COMPOSITIONAL AND THERMAL STRUCTURE OF THE CRUST FROM GEOPHYSICAL AND PETROPHYSICAL DATA

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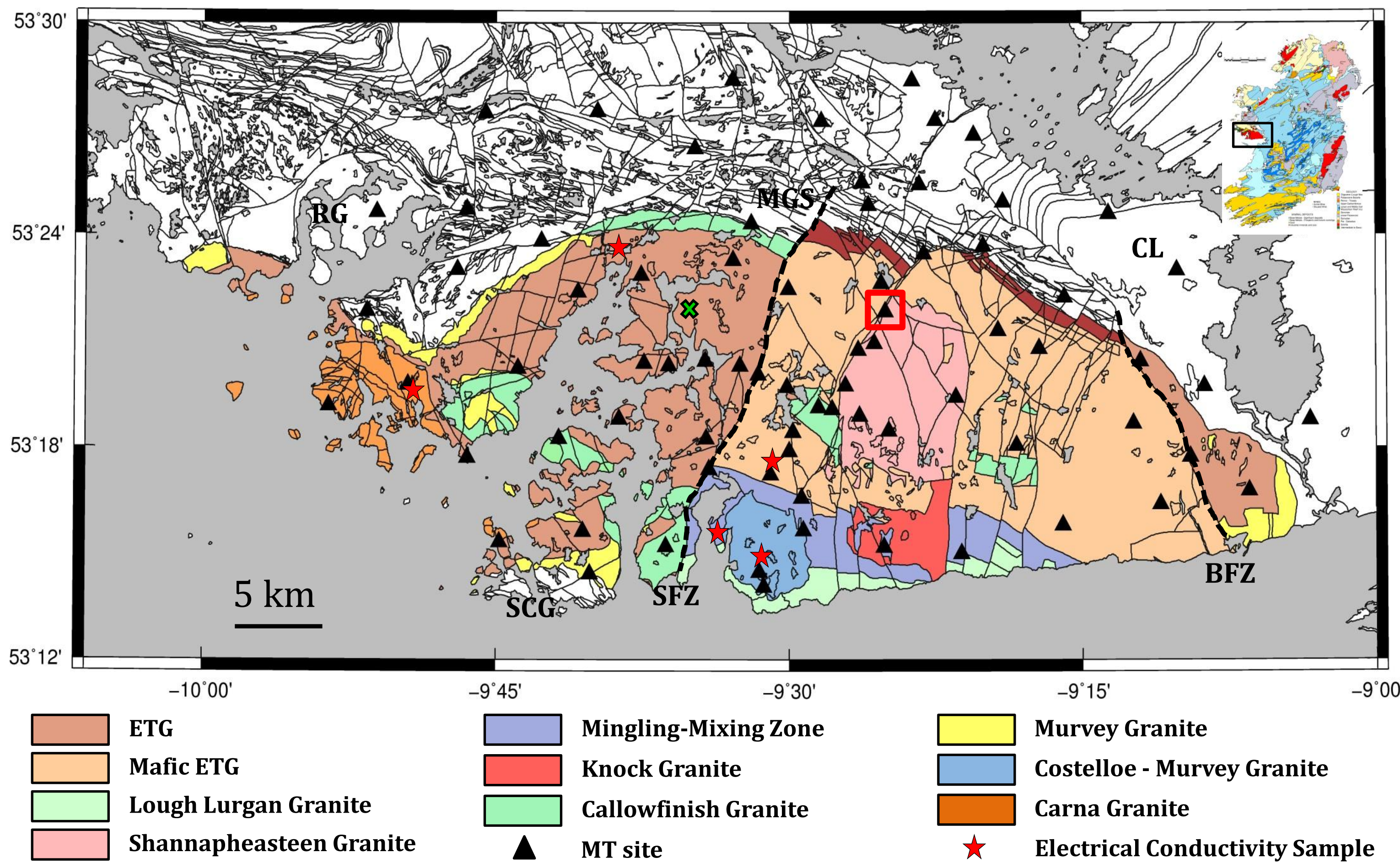
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Abstract

We present an update from ongoing development of methods to constrain the compositional and thermal structure of continental crust in western Ireland. This work focuses on the Galway granite on the west coast of Ireland, which has been the subject of a geothermal investigation as part of the IRETHERM project.

