of normal Phanerozoic crust and lithosphere (in Ireland, Wales, and NW Scotland) and, to the East, S-E Scotland and England where the lithosphere and crust are comparatively thicker (>100 and 30 km, respectively). The thickest crust and lithosphere in the model are located in S-E Great Britain and in the N-E margin of England (>35 and 120 km, respectively). In contrast, the thinnest lithosphere is located beneath western Scotland, Northern Ireland, southern Irish margin and in the N-W oceanic domain.

The predicted Curie temperature depth is shallower than the Moho in some areas, especially onshore. In these locations, the lowermost part of the crust (i.e., hotter than Curie temperature) is not contributing to the crustal magnetic field. Conversely, our predicted Curie isotherm is within the uppermost mantle in some areas (e.g., N-W marine domain). In the later case we take the seismic/petrological Moho as the effective lower magnetic boundary. The rationale for this is that the signal produced by possible sources in the upper mantle is rather weak when compared to crustal sources considering susceptibility values similar to those experimentally derived by *Ferré et al. (2013)* for mantle rocks (*Baykiev et al., 2018*).

Magnetic modelling

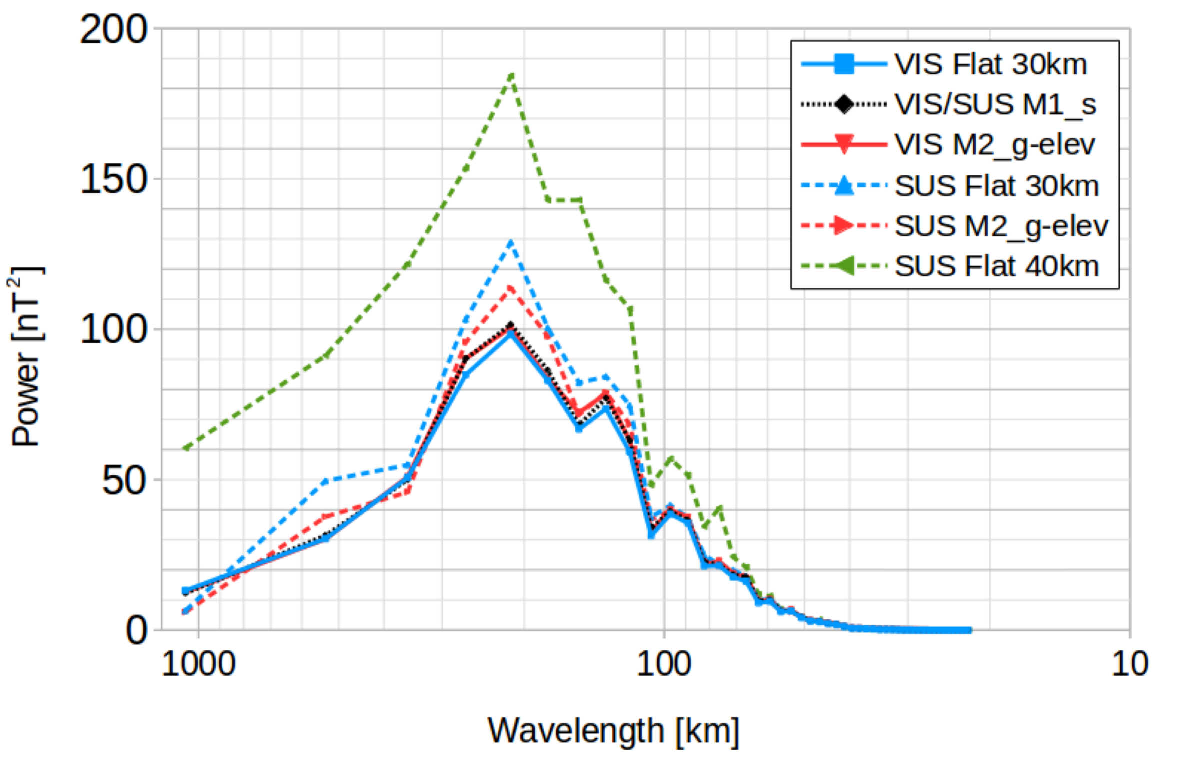


Magnetic field of the model with assigned vertically integrated susceptibility (VIS) from *Hemant et al. (2003)*



EMAG2 dataset – airborne and ship magnetic data compilation, upward continued to 5km altitude

The main goal of our magnetic modeling exercise is to quantify the effect of the lithospheric structure (thermal field) in the synthetic crustal magnetic field. The **V**ertically **I**ntegrated **S**usceptibility model of *Hemant (2003)* is susceptibility multiplied by thickness. VIS model is based on data at satellite altitude where the signal caused by variations in magnetic thickness are negligible *in our study region*. However, at the airborne altitude, magnetic thickness has a non-negligible signal. We calculate the the magnetic field of M1 model (with lateral Curie depth variations), M2 gravity based model and a flat models (30 km deep constant magnetic boundary) for the same VIS model and the same top magnetic boundary (i.e., basement geometry). Note that susceptibilities in these models are not identical, only VIS. We also calculate the field of models with the same susceptibility (SUS) taken from M1 VIS-based model.
Most of the synthetic magnetic signal based in our lithospheric models is not matching the observed anomalies (EMAG2). This misfit along with the fact that some of the short wavelength features inferred in magnetically derived thermal models seem to be artifacts related to remanence or lateral variations in susceptibility points us to our next step: forward model and inversion of airborne and satellite magnetic anomalies for lateral susceptibility (and possibly remanence) variations in the crust using as background an improved thermal model based on gravity, elevation, and seismic data as discussed here.



Power spectrum of models different magnetic boundary (from models and completely flat) and same VIS or same susceptibility (SUS)
The radial power spectrum of the magnetic models computed for a constant VIS is very similar whereas the models computed using a fixed susceptibility are considerably different. Relative weight of typical lateral variations in the Curie isotherm depth in observed crustal magnetic anomalies: 5–15 % with localized areas of > 70%. Therefore, typical variations in the assumed Curie temperature depth in our study region have a considerable effect on the magnetic signal although that is not clearly visible in their power spectra.