Using the LitMod modelling approach (Afonso et al., 2008, Fullea et al., 2011), magnetotelluric (MT) data are integrated with electrical conductivity, density, heat production, thermal conductivity, and geothermal heat flow density data to examine in 1D the thermal and compositional structure of the crust and lithosphere, in which the Galway granite batholith resides. On a shallower scale, geotherms and temperatures are separately calculated to depths of 8 km within the Galway granite.

The results show that the temperatures within the Galway granite have previously been underestimated. This underestimation is primarily due to two reasons. Firstly, the effect of increasing temperature with depth on thermal conductivity was not considered in previous calculations. Secondly, the effects of palaeoclimate conditions on present-day heat-flow and geothermal gradient have been underestimated in the past. The calculated constraints on temperature at depth within the Galway granite batholith are key to assessing geothermal energy prospectivity.

Figure 1 (right): *Geological map of the Galway granite. Black triangles indicate positions of magnetotelluric (MT) data acquisition sites, red stars indicate locations at which granite was sampled for laboratory electrical conductivity measurements, green X indicates the location of the Camus borehole, data in Figure 3 from MT site in red box. RG – Roundstone Granite, MGS – Metagabbro/Gneiss Suite, SCG – South Connemara Group, CL – Carboniferous Limestone, SFZ – Shannawona Fault Zone, BFZ - Bearna Fault Zone.*

Legend: ETG | Mafic ETG | Lough Lurgan Granite | Shannapheasteen Granite | Mingling-Mixing Zone | Knock Granite | Callowfinish Granite | ▲ MT site | Murvey Granite | Costelloe - Murvey Granite | Carna Granite | ★ Electrical Conductivity Sample

Methodology

Temperature in the crust is calculated in two ways.

1. LitMod1D

LitMod is a geophysical-petrological modelling tool that combines a variety of data (namely elevation, surface heat-flow, potential fields, xenolith composition and seismic tomography models) to model the thermal and compositional structure of the lithosphere. A 1D layered model of the lithosphere is built (details in Table 1) from which LitMod computes the geotherm, as well as the surface heat-flow, topography, electrical resistivity, and magnetotelluric response, each of which has some temperature dependence. Boundary conditions are 10°C at the surface and 1315°C at the lithosphere-asthenosphere boundary (LAB).

2. Top-Down Temperature Calculation

Temperature at depth, T_z, may be calculated from surface thermo-petrophysical data using the equation (Wheildon & Rollin, 1986):

$$T_z = a'e^{\left(\frac{q_0 - f(z)}{a'k_0}\right)} - b'$$

q_0 is surface heat-flow, $f(z)$ represents the vertical distribution of heat-production from a surface value A_0, k_0 is surface thermal conductivity, $b' = 823.33°C$ and $a' = b' + T_0$ (T_0 is the surface temperature, 10°C).

There are several differences between the two approaches. The LitMod 1D approach applies an independently observed bottom-side temperature boundary condition at the LAB and tests the computed geotherm against temperature-dependent geophysical data. The top-down method imposes no bottom-side temperature boundary condition, with the approach assuming that the geological structure is known to the depth of interest and providing no test that this is the case.

1D Model Input Parameters

	Layer	Density (kg m^{-3})	Thermal Conductivity (W m^{-1} K^{-1})	Heat Production (W m^{-3})	Resistivity (Ω.m)	D_B (km)
1	Weathered granite	2640	3.50	3.5 x 10^{-6}	2.9 x 10^3	0.2
2	Shallow granite	2640	3.41	3.5 x 10^{-6}	4.7 x 10^4	1.5
3	Shallow granite	2650	3.12	2.7 x 10^{-6}	4.7 x 10^4	7.5
4	Deep granite	2680	2.77	2.0 x 10^{-6}	Arrhenius_1	13.0
5	Diorite	2790	2.89	1.2 x 10^{-6}	Arrhenius_2	15.5
6	Lower crust	2930	2.48	1.0 x 10^{-6}	8 x 10^3	28.0
7	Lithospheric mantle	3360	5.30	0.4 x 10^{-7}	calculated	100.0

Table 1 (above): *Input parameters for the LitMod layered model. D_B = depth to the base of each layer. Depths and composition of layers are derived from geological maps and from inversion and forward modelling of MT and Bouguer anomaly data (Farrell et al., 2016a). Thermal conductivity of layers 1 to 5 are consistent with laboratory measurements (Barton et al., 1989). Resistivities of layers 1, 2, 3 and 6 are derived from 1D modelling of invariant from MT sites in the centre of the granite. Arrhenius_1 and Arrhenius_2 refer to laboratory measured relationship between electrical conductivity and temperature, for samples from the ETG and a diorite enclave of the Mingling-Mixing Zone respectively. These data allow LitMod to calculate the temperature-dependent electrical resistivity of layers 4 & 5. This relationship is not applied at depths less than 7.5 km. The resistivity of the lithospheric mantle is calculated from the constituent mantle minerals, constrained by xenolith samples (Fullea et al. 2011). Moho depth of 28 km from Licciardi et al. (2014). LAB depth from Fullea et al. (2014). Heat-production, Feely and Madden (1989).*
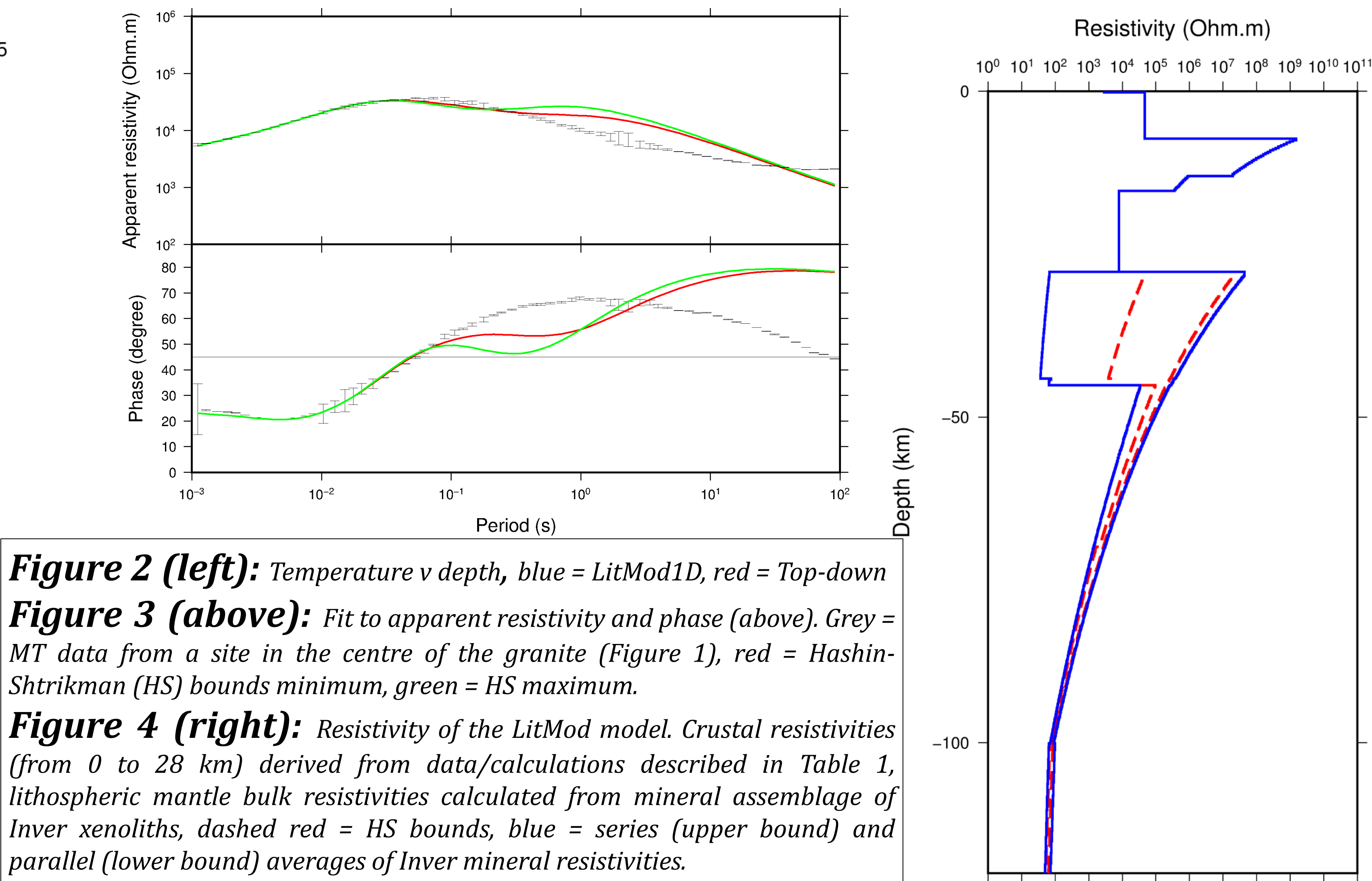
Results

Temperature: Figure 2 shows that the independent temperature calculations of the LitMod1D and top-down methods are in good agreement in the top 7 km. The variation in curvature of the geotherms is due to the differing approaches to accommodation of thermal conductivity.

Electrical Resistivity and MT response: At crustal depths, (periods < 0.1 s) the LitMod model fits the MT data well (Figure 3). At periods above ~0.1 s, the model does not fit the MT data (Figure 3).

Surface Heat-Flow (SHF): and Topography: LitMod1D calcluated a SHF of 81.1 mW m^{-2}, which is approximate to the palaeoclimate corrected SHF for the Camus borehole (84 mW m^{-2} (Farrell et al., 2016a)). 81.1 mW m^{-2} was used as an input for the top-down temperature calculation.

Litmod1D topography is calculated to be 181 m. Topography at the location of the MT data site is 180 m.

Figure 2 (left): *Temperature v depth, blue = LitMod1D, red = Top-down*

Figure 3 (above): *Fit to apparent resistivity and phase (above). Grey = MT data from a site in the centre of the granite (Figure 1), red = Hashin-Shtrikman (HS) bounds minimum, green = HS maximum.*

Figure 4 (right): *Resistivity of the LitMod model. Crustal resistivities (from 0 to 28 km) derived from data/calculations described in Table 1, lithospheric mantle bulk resistivities calculated from mineral assemblage of Inver xenoliths, dashed red = HS bounds, blue = series (upper bound) and parallel (lower bound) averages of Inver mineral resistivities.*

Discussion

Figure 2 shows that the temperature calculations of both LitMod and the top-down approach are in good agreement in the top 7 km of the crust. The slight variation in curvature of the geotherms is due to the differing approaches to the accommodation of thermal conductivity. Our preliminary and conservative geotherms show higher temperatures at depth than those previously calculated by Madden (1989), e.g. 125°C at 5 km, up from 100 – 110°C.

Figure 3 shows that the MT data fits the 1D model at periods below 0.1s. Farrell et al. (2016b) show that periods above 0.1s are sensitive to both the mantle and to the electrically conductive sea. Farrell et al. (2016b) showed that imposing a lithospheric mantle with uniform resistivity of 1,700 Ω.m fits the data. While this is thermodynamically unreasonable, it demonstrates that the upper part of the lithospheric mantle is less electrically resistive than its calculated dry bulk resistivity and must include a conducting phase. This might be explained by the presence of water in the upper part of the lithospheric mantle. Work is ongoing to test this possibility. Work is also ongoing to remove the sea-effect from the MT data to obtain a more representative 1D MT response to be modelled by LitMod1D.

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